VODOHOSPODÁŘSKÉ TECHNICKO-EKONOMICKÉ INFORMACE

(WATER MANAGEMENT TECHNICAL AND ECONOMIC INFORMATION)

# VTEI / 2025 / 4

# 60 years ago in VTEI

The text is selected with regard to some of the topics covered by the expert articles published in the respective VTEI issue. In this case, it relates to the article "Water quality and transport of pollutants in downstream part of the Czech Elbe" by Josef K. Fuksa. We therefore present to you the article "Water quality in streams in 1959", published in the third issue of our Journal in 1960.

## The catchment of the Czechoslovak Elbe, Lusatian Neisse, and Stěnava rivers.

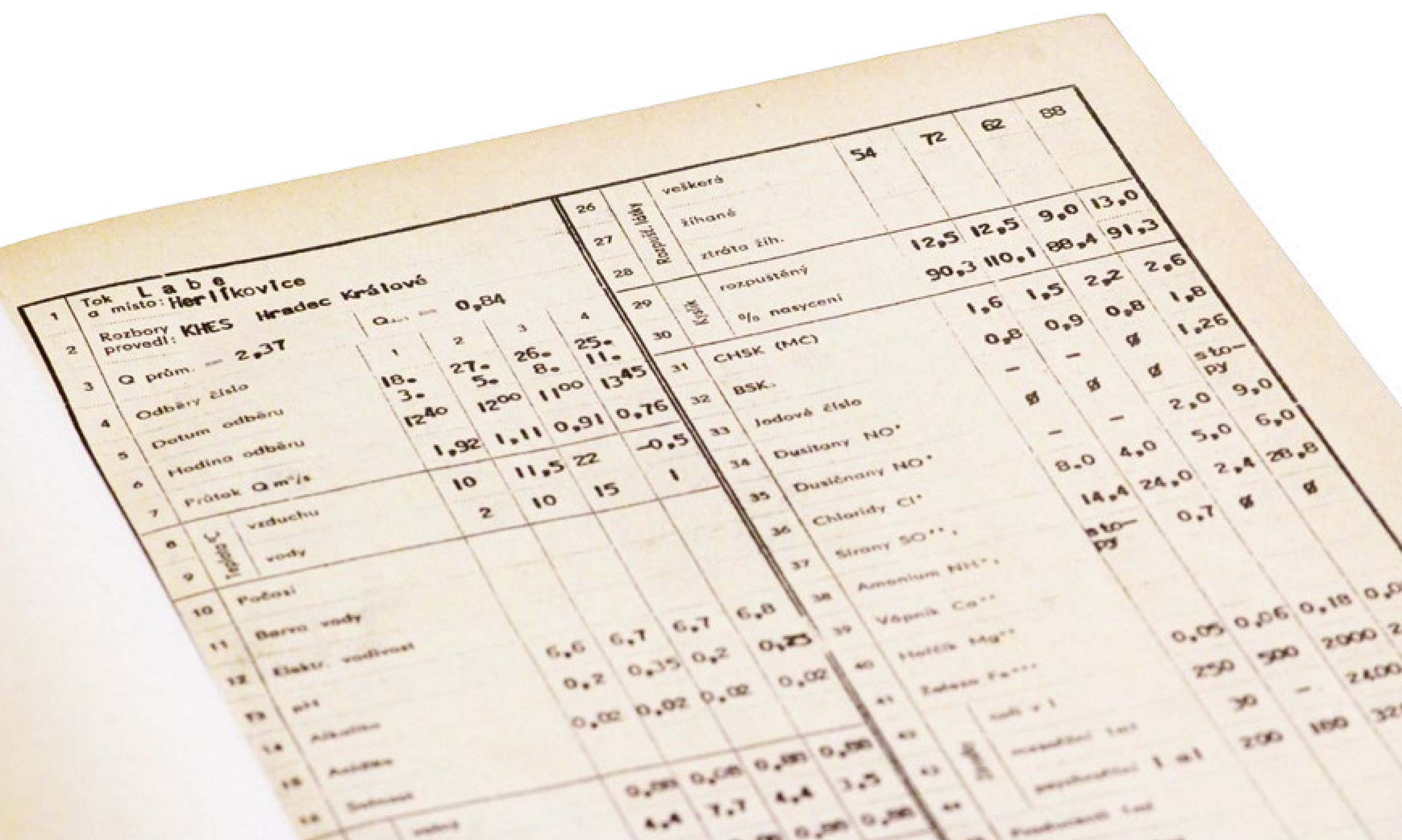
*For technical reasons, the yearbook currently contains only a limited selection from the entire collected material. Initially, 135 sampling sites were selected from 43 watercourses in the catchments of the Czechoslovak Elbe, Lusatian Neisse, and Stěnava. The selection was made to ensure that, even with this limited number of profiles, the overall condition of the monitored river network is represented as accurately as possible. The analyses are compiled into uniformly formatted tables, each containing results from four water samples taken at the same sampling site. Additionally, for each profile, the average annual flow and the 355-day low flow for the period 1931–1940 are provided, allowing an assessment of water volume at the time of sampling.*

*This publication is the first edition of an overview of the quality and cleanliness of watercourses across a large territorial unit. Therefore, significant changes can be expected in future editions. It is possible to expand both the publication itself and its underlying material – that is, the number of profiles, sampling frequency, and selection of conducted analyses. It is also possible to consider including results from other catchments within our country. However, we believe that the most important requirement for publications of this kind is not so much their scope, but rather their truly consistent and uninterrupted continuation. The primary aim of the editorial team of the Water Research Institute – and, we hope, of all external collaborators who have contributed to this book – will therefore be to ensure the conditions necessary for this first attempt to become the opening entry in a continuous series of ever-improving future editions. Those interested can order the yearbook from the Water Research Institute in Prague – Podbaba.*

(Editor's note – the yearbook mentioned in this 1960 period article can be found in the library collection of T. G. Masaryk Water Research Institute.)

From TGM WRI archives

VTEI Editorial Office



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5 Datum odběru 18. 3. | 27. 5. | 26. 8. | 25. 11.
6 Hodina odběru 12⁴⁰ | 12⁰⁰ | 11⁰⁰ | 13⁴⁵
7 Průtok Q m³/s 1,92 | 1,11 | 0,91 | 0,76
8 Teplota °C vzduchu 10 | 11,5 | 22 | –0,5
9 vody 2 | 10 | 15 | 1
10 Počasí
11 Barva vody
12 Elektr. vodivost
13 pH 6,6 | 6,7 | 6,7 | 6,8
26 Rozpušť. látky veškerá 54 | 72 | 62 | 88
27 žíhané
28 ztráta žíh.
29 Kyslík rozpuštěný 12,5 | 12,5 | 9,0 | 13,0
30 % nasycení 90,3 | 110,1 | 88,4 | 91,3
31 CHSK (MC) 1,6 | 1,5 | 2,2 | 2,6
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33 Jodové číslo
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35 Dusičnany NO3'
36 Chloridy Cl'
37 Sírany SO4''
38 Amonium NH4'
39 Vápník Ca''
40 Hořčík Mg''
41 Železo Fe'''

# Content







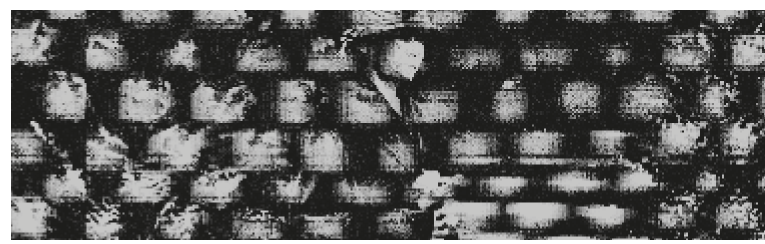



Foto: J. Unucka

# Dear readers,

with the arrival of August, we once again open the pages of our professional journal VTEI to bring you new insights from the world of water management.

When reflecting on the importance of water and its effective management, one cannot overlook the anniversary of one of the most significant events in the history of Czech water management: the catastrophic floods of August 2002. These floods, which affected a large part of the Czech Republic 23 years ago and caused enormous damage, still serve as a reminder of the vital need for ongoing attention to flood protection, integrated river basin management, and adaptation to climate change. They are proof that investment in water management infrastructure and research is not a luxury but a vital necessity. At the same time, the floods sparked a tremendous wave of solidarity and determination, demonstrating our society's ability to confront such challenges.

For the August issue, we have prepared a rich array of articles for you. The first scientific article, "Caffeine and urea as indicators of anthropogenic load on bathing ponds" by Dana Baudišová and her colleagues, presents natural bathing ponds as a specific type of ecosystem in which living organisms play a key role in maintaining water quality. At the same time, these ponds are heavily frequented, making bathers the main source of pollution. The focus of this scientific paper is the presentation and evaluation of potential chemical indicators of anthropogenic pressure – caffeine and urea – at four sites in the Czech Republic during the summer of 2023.

With ongoing climate change, longer periods of higher water temperatures and low flows can be expected, along with changes in precipitation patterns leading to more frequent sewer system overflows. This will significantly increase impacts on river ecosystems while simultaneously reducing the effectiveness of current monitoring systems. The article "Water quality and transport of pollutants in downstream part of the Czech Elbe" by Josef K. Fuksa presents data on water quality in the Czech lower Elbe and Vltava rivers for the period 1961–2020, compared with archival data from the reference period 1880–1913.

The third scientific article, "Hydrotechnical research of flap gates" by Martin Králík and Ondřej Němčanský, deals with the hydraulic analysis of flap gates in Doksany and Strakonice based on the evaluation of experimental measurements carried out on physical and mathematical models at the Water Management Experimental Centre of the Faculty of Civil Engineering at CTU in Prague.

One of the classic yet still relevant tasks of applied hydrology is the analysis of surface runoff paths and accumulation points, aiming to predict and prevent the impacts of pluvial floods on villages and infrastructure. The expert article by Luděk Stouhal and Petr Kavka, "Where does the village end? Delineation of urbanized areas not only for runoff analysis," presents a methodology for spatial delineation of the boundaries of significant urbanized areas in the Czech Republic, primarily for hydrological analyses and flash flood risk assessment.

Following the expert articles in VTEI, there is our regular interview – this time with the recently appointed General Director of the Povodí Odry, state enterprise, Mr. Petr Birklen. It covers not only his professional life, which is connected, among other things, with sustainable land use and urban adaptation to climate change but also plans for flood protection measures in northern Moravia.

The informative section of the journal will once again take us to Jáchymov. This time, colleague Zuzana Řehořová places greater emphasis on balneology and the uniquely specific treatment there using radon baths. Can radon, often called the "silent killer," heal us and relieve chronic pain? And how is Marie Curie-Skłodowska connected to Jáchymov, whose visit to the spa marked exactly 100 years ago this June? We will learn more about the spa's history and treatments in the article "Jáchymov II: at the right time in the right place."

We hope the August issue of VTEI will engage you and provide valuable information for your work and further development. We wish you enjoyable reading and a pleasant remainder of the summer.

VTEI Editorial Office

# Caffeine and urea as indicators of anthropogenic load on bathing ponds

**DANA BAUDIŠOVÁ, LENKA MAYEROVÁ, PETR PUMANN, HANA KUJALOVÁ, MARTIN FERENČÍK**

**Keywords:** bathing ponds — anthropogenic pollution — urea — caffeine — ATP


## ABSTRACT

Bathing ponds represent a specific ecosystem where living organisms play a dominant role in maintaining the quality of water in the water body. At the same time, they are very frequently visited, so the biggest source of pollution is from bathers. The aim of this publication is to present and evaluate possible chemical indicators of anthropogenic load – caffeine and urea at four sites (two of which during the entire bathing season) in the summer of 2023. Furthermore, the results of basic chemical and microbiological indicator detection are presented, including adenosine triphosphate (ATP), which represents a total microbial recovery. The indicators of anthropogenic load (caffeine and urea) show values of up to > 500 ng or µg/l in the peak summer season. The indicators prescribed by current legislation (indicators of faecal pollution *E. coli* and intestinal enterococci) did not capture this increased anthropogenic load. The determination of ATP has shown promise, but further research will be needed, especially in purifying, i.e. very microbially active zones. Total nitrogen could be a suitable indicator of the gradual increase in anthropogenic load during the bathing season.


## INTRODUCTION

Bathing ponds, natural swimming pools, biologically filtered swimming pools, living pools, eco-pools – these are terms used for public or private swimming facilities where the primary role in maintaining water quality is played by living organisms. In the Czech Republic, the first public bathing pond was opened in 2007 in Kovalovice [1], and by 2024, there were already 40 in operation (IS PiVo, 2025). Bathing ponds were incorporated into national legislation in 2011, along with the definition of requirements for parameters, their monitoring, and evaluation. At that time, experience with bathing ponds in the country was still limited, so the requirements were inspired by German and Austrian regulations [1].

At present, the Public Health Protection Act [2] defines a bathing pond as "a facility approved for the purpose of bathing, equipped with a natural water purification system for bathing purposes." Decree No. 238/2011 Coll. of the Ministry of Health [3] requires the monitoring of indicators of faecal contamination, specifically *Escherichia coli* and intestinal enterococci, as well as water transparency. The requirement to monitor *Pseudomonas aeruginosa* was removed in 2014 due to unresolved methodological reasons. The current legislation relating to bathing ponds is certainly not perfect, and it would be appropriate to improve or update the definitions and requirements during the next revision of Czech legislation.

According to data from the IS PiVo system, the numbers of *E. coli* and intestinal enterococci are generally well below the limit values (i.e. below 100 and 50 CFU/100 ml, respectively); however, occasional exceedances occur at most sites. At least once per season between 2018 and 2023, *E. coli* limits were exceeded at 20–30 % of bathing ponds, and the limit for intestinal enterococci at approximately 40 % [1]. In 2023 and 2024, the figures were lower: *E. coli* exceedances occurred at 11 % and 8 % of sites, and intestinal enterococci at 26 % and 28 %, respectively. Unlike natural bathing sites, the dominant source of contamination is bathers themselves.

Given the predominantly anthropogenic nature of this type of pollution, the use of additional indicators could be considered to help identify it, or to distinguish it from more "natural" forms of contamination. Other potential sources include pollution introduced by birds (primarily mallards, which visit bathing ponds) and, occasionally, seepage into the water body during periods of elevated groundwater levels following heavy rainfall.

The article deals with the assessment of additional possible chemical indicators of anthropogenic pollution (namely caffeine and urea) as well as the results of total adenosine triphosphate (ATP) analysis, which reflects overall microbial activity.

## BACKGROUND TO THE ISSUE

Urea $CO(NH_2)_2$ is found in the urine of mammals, amphibians, and some fish. It is synthesised in the liver through the urea cycle. In the body, urea serves as a waste product through which excess nitrogen is excreted in urine, and to a lesser extent also through the skin during sweating. During the urea cycle, the amino acid arginine is broken down into urea and ornithine. Urea is excreted from the body in urine, while ornithine is reused as a precursor in the synthesis of arginine [4]. Another source of urea is the decomposition of algal and cyanobacterial biomass, as well as the breakdown of certain nitrogen-containing organic compounds and zooplankton excretion [5]. Urea concentrations have been monitored, for example, in Poland in the Great Masurian Lakes, where values typically ranged from 30 to 48 µg/l, with the highest levels (up to 1.5 mg/l) detected in spring, and the lowest at the end of summer during peak phytoplankton development [6]. Urea concentration was found to be inversely proportional to the trophic status of the studied lakes, and it was also shown that the rate of enzymatic urea degradation increases exponentially with water temperature [6]. Given the expected anthropogenic load in bathing ponds, the results of urea measurements in swimming pools, where significantly higher values are often detected, are particularly relevant for comparison. Public bathing and swimming in pools are associated with occasional

Fig. 1. View of the biological purifying zone

unintentional (though unfortunately sometimes deliberate) urination in the water. According to a study [7] conducted in Canada in two pools with volumes of 840 $m^3$ and 420 $m^3$, where the concentration of the artificial sweetener acesulfame in pool water was compared over three weeks with its average concentration in human urine, the volume of urine in the pools reached just under 0.01 %. An earlier study [8] reported an estimated input of 60 to 80 ml of urine per swimmer per day, based on changes in potassium concentration in the pool. Karimi [9] monitored water samples from ten swimming pools in Tehran, Iran, which were disinfected using various methods. The average urea concentration in pools disinfected with chlorine was 5.5 mg/l. In pools disinfected with ozone followed by chlorine, the average concentration was 4 mg/l, and in those disinfected with UV light followed by chlorine, the average urea concentration was 3.5 mg/l. Zhang et al. [10] report that urea concentrations in Beijing (China) ranged from 0.07 to 18.73 mg/l. Zhou et al. [11] found urea concentrations ranging from 0.74 to 15.02 mg/l in their study.

Caffeine (1,3,7-trimethylxanthine, $C_8H_{10}N_4O_2$) is a purine alkaloid found both in widely consumed beverages (coffee, Coca-Cola, tea, energy drinks) and in pharmaceutical products. It enters the environment primarily through wastewater from human settlements and industry. Caffeine concentrations in beverages range from tens to hundreds of mg/l; for example, coffee contains 36 to 804 mg/l, tea 122 to 183 mg/l, Coca-Cola and similar drinks 41 to 132 mg/l, and energy drinks 267 to 340 mg/l [12]. After consumption, caffeine is absorbed into the bloodstream relatively quickly, with about one-fifth absorbed directly from the stomach [13]. Almost all ingested caffeine is metabolized in the liver by demethylation into primary metabolites, paraxanthine (80 %), theobromine (11 %), and theophylline (4 %), which can undergo further demethylation and oxidation, resulting in uric acid salts and uracil derivatives [13]. The rate of caffeine metabolism depends on many factors, with its half-life in the body ranging from 2 to 12 hours, most commonly 4 to 5 hours [13]. Only a small portion of caffeine is excreted unchanged in urine, with reported amounts varying between 0.5 % and 10 % according to different publications [14]. Caffeine is primarily excreted from the body through urine along with its main metabolite, paraxanthine, although traces can also be found in perspiration. Rybak et al. [15] studied the concentrations of caffeine and its metabolites in human urine, reporting median values of 3.39 μmol/l for caffeine, 15.2 μmol/l for paraxanthine, 20.3 μmol/l for theobromine, and 1.63 μmol/l for theophylline; when converted to mass concentration, the median for caffeine is 658 μg/l. The detected concentrations vary mainly depending on age, with the highest values observed in the 40 to 59-year age group [15]. Excretion rates differ between caffeine and its individual metabolites, ranging from 0.423 nmol/min to 46.0 nmol/min [15].

The average caffeine consumption per capita per day was 288.58 mg in 2013, according to data from *Food Balance Sheet of the United Nations*, with significant differences between individual countries [16]. Numerous studies have investigated the presence of caffeine in water; there is much more data on its occurrence in wastewater and flowing waters than in bathing waters (including lakes). So far, no one has monitored the presence of caffeine in bathing ponds. Buerge et al. [14] propose caffeine as a useful chemical marker for assessing wastewater contamination in watercourses. They determined its removal efficiency in Swiss wastewater treatment plants (WWTPs) to be between 81 and 99.9 %. These authors also commonly detected caffeine in Swiss lakes and rivers (6–250 ng/l), except in mountain lakes. The proposal to include caffeine as an indicator of anthropogenic pollution is also supported by Portuguese researchers Paiga et al. [17], who reported caffeine concentrations in rivers ranging from 25.3 to 321 ng/l. More recent studies have reported caffeine concentrations in lakes in Maine (USA), with average values ranging from 6 to 11 ng/l and a maximum of 21 ng/l [18]. In our previous research, maximum concentrations detected in standing bathing waters were 296 ng/l for caffeine and 0.127 mg/l for urea [16]. In the Vltava River at Prague–Podolí, the average caffeine concentration recorded between 2005 and 2018 was 220 ng/l, with a maximum of 960 ng/l and a minimum of 100 ng/l [19]. Given the relatively effective biodegradation of caffeine at WWTPs, the presence of caffeine in surface waters is more indicative of recent contamination by raw sewage rather than pollution via effluents from WWTPs. Caffeine degradation also occurs in natural waters, primarily through the activity of bacteria from genera such as *Pseudomonas*, *Klebsiella*, *Bacillus*, *Rhodococcus*, and others [20]. In 12 chlorinated swimming pools in Australia, caffeine concentrations of up to 1,540 ng/l were detected, with significant fluctuations observed throughout the day depending on visitor numbers [21]. In thermal pools in Slovakia, caffeine was found at 44 out of 49 sites, with the highest concentration reaching 69,000 ng/l (median 310 ng/l and arithmetic mean 1,140 ng/l) [22].

Urea and caffeine are not as stable in the aquatic environment as certain pharmaceuticals, for example. Urea gradually breaks down in water into ammonium cyanate and subsequently into ammonia and carbon dioxide. Both acidic and alkaline conditions accelerate this reaction, as does elevated temperature. Even minimal urea decomposition causes an increase in pH, and this alkaline pH in turn catalyses further breakdown. The optimal pH for urea is 6.2 [23]. The alkaline environment in bathing ponds would further accelerate the breakdown of urea (in our cases, the pH ranged from 8.51 to 8.53 – see Results). Caffeine is readily broken down during wastewater treatment (81–99.9 % elimination according to [14]), so its degradation can also be expected in bathing ponds. Other authors [24] report complete biodegradation of caffeine by a pure culture of *Pseudomonas* spp. at an optimal pH of 6.0 within 24 hours, and also mention the inhibitory effect of both organic and inorganic nitrogen compounds, with the effect of urea found to be stronger than that of ammonium salts. In another study [25], also working with *Pseudomonas* bacteria, the maximum rate of caffeine biodegradation was quantified at 0.345 μmol/min, with an optimal pH for biodegradation 8.0. It was also observed that among metal ions, $Cu^{2+}$ and $Zn^{2+}$ ions had a strongly inhibitory effect on caffeine biodegradation, whereas $Fe^{2+}$, $Ca^{2+}$ and $Mg^{2+}$ ions had a stimulating effect [25]. In the aquatic environment, caffeine may undergo hydrolysis and, under suitable conditions, also photodegradation or biodegradation. Alhassen et al. [26] investigated caffeine photodegradation induced by artificial light with a wavelength of 400 to 500 nm simulating sunlight and recorded a caffeine half-life of 2.3 to 16.2 hours depending on the type of matrix (demineralised water, river water alone, and river water with

Fig. 2. Bathing pond Kosmonosy

added leaves). It was found that certain organic substances reduce the rate of caffeine degradation, and that in addition to photodegradation, hydrolysis also contributes to breakdown, although it is significantly slower [26]. In another study, a half-life of six days was observed following inoculation with effluent from a WWTP, or ten days in the case of biodegradation by microorganisms from activated sludge [27].

The ATP test analyses the presence of overall microbial contamination and is a process that measures active microorganisms. The test is based on the detection of adenosine triphosphate (ATP), a molecule that serves as the primary energy carrier in and around living cells, thus providing a direct measure of biological concentration in the sample. ATP is detected by measuring light, and the amount of light produced is directly proportional to the amount of ATP present in a given sample. The measurement is expressed in relative light units (RLU). A direct proportionality is always applied during measurement – the higher the ATP level, the higher the RLU value. We discussed this indicator in detail in our previous article, which also cites relevant literature and examines the issue of free (extracellular) and total ATP [28].

## METHODOLOGY

Grab samples were analysed, collected in accordance with the applicable sampling regulations at several bathing ponds in 2023. These were public bathing ponds located in Prague – Radotín (hereinafter A), Prague – Lhotka (B), Kosmonosy near Mladá Boleslav (C), and Lipany (D), situated approximately 3 km west of Říčany. Site D is not a typical bathing pond. It is an open-access reservoir with a partial bypass; however, a natural method of water treatment is also applied. The capacity of bathing pond A is 700 and that of pond B 1,000 visitors per day. The design capacity of the water area at bathing pond C is 100 people at any one time, and 300–500 persons per day. *Fig. 3* shows the maximum daily air temperature, precipitation in the study area (archive on the website https://www.in-pocasi.cz/ [29]), and the sampling days for the individual sites. These data allow at least partial inference of the usage intensity of the bathing ponds before sampling. Tropical days are defined as days with a maximum daily temperature exceeding 30 °C; however, the attendance at bathing ponds increases steadily from the threshold for summer days (i.e., maximum daily temperature > 24 °C) [30]. Precipitation, cloud cover, and other factors also have an influence. During sampling, air temperature and recent visitor numbers were always recorded. In terms of visitor attendance, and therefore the expected loading of the bathing pond, it is important to consider not only the weather on the day of sampling but also the conditions over the preceding few days. As shown in *Fig. 3* (and supported by our records), the days leading up to the June and July sampling dates at sites A and B were warm, and those before the August and September sampling dates were very warm (site B was out of operation during July). At Site C, samples were taken on a scheduled closing day; however, the days preceding the sampling were warm and without precipitation.

At sites A–C, two samples were taken from opposite sides of the bathing pond (*Fig. 4*) for microbiological analysis and determination of urea and caffeine. At site D, samples for these parameters were taken from a single location. Samples for chlorophyll-a were collected at sites A–C from only one sampling point (*Fig. 4*). Samples for basic chemical analysis were taken at sites A and B: from one location at site A and from two locations at site B (*Fig. 4*). Total ATP was measured *in situ* at the above-mentioned sampling points.

Two bathing ponds (A and B) were sampled repeatedly at four-week intervals throughout the entire bathing season, while two sites (C and D) were sampled only once (*Fig. 3*).

Total number of samples collected at each site is shown in *Tab. 1.* Samples were transported under constant cooling to the laboratory and processed immediately, except for caffeine determination, where samples were frozen at -18 °C and analysed collectively at the end of the bathing season. Possible changes in urea and caffeine in the samples during transport and storage were verified (considering the effect of sample containers, duration, and storage method), using an internal standard (urea) or blank and duplicate samples (caffeine). Total ATP was measured on-site.

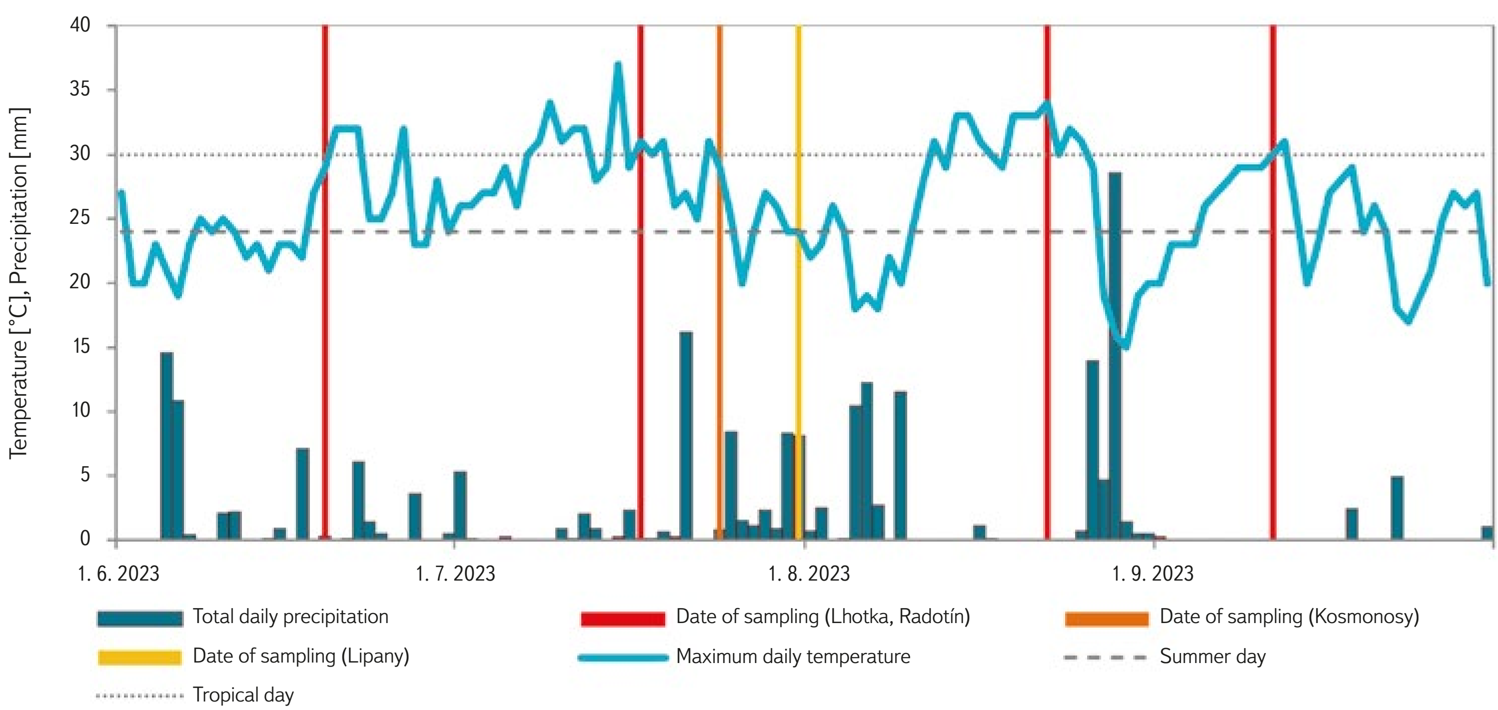



Fig. 3. Maximum daily air temperature and daily precipitation at the Prague – Libuš station and sampling days in the summer season 2023


Fig. 4. Position of sampling points at bio-swimming pools A–C; red marks sampling points for all indicators, orange marks microbiological indicators, chlorophyll-a, caffeine and urea, yellow marks microbiological indicators, caffeine and urea (source photomap: www.mapy.cz)

*Tab. 1. Total number of samples collected at individual sites*

| Site | Number of samplings | Number of samples / determinations | | | | | |
|---|---|---|---|---|---|---|---|
| | | Caffeine | Urea | ATP | Microbiological analysis | Chemical analysis | Chlorophyll |
| A | 4 | 8 | 8 | 8 | 8 | 4 | 3 |
| B | 4 | 8 | 8 | 8 | 8 | 8 | 3 |
| C | 1 | 2 | 2 | 2 | 2 | - | 1 |
| D | 1 | 1 | 1 | 1 | 1 | - | - |

Urea was determined using a method based on the enzymatic breakdown of urea by urease into ammonium ions, which were then measured spectrophotometrically (a modification of the method according to [31]; for details, see [16]). The method's detection limit is 60 µg/l and the quantification limit is 110 µg/l. Caffeine was determined by LC-MS/MS with a detection limit of 25 ng/l and a quantification limit of 50 ng/l (a modified procedure based on the ČSN ISO 21676 standard [32]).

The indicators of faecal contamination, *E. coli* and intestinal enterococci, were determined using standardized methods according to ČSN EN ISO 9308-2 [33] and ČSN EN ISO 7899-2 [34], respectively. Total ATP was measured luminometrically (Aquasnap, Hygiena) directly at the site. During the first sampling at sites A and B, we also measured bound ATP, but since these were revitalized sites, the differences between total and bound ATP were small (up to 10 %), as opposed to other previously studied matrices [28]. For this reason (and because it is simpler for potential operational measurements), we decided to measure only total ATP at the bathing ponds.

*P. aeruginosa* was analysed using an optimised method for bathing waters (i.e. for waters with a high content of accompanying microflora) [35]. Chlorophyll-a was determined according to the procedure specified in ČSN ISO 10260 [36].

Basic chemical analysis included organic carbon, total nitrogen, inorganic forms of nitrogen (nitrite, nitrate, and ammoniacal), orthophosphate phosphorus, total phosphorus, dissolved oxygen, and pH value. Water transparency was measured on site using a Secchi disk, and the concentration of dissolved oxygen (as well as oxygen saturation and water temperature) was measured with a Hach LDO HQ 10 oximeter with an optical probe, at three depths: 30 cm, 1 m, and 2 m. As the values did not vary significantly with depth, only the 'surface' values (i.e. 30 cm below the surface), where all samples for analysis were taken, are reported. pH value was measured immediately after transfer to the laboratory using a WTW inoLab® pH level 2 meter with a combined THETA 90 electrode. Organic carbon and total nitrogen were determined using a Shimadzu TOC-V CPH analyser. Spectrophotometric methods in accordance with ČSN EN 26777 [37], ČSN ISO 7890-3 [38], and ČSN ISO 7150-1 [39] were used to determine nitrite, nitrate, and ammoniacal nitrogen. For the determination of orthophosphate phosphorus and total phosphorus (after mineralisation with peroxodisulphate), the spectrophotometric molybdenum blue method was used in accordance with ČSN EN ISO 6878 [40]. Samples were filtered through Whatman GF/C glass fibre filters. The concentration of organically bound nitrogen was calculated as the difference between the total nitrogen ($N_T$) concentration and the sum of the inorganic forms of nitrogen ($N\text{-}NO_2^-$, $N\text{-}NO_3^-$ a $N_{amo}$).

# RESULTS

The following tables present the results of all analyses carried out during the 2023 bathing season. *Tab. 2* shows the basic chemical analysis at bathing ponds A and B, while *Tab. 3* presents the results for caffeine, urea, and microbiological and biological indicators (*E. coli*, intestinal enterococci, *P. aeruginosa*, total ATP, and chlorophyll) in all four bathing ponds.

## Basic chemical indicators

The values of chemical indicators in bathing ponds A and B (*Tab. 2*) demonstrate a very low level of pollution by both organic substances and nitrogen compounds. The concentrations of orthophosphate and total phosphorus were below the detection limits in all samples, which are 0.03 mg/l and 0.04 mg/l, respectively (not shown in the table). The water trophic potential is therefore very low, and any development of phytoplankton is strongly limited by phosphorus. This is reflected in the low concentrations of chlorophyll-a (*Tab. 2*). During the bathing season, a slight increase in the concentration of organically bound nitrogen was observed at both sites, occurring as early as June at site A, and only during summer holidays at site B. The highest recorded concentrations of $N_{org}$ were 5.41 mg/l at site A and 4.27 mg/l at site B. The concentration of ammoniacal nitrogen fluctuated, with no clear consistent increase, trend, or correlation observed between the concentrations of $N_{amo}$ and $N_{org}$. Nitrite nitrogen concentrations were usually below or just above the detection limit (0.005 mg/l), and nitrate nitrogen concentrations were also very low. Transparency at both monitored sites always reached the bottom (3.25 m), except for the August measurement at site B, when it was only 2 m (chlorophyll-a was unfortunately not determined on that day). In terms of organic matter content, the water was only minimally polluted, and during the summer a slight increase in the concentration of $C_{org}$ was observed, which, together with the temperature drop in September, fell back to the June level. pH values at both sites ranged within the mildly alkaline range. Changes in pH can be attributed to ongoing photosynthesis. The concentration of dissolved oxygen remained around or slightly above the equilibrium value throughout the monitored period at both sites, except for the August measurement at site B, where oxygen saturation rose to 122 %, possibly due to relatively intense photosynthetic activity of the present producers. Apart from this isolated fluctuation, none of the monitored indicators changed significantly over time. This suggests chemical stability of the water and, considering the low concentrations of nutrients and organic substances, also high efficiency of the water's self-purification. Comparison of the measured indicator values from two sampling points at site B shows that the water in the bathing area is very well mixed.

The chemical indicators included in the basic analysis provide information on water quality and the effectiveness of self-purification processes; however, some determinations, such as organic carbon, do not give information on the nature of the pollution. Therefore, they are mainly suitable as supplementary parameters. The most promising results are those for total nitrogen ($N_T$), which show higher values from July onwards at site A, and from August (with the site out of operation in July) at site B, compared to the beginning of the season.

*Tab. 2. Basic chemical analysis; at site A, only one sample was taken from the bathing area for basic chemical analysis*

| Date | Site | T [°C] | $O_2$ [mg/l] | $O_2$ [%] | pH | $C_{org}$ [mg/l] | $N_T$ [mg/l] | $N\text{-}NO_2^-$ [mg/l] | $N\text{-}NO_3^-$ [mg/l] | $N_{amo}$ [mg/l] | $N_{org}$ [mg/l] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19. 6. | A | 24.5 | 7.62 | 98 | 8.39 | 4.80 | 2.55 | < 0.005 | 0.093 | 0.030 | 2.52 |
| 17. 7. | A | 27.1 | 8.51 | 109 | 8.40 | 5.86 | 6.20 | 0.018 | 0.660 | 0.128 | 5.41 |
| 22. 8. | A | 28.5 | 8.03 | 106 | 8.33 | 5.83 | 5.71 | 0.013 | 0.453 | 0.036 | 5.22 |
| 11. 9. | A | 24.3 | 8.82 | 108 | 8.09 | 4.58 | 3.62 | 0.006 | 0.312 | 0.053 | 3.26 |
| 19. 6. | B | 23.1 | 8.52 | 104 | 8.46 | 4.11 | 1.81 | < 0.005 | < 0.05 | 0.029 | 1.78 |
| 19. 6. | B | 22.7 | 8.63 | 103 | 8.46 | 4.08 | 1.69 | < 0.005 | < 0.05 | 0.023 | 1.67 |
| 17. 7. | B | 26.3 | 8.02 | 102 | 8.51 | 4.26 | 1.35 | < 0.005 | < 0.05 | 0.096 | 1.25 |
| 17. 7. | B | 26.4 | 7.97 | 102 | 8.53 | 4.33 | 1.38 | < 0.005 | < 0.05 | 0.085 | 1.29 |
| 22. 8. | B | 26.9 | 9.46 | 121 | 8.78 | 4.31 | 4.34 | < 0.005 | 0.293 | 0.071 | 4.27 |
| 22. 8. | B | 27.5 | 9.41 | 122 | 8.74 | 4.08 | 3.59 | < 0.005 | 0.131 | 0.085 | 3.50 |
| 11. 9. | B | 23.4 | 7.74 | 94 | 8.03 | 3.80 | 3.88 | 0.016 | 0.387 | 0.126 | 3.36 |
| 11. 9. | B | 23.4 | 7.84 | 95 | 8.05 | 4.00 | 3.85 | 0.018 | 0.400 | 0.185 | 3.27 |

## Microbiological and biological indicators

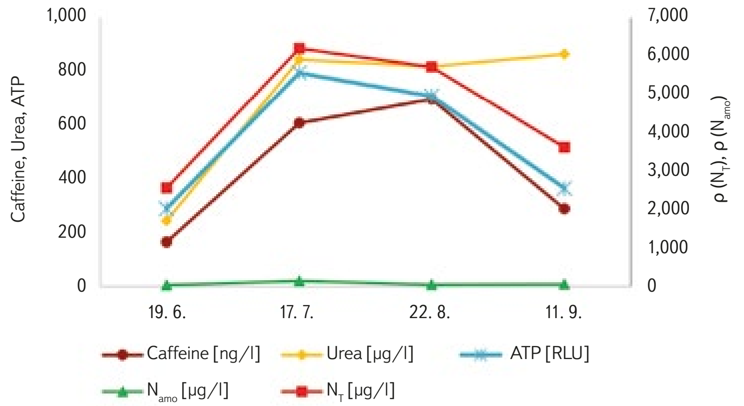
*Tab. 3* presents microbiological and biological indicators for all four sites. Nearly all *E. coli* and intestinal enterococci numbers complied with current legislative requirements (in accordance with Decree No. 238/2011 Coll. of the Ministry of Health), i.e. 100 CFU (MPN)/100 ml and 50 CFU/100 ml, respectively, and *P. aeruginosa* numbers exceeded the former limit value of 10 CFU/100 ml in only one sample. Total ATP values corresponded with our theoretical expectations: at site A, they were significantly higher in July and August during peak visitor numbers, and lower in June and September. At site B, they were lowest in the July sample, when the bathing pond was out of operation due to technical reasons. Despite high ATP values (above 200, and even exceeding 500 RLU), no elevated *E. coli* numbers were recorded at the same time, in contrast with urban water features [41]. This suggests the presence of different, much more natural microbial communities, and in this case ATP did not demonstrate a direct indicative value for faecal contamination. On the other hand, the presence of opportunistic pathogens associated with anthropogenic pollution cannot be entirely ruled out. As results of ATP determination in surface waters, including bathing and natural ponds, have not yet been published, we are unable to compare or discuss them further.

## Chemical indicators of anthropogenic pollution – caffeine and urea

The results of the urea and caffeine analyses are also presented in *Tab 3*. The measured values were predominantly above the limit of quantification, with the highest concentrations again recorded during the summer period when visitor numbers peaked (with the exception of site B, which was out of operation in July; the values recorded at that time were therefore the lowest). The results for both indicators showed a certain degree of correlation ($R^2 = 0.82$). A degree of correlation was also observed between caffeine and ATP ($R^2 = 0.65$), and between ATP and urea ($R^2 = 0.66$). The coefficients of variation for duplicate samples ranged from 9 to 26 % for caffeine determination and from 5 to 48 % for urea determination. These correlations are also illustrated in *Figs. 5a* and *5b*.

*Tab. 3. Results of caffeine, urea, total ATP, microbiological and biological indicator detection (NA = not analysed)*

| Date | Site | Urea [µg/l] | Caffeine [ng/l] | ATP [RLU] | *E. coli* [MPN/100 ml] | Enterococci [KTJ/100 ml] | *P. aeruginosa* [KTJ/100 ml] | Chlorophyll-a [µg/l] |
|---|---|---|---|---|---|---|---|---|
| 19. 6. | A | 243 | 142 | 257 | 96 | 27 | 0 | 4.4 |
| 19. 6. | A | 244 | 186 | 319 | 46 | 14 | 3 | |
| 17. 7. | A | 828 | 688 | 709 | 19 | 9 | 14 | 13.0 |
| 17. 7. | A | 861 | 526 | 880 | 28 | 7 | 13 | |
| 22. 8. | A | 847 | 829 | 634 | 28 | 12 | 6 | NA |
| 22. 8. | A | 790 | 562 | 780 | 16 | 4 | 9 | |
| 11. 9. | A | 859 | 200 | 278 | 11 | 7 | 0 | 2.7 |
| 11. 9. | A | 871 | 375 | 450 | 6 | 5 | 0 | |
| 19. 6. | B | 147 | 249 | 299 | 62 | 17 | 1 | 2.4 |
| 19. 6. | B | < 110 | 317 | 278 | 105 | 20 | 3 | |
| 17. 7. | B | < 110 | < 50 | 28 | 36 | 3 | 3 | 1.9 |
| 17. 7. | B | < 110 | < 50 | 58 | 24 | 4 | 3 | |
| 22. 8. | B | 715 | 748 | 399 | 8 | 3 | 4 | NA |
| 22. 8. | B | 742 | 879 | 189 | 6 | 6 | 8 | |
| 11. 9. | B | 532 | 470 | 291 | 12 | 3 | 2 | 1.4 |
| 11. 9. | B | 544 | 492 | 292 | 10 | 3 | 5 | |
| 24. 7. | C | 125 | 297 | 231 | 19 | 3 | 1 | 5.9 |
| 24. 7. | C | < 110 | 184 | 214 | 12 | 15 | 1 | |
| 31. 7. | D | < 110 | 106 | 925 | 22 | 18 | 1 | NA |



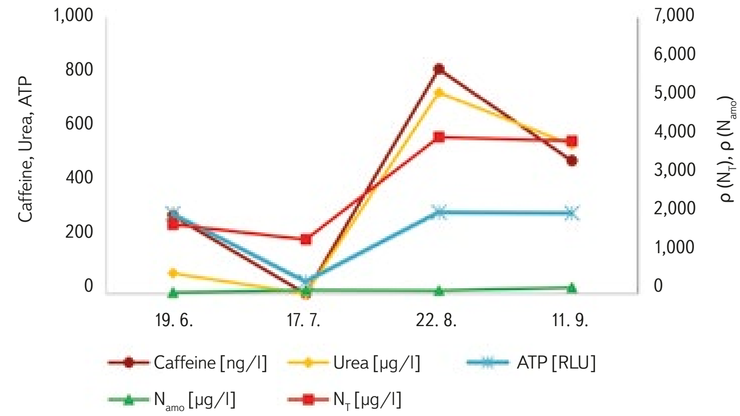




Fig. 5 a, b. Seasonal course of average concentrations (from sites A and B) for caffeine, urea, ATP, ammonia ($N_{amo}$) and total nitrogen ($N_T$)

## DISCUSSION

The work presented in this article builds upon our previous study of bathing waters [16], which, however, focused on significantly larger water bodies (ponds and sand pits) with relatively lower visitor numbers (i.e. a higher ratio of water volume to anthropogenic pollution input). As a result, caffeine and urea concentrations were considerably lower than those observed in the bathing ponds and only rarely exceeded the limit of quantification (for comparison, caffeine (in ng/l): Mělice sand pit < 50–170, Šeberák pond < 50–204, Pilský pond 84–93, Poděbrady sand pit < 50–121, Eliška pond < 50–296). Measured values in lakes reported in the cited literature were also lower; for example, in Maine (USA), concentrations ranged from 6 to 11 ng/l, with a maximum of 21 ng/l [18]. The anthropogenic load of bathing ponds is therefore more comparable to that of artificial swimming pools, where average caffeine concentrations of up to 1,540 ng/l [21] and 1,140 ng/l [22] have been reported. High concentrations of urea have also been detected in swimming pools, namely 3.5–5.5 mg/l [9], 0.07–18.73 mg/l [10], and 0.74–15.62 mg/l [11]. Zhang et al. [10] also report that the average volume of urine released per swimmer could be between 25 and 77 ml. Urea is considered the main nitrogen-based contaminant introduced into pool water by swimmers and is therefore an important indicator of water quality and hygiene in swimming pools. In China, it is regulated at 3.5 mg/l (i.e. 3,500 µg/l; our highest recorded value was 871 µg/l).

Relatively high caffeine concentrations in the bathing ponds were recorded despite the fact that only a small proportion (0.5–10 %) of caffeine is excreted in unchanged form [14], and metabolites were not analysed.

Among other (as yet unpublished) results, caffeine concentrations were as follows: wastewater outflow system (1,160 ng/l), treatment pond (273 ng/l), fishing pond (upper section 66 ng/l, lower section < 50 ng/l), and bathing pond (258 ng/l). Urea in these samples was mostly below the limit of quantification, probably having already degraded into ammonium ions, with detected concentrations of 916, 471, 161, 250, and 185 µg/l. These results also indicate that caffeine and urea levels are higher in bathing ponds than in ponds of any other type.

The indicators we monitored (particularly caffeine, urea, as well as ATP and total nitrogen) exhibited a significant seasonal pattern in the bathing ponds (*Fig. 5*). Therefore, results for the entire season cannot be averaged; each individual measurement must be evaluated separately. At site B, high 'summer' caffeine and urea values were already recorded during the peak bathing season of 2022 (27 July at a concentration of 993 ng/l and 12 August at 432 ng/l; results not previously published), which are comparable to the values we measured during the same period in 2023. Although duplicate samples (in 2023 always taken from two different locations within the bathing area) generally showed only minor differences (mostly within 20 %) in some cases greater variation between duplicates was observed (caffeine 9–26 %, urea 5–48 %). Therefore, especially for newly tested bathing ponds, it would be advisable to collect multiple samples or, preferably, to always take a composite sample.

Confirmation of the correlation between caffeine concentration and the actual number of bathers can be found in the work of Lempart et al. [42], who conducted caffeine monitoring deliberately unaffected by current pool attendance (early morning). The highest average caffeine concentration detected was only 12.81 ng/l at the waterslide, while the average concentration in the swimming zone of the pool was 3.68 ng/l.

Although this research has yielded many interesting insights, it has also raised a number of further questions that would be advisable to address, especially in connection with anticipated future changes to Czech legislation. The indicators currently used to assess water quality in bathing ponds are inadequate (in addition, results take three days to obtain) and do not fully capture the main issues at the sites. In contrast with natural swimming waters, the situation in bathing ponds can be influenced, for example, by increasing the intensity of purification processes. Furthermore, these findings can be used when establishing new bathing ponds. However, for the actual operation of bathing ponds, there is a particular lack of operational indicators that provide rapid results, which the operator can determine independently and use to adjust management in a timely manner. Unfortunately, the determination of caffeine, urea, or total nitrogen does not meet this requirement, as these analyses must be carried out in a laboratory. The potential use of *in situ* total ATP measurement will require further study, particularly its variations in the treatment section, which is highly biologically active. From a hygiene perspective, it is important to consider the long-term loading of bathing ponds. Prolonged and high loading of bathing ponds may also introduce numerous other substances (such as pharmaceuticals, hormones, cosmetic residues) and occasionally pathogenic microorganisms originating from the skin or mucous membranes, even in cases where existing indicators of faecal contamination do not exceed prescribed limits. This was confirmed, for example, in the case of the occasional ear pathogen *Pseudomonas otitidis* in bathing ponds during the peak bathing season [35], when the highest counts were found at the end of the season. However, no correlation was observed with caffeine or urea. For monitoring long-term loading, caffeine, urea, and total nitrogen could find application. However, caffeine determination is expensive and is carried out in only a limited number of laboratories. Similarly, urea analysis is not commonly available in laboratories and is relatively labour-intensive. From this perspective, total nitrogen appears the most promising, as it is measured by more laboratories and is more affordable.

# CONCLUSION

Bathing ponds are unique systems in which living organisms play a key role in maintaining water quality, while simultaneously a large number of people bathe in a relatively small area during the peak season. Although bathing ponds have been studied for some time, the knowledge gained remains limited and further questions continue to arise. The prevailing pollution is of anthropogenic origin (with bathers representing the main source of contamination), and the monitored indicators of anthropogenic load (caffeine and urea) reach values of over 500 ng/l and µg/l, respectively, during the peak summer season. The indicators prescribed by current legislation (faecal contamination indicators *E. coli* and intestinal enterococci) did not reflect the increased anthropogenic load. The results of total ATP determination proved to be of interest, but further research is needed, particularly in the treatment zones, which are highly microbiologically active (including its relationship with overall biological activity, etc.). Total nitrogen could be a suitable indicator for tracking the gradual increase in anthropogenic load throughout the season.

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# ABBREVIATIONS

ATP – adenosine triphosphate
IS PiVo – information system for drinking and bathing water
RLU – relative light unit
CFU – colony-forming unit
MPN – most probable number
$N_T$ – total nitrogen

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Fig. 6. Bathing pond Radotín

# Water quality and transport of pollutants in downstream part of the Czech Elbe

**JOSEF K. FUKSA**

**Keywords:** Elbe — Vltava — nitrogen — phosphorus — eutrophication — wastewater treatment plants — health — pharmaceuticals

## ABSTRACT

The paper presents an analysis of water quality data from the downstream part of the Czech Elbe and the Vltava for the period 1961–2020 and compares it with archive data (reference period 1880–1913). The transport of nitrogen and total phosphorus within the catchment was compared with the output from wastewater treatment plants (WWTPs). In general, water quality in the lower reaches of the Czech Elbe has significantly improved and remains stable since 1995–2020.

Compared to the reference data, concentrations of chloride, sulphate, and total phosphorus have generally increased. Ammonia nitrogen is currently at levels comparable to those around 1900, but it only dropped back down again after 1990. However, rivers now carry significant amounts of nitrate to the ocean – previously almost unknown. A substantial proportion of the nitrate originates from diffuse sources.

Phosphorus (determined as $P_{total}$) is still in excess in rivers, with municipal wastewater treatment plants (WWTPs) being its principal source. The high primary production of phytoplankton in reservoirs and lower river reaches is now regulated primarily by the seasonal cycle and hydromorphological conditions for phytoplankton growth.

New pollutants have emerged, such as pesticides and pharmaceuticals. The input of pharmaceuticals occurs year-round, and the prospects for their complete removal in wastewater treatment plants remain limited.

With progressing climatic change, the following changes are to be expected: longer periods of higher water temperatures and of low flow values, and a change in precipitation regime leading to higher frequencies of sewerage system overflows. Legislation is not prepared to control it, and we should rely on implementation of the new EU Directive 2024/3019(EU). With ongoing climate change, we expect longer periods of elevated water temperatures and low flow values, as well as a higher frequency of sewer overflows due to changes in precipitation patterns. This will significantly increase the impacts on river ecosystems and also reduce the effectiveness of current monitoring systems. Legislation is not prepared to control it, and we should rely on implementation of the new EU Directive 2024/3019 (EU).

## INTRODUCTION

We now have data on water quality in Czech rivers spanning more than 50 years, and we can state that water quality in Bohemian and Moravian rivers has improved significantly over the past 30 years. Although the process had begun earlier, it was driven primarily by the "end of socialism", which in practice meant the extinction closure of many polluting companies, as well as the adoption of an international approach to large river basins (the International Commissions for the Protection of the Elbe, Danube, and Oder – ICPER, ICPDR, ICPO), European support to the construction and upgrading of wastewater treatment plants, and so on. Another key factor is implementation of the EU Water Framework Directive (2000/60/EC), which brought a fundamental shift in the assessment of water status: it regards water bodies primarily as a heritage to be protected and evaluates rivers and stagnant waters (classified as water bodies) in a comprehensive manner – that is, not only in terms of water quality but also in terms of habitat quality, e.g. as the extent to which hydromorphological characteristics deviate from their natural state. Today we can see that around the year 2005, water quality in rivers improved significantly at the vast majority of regularly monitored sites and according to standard indicators, and it has remained relatively stable ever since. However, this also means that it is no longer improving significantly. We can therefore ask whether water quality has truly stabilised or whether improvement has merely stagnated, and we may conclude that the traditional approach to assessing water quality – based on the notion of "continuous improvement" – needs to be reconsidered, with greater attention paid to sources of pollution and the mechanisms behind anthropogenic changes in water quality. Following the already mentioned resolution of the WWTP issue, two "new aspects" have emerged in particular: (1) new pollutants – some genuinely new, others merely "discovered" thanks to advances in analytical techniques; and (2) significant changes in the rainfall-runoff regime, related to climate change. In the following section, we will focus on the Czech section of the Elbe catchment downstream from its confluence with the Vltava, represented by the monitoring sites at Obříství, Zelčín, and Hřensko.

### Water quality and how it is assessed

Water quality is the sum of the physical, chemical, and biological properties of a specific water, always assessed against some standard. This standard is either its suitability for use (e.g. drinking, industrial, etc.) or its deviation from natural conditions. The natural state is primarily shaped by the region's geology and precipitation patterns, while deviations are generally anthropogenic, i.e., pollution. Assessing water quality involves a series of interconnected activities – including sampling and field measurements, laboratory analyses, and subsequent evaluation of results – collectively known as monitoring. The outcome of this process is a set of data tables corresponding to each monitored site, stored in primary databases. It is only at this point that the actual assessment begins, which can be conducted using various approaches.

The next step is to present the results, which may be:

1. general – the processing of measured values,
2. "limit-based" – assessed against commonly recognised threshold values,
3. classification into categories (such as quality classes, ecological status categories, etc.).

In the first case, we obtain data series and statistically processed values (e.g. averages) expressed in absolute SI units (such as concentrations in mg/l, substance flux through a profile in g/s or t/day). In the second case, the outcome is merely a statement that values are "within the limit", a limit we may not even know and which can be changed or "updated" at any time. In the third case, we receive only a "class" that represents a complex combined assessment of multiple factors (and the definition of the class may also be "updated" over time). All three basic types have their advantages and disadvantages. The first case is the "only correct" approach because its published results are and will remain usable and comparable over long time series and can be further processed. However, it is problematic for simple assessment, as a lay user does not know "what is correct." The second case provides information in the context of the present, because as long as the (currently accepted) limit is not exceeded, there is no qualified reason to take any measures. The third case – categorisation into classes – has a long history. Currently, two types are in use in our country. We have a unique national standard, ČSN 75 7221 Water Quality – Classification of Surface Waters according to selected physical, chemical and biological quality indicators. Waters are then classified into five classes ranging from "Unpolluted" to "Heavily Polluted." For the basic indicators (BOD-5, COD-Cr, N-$NH_4$, N-$NO_3$, $P_{total}$, and the saprobic index of macrozoobenthos), the class is determined by the most adverse classification among the individual indicators, according to the threshold values in the class table. Additionally, a range of "other" indicators can be used as needed, in accordance with prescribed procedures. At the end of the classification process, the relevant sections of watercourses are marked on a map with the corresponding colour (ranging from light blue to the worst – red). Based on these, changes in the coloured sections on the map can be compared over two-year periods to assess "improvement." For a lay user or for summary information, this is almost perfect; for an objective professional, less so. The first issue lies in setting fixed class limits along a continuum of results, which is, however, a problem inherent to any categorisation. The second issue is more serious: the standard has been updated several times – namely in 1989, 1998, and 2017. This, of course, always changed the classification of the same river sections without anything actually happening on them – so, generally, it can lead to misunderstandings or even misinformation: for laypeople, suggesting "things are improving," and for some professionals, fostering an undue optimism that "we are improving because we are treating well." A different approach to classification is part of the assessment of water body quality for the purposes of the Water Framework Directive. For this, water quality is only one part of the ecological status assessment of water bodies, which are defined as parts of catchments, not just sections of watercourses. The levels of basic physico-chemical indicators and nutrients (nitrogen, phosphorus, etc.) are assessed as factors supporting the biological elements of the ecosystem (which includes macrozoobenthos, phytoplankton, and fish). At the start, there are basic tables of measured data; however, the evaluation focuses on deviation from an established reference condition for individual types of water bodies – which, among other things, means that water quality is never compared between a spring and the lower course of a river. The philosophy of the Water Framework Directive generally also accounts for shifts in reference conditions. The chemical status of water bodies is assessed separately, based on the presence of priority substances listed in progressively updated annexes. Across Europe, the chemical status remains unsatisfactory even today; by 2021, only 21 % of European water bodies had achieved a good chemical status [17]. This is partly result of advances in analytical methods, as priority substances and various hazardous or risky compounds are gradually being detected in more water bodies, so "simple improvement" cannot yet be expected here. However, water bodies are assessed in six-year cycles as part of the River Basin Management Plans. This differs from regular water quality monitoring, conducted at a basic frequency of 12 times per year by watercourse managers (River Basin Authorities), whose data we use here.

We will further use only the first type of data processing – that is, results from regular monitoring conducted 12 times a year, presented as annual averages or annual cycles – and we will "assess" only changes and their possible causes and correlations. We thank the Vltava and Elbe River Basin Authorities for the data.

## DATA SOURCES AND METHODOLOGICAL APPROACH

Even Cosmas knew (and wrote at the very beginning of his chronicle [1]) that Bohemia is drained by a single river, called the Elbe. He mentions the Vltava a few lines later and describes how people stopped by it (in what was reportedly a deserted landscape) and named it after their chieftain. Although northern Bohemia is drained by the Nisa and Smědá into the Oder, we shall remain within the Elbe catchment. It can be divided into three parts: (1) the Vltava catchment, (2) the Elbe catchment upstream of its confluence with the Vltava, and (3) the "common section" from the confluence (Mělník) to the border profile at Hřensko. In this text, we work only with data taken from yearbooks, databases, and the cited literature. For comparison, we have excellent historical data from F. Ullik [2], who published daily measurements of basic water quality parameters in Děčín for 1877, and from F. Schulz [3], who processed annual measurements taken at monthly intervals upstream and downstream of Prague in 1913. Their analytical methods are reliable, and the data have only been recalculated to match today's standard for expressing results. In the 1960s, regular monthly monitoring of water quality in Czech (Czechoslovak) rivers gradually began, and the results have been stored by the Czech Hydrometeorological Institute (CHMI). They were first published in printed yearbooks and later, up until 2009, were publicly accessible on the CHMI website; this is described in more detail

*Tab. 1. Monitored profiles and their basins*

| Section | Profile | Code | CHMI code | River km | Number of inhabitants | Area [km$^2$] |
|---|---|---|---|---|---|---|
| (1) Vltava above confluence | Zelčín | ZEL | PVL_1005 | 4.50 | 3,550,347 | 28,043 |
| (2) Elbe above confluence | Obříství | OBR | PLA_1044 | 842.05 | 1,662,554 | 13,714 |
| (2) Elbe below confluence (whole) | Hřensko | HRE | PLA_246 | 726.59 | 1,155,616 | 9,595 |
| Total | Hřensko | HRE | PLA_246 | 726.59 | 6,368,517 | 51,352 |

in [4]. In 2010, the International Commission for the Protection of the Elbe also issued the final "Value Tables" [5], covering profiles from Němčice and Zelčín all the way to the sea; data from the German profiles are still freely available online. More recent data are accessible only upon request and agreement with their providers – the Povodí Labe and Povodí Vltavy, state enterprises, to whom we would once again like to express our thanks for making the data available. For the key indicators of water quality, we now have monthly data (concentrations, discharges, etc.) covering 50 years or more, and we can retrospectively confirm that these are reliable data, verified by European analytical standards and quality management systems. For calculating transport, we used published daily discharge values for the dates on which samples were taken; for each year, we therefore have 12 "situations" that serve as the basis for calculating annual transport and the contributions from individual sub-catchments. The analytical methods used throughout the entire period are comparable. In addition to gradual modernisation – the introduction of instrumental laboratory methods – it is important to note a methodological change around 1999 concerning the determination of ammonia and nitrate nitrogen, phosphorus (total and P-$PO_4$), and chlorophyll. This involved the introduction of more selective methods and also the unification of procedures across the whole of the Czech Republic, which was particularly significant for phosphorus and chlorophyll. What is essential is that the change did not affect the time series of nitrogen concentrations, and since then, the concentration values for total and phosphate phosphorus as well as chlorophyll have been entirely reliable. *Tab. 1* presents three key monitored profiles representing the aforementioned three river sections or catchments. The Obříství and Zelčín profiles were introduced in 1993 to replace the previously used Na Štěpáně and Vepřek profiles – this was only a slight downstream shift, and the time series were seamlessly continued.

Changes in water quality and the controlling factors in the Vltava upstream of the Slapy Reservoir have been thoroughly analysed by the teams of L. Procházková and J. Kopáček [6–8]. We have already attempted to process data from the lower section down to the confluence (excluding reservoirs), which is significantly influenced by Prague, and to generalise the trends

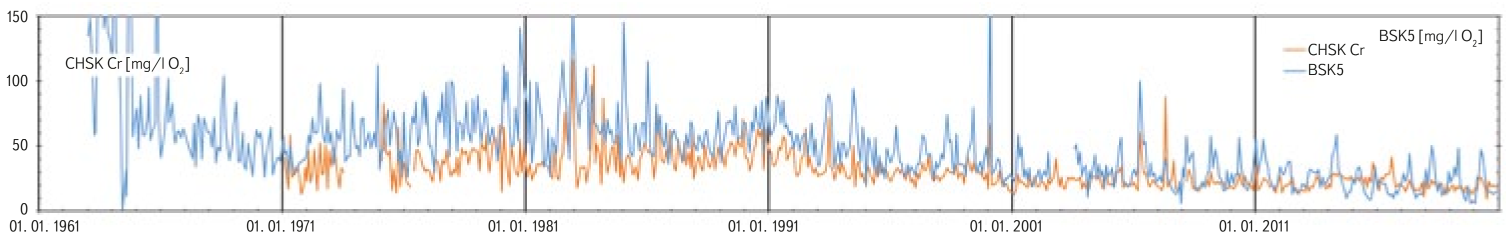



Fig. 1. Trends in BOD- and COD values 1961–2020

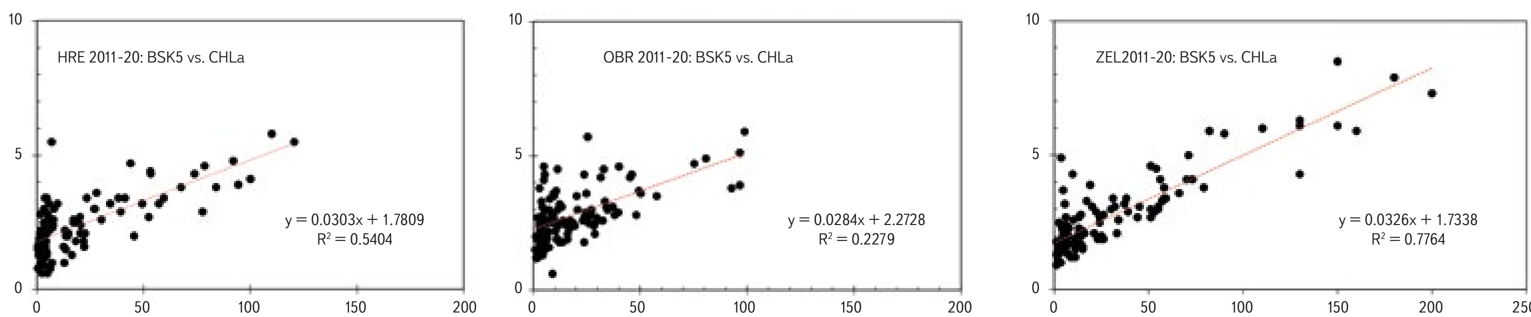



Fig. 2. Correlations of BOD-5 values and chlorophyll-a concentrations 2011–2020

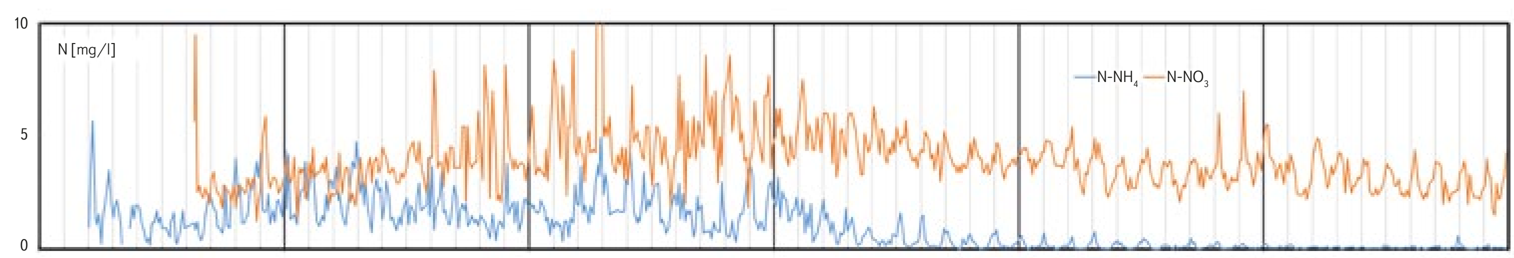



Fig. 3. Trends in ammonia and nitrate nitrogen concentrations 1961–2020

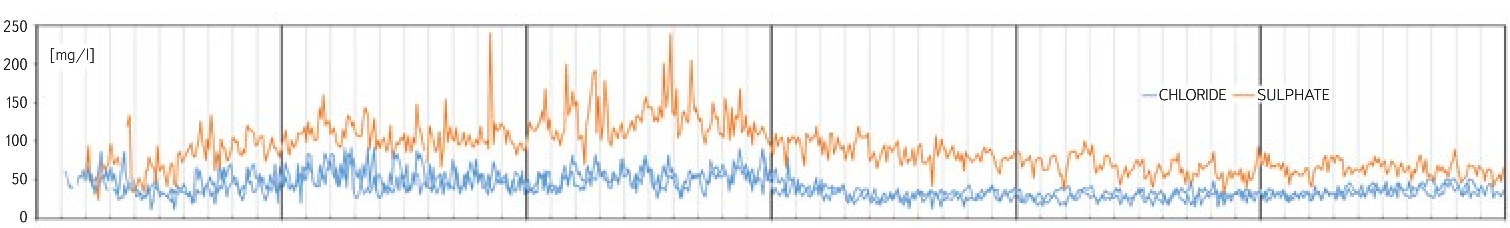



Fig. 4. Trends in chloride and sulphate concentrations 1961–2020

in water quality in the major Czech rivers [4, 9, 10]. We now present, for the first time, overviews of the entire temporal development up to 2020.

For comparing transport and "sources", we used data on discharges from point sources – WWTPs – for the key indicators of water quality. There are several databases available; here, we used publicly accessible data from the Public Administration Information System (Informační system veřejné správy, ISVS) for 2022, focusing on municipal WWTPs serving more than 1,000 inhabitants. In summary, this represents approximately 75 % of the population calculated according to population registers (as shown in *Tab. 1*), or over 90 % of the population connected to public sewerage systems and WWTPs.

The Vltava differs significantly from the Elbe as a river, and not only because upstream of their confluence it has twice the catchment area despite having the same average discharge. The Elbe rises in higher mountains, flows through flat terrain, and, although it has numerous weirs, it has no major reservoirs. From the confluence, it continues all the way to the sea, passing through a short gorge between Děčín and Pirna. The Vltava flows from Lipno Reservoir through a deeply incised valley that opens out in the České Budějovice Basin and broadens slightly near Prague. Number of significant hydraulic structures are built on the river – deep reservoirs with long average retention times and probably considerable sedimentation. During dry periods, the lower Vltava is supplemented by releases from the Orlík Reservoir, which influences the flow regime as far downstream as Hřensko, or rather at the Děčín gauging profile.

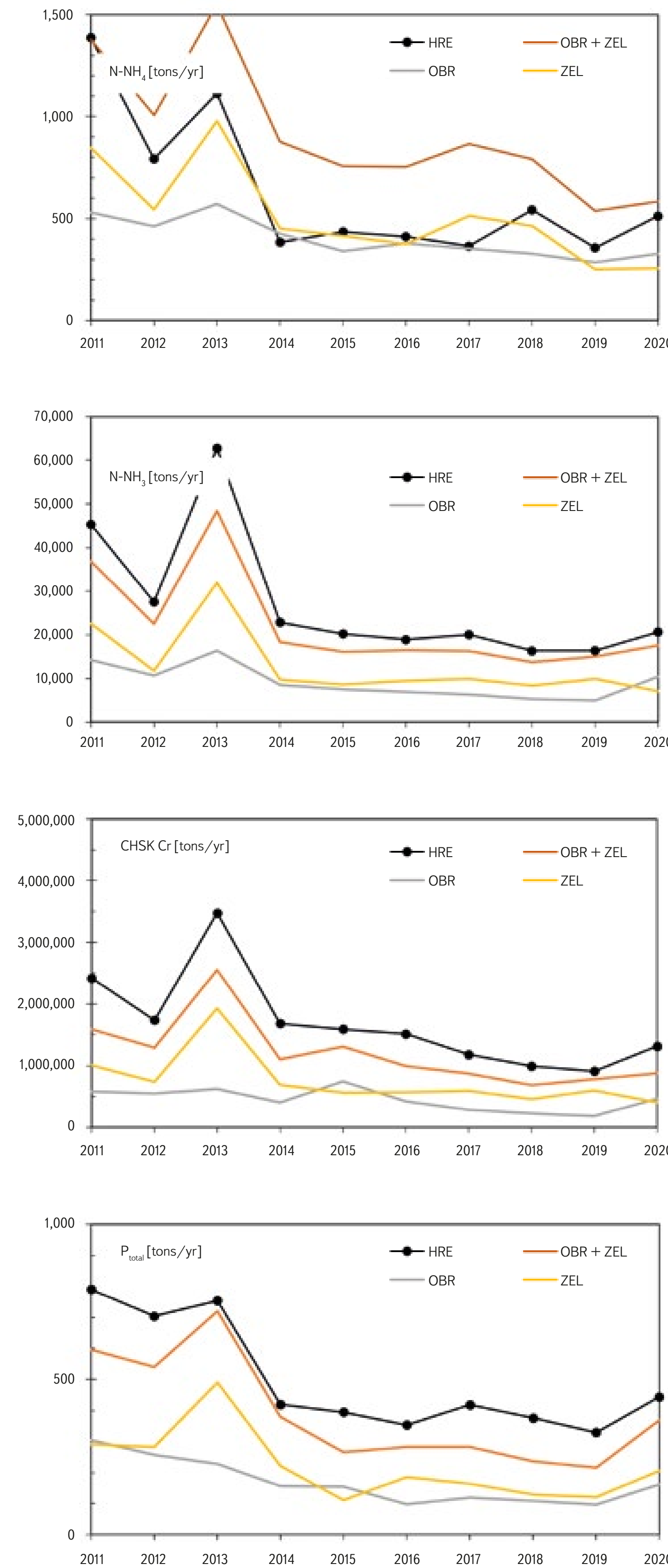
# RESULTS

## Development of water quality at the Hřensko border profile

The development of key water quality characteristics at the Hřensko profile largely reflects overall trends in the Czech Basin, both in terms of pollution from point sources (municipal and industrial) and changes in agriculture and land management, meaning pollution from diffuse sources. The contribution from point sources can be quantified based on data from pollution producers, although with a certain degree of uncertainty; however, the overall uncertainty for diffuse sources is much higher, especially for the lower reaches of large rivers. Furthermore, diffuse sources "respond" to current weather conditions (precipitation, drought, etc.), whereas when balancing point sources, we have so far been unable to fully address the issue of sewer system overflows.

A typical example of the historical development of water quality is the monthly variation of BOD-5 and COD-Cr values at the Hřensko profile from 1961 to 2020, presented in *Fig. 1* (COD measurements only began in 1971). It is clear how organic carbon load in the watercourse gradually decreased (with a turning point around 1995) and has since remained relatively stable. The graph shows seasonal fluctuations, and upon closer analysis (*Fig. 2*), it becomes apparent that the seasonal pattern of BOD-5 in recent years correlates significantly with chlorophyll-a concentration, that is, it is controlled by the current production of phytoplankton. This correlation is even stronger in the Vltava at the Zelčín profile and lower at the Obříství profile. *Fig. 2* presents correlations for the most recent decade, 2011–2020 (n = 120), covering markedly different years. In all profiles, phosphorus concentration ($P_{total}$) remains in surplus throughout the year, so the varying phytoplankton production (besides the seasonal cycle) is probably determined by differences in the watercourse morphology.

Significant changes are observed in the concentrations of ammonia nitrogen (N-$NH_4$) and nitrate nitrogen (N-$NO_3$, measured only since 1967). Ammonia nitrogen practically disappeared between 1990 and 1995, and measurable concentrations in the monitored profiles today occur only sporadically, mainly in winter. A comparison with the Podolí profile (Vltava above Prague) shows that in the Obříství, Hřensko, and partly Zelčín profiles, N-$NH_4$ originated from point sources, particularly



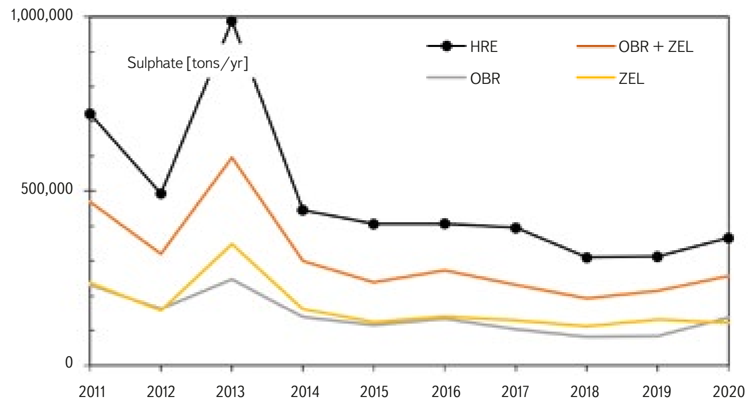



Fig. 5. Transport [tons/yr] through Hřensko, Obříství, and Zelčín profiles 2011–2020; OBR+ZEL means the sum of entries at the Vltava/Elbe confluence

municipal but also non-municipal sources on the Elbe. The theoretical oxygen demand for N-$NH_4$ nitrification was comparable to the BOD-5 values at that time. Currently, nitrogen in the rivers is present almost exclusively as nitrate. WWTPs now mostly discharge nitrogen in the form of nitrate, and wastewater discharge balances indicate that a significant source of nitrate today is the "landscape," meaning input from diffuse sources. This, however, is a general problem because nitrate is stable and can only be removed from watercourses through denitrification, that is, bacterial reduction to atmospheric nitrogen (with a certain proportion of the greenhouse gas nitrous oxide). Given today's minimal discharge of organic carbon (*Fig. 1*), oxygen conditions in large watercourses remain stable, and nitrate flows into the ocean, where it positively influences primary production and contributes to global climate change. Nitrate concentrations and their transport by rivers now show significant seasonal variations (generally peaking in January/February), corresponding to runoff from the landscape linked to precipitation and flow regimes, as well as biological processes dependent on temperature cycles. This should not reduce the obligation of WWTPs to remove nitrogen from wastewater; however, the era of massive N-$NH_4$ concentrations is behind us. Phosphorus (unlike nitrogen, which can be "returned to the atmosphere") does not disappear once it enters the river and is transported to the ocean. During the growing season, the persistent excess of phosphorus supports primary production of phytoplankton, especially in reservoirs and the lower reaches of rivers.

In recent years, chloride concentrations in the Elbe have remained fairly stable, whereas sulphate concentrations have steadily declined, reflecting the abatement of the acid rain period documented for the upper Vltava by Kopáček et al. [8], including decreased fertiliser use in the upper Vltava catchment since 1990. The situation in the German section of the Elbe is comparable today – published data from the Magdeburg profile are similar to those from Hřensko and Schmilka; however, chloride and sulphate levels there are influenced by the relatively mineral-rich Saale River.

## Input from the Upper Elbe and the Vltava

For comparison of inputs, it is necessary to convert concentrations and discharges into transport, which can be quantified in units of [g/s] or [tons/yr]. Calculating the value of concentration and daily discharge yields 12 "situations" per year at regular intervals, which can be used to compute the annual total transport. It must be emphasised, however, that a substantial portion of the calculated variation in transport is attributable to fluctuations in discharge. *Fig. 5* presents annual transport values in tonnes/year for 2011–2020. Total transport at the confluence of the Elbe and the Vltava has been added to the data from the gauging profiles. Given the size of the river, there is no relatively large pollution source between the confluence and the Hřensko profile (in terms of the ratio of discharged wastewater volume to river flow), and the difference between the summed values reflects the effects of biological processes along the stretch from the confluence to Hřensko: the gradual nitrification of ammonia nitrogen to nitrate, and a decline in residual BOD with an annual cycle corresponding to phytoplankton production. Temporal changes also show the impact of the 2013 flood, which significantly increased transport (except at the Obříství profile, as its catchment was not affected). For most of the monitored conservative indicators, the input from the Vltava at the confluence is generally slightly higher than from the Elbe; however, simple comparisons are problematic, as the Vltava regularly has higher summer flows due to releases from Orlík Reservoir. As seen in *Figs. 1*, *3*, and *4*, the past decade also shows a decline in total phosphorus and sulphate loads; chloride input has remained fairly constant.

## A civilisational issue – pharmaceuticals

In the previous two chapters, we have shown that pollution in the Czech part of the Elbe catchment is entering a stationary phase, with only the remaining persistent and still unresolved issue of nitrate and phosphorus – in other words, eutrophication. However, this applies only to the "standard indicators"; with progress and greater comfort come new pollutants of all kinds. Some are genuinely "new", while others are "old" substances that we are now identifying thanks to new analytical methods and a broader interest in environmental quality. One important group consists of pesticides used in agriculture; another is the so-called PPCPs – "pharmaceuticals and personal care products" – such as

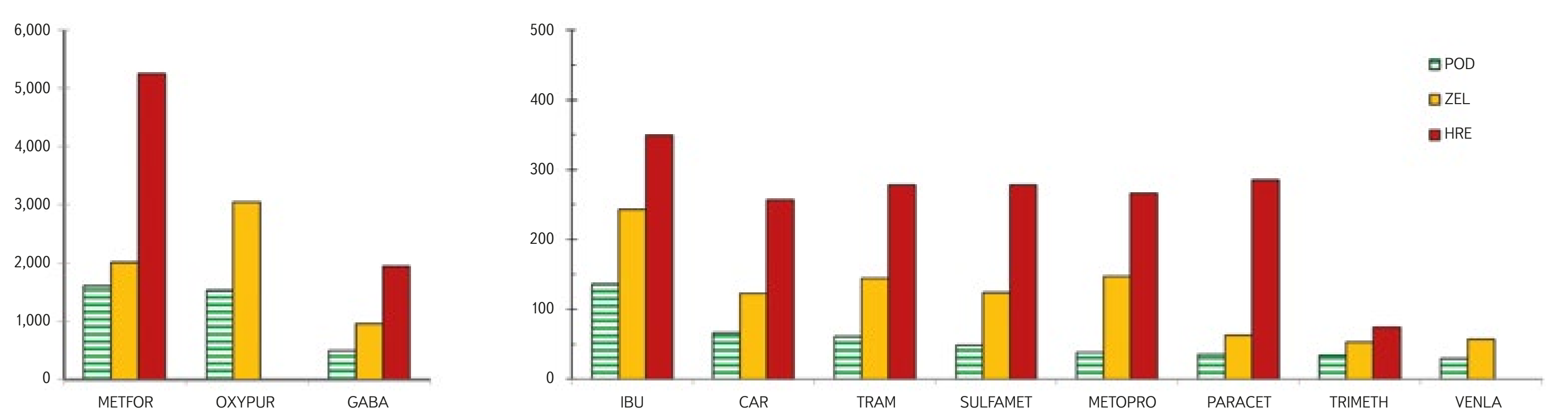



Fig. 6. Transport of pharmaceuticals through profile Hrensko; sequence on the X-axis corresponds to that in *Tab. 2*

*Tab. 2. Transport and consumption of pharmaceuticals in the whole basin*

| Farmakum | Consumption [kg/year] | | | | Transport [kg/year] | | | Transport in % of consumption | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CR total | POD | ZEL | HRE | POD | ZEL | HRE | POD | ZEL | HRE |
| METFORMIN | 221,539 | 37,662 | 70,892 | 128,493 | 1,603 | 2,012 | 5,249 | 4.3 | 2.8 | 4.1 |
| OXYPURINOL | 19,956 | 3,393 | 6,386 | 11,574 | 1,527 | 3,044 | | 45.0 | 47.7 | |
| GABAPENTIN | 14,159 | 2,407 | 4,531 | 8,212 | 490 | 958 | 1,939 | 20.4 | 21.1 | 23.6 |
| IBUPROFEN | 135,679 | 23,065 | 43,417 | 78,694 | 136 | 243 | 349 | 0.6 | 0.6 | 0.4 |
| CARBAMAZEPIN | 3,427 | 583 | 1,097 | 1,988 | 66 | 123 | 257 | 11.3 | 11.2 | 12.9 |
| TRAMADOL | 3,166 | 538 | 1,013 | 1,836 | 61 | 144 | 278 | 11.3 | 14.2 | 15.1 |
| SULFAMETOXAZOL | 5,597 | 951 | 1,791 | 3,246 | 48 | 124 | 278 | 5.0 | 6.9 | 8.6 |
| METOPROLOL | 11,496 | 1,954 | 3,679 | 6,668 | 38 | 147 | 266 | 1.9 | 4.0 | 4.0 |
| PARACETAMOL | 90,835 | 15,442 | 29,067 | 52,684 | 35 | 63 | 285 | 0.2 | 0.2 | 0.5 |
| TRIMETHOPRIM | 1,119 | 190 | 358 | 649 | 34 | 53 | 74 | 17.9 | 14.8 | 11.4 |
| VENLAFAXIN | 2,570 | 437 | 822 | 1,491 | 29 | 57 | | 6.6 | 6.9 | |

dietary supplements, cosmetics, and similar substances. Pesticides enter water bodies from diffuse sources, while pharmaceuticals and PPCPs reach aquatic ecosystems exclusively after use, via sewer systems and municipal WWTPs – that is, from point sources. These are organic compounds that can be identified as individual chemicals or narrow groups, and are subject to various environmental protection standards, including requirements to determine their environmental toxicity. With pharmaceuticals in particular, the challenge lies in the fact that different types of toxicity only manifest at concentrations significantly higher than those typically found in nature, specifically in rivers. These "residual" concentrations do not act as toxic substances but as biologically active compounds that influence the behaviour of aquatic communities in general, for example, their reproductive cycles or responses to predators. Moreover, these substances act jointly and cumulatively and also pose a significant risk to water use. Pharmaceuticals cannot be banned, and their consumption is generally increasing worldwide. According to public reports (State Institute for Drug Control, SÚKL), the average resident of the Czech Republic (and Europe) now consumes roughly 650 DDDs (Defined Daily Doses) of pharmaceuticals per year; moreover, these reports do not include dermatological applications, such as the relatively toxic diclofenac. Fifteen years ago, the figure was only around 500 DDDs [4], although reporting practices may also have changed. For the most commonly used pharmaceuticals, transport via the Vltava through Prague and to Hřensko for 2017–2020 (n = 48) is presented in *Fig. 6*, adapted from publication [11]. *Tab. 2* is important, as it presents theoretical consumption figures within the catchments of the gauging profiles, calculated based on total pharmaceutical consumption in the Czech Republic and the population of the respective sub-catchments. Seasonal variations in transport can be demonstrated only in certain cases (e.g. medicines for upper respiratory tract infections). The scope of this article does not allow for an analysis of pharmacological studies on excretion rates of the monitored pharmaceuticals by users themselves. Therefore, based on the transport data, only the percentage of pharmaceutical consumption that ends up in rivers was calculated. The highest percentage is observed for Allopurinol/Oxypurinol, followed by the psychopharmaceuticals Carbamazepine, Gabapentin, Tramadol, and the antibiotic Trimethoprim. As shown in *Fig. 6*, resistant pharmaceuticals are already entering Prague (as a major source area from the Vltava catchment) even after passing through the Orlík and Slapy reservoirs, which together have an average retention time of over 100 days. Both the graph and the table refer to the "parent compounds," not to pharmaceutical metabolites, whether excreted directly by patients, transformed in WWTPs, or further transformed in the watercourse itself. Some metabolites are known and monitored (e.g. ibuprofen metabolites); however, in most cases such analyses are rare for various reasons.

Further analysis can be conducted using WHO data on the excretion of consumed pharmaceuticals, although this inevitably increases the degree of uncertainty and speculation. For example, Metformin and Gabapentin are reported to be excreted 100 % as the parent compound, as is the active metabolite Oxypurinol for Allopurinol. A fundamental problem remains that effective technological processes for the removal of all pharmaceuticals in WWTPs are not yet available. Although the increasingly implemented advanced treatment of drinking water sourced from surface waters offers protection to consumers, this does not address the core issue at its source. Once again, we must rely on the new Directive 2024/3019 [12], which aims to gradually tackle this problem. The further fate of pharmaceuticals along the stretch from Hřensko to the sea can only be speculated upon, based on the limited data available from the FGG Elbe servers [18]. Currently, only data from the year 2023 are available for comparison. In general, concentrations correspond to those observed in the Czech Republic; however, the difference is that on the 315 km-long section from Schmilka (the border) to Magdeburg, there are no relatively large sources (the ratio of WWTP output to river flow is low). Metformin concentrations decrease along this stretch, while concentrations of Carbamazepine, on the other hand, increase. Pharmaceutical consumption and the level of WWTP treatment are certainly comparable.

## DISCUSSION

In the previous chapter, based on the results we demonstrated that pollution in the lower reaches of the Czech sections of the Elbe and Vltava rivers continues to decrease; however, the problems of eutrophication persist, and new pollutants are emerging. This implies further development in water quality monitoring, both in terms of analyses and in the evaluation of their results. Besides the search for and monitoring of additional pollutants, it is essential to improve the sensitivity of methods for detecting "standard" pollutants, because they have not disappeared; rather, their concentrations have fallen below the detection limits of current methods. This is especially critical for pharmaceuticals, but it also applies, for example, to mercury and ammonia nitrogen.

An analysis of these issues and general guidelines for addressing them (including ways to establish limits) are provided, for instance, in the European standard ČSN ISO EN 5667-20 [13]; nevertheless, the issue of overall assessment remains, as described in the introduction to this article.

There are two types of pollution sources, which differ significantly both in the nature of the substances they produce and in their characteristics. Diffuse sources are fundamentally dependent on the annual cycle (including agricultural activities) and precipitation. Point sources represent a steady (or predictable) input in terms of the content and "production" of substances; however, they typically discharge treated wastewater into variable rivers or recipients. The amount of pollution in watercourses further depends on *in situ* transformation processes, which are influenced by temperature as well as flow (dilution and longitudinal transport). The temperature cycle fundamentally influences the transformations of nitrogen (nitrification, possibly denitrification and losses to the atmosphere), organic carbon (BOD-5 and COD), and phytoplankton production (chlorophyll-a concentration), since phosphorus, as a key component of eutrophication, is generally in surplus in large rivers. In contrast, conservative constituents such as chloride and sulphate remain unchanged in the watercourse. When calculating transport (concentration × flow), it generally holds that concentrations are relatively conservative components, and the main cause of variability is fluctuation of flow values. Regarding the development of concentrations of "standard water quality indicators": ammonia nitrogen concentrations have decreased since their peak around 1985 to levels reported in the Elbe by Ullik in 1887, and also "below Prague" in 1913 [2, 3]. However, current concentrations remain stable at around 4 mg/l of nitrate nitrogen, which was a relatively unknown anion in their time. Currently, we must acknowledge the "nitrogen paradox" [14], which essentially states that the cleaner a (large) river is, the higher its nitrate nitrogen concentrations tend to be. Given the significant contribution from diffuse sources, the possibility of reduction is nowhere near. As opposed to phosphorus in inland waters, nitrogen is the key problem for the sea, and the risk of ocean eutrophication is already manifesting in coastal seas [15]. We also currently observe significantly higher concentrations of chloride and sulphate, as well as phosphorus, although the issue of eutrophication in the entire river network is only about 50 years old.

Phosphorus, as opposed to carbon and nitrogen, cannot leave the river and return to the atmosphere, and is gradually transported downstream to the sea. Its transport can therefore be compared with the balance of inputs into the catchment. Several reports of annual performance by municipal WWTPs are available, with the most comprehensive and accessible being the ISVS. According to ISVS (2022), annual phosphorus discharges from WWTPs within the Hřensko profile catchment ranged between 450 and 540 tonnes per year in 2018, 2020, and 2022. Transport through the Hřensko profile showed considerably greater variability (due to differences in flow), ranging from 580 to 1,070 tonnes per year. Phosphorus removal efficiency in WWTPs was approximately 87 %, which, among other things, is the efficiency required by the new UWWTD directive [12] *only* by 2039. Overall, the proportion of phosphorus transport through the Hřensko profile in individual years corresponds to 50–77 % of the discharge reported by municipal WWTPs in the catchment. Only WWTPs serving more than 1,000 population equivalents were included in the calculation. However, from the perspective of the overall phosphorus balance, the reported WWTP discharges represent a significant underestimate, as they do not account for combined sewer overflows. Assuming that just 10 % of untreated wastewater enters recipients through overflows during the year, and given the current phosphorus removal efficiency of 85 %, the total load from WWTPs and sewer overflows would already exceed the reported discharges by more than 50 %. Combined sewer overflows are currently the subject of intensive research, so the estimates presented here will surely be refined in the near future. However, discharge data are only available for total phosphorus, not for phosphate phosphorus, which strongly correlates with chlorophyll-a concentration – the key indicator of phytoplankton biomass. The debate on how low phosphorus concentrations must be (and must be kept) continues and is likely to continue for some time. Nevertheless, the balance suggests that undesirable phytoplankton production can indeed be limited by significantly reducing phosphorus discharges from municipal sources. This reduction must involve not only improved removal technologies at WWTPs but also better functioning of sewer systems. This aligns with the gradually introduced requirements of the new European Urban Wastewater Treatment Directive (2024/3019 EU) [12].

As already mentioned, technically feasible methods for the systematic removal of pharmaceuticals (and other PPCPs) in municipal WWTPs are not yet available. Pharmaceuticals are a group of highly diverse organic compounds that, apart from nonspecific pollution, do not constitute a significant substrate (i.e. carbon source) for microbial communities in WWTPs, and therefore do not trigger the selection of specific metabolic pathways. Their degradation thus proceeds primarily through cometabolism with the standard sewage load, mediated by rather nonspecific bacterial oxidases, and occurs gradually, often producing unknown intermediate products or metabolites. Therefore, progress in this area is expected to be slow and must begin with support for systematic monitoring of pharmaceuticals in WWTPs and watercourses.

## CONCLUSION

We have analysed archival data on water quality in the lower reaches of the Czech sections of the Elbe and Vltava rivers – border profile Hřensko and profiles Obříství and Zelčín at the confluence of the Elbe and Vltava.

Water quality in the lower Elbe has improved significantly and has remained stable since 1995–2020.

Ammonia nitrogen, after peaking in the 1980s, has almost disappeared; however, it has been replaced by persistently high concentrations of nitrate nitrogen, which is transported downstream to the ocean. The nitrogen balance in river systems is complicated by exchanges with the atmosphere, particularly through denitrification processes that produce nitrous oxide. At present, a substantial proportion of nitrate nitrogen originates from diffuse sources.

Phosphorus (determined as $P_{total}$) remains in excess in the rivers, with municipal WWTPs representing a major source; total phosphorus loads discharged within the catchment correspond to well over 50 % of transport measured at the gauging profiles. Eutrophication remains generally high, and the elevated primary production of phytoplankton in reservoirs and lower river reaches is influenced mainly by seasonal dynamics and the hydromorphology of the watercourses. As opposed to the past, the annual cycle of BOD-5 values at the monitored profiles is now significantly influenced by phytoplankton production. New pollutants such as pesticides and pharmaceuticals have also emerged. The input of pharmaceuticals occurs year-round, and the prospects for their complete removal at wastewater treatment plants remain limited.

It is necessary to take into account the impact of climate change on watercourses. In general, it leads to an increase in maximum summer water temperatures (resulting in higher respiratory activity and lower oxygen solubility), prolonged drought periods (with very low flows), and intense torrential rainfall events (which typically trigger sewer overflows). Current regulations governing wastewater discharges do not yet adequately reflect these conditions. Requirements for monitoring sewer overflows and for considering the "recipient characteristics" – specifically, the proportion of discharged wastewater in the river flow at the discharge point (monitored over five years) – are only now being introduced in the newly adopted UWWTD [12]. In the Czech Republic, there are nearly 1,000 municipal WWTPs (according to ISVS) serving more than 1,000 inhabitants, and at least 60 of them discharge more than 50 % of the recipient's flow during dry weather conditions [16]. The working database (WWTP performance vs. flows at discharge points) is still being refined.

Since 2000, Czech legislation has failed to even meet the letter of Section 36 of the Water Act, which concerns the minimum residual flow and its determination. This provision underpins the requirements for the "environmental flow" included in the UWWTD and other European documents. If progress in pharmaceutical degradation is slow due to real technical challenges, could legislative progress be even slower?

## Acknowledgements

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# Hydrotechnical research of flap gates

**MARTIN KRÁLÍK, ONDŘEJ NĚMČANSKÝ**

**Keywords:** flap gate — baffles — hydraulic model — curve of overflow coefficients


## ABSTRACT

This article deals with the hydraulic analysis of a flap gate in Doksany and Strakonice based on the evaluation of experimental measurements performed on a physical and mathematic model at the Water Management Experimental Centre, Faculty of Civil Engineering, CTU in Prague.

The measurements within the Doksany weir were carried out on a physical model at a scale of 1 : 12.5 and on a mathematical 3D model in Ansys CFX. Both models were set up for ordinary and extraordinary situations, i.e. without aeration and with exceeding the maximum operating level. For the Strakonice weir, a physical model was built at a scale of 1 : 7, on which levels and flows were measured for ordinary operating conditions.

In connection with climate change, there has been an increase in the frequency of intense rainfall events, which often lead to sudden flooding. These extreme meteorological phenomena pose a significant risk to both property and human lives. Given this reality, it is essential to refine coefficients of overflow discharge, which are used to determine discharge rating curves. These discharge rating curves used in operation regulations and automated control systems are more in line with reality, which helps in the operational management of flooding through hydraulic structures, e.g. to improve transformation at reservoirs, where decisions need to be made quickly and efficiently about operations in water management systems to minimise possible negative impacts.

The aim of the research is to complement the existing curves of overflow coefficients for higher degree of downstream flooding and for extraordinary conditions. The research includes a comparison of different types of baffles and a mathematical description of flap gate movement.


## INTRODUCTION

Flap gates are currently the most common type of movable gate found on weirs and dams in the Czech Republic; simultaneously, they can also be described as the most widely used type of gate in the reconstruction of weirs along the Elbe–Vltava waterway and other weirs in the Czech Republic, as well as in overflow control structures of dams such as Nechranice Reservoir. This is due to their advantages, particularly the possibility of precise operation and the cost-effectiveness of both construction and operation.

Flap gates were the subject of research by Jaroslav Čábelka, Gerhard Wickert, and Gerhard Schmausser at the end of the 20th century [1, 2]. However, these publications focus only on ordinary conditions without significant influence from downstream flooding.

For this reason, and in view of the accelerating pace of climate change, which is bringing more frequent occurrences of extreme rainfall, Czech research has been extended to include ordinary conditions with greater downstream influence as well as exceptional situations. Exceptional situations refer to conditions in which the water level in the watercourse rises above the ordinary operating level due to increased flow, or when the aeration pipe of a flap weir becomes clogged, resulting in increased discharge over the control structure.

## METODOLOGY

As part of the research, sectional physical models of weirs fitted with flap gates were constructed at the Water Management Experimental Centre of the Faculty of Civil Engineering at CTU in Prague. At the same time, 3D mathematical models were created for one of the weirs. The aim was to analyse the hydraulic behaviour of the overflows under various flow rates, geometric modifications to the overflow crest of the flap gate, and water flow around the overflows. The measured and calculated values were used to obtain water surface profiles, which could be compared across the different methods, including numerical calculations based on graphs from existing research.

## DATA

### Doksany hydraulic structure

Doksany hydraulic structure (*Fig. 1*) is located on the Ohře river in the southern part of the municipality of Doksany in the Ústí nad Labem Region. The components of the structure include a machine room, a weir, a small hydropower plant, and a fish pass. The weir consists of a reinforced concrete structure with a movable control element mounted on top – namely, a steel gate in the form of a hollow flap. Flap gates have large U-profile baffles and small L-profile baffles installed on the overflow crest. The raising structure has a total of two overflow spans, each 20 m long, with a fixed overflow elevation of 150.81 m a.s.l. The maximum water level of the weir reservoir, according to the operational regulations, is 153.25 m a.s.l. At each weir span, the pier houses a DN300 aeration pipe and an opening for the flap locking pin. Below the weir, there is a 13.2-metre-long stilling basin, 1.6 m deep, ending with three steps and a raised threshold that is 0.3 m above the reinforced channel bed. The riverbed area around the weir is reinforced with stone paving and topped with a stone embankment. It should be noted that the height difference between the upstream and downstream beds is 1 m, which significantly limits the influence of downstream overflow flooding.

### Strakonice hydraulic structure

Strakonice hydraulic structure – also known as Strakonice stabilising weir – is located on the Otava river in the town of Strakonice in the South Bohemian Region. The structure consists of a reinforced concrete weir with two spans, each 20 m

Fig. 1. Doksany weir

Fig. 2. Strakonice weir

long, on which a pair of flap gates with seals are mounted between the transverse braces. It is equipped with lifting mechanisms, machine rooms above the pillars, and a sluiceway that also functions as a fish pass. The fixed overflow elevation is 387.00 m a.s.l., which is the same as the bed elevation downstream of the overflow. The ordinary operational reservoir level is 388.30 m a.s.l., while the maximum reservoir level, according to operational regulations, is at an elevation of 388.50 metres a.s.l. The downstream stilling basin was 6 m long and 0.8 m deep. In 2019, the stilling basin was reconstructed to meet hydraulic conditions required for sufficient dissipation of the kinetic energy of water flowing over the weir gate.

## Physical models

Hydraulic phenomena, water flow, and hydraulic characteristics can be studied on an actual hydraulic structure; however, for practical reasons, such research is significantly more difficult, and therefore, investigations are conducted on a scaled-down model in the laboratory. Initial, boundary, and limiting conditions are determined by dimensional, force, and mass analysis, which are based on the conditions for studying phenomena on the model using Froude's law of mechanical similarity [3].

Two physical models were constructed for measurements in the water management laboratory. The first model, 0.4 m wide, representing Strakonice weir with a flap gate and seal, was built at a scale of 1 : 7. On this model, water levels and flow rates were measured for various flap positions with increased downstream influence, as the difference in bed elevation between the upstream and downstream

Fig. 3. Physical model of Doksany weir

sides is 0 m. The second model, 0.52 m wide and built at a scale of 1 : 12.5, represented Doksany weir (*Fig. 3*). Water levels and flow rates were measured on this model for extraordinary situations, such as when the aeration pipe is non-functional or when the reservoir level exceeds the maximum operating level.

Within this model, different types of baffles (types RV.x and RM.x) were also mutually assessed in terms of flow capacity (*Fig. 4*). However, due to the model conditions, it was not possible to determine the impact on the overflow coefficient. The conversion of individual characteristics from physical models to actual hydraulic structures can be performed using the following formulas:

length scale $M_L$
velocity scale $M_v = M_L^{1/2}$
flow rate scale $M_Q = M_L^{5/2}$ [3]

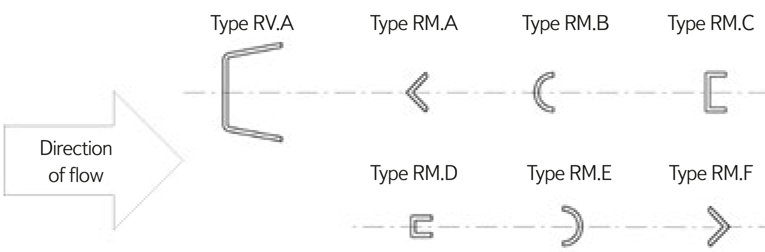


Fig. 4. Types of baffles

## Mathematical model

A mathematical 3D model was only created for Doksany weir (*Fig. 5*), with the same conditions maintained as in the physical model, except for the model width; only half of the weir field with a length of 10 m was modelled. The computational mesh was created using ICEM CFD software, and all calculations were performed in Ansys CFX. In connection with the use of the symmetry function in the model, subsequent verification revealed that a certain degree of error had been introduced into the model, resulting in a higher flow capacity [4, 5].

The aim of selecting a computational method for determining water flow and discharge was to identify calculation uncertainties using CFD technologies. The choice of an appropriate method is crucial for minimising uncertainty in mathematical modelling; it is essential to carefully select the method with regard to hydraulic behaviour and to minimise risks during the measurement of flow in the hydraulic structure [6].

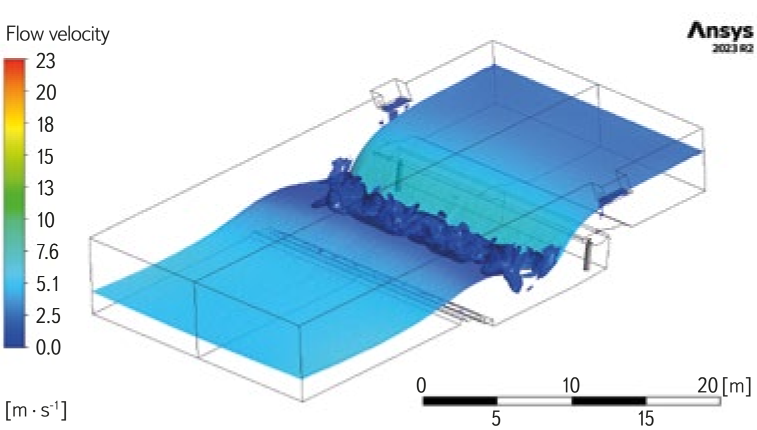


Fig. 5. Mathematical model of Doksany weir

## Mathematical model of flap gate movement

In engineering practice, when calculating overflow discharge over a flap gate, water levels are often measured from the flap's pivot point at its lowest edge. However, this approach does not accurately reflect reality. This introduces an error into the calculation of the overflow head due to a discrepancy in the tilt of the flap gate compared to its actual position, which affects the discharge curve – a critical factor for operational control. As a result, operations at the hydraulic structure become inaccurate, leading to reduced effectiveness of operational control within water management systems.

For this reason, equations describing the movement of a flap gate were derived, incorporating eccentricity between the gate plate and the bearing axis (*Fig. 6*). It should be noted that the equations relate to the movement of a flap gate with a radius of R = 2.25*H. Equations were also derived for the simultaneous movement of baffles together with the flap gate. All equations, including their application within calculation tools, are described in detail in the Master's thesis titled *Hydraulic Analysis of Flap Gates and Jambor Sills* [7].

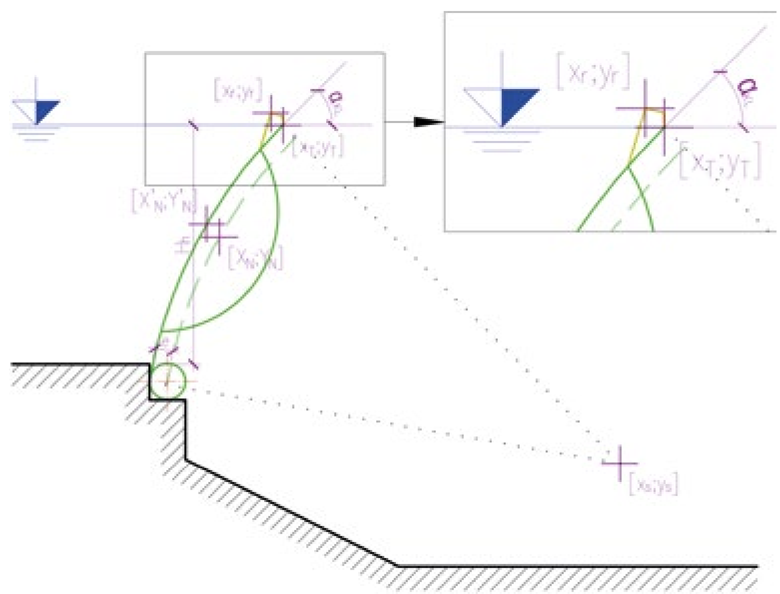


Fig. 6. Diagram of a flap gate

# RESULTS

The measured and calculated data from the Doksany weir models for extraordinary situations were inserted into an existing graph with curves by J. Čábelka (CR), which allows the coefficient of the overfall $\mu_{p\sigma}$ to be read (*Fig. 7*). These data are presented in the form of points from the physical model (PM) and the mathematical model (MM), and it is not possible to construct curves from them, as each measured value corresponds to a different pressure and level of aeration beneath the flap, which cannot be measured in practice during extraordinary situations. For this reason, the values in the graph (*Fig. 7*) are divided according to the degree of downstream flooding for practical application, as this degree plays a more significant role in calculations for other hydraulic structures.

Similarly, data from measurements on the physical model of Strakonice weir were inserted into the same graph by J. Čábelka (*Fig. 8*). However, in this case, it was possible to fit curves to the data due to the typical situation involving a raised downstream level. Compared to the current research (CR), where the ratio $H_o/H$

reached a value of 0.7, it was now possible to achieve a value of up to 0.92 on the physical model (PM), which will aid in the calculation of discharge curves for other hydraulic structures, such as Klášterec weir on the Ohře river. The use of the overfall coefficient is evident in the following overflow equation:

$$Q = \frac{2}{3} \cdot \mu_{p\sigma} \cdot b_0 \cdot \sqrt{2g} \cdot h_0^{\frac{3}{2}}$$

where:

| | | |
|---|---|---|
| Q | is | discharge [$m^3 \cdot s^{-1}$] |
| $\mu_{p\sigma}$ | | overfall coefficient [-] |
| $b_0$ | | effective overflow width [m] |
| g | | gravitational acceleration [$m \cdot s^{-2}$] |
| $h_0$ | | energy head of the overflow [m] |

The energy head of the overflow is calculated using the following equation:

$$h_0 = h + \frac{\alpha \cdot v_0^2}{2g}$$

where:

| | | |
|---|---|---|
| $h_0$ | is | energy head of the overflow [m] |
| α | | Coriolis coefficient [-] |
| $v_0$ | | inflow velocity [$m^3 \cdot s^{-1}$] |
| g | | gravitational acceleration [$m \cdot s^{-2}$] |

To understand how to read the overfall coefficient μpσ, it is important to be familiar with the parameters used for its determination:

| | | |
|---|---|---|
| H | is | overflow head |
| H | | height from crest of the fixed weir to the upstream water level |
| $H_\sigma$ | | height from crest of the fixed weir to the downstream water level |

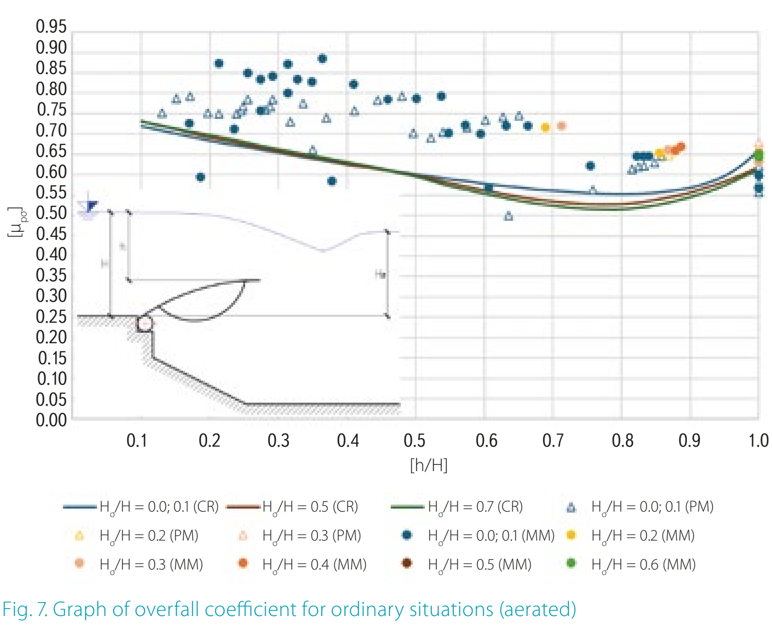


Fig. 7. Graph of overfall coefficient for ordinary situations (aerated)

In the course of investigations on flap gates, a practical question arose regarding the similarity of the hydraulic behaviour of a flap gate and a Jambor sill, with the focus placed on identifying a flap position that would correspond to this configuration. Based on the research of Prof. Čábelka on flap gates and V. Laco [1] on Jambor sills, it was concluded that similar hydraulic behaviour of the flap gate occurs either when the flap is fully lowered or when it is raised by approximately 5 cm above the fully lowered position, depending on sill height p (*Fig. 9*).

Research on the flap gate equipped with additional large baffles and interchangeable small baffles led to the identification of optimal baffle types for use on real hydraulic structures (*Fig. 11*), where they help to mitigate flap gate oscillation at low discharges. Optimal baffle shapes are L-profile (type RM.A) and semicircle (type RM.B), with the leading edge oriented against the direction of water flow. On the physical model of the flap gate, the baffles were arranged in the following sequence: 1× RM.x, 1× RV.A, 2× RM.x, 1× RV.A, 2× RM.x, 1× RV.A, 1× RM.x. The centre-to-centre distance between RM.x baffles was 52 mm, and between RV.A and RM.x baffles it was 60 mm. In cases without a combination with RM.x, the centre-to-centre distance between RV.A baffles on the model was 172 mm. The dimensions of the baffles themselves were adopted from or standardised according to the flap gate at Doksany weir. As part of the observations on the model, the effective overflow widths at lower discharges were monitored (but not measured). For combinations of RV.A and RM.A baffles, individual jets overflowing the flap gate were observed. In contrast, for combinations of RV.A with RM.B, RM.C, or RM.D baffles, unification of the jets at the edges of the flap gate was observed. In the case of the combination of RV.A with RM.E or RM.F baffles, the jet became unified across the entire centre-to-centre distance between the RV.A baffles. As a result, no narrowing of the effective overflow width around the RM.E or RM.F baffles was observed [7].

## DISCUSSION

The results for the overfall coefficient under extraordinary conditions (*Fig. 7*) indicate that varying degrees of flooding of the aeration pipe result in an increase in discharge capacity. The graph also reveals a noticeable fluctuation in the results. This fluctuation was caused by the effect of unstable pressures, or rather negative pressures, which must not occur in practice, as they induce vibrations in the structure, leading to its eventual damage. Given that the percentage of flooding of the aeration pipe cannot be directly measured at the hydraulic structure during an extraordinary situation, it is also possible to use such measured and calculated values from models for other applications. However, it is necessary to include the variability of the overfall coefficient values in subsequent calculations.

In the case of the overfall coefficient for ordinary conditions (*Fig. 8*), higher coefficient values can also be observed with greater flap gate inclination combined with a higher degree of flooding. This may also be caused by negative pressures, as in the previous case, despite the presence of a functioning aeration pipe. However, with increasing overflow head and greater flap gate inclination, the values of the overfall coefficient in the graph demonstrate the effect of a functioning aeration pipe, as these coefficient values are noticeably lower than those observed under conditions of minimal downstream flooding. Confirmation of this hypothesis can be expected following recalculation of the discharge curves for Klášterec weir by the staff of the state enterprise Povodí Ohře, with verification based on the water management balance results between the profiles upstream and downstream of this hydraulic structure.

In connection with the above statements and in relation to the graph showing the correlation between the flap gate and the Jambor sill (*Fig. 9*), the values presented in this graph can be confirmed. At the same time, the graph of percentage deviations between the flap gate and the Jambor sill (*Fig. 10*) clearly

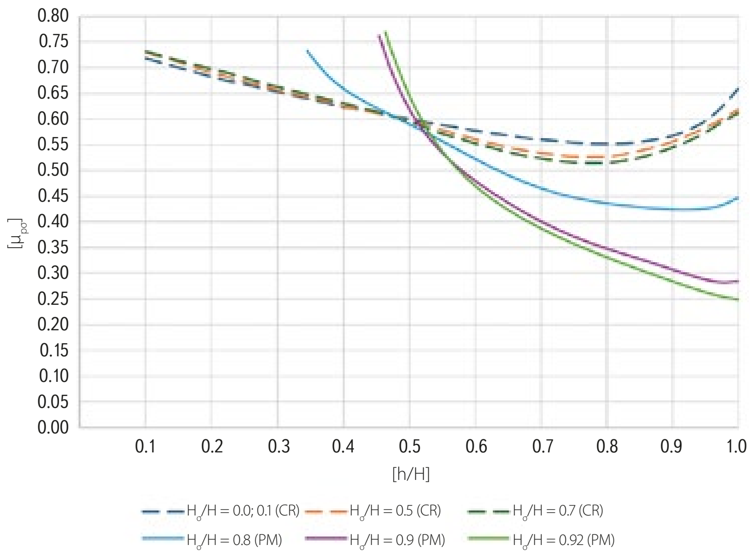


Fig. 8. Graph of overfall coefficient for ordinary situations (aerated)

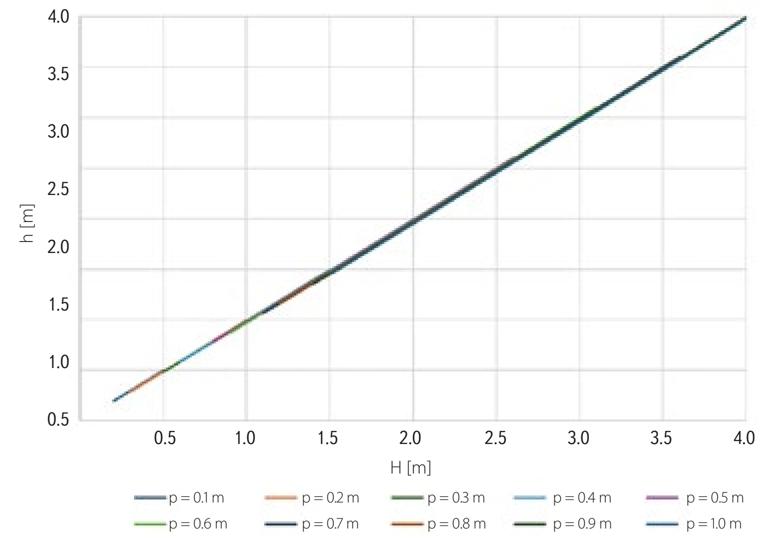


Fig. 9. Graph of dependence of a flap gate and Jambor sill

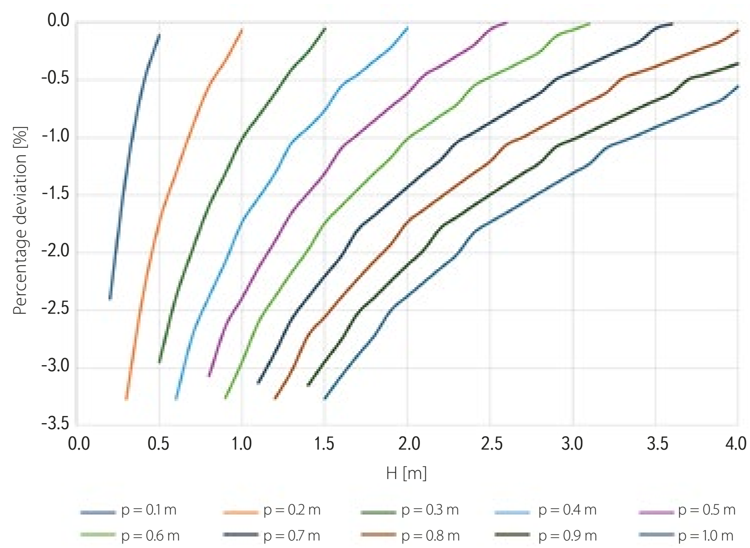


Fig. 10. Graph of percentage deviation of a flap gate and Jambor sill


Fig. 11. Graph comparing types of baffles

shows the percentage deviation for different values of H. This graph confirms the similar hydraulic behaviour of the flap gate even when the flap is slightly raised by approximately 5 cm compared to the fully lowered position, for various sill heights p. To better understand the connection between the two graphs (*Figs. 9* and *10*), one can, for example, read from *Fig. 9* that for a height H = 2 m (i.e. from the crest of the fixed weir to the upstream water level), the overflow head h ranges from 0 to 5 cm. With increasing sill height p, both the overflow head and the percentage deviation increase.

Based on the comparison of baffle types, it must be concluded that determining the overflow coefficient for various baffle geometries is, in fact, irrelevant for practical use. Nevertheless, research into the hydraulic behaviour of these baffles has made it possible to identify the optimal baffle geometry for further applications – one that fulfils its function without reducing discharge capacity. The comparison graph of baffle types (*Fig. 11*) shows a comparison of the baffles presented in the illustration of baffle types (*Fig. 4*). The graph can be interpreted as indicating how much worse the baffle variants shown in the legend columns perform in comparison to the respective reference column of each baffle. For example, in the first column representing baffle RV.A, all the columns corresponding to combinations of RV.A with RM.A through RM.F show negative percentages, as these baffle combinations reduce the overall discharge capacity of the flap gate.

## CONCLUSION

The results of the research described above provide new insights into various conditions and scenarios encountered on flap gates. By employing physical and mathematical models, it was possible to measure and calculate data that had been missing in previous studies, making it now possible to apply these new findings in engineering practice. Given that the flap gate is the most commonly used type of gate closure on weirs and dams in the Czech Republic and Slovakia, this research makes it possible to refine the discharge curves in existing operating rules and to correct values in automated control systems of hydraulic structures. This, in turn, enhances the safety of the structure and improves water management within the broader water management system.

For hydraulic structures equipped with flap gates designed according to J. Čábelka's geometry, i.e. with $R = 2.25H$, equations describing the flap motion with introduced eccentricity can be used. This simplifies calculation procedures and eliminates errors associated with reading values from design drawings. This innovative approach offers practical benefits both in the design phase and in subsequent reassessments. At the same time, regarding the issue of flap gate vibrations caused by dynamic water loading, this research enables the use of a suitable type of baffle as a damping element, which extends the structure's lifespan and reduces negative effects during both ordinary and extraordinary situations.

It is important to say, however, that an unexplored area of the overfall coefficient graph according to J. Čábelka is the interval of the ratio of overflow head to water level height (h/H) for values less than 0.1. Determining this would require access to a larger physical model than those used so far.

## Acknowledgements

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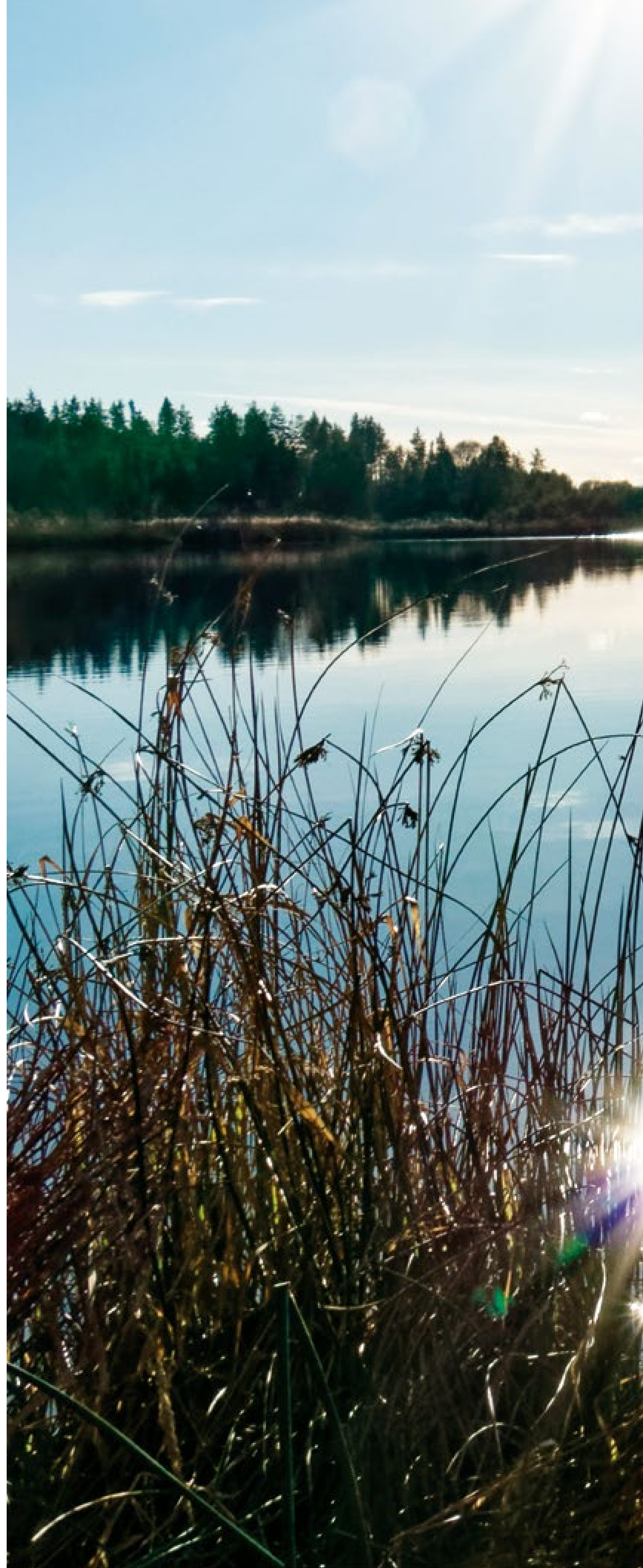

Foto: 123rf.com

# Where does a settlement end? Defining urban areas for more than just runoff analyses

**LUDĚK STROUHAL, PETR KAVKA**

**Keywords:** urban areas — runoff analyses — spatial data sources — ZABAGED


## ABSTRACT

The article presents a methodology for the spatial delineation of significant urban areas in the Czech Republic, primarily for the purposes of hydrological analyses and flash flood risk assessment. First, the definition of urban areas was refined in relation to existing terminology, followed by the development of a comprehensive procedure for creating layers of urban and natural features using the planimetric layers of the Fundamental Base of Geographic Data of the Czech Republic (ZABAGED®) supported by additional open data sources. The methodology includes hierarchical classification and concurrent geometric processing of selected topographic layers, as well as subsequent cleaning and filtering of the final polygons of both urban areas and natural features. The result is a dataset of significant urban areas that supports better evaluation of rainfall-runoff processes in their vicinity and analysis of their internal structure, providing a starting point for designing and assessing adaptation measures. The outputs will soon be publicly available for further hydrological applications and research.


## INTRODUCTION

One of the classic, yet still highly relevant tasks of applied hydrology is the analysis of flow paths and areas of surface runoff concentration, with the aim of predicting and preventing the impacts of pluvial flooding on settlements and infrastructure [1]. Although the basic principles of runoff analysis are straightforward and the development of GIS and data sources over the past 20 years has provided powerful tools for their objectification and automation, two major challenges await those undertaking large-scale territorial studies.

The first challenge relates to the extent, detail, and limitations of elevation data (terrain models) and the computational methods used to analyse them. Put simply, the goal is to ensure that water in the model 'flows' along paths that reflect reality and take into account both the terrain and built structures. The second challenge concerns the quality, interpretation, and processing methods of planimetric data. Determining a catchment area or the point where a runoff path enters a water reservoir is relatively straightforward, as there are data layers of moderate quality available for water bodies. However, when attempting to identify high-risk points where surface water may enter major settlements or, more generally, urban areas, researchers face the issue of how to define such areas and how to delineate the boundary between open landscape and settlement.

In neither general nor specialised planimetric databases of the Czech Republic does a dataset exist that delineates the boundaries of settlements or urban areas. The concept of the built-up area, or areas designated as built-up and developable, is used in spatial planning, but their spatial definition exists only in a decentralised form and is created as part of individual land-use plans. Land consolidation projects (LC), which are primarily focused on agricultural land, use the term *Internal boundary of the LC area*. This boundary delineates the extent of the land consolidation, including its interface with settlement areas, and is also prepared for the purposes of a specific project. However, for hydrological analyses at larger scales, these boundaries are neither readily accessible nor suitable for use. In a number of research projects addressing similar issues ("*Risk Maps Resulting from Flood Hazards in the Czech Republic*" – MoE, no. SMZP2007SP SP/1C2/121/07, "*Impact of Erosion on Water Bodies*" – MoI, no. BV VG20122015092, "*Enhancing the Preparedness of Urban Areas in the Czech Republic by Linking the Critical Point Method with a Flash Flood Indicator*" – TA CR, no. SS06010059), the delineation was therefore always derived by the researchers ad-hoc according to their own methodology (e.g. [2]) and the intended purpose. The level of detail in the documentation of the data sources and derivation methods used was highly variable and not always satisfactory.

This article focuses specifically on the second challenge highlighted by runoff studies, i.e. clarifying the boundary between settlements and the surrounding landscape from the perspective of the hydrological regime and potential adaptation to climate change. Approaches to managing rainfall, as well as the risks and options for adaptation measures associated with extreme precipitation, differ between open countryside and settlements. The boundary between them is not sharply defined and depends, among other factors, on the size and fragmentation of urban areas. This paper describes the delineation of only *Hydrologically significant urban areas*; however, for the sake of readability, the shortened term *Urban areas*, or its abbreviation UA, will be used in the following text. The delineation of their boundaries utilised detailed and openly accessible national data from the Basic Geographic Data Database of the Czech Republic (ZABAGED®) [3], supported by additional specialised data sources (Digital Technical Map, Register of Territorial Identification, Addresses and Real Estate, etc.). This article presents, in limited detail, the procedures used to define the boundaries of UA, which were created as auxiliary outputs within the framework of the TA CR project no. SS06010386 "*Adaptation of Urban Areas to Flash Floods and Drought*". Parts of the text are based on the interim report on the project's progress for 2024 [4].

## METHODOLOGY

### Definition of the built-up area of a settlement and urban areas

Before spatially delineating the boundaries of an urban area, it is first necessary to define it as precisely as possible. Despite the common use (*in Czech, translator's note*) of the term 'intravilán' (of settlements), it is not a terminologically well-defined concept. It also does not translate well into English – it is simply 'built-up area' or 'inner urban'. There are differences between the property-law perspective and the spatial planning or urbanistic perspective. From a legal standpoint (Act No. 128/2000 Coll., on municipalities), intravilán is defined as the built-up area of a municipality that was recorded as intravilán in the cadastral map as of 1 September 1966. This is a historical legal term, primarily relevant in connection with soil fund protection. Both older and current building legislation (Act No. 183/2006 Coll. and Act No. 283/2021 Coll.) no longer use this term directly; instead, they operate with the concepts of built-up area (zastavěné území; ZÚ) and developable area (zastavitelné plochy; ZP), which are delineated in the spatial plan. According to the wording of § 116 of Act No. 283/2021 Coll., the built-up area (ZÚ) includes:

— built-up building plots,
— building gaps,
— other fenced gaps between built-up building plots,
— public spaces,
— roads or parts thereof, including entrances to other plots within the built-up area and railway tracks where they pass through the intravilán and other plots within the built-up area,
— other plots that are surrounded by other plots of the built-up area, excluding vineyards and hop gardens.

From an urban planning and spatial development perspective, the built-up area is understood as the compact part of a municipality or town where built-up functions predominate (residential, commercial, industrial). Considering possible spatial arrangements, settlements can be distinguished as compact (the main contiguous built-up area of the municipality), dispersed settlements, and isolated homesteads. The spatial delineation of urban areas itself is a relatively complex and expert process within this field. For example, the *Methodology for the Identification and Classification of Areas with Urban Values* [5], which establishes an objective framework for identifying and classifying areas with urban values as one of the phenomena monitored for Territorial Analytical Documents, recommends the use of a combination of diverse cartographic materials and results from field surveys. The precise delineation is left to expert assessment and analysis of the character of the specific area.

From both of the above-mentioned approaches (property-law and urban), it is evident that delineating the built-up area is not an easy task, where individual classes of topographical features could simply be grouped without regard to other spatial relationships with their surroundings. The definition of (*hydrologically significant*) *Urban areas* applied in the aforementioned project no. SS06010386 is also based on a combination of these approaches. It refers to spatially extensive compact areas consisting of contiguous zones with residential or commercial-industrial functions, along with smaller internal islands or plots of a predominantly natural character. Areas of UA defined in this way have, compared to the surrounding *Natural features* (NF), despite including a certain proportion of anthropogenic areas, a different management of stormwater, risks, and impacts of fluvial and pluvial floods, and employ different methods of mitigation. Threshold values and criteria for classifying objects or their classes were established during the development of the methodology on a test area exceeding 2,300 km$^2$, which included parts of the capital city Prague, medium-sized and smaller towns, as well as dispersed village settlements. The GIS analyses described below were further processed using the ArcGIS Pro environment.

## Processing topographic objects and iteration of the natural features layer

The methodology for creating the data layer of urban areas was developed using positional data from the ZABAGED® database from spring 2024 concerning the test area and was applied to the entire Czech Republic using the updated content of the same database from December 2024. After an initial analysis of the spatial relationships between individual object classes (layers) and their attribute sets, a gradual classification of the positional data layers or their individual objects into natural and urban areas was carried out, starting with the most numerous and clearly natural features and progressing to less numerous and ambiguously classifiable layers, including possible adjustments to the geometry of certain objects. The gradually expanded layer of natural features (NF) was used to classify objects of ambiguous classes, with one of the main criteria being the ratio of each object's shared boundary with this layer. At the end of the classification process, the selected urban areas were aggregated into an initial approximate layer of urban areas (UA). In the final phase, topological cleaning and filtering were performed based on the size and significance of the resulting UAs. In various parts of the process, besides ZABAGED, selected classes of objects from the Register of Territorial Identification, Addresses, and Real Estate (RÚIAN) [7] and the geometric delineations of land parcels recorded in the Land Parcel Identification System (LPIS) [6] were also used.

### Classification of overlapping ZABAGED layers

In the Czech context, the indispensable topographic database ZABAGED contains, in terms of spatial relationships, two types of polygon object classes: overlay and base (background). All base classes represent continuous areas with relatively homogeneous ground cover or type of use (e.g., permanent grassland, functional development) and together create a topologically clean, continuous representation of the entire territory of the Czech Republic. In contrast, overlay classes most often represent man-made objects of various kinds (buildings, castles), but also natural features (swamps, peat bogs), which overlap with one or more base layers. In terms of their mutual positions, they are disjoint, but sharing a common boundary is not excluded. Relevant overlay objects provide valuable information when deciding on the classification of certain base layer objects into urban areas and defining their boundaries. Following an exploratory analysis, relevant classes were selected from the overlay layers according to *Tab. 1.* All base layers were used to ensure the integrity of the derived UA/NF polygons.

*Tab. 1. Selection of relevant ZABAGED overlay layers for sorting of the base layers*

| **Relevant** | **Irrelevant** |
|---|---|
| Individual building or block of buildings | Swamp, marsh |
| Castle | Cooling tower |
| Shed, greenhouse, polytunnel, shelter | Heliport |
| Covered structure | Above-ground storage tank |
| Chateau | Ground storage tank |
| Airport runway perimeter | Peat bog |
| | Ruin, remains |
| **Irrelevant – regions** | Landslide, scree |
| Small-scale protected area (ZCHÚ) | Rock formations |
| Large-scale protected area (ZCHÚ) | Grandstand |
| Special protection area | Tower-like structure |
| Special area of conservation | Railway turntable, transfer table |

As is evident from their names in *Tab. 1*, even the selected overlay object classes do not necessarily have the same relevance when deciding whether to classify a base layer object as part of a significant urban area or not. The most problematic class is the largest layer, *Individual building or Building block* (hereafter *Buildings*), which includes an enormous number of objects of varying sizes and importance. The attribute data of this layer contributes only partially to their differentiation, as less than 2 % of nearly 3.9 million objects have a defined specific building type from about 40 categories; the remainder of the objects are classified as *Unspecified buildings*. Therefore, a supplementary attribute called *ZB_podklad*, named after the base ZABAGED layer, was first assigned to these objects.

Because many of the background layers (e.g. *Functional development area*) include more detailed information on land use, which can play a role in classification of *Buildings*, this specific attribute was transferred to an additional field called *ZB_detail*. Subsequently, *Buildings* were classified according to these three attributes, and where applicable, by the auxiliary criterion of their area, into three levels of significance (0–2) based on a key, which is not detailed here due to its excessive length. In general terms, buildings of a rather non-urban type (e.g. pumping stations, livestock farms, etc.) are initially marked as insignificant (significance = 0), while most of the remaining specific types are assigned significance level 2. Furthermore, buildings that are unspecified but located on a clearly non-urban background (such as forest land, solar power plant) are also marked as insignificant, with varying area limits of 16/500/1,000 $m^2$ applied in cases of ambiguous data. Specific combinations of characteristics were used for smaller buildings situated on the *Functional development area* layer. Remaining unspecified buildings were assigned a significance level of 1. In the following phase, significance of *Buildings* was taken into account when classifying objects in the background layers; in some cases only significant *Buildings* were considered, while in specific cases all *Buildings* were used.

## Sorting and adjustment of base ZABAGED layers

All polygon object classes in ZABAGED – both overlapping and background – were analysed during the exploratory phase in terms of the existence, reliability, and relevance of their internal attributes. Careful classification of more than 60 categories of *development types* required the use of objects from the *Functional development area* layer, which includes similar but not identical categories to the *building type* from the overlapping *Buildings* layer.

Objects from the *Arable land* layer and *Other unspecified areas* – specifically one of its two categories, *Other unspecified areas* – as well as the layers *Other area in settlements* and *Ornamental garden, park*, were found to be highly problematic and required advanced approaches when deriving urban areas (UA).

From the linear object classes in ZABAGED, datasets related to transport infrastructure were used, specifically: *Motorway, Unregistered road, Road under construction, Street, Railway line,* and *Railway siding*. In cases where a *Tunnel* object was found to run concurrently along the route of any of these objects, the covered sections were removed from the dataset.

The process of classifying and modifying individual ZABAGED background layers for subsequent compilation into the final UA/NF layer was tested and then automated using the graphical programming environment ModelBuilder, combined with simple Python scripts within ArcGIS Pro. A set of approximately 30 interconnected tools was created to support a more transparent workflow and allow for intermediate product checks. Rather than directly aggregating objects that make up urban areas, the proposed method focuses on the inverse task – identifying which objects represent typical natural features and, with a high degree of certainty, do not belong to urban areas. Objects with ambiguous classification are then gradually analysed and sorted into either natural features (NF) or candidates for inclusion in UA, based on the proportion of their shared boundary with a NF. Geometric adjustments are made throughout to complex objects, and finally, all potential UA objects are aggregated. Both working layers – NF and UA – are maintained in two variants throughout the process: the MERGE variant preserves internal object boundaries and retains the relevant portion of their original attribute set, supplemented with a source attribute indicating the name of the parent input layer. The DISSOLVE variant consists only of merged polygons without internal boundaries, containing overall or average characteristics of the area (e.g. area size, total surface area and building footprint, shape index, etc.). A brief description of the processing of background layers follows below; a detailed explanation exceeds the scope of this article.

## Hexagonal grid for decomposition of complex objects

For analysis and adjustment of complex topographic classes, an auxiliary polygon grid of regular hexagons – hexes – was created at two scales. In the base resolution, hexes were defined with an area of 400 $m^2$, corresponding to a height of approximately 21 m. In the lower-resolution version, the hex height was set to 60 m. In both cases, the hex grid covered the entire territory of the Czech Republic with a slight overlap. To reduce computational demands, hexes located entirely within polygons of arable land and all forest land classes were removed, each reduced by an 80 m buffer. To support spatial analysis, hexes containing significant *Buildings*, *Castle*, or *Covered structures* were then marked with attribute tags, as were their neighbouring hexes. Optionally, hexes containing all *Buildings*, and those adjacent to them, were also marked.

*Tab. 2. Buffer widths for linear transport infrastructure according to type for purpose of their separation from Other unspecified areas*

| Road type | Code | Buffer [m] |
|---|---|---|
| 1st- or 2nd-class motorways | D1, D2 | 18 |
| Roads for motor vehicles | M | 15 |
| Branches and spurs of 1st- and 2nd-class motorways | D1v, D2v, D1p, D2p | 9 |
| Branches and spurs of roads for motor vehicles | Mv, Mp | 7.5 |
| 1st-class roads | S1 | 7 |
| 2nd-class roads | S2 | 5 |
| 3rd-class roads and unregistered roads | S3, – | 4 |
| Branches and spurs of 1st-class roads | S1v, S1p | 3.5 |
| Branches and spurs of 2nd-class roads | S2v, S2p | 2.5 |
| Railway line and siding | – | 2.5 |
| Branches and spurs of 3rd-class roads | S3v, S3p | 2 |

## Other unspecified areas

In the first step of processing the base layers, adjustments were made to the *Other unspecified areas (OUA)* within the polygon layer *Arable land and other unspecified areas*. As shown in *Fig. 1*, *OUA* include both linear land objects such as roads in non-urban areas, along with adjacent greenery, and polygonal elements that may potentially contain buildings or other anthropogenic structures. These polygonal elements were automatically separated for potential later inclusion in the UA layer. First, uniform buffers around linear road objects were extracted from the *OUA* objects, as well as any overlaps with the LPIS layer. The buffer widths listed in *Tab. 2* were determined for individual road classes based on a review of technical standards, experience from previous projects, and random verification using aerial imagery. The areas remaining after the separation of road buffers were subsequently divided using the basic hexagonal grid. For each fragment, the relative position with respect to the edge of the original polygon, to the road, and an indication of the presence or proximity of *Buildings* was determined. Fragments with a suitably chosen combination of the described attributes were re-aggregated into a contiguous unit (see the red-hatched object in *Fig. 1*), and the total area of included *Buildings*, shape index, etc., were calculated. Finally, the resulting polygons were filtered and classified – based on experimentally determined parameter combinations – into potential UA elements and elements to be incorporated into the NF layer.

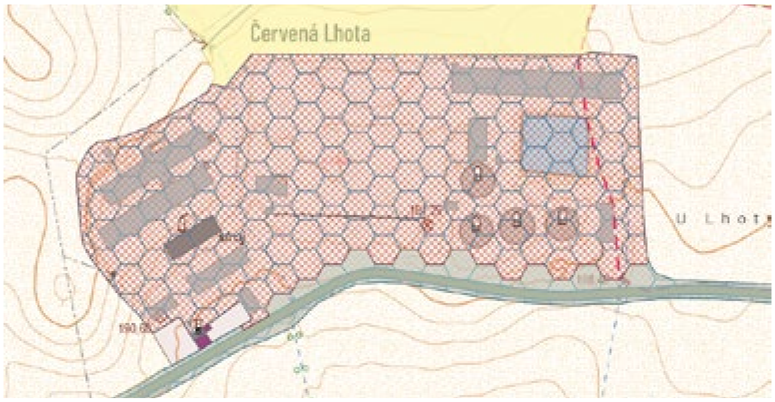


Fig. 1. *Other unspecified areas* including both the areal feature of anthropogenized area (red hatch) and the pseudo-linear road parcel (grey) subject to automated separation

### Permanent grassland

Before creating the first iteration of the NF layer, a hypothesis was tested that, in the case of compact development, buildings are always situated on a typically urban-type base layer, such as *Other settlement area*, *Ornamental garden/park*, *Orchard/garden*, etc. This assumption proved invalid in the case of the *Permanent grassland (TTP)* layer. Although this layer includes more or less maintained grassy areas in the non-urban area, it also fills small gaps within settlements or even serves as the base layer for relatively compactly arranged *Buildings* in settlements located in specific landscape types, such as mountain villages. An example of such a settlement is shown in *Fig. 2*, where it is evident that a blanket classification of *TTP* as natural feature in these locations would lead to unacceptable fragmentation and the subsequent exclusion of urban areas that in reality form a fairly compact settlement centre. Therefore, significant segments of *TTP* within a 20 m buffer around *Buildings* were excluded, with the selection criteria being an area larger than 0.25 ha, the presence of at least three buildings, and contact with or proximity to objects from the layers *Other settlement area*, areal features with buildings, and polygons of roads extracted from *OUA*. The remaining *TTP* areas were then incorporated into the first iteration of the NF layer.


Fig. 2. Significant clipped areas of permanent grassland (deep yellow) for inclusion in urban areas; light yellow is open grassland and shaded insignificant clipped areas with scattered settlements

*Tab. 3. Selection of base layers or their subsets for the first iteration of the Natural Feature layer*

| Base layer | Category / subset |
|---|---|
| Orchard, garden | Category Orchard and other permanent crops |
| Arable land and other unspecified areas | Category Arable land |
| OUA roads | Road polygons extracted from OUA |
| OUA without buildings outside roads | Areas extracted from OUA |
| OUA LPIS | Overlap of OUA and LPIS excluding buildings |
| Permanent grassland other | Permanent grassland without significant buffers around buildings |
| Forest land with trees | |
| Forest land with shrubs | |
| Forest land with dwarf pine | |
| Hop field | |
| Water body | |
| Surface mining, quarry | |
| Storage site | |

### Ornamental parks and gardens

In the third step, the first iteration of the polygon layer for NF was created, incorporating either entire classes of objects or their subsets according to *Tab. 3*. This was followed by a rather complex processing of the *Ornamental parks and gardens* feature (hereinafter *Parks*), which unfortunately lacks any relevant internal attributes and includes mainly urban residential greenery, but also larger maintained suburban green areas such as Průhonice Park. These polygons often contain more or less significant buildings, both isolated and in groups, as well as numerous internal islands (especially around water bodies), which complicates spatial analyses and decisions regarding the classification of the object as part of either UA or NF, as shown in *Fig. 3*. First, polygons in *Parks* that are potentially natural (*P_Park*) are separated if their shared boundary with NF accounts for at least two-thirds of their outer perimeter (excluding internal islands). This forms the second iteration of the NF layer. From the potentially settlement-related *Parks* (*U_Park*), 75 m buffers around significant buildings and *Castles* are extracted. Due to frequent overlaps with neighbouring polygons, only those parts in direct contact with buildings or near *Chateau* are isolated, while buffer areas forming isolated islands within the original *U_Park* are disregarded. Small fragments of *U_Park* or fragments without contact with NF are reassigned back to the subsets around *Buildings*. For large fragments and those adjacent to PP, the length of their outer perimeter (again excluding internal islands) and the proportion of this perimeter shared with NF are calculated. Golf courses (a category of the *Functional development area* layer) are temporarily included in the NF set. The shared perimeter is determined using a 10 m buffer around NF to include cases where parks are separated from the non-urban area by only a narrow road (most often represented by the *Other settlement area* base layer). Large fragments with less than 20 % shared perimeter with NF form the final component that, together with the building buffers, constitute the resulting *U_Park*. The remaining objects, along with the primarily designated *P_Parks*, are assigned to the NF layer, creating its third iteration.

Fig. 3. Průhonice park as the biggest challenge for processing and sorting *Ornamental parks and gardens (green objects with circles)*. A typical natural feature, only sharing a high percentage of perimeter with residential elements and containing a number of isolated buildings and island objects; light green elements were included into the first version of *Urban areas* layer

## Gardens

After processing the *Parks*, the objects from the *Orchard, garden* layer, specifically its *Garden* category, were classified (the remaining categories, *Orchard* and *Other permanent crops*, had already been included in NF in previous steps). From the perspective of inclusion in UA, this category is also ambiguous, as it encompasses both family house plots within contiguous settlement areas and scattered complexes of suburban satellites, villages, or former allotment gardens whose function has gradually shifted to residential use (*Fig. 4*). Compared to *Parks*, however, these objects are much simpler and more compact, which was reflected in the classification approach applied to them. First, gardens not containing centroids of significant *Buildings* (*Gardens without buildings*) were isolated, and their objects with a boundary shared with NF over two-thirds were assigned to the fourth iteration of NF. Again, internal islands within the polygons were disregarded. From the remaining *Gardens without buildings*, objects with no contact with any *Building* polygons and with a boundary shared with NF over 40 % were further removed and assigned to NF, resulting in the fifth iteration of this layer. The remaining *Gardens without buildings*, as well as all gardens containing centroids of significant *Buildings*, proceeded to further processing as potential UA features.

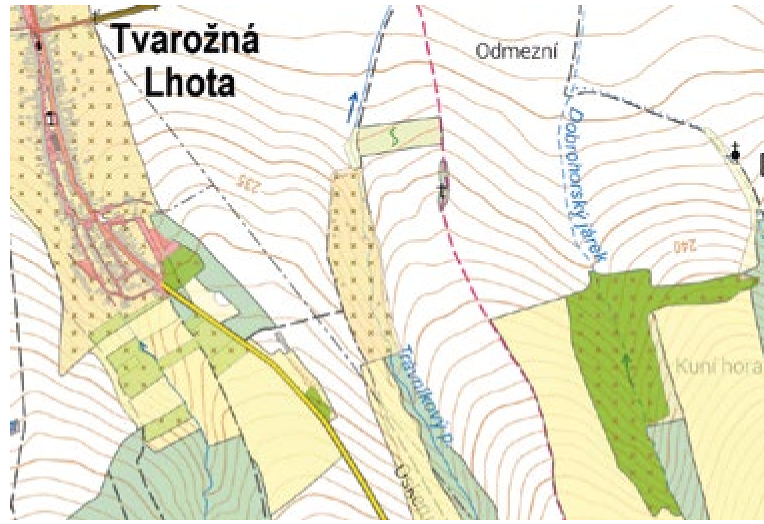


Fig. 4. The layer *Orchards and gardens* (objects with crosses) consists of orchards (light green) classified as *Natural feature and gardens* differentiated according to the built-up area to be classified as NF (dark green) or UA (ochre)

## Classification of simple features

In the next step, a relatively straightforward classification of a number of features was carried out purely based on their shared boundary with NF. Features with a proportion of natural boundary exceeding 66 % (or 50 % in specific cases) were excluded from the potential UA features and incorporated into the next

iteration of the NF layer. The following features were processed in this manner: *Vineyards, Cemeteries, Substations, Power stations, Landfills, Car parks/Rest areas, and Pipeline pumping stations*. In the case of *Power stations*, it was necessary to merge neighbouring features by type in advance, due to the occasional presence of multiple adjacent objects. This was followed by a more complex processing of features from the *Airport* layer, in order to distinguish small rural airfields with few features and often natural runways from larger airports with complex infrastructure and a significant degree of surface anthropogenization, such as Vodochody Airport shown in *Fig. 5*. First, surface type information was assigned to the *Airport runway boundary* features based on the attribute in the *Runway axis* feature. Next, a 40m buffer was clipped from the *Airport* polygons around all *Buildings*, including *Shed, Greenhouse, Polytunnel*, and *Shelter* features. A convex hull was then defined around these subsets and the paved runways, and used to extract a portion of the original *Airport* polygons. Small fragments were merged with adjacent polygons. Larger fragments (often nearly entire airports) were considered natural features and incorporated into what is now the thirteenth iteration of the NF layer. In the next, fourteenth iteration, anthropogenized subsets of the airports were finally classified into UA and NF category, this time using stricter criteria: at least 80 % natural boundary share and a maximum area of 10 ha for inclusion in the NF category.

*Tab. 4. Specific treatment for groups of development types in the object Functional development area*

| | |
|---|---|
| **Unconditionally urban areas** *included in UA* | Castle grounds; bus station; other health and social facilities; depot; wood processing and paper industry; fire station; playground; metallurgical industry; chemical industry; barracks and military facilities; monastery; swimming pool; other cultural building; summer stage; museum; hospital; other unspecified industry; swimming complex; police complex; printing industry; food industry; glass, ceramics, and building materials industry; port; open-air museum; warehouse; hangar; greenhouse crop cultivation; group garages; stadium; engineering industry; school; educational facility; technical services; textile, clothing, and leather industry; prison; underground water tank; exhibition grounds; amusement park. |
| **Conditionally urban areas** *clipping and based on surroundings* | Auto-moto-cycling area, botanical garden, campsite, golf course, holiday cottage area, meteorological station, recreational development, water treatment plant, zoo, safari. |
| **Other types** *classified based on surroundings* | Castle grounds (ruins); archaeological site; fuel filling station; wastewater treatment plant; racecourse, show jumping arena; deep mining; observatory; livestock breeding; church; dog training ground; areas for UL aircraft; sports complex; shooting range; transmitter; other agricultural area. |

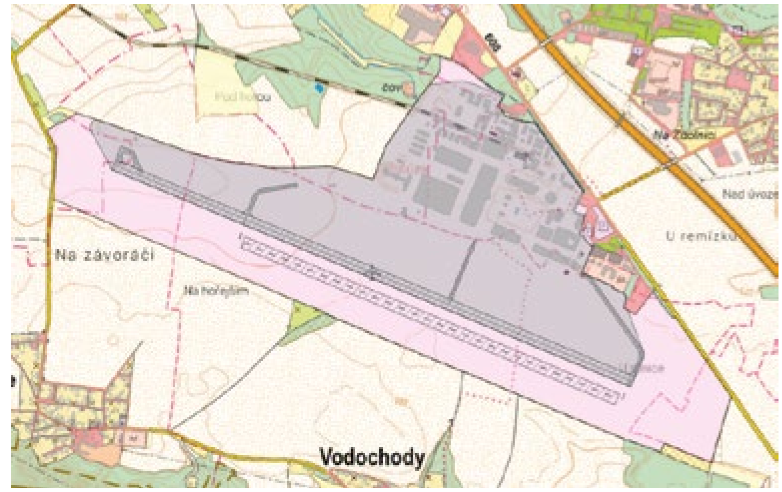


Fig. 5. Separation of anthropogenized (grey) and rather natural areas (pink) of Vodochody Airport

### Functional development area

Processing the *Functional development area* layer presented numerous challenges. This layer contains a large number of areas with various types of use, specified in the attribute field *typzast*. A total of 61 development types were divided into three groups according to *Tab. 4*, with each group subsequently handled in a different manner. For so-called conditionally UA features, 100 m buffers were clipped around significant buildings. These subsets were then merged with the unambiguous (i.e. unconditionally UA) categories. The remaining types, along with spatially significant fragments from the conditional categories, were ultimately classified as either UA or NF categories based on the proportion of natural external boundary. To determine the shared boundary, the NF layer was expanded by 10 m in order to suppress artificial separation caused by roads or narrow polygons of *Other areas in settlements* (highlighted in red in *Fig. 6*).

Fig. 6. Separation of the anthropogenized part of the botanical garden (orange) from the areas of natural character (hatched) within the layer of the *Functional development area*; the blue background is an iteration of the *Natural Feature* layer

### Other areas in settlements

The most problematic class of ZABAGED objects is undoubtedly the layer *Other areas in settlements* (hereinafter *OAS*), whose features cannot be unequivocally classified as part of settlements and, moreover, complicate the classification of surrounding layers. As shown in *Fig. 7*, despite its name, this layer also includes a large number of non-urban areas, but primarily problematic polygons along all types of roads. It is desirable to remove these and reclassify them into the NF layer, but due to their vast quantity, this cannot be done manually. For automating the process, an approach similar to that used for *OUA* was chosen. In this case, buffer polygons along roads were not generated, because a large portion of *OAS* run alongside the linear *Street* object, and clipping these would create an enormous number of problematic cases within settlements. The *OAS* layer was therefore divided using a regular hexagonal grid, and hexagons containing two or more segments of the external boundary of *OAS* were identified. These "source" hexes were then iteratively expanded by adding their neighbours until the resulting subset encountered proximity to a *Building*, a potential UA object, or hexes located deeper within the polygonal parts of *OAS*. The resulting subsets were further classified based on geometric attributes (number of hexes, shape coefficient, etc.). The entire process had to be performed twice with different scales of the hexagonal grid because, besides narrow polygons along streets and lower-class roads, the *OAS* layer also includes much wider strips around motorway and major access roads and feeder roads, which somewhat inconsistently are not classified in the *OUA* layer. Even hexes of 60 m size were insufficient to identify all cases, such as Prague Ring Road before Komořany Tunnel (*Fig. 7*). However, these polygons were filtered out from the UA layer at a later stage thanks to the successful separation of the narrow *OAS* strips using the described procedure.

Fig. 7. The complex object *Other areas in settlements* (red) includes linear and areal features both within and outside of settlements; unwanted linear features along various road types, removed by automated process, highlighted in black

### Railway stations and rail yards

As the final base layers of topography, features of the classes *Railway station area, Stops* (hereinafter *Stop area*), and *Rail yard* were processed. Due to their frequent but not always simultaneous occurrence, as well as the specific nature of both types of features and their location relative to settlements, these layers were processed using slightly different methods. First, subsets of the *Stop area* within a 50 m buffer around features from the *Buildings, Covered construction*, and *Shed, Greenhouse, Polytunnel, Shelter* layers were performed. Remaining larger fragments in contact with NF were reassigned to this layer, and buffers around features were included in the UA layer only if they had contact with previously identified UA features, regardless of *Rail yards*. In this way, *Stop areas* isolated further from settlements were excluded. Finally, *Rail yard* features were processed using a similar approach employing hexagons as in the case of *OAS*.

### Refinement of urban areas and gap infilling

After adjustment and classification of all base ZABAGED topographic layers, features identified primarily as settlement-related were aggregated into the first rough version of the *Urban area* layer, both in the MERGE and the DISSOLVE variant. Alongside this, the latest iteration of the NF layer also existed in both MERGE and DISSOLVE variant. Together, these layers covered the entire study area completely and without overlap. As shown in *Fig. 8*, the initial UA version (in orange) exhibits several shortcomings and complications for defining meaningful urban area boundaries. Notably, there is undesirable fragmentation of UA by watercourses where these are represented not only as linear features but also as corresponding polygons in the water body layer. Furthermore, the first iteration of the UA layer contains a large number of gaps – internal islands of varying sizes. This fact is evidenced by more than 36,000 polygons in the NF layer, of which over 33,000 do not exceed an area of 1 ha.


Fig. 8. First incomplete version of the UA layer with sub-areas separated by watercourses and with a number of gaps

Before performing any filtering of UA polygons, it was first necessary to remove fragmentation caused by watercourses. Therefore, a double buffering of UA feature hulls was performed – 40 m outward and 50 m inward – after which the area of the original UA features was removed. Within the resulting polygons larger than 0.25 ha, "linear" polygons of flowing water bodies, roads from the *OUA* layer, strips of *OAS*, and fragments of *Rail yards*, which had previously been assigned to the NF layer, were extracted and transferred to the second iteration of the UA layer.

Given the previously stated definitions of intravilán and built-up area, the process then proceeded with the controlled infilling of gaps in the following steps:

- Potential settlement features from the NF layer within gaps up to 5 ha were transferred to the UA layer.
- Features of all NF categories within gaps up to 1 ha were transferred to the UA layer.
- Features of all categories within gaps up to 5 ha located more than 40 m from other NF were transferred to the UA layer.

After the described infilling of gaps, especially due to the removal of "linear" interruptions caused by watercourses, the number of UA polygons slightly decreased to just over 97,000. However, the infilling of smaller gaps led to a dramatic reduction in the number of NF polygons, from the original 36,000 to only 1,120 features.

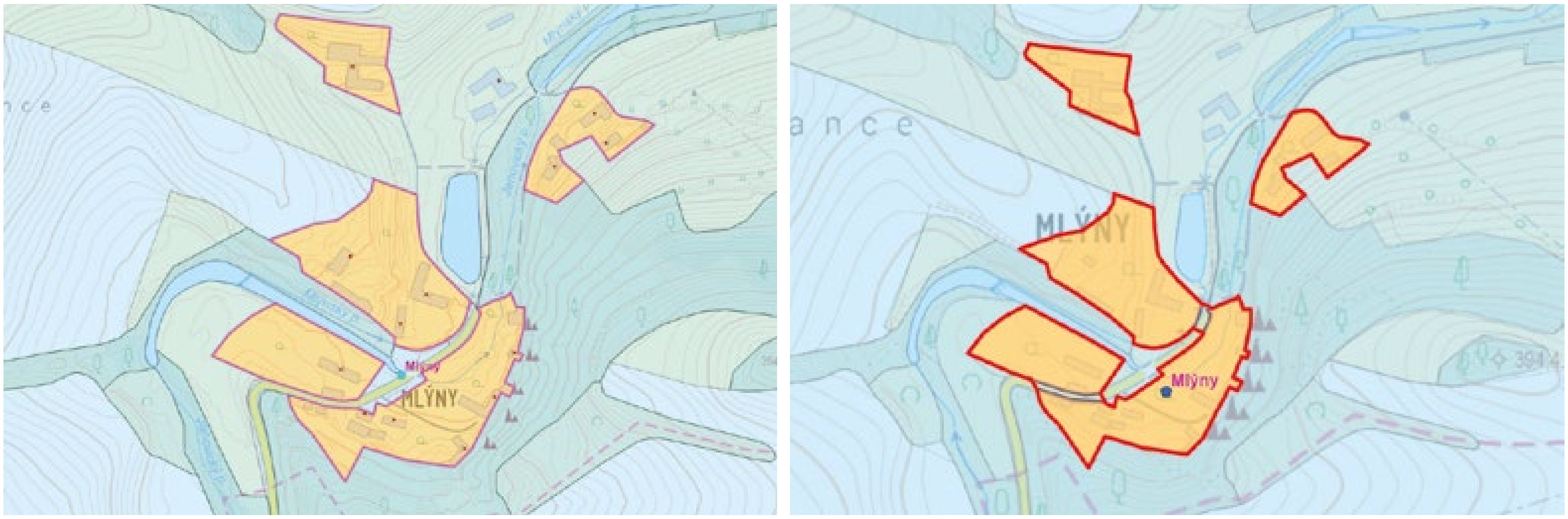


Fig. 9. On the left, separated polygons of the urban area of the Mlýny village with the definition point outside the derived settlement boundaries; on the right, polygons connected by the Aggregate polygons tool and after definition point correction

**Filtering of significant UAs**

As shown in *Fig. 8*, the derived UA layer contains a number of small, isolated polygons outside the main settlements. Compared to large contiguous urban areas, these patches have a negligible impact on the hydrology of the region; therefore, they were filtered out. In the first step, filtering was performed on UA features significant from the perspective of administrative units.

To determine significant UA features, besides size, the presence of a settlement's defining point was also considered. Within ZABAGED, two point features are available: *Defining point of administrative unit* and *Defining point of part of municipality*. The former proved too conservative, as too many compact UAs of significant municipalities would be excluded, so the latter, more detailed feature was used. This object also showed minor flaws, particularly positional inaccuracies – several points were clearly located outside the defined UA boundaries. Since it is a borrowed point layer, the original, more complete data source – the *Part of municipality* layer from the RÚIAN database – was used instead of ZABAGED. Spatial inaccuracies were also found here, with some defining points lying completely outside the delineated UA, with errors of up to hundreds of metres. For points with larger errors (distances from UA layer features), manual position corrections were therefore necessary.

A second complication for filtering insignificant UA features is shown in *Fig. 9*. Some otherwise compact settlements, significant enough to have their own defining point, consisted of several disconnected but nearby polygons in the UA layer, because the commonly used *Other areas in settlements* object was not delineated in the ZABAGED source data. Therefore, before filtering, the Aggregate polygons tool with a threshold of 40 m was applied to merge polygons closer than this threshold. Additionally, all newly formed internal NF gaps up to 1 ha in size, which arose as a result of merging nearby UA polygons, had to be infilled.

For the final filtering, two threshold values were chosen based on the analysis of size and spatial relationships of all UA features defined so far: 1 ha (approximately the area of two football pitches) and 5 ha. All isolated UA features with an area up to 1 ha were classified as insignificant and transferred to the NF layer. All UA features larger than 5 ha are considered significant, even without the presence of a *Defining point of part of municipality*, thus preserving large logistics parks and warehouse complexes. In the category between 1 and 5 ha, at the current stage of the project (methodology validation is ongoing), UA polygons are regarded as significant if they meet at least one of the following conditions:

They contain a *Defining point of part of municipality*.
- A dominant building (church, chateau, etc.) is located within their area.
- They intersect with the sewer layer from the Digital Technical Map.
- A discharge record point (WWTP) is located nearby (within 100 m).
- They are crossed by a first-class road or a motorway.

## CONCLUSIONS

This article presented a methodology for delineating the boundaries of significant urban areas (built-up areas) primarily for hydrological analysis purposes, using Czech open data from ZABAGED. The resulting datasets of natural features and urban areas will be publicly available at rain.fsv.cvut.cz in two versions. The first is a clean version in the form of the final product of significant urban areas as presented above; the second is a broader version that also includes all originally defined urban area patches between 1 and 5 ha in size. These layers are intended primarily for hydrological analyses, especially in relation to assessing risks from surface runoff and pluvial (flash) flooding.

The criteria for filtering small urban areas between 1 and 5 ha may evolve slightly in the future, primarily in connection with the gradual completion of the Digital Technical Map, which is not yet complete for the whole country but is undergoing intensive development.

The vulnerability of individual urban areas to pluvial flooding and soil erosion, as well as the potential impacts of drainage from these areas on the condition of watercourses, are related to the use of surrounding natural areas, their morphology, and technical features (ditches, road networks, etc.) that influence the path of concentrated surface runoff. Equally important are the characteristics of the urban areas themselves, such as the proportion and connectivity of permeable and impermeable surfaces, and the condition of settlement infrastructure. Correct spatial delineation of significant urban areas is a crucial initial prerequisite for assessing these aspects, which are the subject of ongoing research activities.

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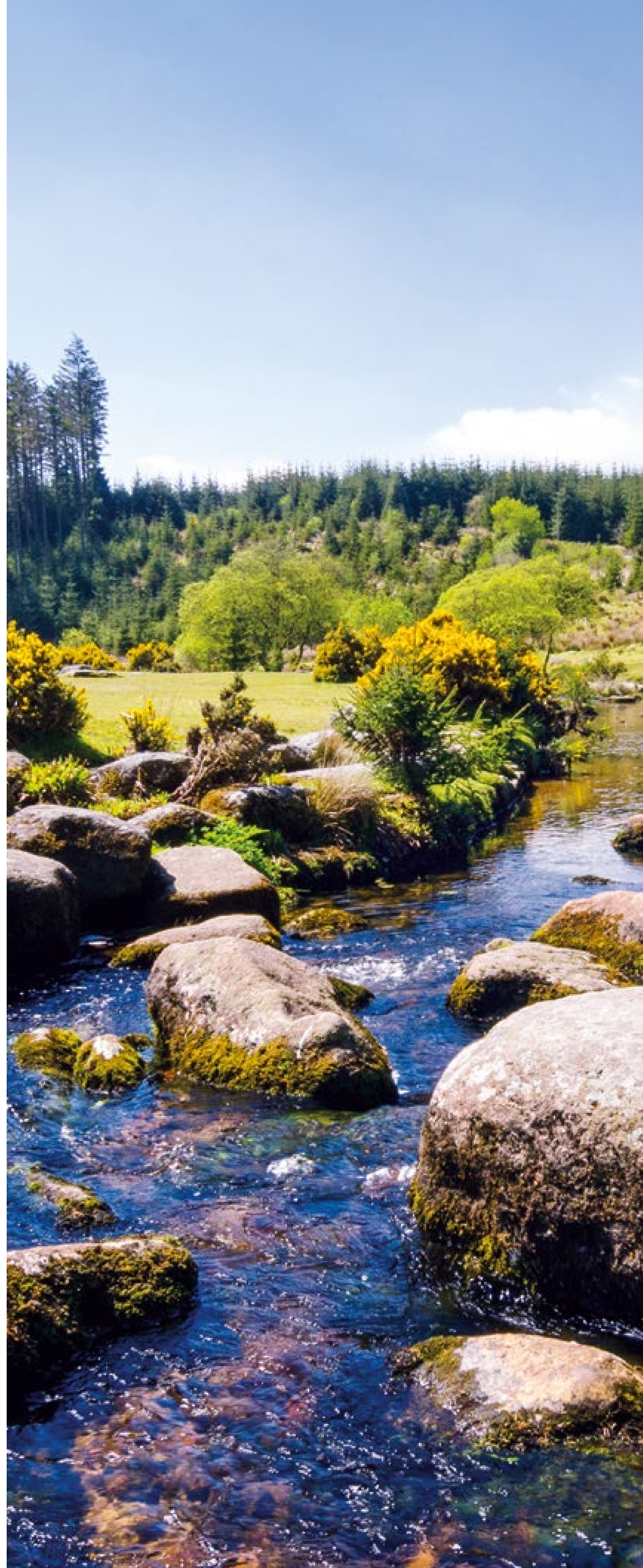


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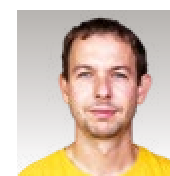


Ing. Luděk Strouhal, Ph.D., completed both his Master's and doctoral studies in Environmental Engineering at the Faculty of Civil Engineering, Czech Technical University in Prague (CTU), defending his doctoral thesis in 2017. As part of his doctoral studies, he spent six months at the University of Zurich in Switzerland. Since 2017, he has been employed in the Department of Hydrology at TGM WRI, p. r. i. He continues to work at CTU as a researcher and co-investigator on a number of projects. His expertise lies in modelling hydrology and erosion processes in small catchments and in experimental research. He is involved in projects such as "*Adaptation of Urban Areas to Flash Floods and Drought*", "*PERUN*", and others.


# Interview with Mgr. Petr Birklen, Director General of the Povodí Odry, state enterprise

At the beginning of March this year, Petr Birklen became Director General of the state enterprise Povodí Odry. How long was the journey to this position and what does it mean to him? How did he cope with the aftermath of the 2024 floods, and how does he manage to fight against misinformation? And will the long-discussed Nové Heřminovy dam finally be built? Mgr. Petr Birklen answers our questions.

**Mr. Birklen, you studied Systematic Biology and Ecology with a focus on Hydrobiology at Palacký University in Olomouc. What was the motivation, or rather, what led you to this field?**

Even as a boy, I was fascinated by two phenomena: the world of living organisms – how the entire complex system functions – and, more specifically, the human body. When I was deciding which path to take after secondary school, studying medicine was my first choice. I am from the strong generation of the 1970's; so the numbers of applicants to study were staggering then, which, combined with my somewhat rebellious years, ultimately led to me not getting accepted to any university. It was a hard blow, but as time had shown, a rather useful one. By chance, I came across a newly opened post-secondary study programme in Ostrava focused on applied ecology. It felt close to my interests, so I gave it a try, planning to use that year for intensive preparation for further admission exams. In the end, my decision proved to be an excellent choice. At that time, the field was just beginning, little was known about it, and there were only a few students enrolled. The lecturers were from the Department of Biology and Ecology at the Faculty of Science, University of Ostrava. There, I encountered personalities such as Zdeněk Ďuriš, Zdeněk Majkus, Jaroslav Ašmera, and Aleš Dolný, who had an absolutely fantastic approach to us. Moreover, since there were so few of us, a great group formed, and we had lots of fun together. This short but intense experience ultimately became a crucial impulse for me to apply to the field of Systematic Biology and Ecology. I began my studies at the University of Ostrava, so I was, in effect, continuing with the same lecturers. I then completed my master's degree at Palacký University in Olomouc.

**After completing your studies, you worked – with a brief break – for more than eight years as the head of the regional office of the Nature Conservation Agency of the Czech Republic (NCA) in Ostrava. What ambitions did you have when you took up this position? Can you recall your first project?**

Although NCA was a career goal for me after graduation, it was not my first work experience. I faced compulsory civilian service, and I set myself the goal of doing something that would not be a complete waste of time and would be useful for my future professional career. At that time, I came to the NCA office in Olomouc and asked if they could use me as a civilian service worker. The head, Jiří Šafář, patiently listened to me but told me to come back after I had completed my civilian service. So, I had to forget about NCA for the time being. However, I found an advertisement in the newspaper for a selection procedure for a water management technician at the Czech Fishing Union office in Ostrava. Boldly, I went there with the condition that if they hired me, they would first have to allow me to complete my civilian service there – which, as I found out, was possible at the Fishing Union. And they actually took me on! Although it was not entirely in line with the civilian service rules at the time, I was immediately able to perform the work of the advertised position. This fulfilled my goal, and I ended up staying there for another two years as an employee. I mention this mainly because it was a crucial experience for my further career. There, I immersed myself in water management practice and, thanks to the area managed (which included the entire Oder basin and partly the Morava basin), I gained detailed knowledge not only of the hydrographic network in the region but also of local specifics. One of my important professional encounters also took place here – with Associate Professor Milan Jařabáč, a forestry and water management researcher who was then a member of the Union's governing bodies. With him, I went on countless field trips and meetings with watercourse managers and designers, which essentially supplemented my water management education. Those years of our cooperation were truly a great learning experience. Only after this first work experience did the offer to work at NCA come – at the Ostrava regional office. When working on the restoration of the Jičínka river, the head of the regional office, Vladimír Mana, approached me to see if I could help with the declaration of Skalická Morávka National Nature Monument and prepare the materials for the management plan. This project thus became my first at NCA, which I began while still an external collaborator. I was soon hired by NCA as a zoologist, and even before I had a chance to settle into the role, I was appointed head of the Ostrava office. That was a big leap for me. At NCA, I then mainly focused on water, river restoration, and the removal of migratory barriers.

**Your professional career has also been connected with the private sector. For over five years, you worked at Ekotoxa, s. r. o. How strongly did you feel this change compared to your previous professional experience?**

Anyone who has experienced such a change will surely agree that the difference between the public and private sectors is truly significant. Although Ekotoxa always had research ambitions and was primarily focused on supporting public administration, it was still a limited liability company that had to sustain itself mainly through contracts – which is not always straightforward in the field of environmental consulting. Until then, I was used to working with an allocated budget and did not have to worry so much about where the money for expenses would come from or how to pay the staff. Suddenly, as executive director, this became my daily routine, and it was essential to understand knowledge and experience as capital that either has current market demand or does not. In simple terms, on one hand it meant constantly thinking about new products based on demand or competition and, on the other hand, managing cash flow – that is, ensuring a steady influx of money into the company. I believe that during our time working together, we managed to achieve a few things, especially in areas I had focused on before, such as at the Ministry of the Environment. I launched products such as the Climate Change Adaptation Strategies and the Territorial Landscape Studies, which we helped the Ministry of Regional Development to set up both methodologically and through the implementation of a pilot project. During my tenure, we were also quite successful in the research field and managed to secure several research projects supported by the Technology Agency of the Czech Republic.

**The next five years or so of your professional life were connected with the regional development agency Moravian-Silesian Investments and Development, a. s. (MSID). Within a few months, you progressed from the position of an environmental expert to company management, with responsibility for the successful implementation of projects. Which projects are you proud of, and which, on the other hand, were not implemented?**

I am undoubtedly proud of the first project, the management of which actually brought me to MSID. It is the ten-year integrated LIFE COALA project, which I came up with together with a friend, and then went on to prepare the funding application. The Moravian-Silesian Region and twelve other partners succeeded in securing a grant for it from the LIFE programme amounting to nearly ten million Euro, which represents sixty per cent of the total costs. The project is still ongoing and to this day remains only the second integrated LIFE project in the Czech Republic and the first to be implemented solely at the regional level. I believe it will help the Moravian-Silesian Region strengthen its climate change resilience and support the broader transformation of our coal-mining region. I am also proud of the POHO 2030 development programme, which I built with my team on the basis of the Post-Mining Area Development Concept for the Karviná region created by my predecessors. One of the region's flagship strategic transformation projects – POHO Park Gabriela – eventually emerged from this programme. It focuses on transforming a former hard coal mine – now a listed cultural monument – into a cultural and educational centre for the Karviná area. The project has obtained planning permission, secured funding of CZK 400 million from the Just Transition Operational Programme, and construction work is scheduled to begin next year. What has not been successful within the POHO 2030 programme, however, is the conversion of two decommissioned hard coal mines into economic zones. This is crucial for the region, as the coal phase out has resulted in the loss of economic activity in parts of the region. It is therefore necessary not only to replace that activity, but also to actively create conditions for the re-development or establishment of new and forward-looking industrial sectors. As far as I know, the newly established state-owned company SIRS is expected to take over these pre-prepared MSID projects and carry them forward. What matters most is that the work was not in vain.

**Since 1 March this year, you have held the position of Director General of the Povodí Odry, state enterprise. As you yourself noted, you took up this position at a crucial time for removing flood damage, implementing flood protection measures, and meeting the schedule for preparing the construction of Nové Heřminovy reservoir. What has been achieved in terms of removing flood damage since you assumed the role of Director General?**

It would be rather presumptuous to speak of any accomplishments after such a short time in the role. I inherited, among other things, an already initiated process of addressing flood damage from my predecessor, including a timetable for the following period, which I am more or less adhering to. There is not much room to speed up the process, but I want to focus in particular on removing potential barriers that could delay preparation and subsequent implementation. This means, above all, intensive cooperation with local authorities and the public, especially landowners in the affected areas. To take it step by step, since last year approximately CZK 240 million has been effectively spent on addressing flood damage. These funds were primarily allocated to urgent stabilisation works wherever necessary, in order to at least provisionally prevent further damage. We have also partly begun the restoration of water management infrastructure. We completed the restoration of damaged embankments in Opava – Palhanec, in Krnov – Kostelec, and at the confluence of the Oder and Opava rivers in Ostrava. Given that the damage to water management assets alone at the Povodí Odry has been estimated at CZK 6.1 billion, we still have a major workload ahead. We are currently cooperating on a flood protection restoration study for selected sections of the Opava and Opavice rivers, which is being prepared by the NCA CR. We will follow up the results, which we will have by the end of July, with design work (*the interview was conducted in May, ed.*). In many places – particularly along the Opava river between Vrbno and Nové Heřminovy – it will probably involve a complete shift in the concept of flood protection towards more semi-natural approaches. Although there will be no such studies at the Bělá and Vidnávka, we will consult with AOPK on the design preparation of the restoration. However, on many watercourses, we have already independently launched the design phase for restoring sections located primarily within built-up areas, which are not covered by the aforementioned study. In these locations, restoration is generally only possible within the original parameters. We are also currently finalising the documentation required to apply for a building permit for the Nové Heřminovy reservoir, including the resolution of property and legal relationships. As part of the complex of measures on the Upper Opava, in addition to the reservoir itself, we are also preparing modifications to the streams below the dam from Zátor to Krnov. Building permits have already been issued for two sections, and documentation for the others is nearing completion. This year, we also plan to launch the design phase for flood protection measures within the town of Krnov – a process that, thanks to an agreement with the town, we are bringing forward by several years.

**Which current flood protection projects are now in the implementation phase, and for which do you anticipate a "ribbon-cutting" ceremony?**

First and foremost, I must mention the flood protection measures in Bohumín–Pudlov. This CZK 400 million project is expected to be completed in 2026. Once the technical measures have been implemented, the built-up areas of the affected site will be protected from flooding during a discharge of 1,555 $m^3/s$, which currently corresponds to a one-hundred-year flood flow on the Oder – with a 0.5 m safety margin. It is also one of the closely watched construction projects that will significantly contribute to the protection of the town of Bohumín. This year, we will be symbolically cutting the ribbon at Baška hydraulic structure, where the reconstruction of the spillway is nearing completion. This CZK 130 million investment will ensure the safe and reliable transfer of extreme flood flows and enable the structure to withstand the impact of a control millennial flood. This hydraulic structure operates as part of the multi-purpose Oder River Basin Water Management System and, with a total reservoir capacity of around 1.1 million $m^3$, it is the smallest reservoir in the Oder catchment. The construction of the Ráj – Karviná weir, with a budget of CZK 94 million, is scheduled for completion by the end of the year. This weir is located in an area affected by mining activity and had deteriorated to the point where it could no longer fulfil its primary function – water abstraction. The reconstruction is co-financed by OKD, which bears responsibility for the damage caused by mining operations.

Launch of the Let's Clean Up the Czech Republic event at the Slezská Harta dam. On the left in the photo is Petr Birklen, on the right is dam manager Petr Poledna (source: P. Birklen archive)

**The zoning decision for the Nové Heřminovy reservoir was challenged by the environmental organisation Děti Země/Children of the Earth, and at the same time, it was necessary to resolve property rights concerning eighteen landowners in the cadastral area of the village. How are you progressing in this area?**

The court's decision is now known. The lawsuit filed by Děti Země was dismissed, thereby eliminating a significant source of uncertainty in the preparatory work for the reservoir's construction. However, for the sake of accuracy, it should be noted that an appeal is still possible – specifically, a cassation complaint to the Supreme Administrative Court, which Děti Země may yet choose to pursue. However, I would like to point out that one thing is the challenged course of the administrative procedure concerning the siting permit for the reservoir – specifically, the way Děti Země's comments were addressed in the challenged decision – and another matter is the actual content of those comments. What I can influence is how we work with these comments, regardless of the current ruling. That is why I met with Mr. Patrik from Děti Země to go over the comments. We agreed that we would work with them in the documentation for the project permit, or subsequently in the construction procedure and the implementation of the construction. As for property settlement, we have reached an agreement on purchase terms with the majority of landowners. Expropriation is probable in only one case; we are continuing negotiations on two others, but we are already dealing with a very specific form of land acquisition. It is also worth mentioning that on 26 April, Nové Heřminovy held a referendum in which the citizens expressed their support for the construction of the reservoir and the associated flood protection measures in the village, effectively removing a long-standing obstacle to further negotiations. I am in close contact with the village management. We need a change to the local development plan, and we will begin preparing compensation measures for the village, the preparation of which was halted around 2010. We have already presented the proposed measures at a public hearing. We have also set up a joint working group involving representatives of the village, citizens and the designer to refine these measures and improve communication.

**The last important point you highlighted upon taking up the position of Director General was the importance of effective communication with village and town authorities. How do you address misinformation in this context?**

Yes, in my view, this is fundamental. It is not some superficial policy, but an absolutely key part of the company's operations that can save a great deal of complications, especially in times of crisis or when pushing through important projects. I will mention only the basic principle here, as the topic is very broad given the scope of the company's activities. It is important to realise that misinformation or incorrect information spreads very easily nowadays because it is often attractive either in form or content. If there is no intelligible and objective alternative, such information becomes the sole source for many and spreads quickly. Then all that remains is to defend oneself, which is usually a disadvantageous position, even though we have support in legislation, technical standards, or some kind of socio-cultural consensus. My goal is therefore to establish the level of information about the company's activities at a standard that will lead to a general awareness of what we do and how the population benefits from it in the long term. To gain public support, so that in times of crisis we have a foundation to build on and can rely on a certain level of understanding that things happen for a reason. I understand that this explanation is rather general, but from my previous experience with such ongoing campaigns, I know its value. We are currently developing this in more detail in the company's new communication strategy we are currently working on, which will help us both with targeting and with the main topics we want to communicate on an ongoing basis.

**To conclude, could you share with our readers where you see your future involvement in water management?**

That is not on my mind at the moment. Right now, I have only one ambition – to work with full commitment for the Povodí Odry, focusing on the tasks I have outlined in response to the previous questions. However, I believe water management must be systematically interconnected with broader environmental aspects, particularly in the context of climate change and other global challenges. Therefore, I consider it natural to continue developing and applying my existing experience and professional expertise in my field.

*Mr. Birklen, thank you for taking the time to speak with us.*

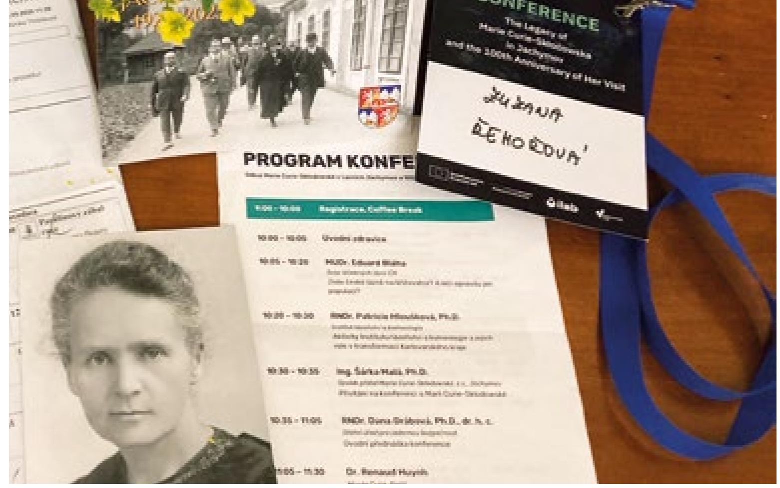
**Ing. Josef Nistler**

## Mgr. Petr Birklen

Mgr. Petr Birklen was born on 27 October 1974 in Opava. After graduating from Mendel Grammar School in Opava, he studied at the Faculty of Science of the University of Ostrava and later at Palacký University in Olomouc, where he specialised in hydrobiology. After completing his studies, he worked for ten years in state nature conservation, where he held the position of head of the Nature Conservation Agency regional office in Ostrava, director of the Department of Landscape Management at the Ministry of the Environment, and later head of the Poodří PLA Administration. After leaving public administration, he served as Executive Director at Ekotoxa, s. r. o., and subsequently held a position on the board of the regional development agency MSID, a. s. He is the author and co-author of numerous projects focused on the sustainable use of the landscape and the impacts of climate change. Since 1 March 2025, he has been the Director General of the Povodí Odry, state enterprise. He currently lives in Ostrava, is married, and has two adult children.


Foto: 123rf.com

# Jáchymov II.: at the right time in the right place




The town of Jáchymov in the Ore Mountains foothills is part of the Karlovy Vary Region and is situated near the border with Germany. As mentioned in this year's April issue of VTEI [1], covering 51 km² and with less than two and a half thousand permanent inhabitants, it is the smallest, and perhaps therefore sometimes neglected, member of the West Bohemian spa family. However, Jáchymov offers a very specific treatment; thanks to the high concentration of radon in the local natural mineral water, the world's first radon spa was established here and is still operating successfully today.

## Glimpses into Jáchymov's History

The story of the Jáchymov region, a landscape lying beneath the massive ridge of Klínovec (*Fig. 1*), began hundreds of millions of years ago, when various ores and minerals flowed into rock fissures and were deposited there in the form of veins. The richness of some of these deposits led early 20th-century regional historians to simplify the past of the landscape into an age of silver and an age of uranium. The former also included the mining of lead, bismuth and cobalt, while the latter encompassed the era of radium.

The growing European market at the end of the 15th century, combined with a shortage of gold coins in circulation, created a kind of "hunger for large silver coinage". [2]. Its minting and entry into the market depended on the quality and quantity of raw material sources. Neighbouring Germany had long excelled in silver mining at that time, but as the reserves of this precious metal were gradually depleted, a "silver rush" began to grow on the Bohemian side as well. The first discoveries of silver in 1512 were almost incredible (the ore veins were very close to the surface and silver was even found in the roots of uprooted trees) and testified to great wealth. At that time, the owner of the Ostrov estate, Count Štěpán Šlik, took over the mining business in the Jáchymov region. He demonstrated the entrepreneurial and diplomatic skills of his ancestors by forming an association of like-minded feudal lords, establishing links with the finance houses in Augšpurk (*now Augsburg, author's note*) and Nuremberg, raising the necessary capital and thus being able to buy the land from the previous owner to lay the foundations for the future mining district. He subsequently invited the best mining experts, and from 1516 onwards, the previously insignificant and unknown settlement of Konradsgrün became a mining town, with its original name gradually disappearing. As a town of several thousand inhabitants, it was then given the noble name Sankt Joachimsthal (St. Joachim's Valley). The explanations given by local chroniclers and historians for the presence of Joachim/Jáchym in the name are more than logical – near the border on the German side, mining towns dedicated to Anna, Joseph, and Mary already existed, so this was essentially a way to complete the Holy Family.

Mining and the associated development of extraction technologies experienced unprecedented growth, which was even reflected in the Šlik family coat of arms (*Fig. 2*). It is estimated that between 1516 and 1554, more than 250,000 kg of silver was mined in Jáchymov [3]. Mining activities were also associated with increased wood consumption, as well as the development of industry and trade. When Jáchymov was elevated to a free mining town in 1520, its permanent population had already reached nearly 5,000. Thirteen years later, the population had grown to 18,000, making Sankt Joachimsthal the second-largest city in Bohemia after Prague and one of the most populous cities in Europe at the time [3].

With the development of the city, trade flourished, and so in 1520, the aforementioned silver coins began to be officially minted here, thanks to Count Štěpán Šlik. Since the Šlik family was of German nationality, the coin was given the Upper German name 'joachimsthaler'. The name was shortened to thaler or taler (in Czech 'tolar'). Cross-border trade flourished in the Middle Ages, with Czech tolars (*Fig. 3*) valued for their high silver content; they reached various parts of Europe and influenced the names of many other coins (e.g. in Poland, Hungary, Italy, and the Netherlands). From there, they made their way to America, where they became known as dollars. Today's American dollars are thus named not only after the Czech currency but directly after the silver tolars of Jáchymov.

The boom years of Jáchymov in the 16th century are still evidenced by the town hall buildings (the original Šlik Palace) and the Mint in the upper part of the town (*Figs. 4, 5*). The Royal Mint is now a museum with a permanent exhibition dedicated to the history of silver mining and coin minting, the city's dark past linked to uranium mines and political prisoner camps in the 1950s, up to the present-day radon therapy. The tour also includes extensive underground passages. Directly opposite the town hall, on today's Náměstí Republiky (Republic Square), stands the still-functioning Krušnohorská Apothecary, which continues the tradition of the original herbal pharmacy. It was founded in 1520 and became the first pharmacy in Bohemia. To this day, it sells only purely natural handmade products from the Ore Mountains (*Fig. 6*).

The deposits of silver-bearing ore in Konstantin mine (*today's Svornost mine, author's note*) (*Fig. 7*) and in other mines gradually diminished, and extraction from ever greater depths became increasingly challenging both technically and financially. Demand for silver on European markets was also slowly declining. Mining activity waned, the mines yielded diminishing returns, and miners began leaving in search of better deposits. The population decreased, and Jáchymov entered a period of decline. It experienced a modest revival in the 18th century, when attention shifted from silver to other metals, especially cobalt, which was used in a local factory to produce colours for glass and porcelain. The town gradually began to come back to life. But the best was yet to come.

## Marie Curie-Skłodowska

Marie Curie-Skłodowska (1867–1934), an extraordinarily gifted and intelligent woman who, despite adversity, attained a university education and became a world-renowned scientist, has become a symbol of Jáchymov's modern history. She was born in Warsaw, which at the time belonged to the Russian part of Poland, as the youngest of five children. She lost her mother at the age of just 12. After finishing secondary school, she yearned for further education, which was, however, denied to women. That is why she attended the so-called 'flying university' (Uniwersytet Latajacy), which, according to historian and Jáchymov patriot Ing. Jaroslav Ochec, meant that the students met in a different apartment each time (*Fig. 8*) [4]. In 1891 she left Poland and moved to Paris, where she continued her studies at the Sorbonne. She was the first woman in history to earn doctorates in

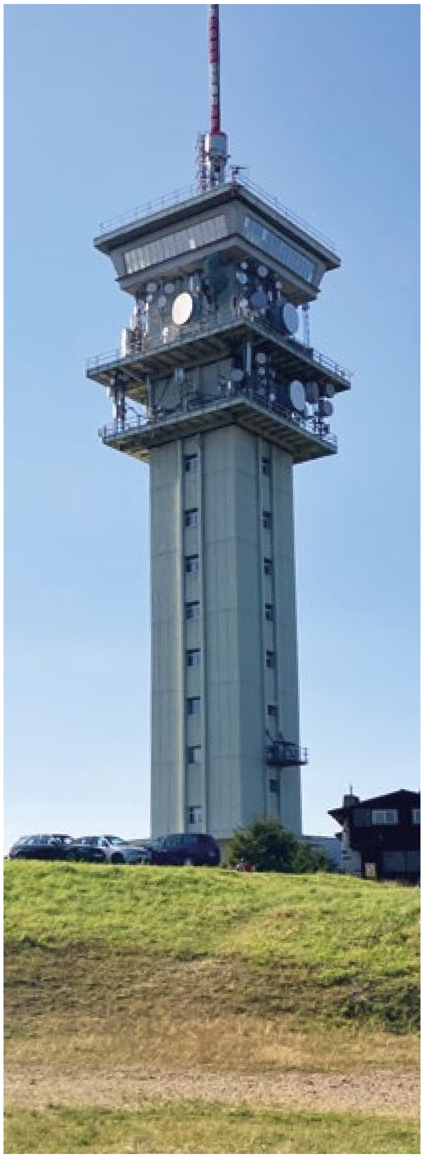


Fig. 1. Klínovec TV transmitter


Fig. 2. Changes in the Šlik family coat of arms

Fig. 3. Jáchymov thalers

Fig. 4. Town hall and museum today


Fig. 5. Emblem of the original Royal Mint


Fig. 6. The first Czech pharmacy was established in Jáchymov

Fig. 7. Svornost mine

Fig. 8. Ing. Jaroslav Ochec after his lecture

Fig. 9. Objects preserved from the time of radon fever


Fig. 10. Model of Josef Prennig's back bucket


Fig. 11. Wooden tubs were used for bathing

physics and chemistry there, later also in mathematics. Her research focused primarily on uranium and radioactivity, and during her work, she met her future husband Pierre, who was then a doctoral student in Henri Becquerel's laboratory, specializing in magnetism. They then worked together, resulting in the discovery of polonium (July 1898), a new element which Marie named after her native Poland. In December of the same year, she discovered another element, the highly radioactive radium. For this achievement, Marie, together with her husband Pierre and colleague Henri Becquerel, won the Nobel Prize in Physics in 1903. And it did not end there. In 1911, the Royal Swedish Academy of Sciences awarded her the Nobel Prize in Chemistry for the isolation of pure radium. This time she received the prize alone, as Pierre had died in 1906.

## Jáchymov pitchblende

But let us go back to Jáchymov. The year 1898, already noted for the discovery of the new elements polonium and radium, also marked the first contact the Curies had with the Czech lands and with Jáchymov. Both elements were isolated from waste material provided to Marie and Pierre by the local uranium pigment factory. After four years of effort, the couple succeeded in obtaining one-tenth of a gram of the newly discovered element, radium. With this historic achievement, they laid the foundations for a new era of human knowledge, and brought the name of the town of Jáchymov to wider attention [2].

Any thoughts of limiting or even shutting down the unprofitable Jáchymov mines were immediately abandoned. As the Curies continued their research, they required increasing amounts of mining waste – first kilograms, then hundreds of kilos, and eventually tonnes. This valuable waste material was pitchblende (uraninite, or uranium oxide), a black mineral that miners, even during the silver rush, referred to simply as 'smolinec' (*from the Czech word 'smůla', meaning 'bad luck', translator's note*). They believed that it was bad luck because, whenever they came across it in the mines, it was clear that the silver vein had ended and only pitchblende was to be found further down. So the pitchblende had to wait more than 300 years for its moment of glory.

Preparations for the industrial production of radium and radium compounds near the raw material source began in Jáchymov relatively soon. The first gram of pure radium was produced at the Jáchymov factory in 1907. Annual production eventually reached as much as five and a half grams of radium, which at the time accounted for a significant portion of the world's supply [2]. Interest in radium grew alongside the unfolding possibilities of its applications. Let us set aside for now the somewhat mad era of the radon craze, when trade in the element was booming and radon, admired for its fascinating radiation, was added to everyday consumer products – such as soaps, perfumes, cigarettes, and ink – long before its harmful effects were understood (see the photo from the international conference on the 100th anniversary of Marie Curie Skłodowska's visit to Jáchymov, taking place in Jáchymov on 12–14 June; *Fig. 9*) [5], and instead turn our attention to its healing properties. These, after all, marked the beginning of a new chapter in the town's history.

## The valley of the 'water of life'

As early as at the beginning of the 16th century, miners were aware of the healing effects of the mining waters in Jáchymov. After work, they would go into the flooded parts of the shafts not only to wash themselves but also to relax, and they soon realised that the mine water had a beneficial effect on their weary bodies and relieved their pain. This is also documented in the writings of their physicians [3].

The first attempts to establish a spa in Jáchymov were very modest. Initially, the local baker Josef Kühn provided bathing facilities in house No. 282 on the square (*now Republic Square, author's note*), where the district physician Dr. Leopold Gottlieb, who had his office in the same house, set up two bathing cabins. Josef Prennig, a retired miner, brought him healing water from the springs discovered in the Werner mine in a covered wooden tub (*Fig. 10*). At that time, it was not yet clear exactly what the bathing process did for these first patients, but the healing power of the 'water of life', as it came to be called, was already unquestionable.

## The world's first

The radioactivity of the mine springs was not scientifically verified until 1905 thanks to the research of the Curies. After that, nothing stood in the way of efforts to build a spa in Jáchymov. In the uranium pigment factory building, space was allocated for additional bathing cabins (*Fig. 11*), which among other things involved constructing a four-kilometre-long pipeline to supply radioactive water to them. It can thus be said that Marie and Pierre Curie were at the birth of the local spa; the official beginning is said to be in 1906. While Pierre tragically died under the wheels of a horse-drawn carriage in April that year, and Marie thus lost not only her colleague but also her husband and father of their two young daughters, Irène and Ève, a small private spa wase established in Jáchymov. And, thanks to the truly unique mineral water enriched with radon, it became the first radon spa in the world.

As the number of spa guests grew, it became necessary to build respectable accommodation for them. The first spa building was the Kurhaus in 1911 (today the central part of the Agricola Spa Centre; *Fig. 12*). The neoclassical building with


Fig. 12. Agricola spa centre


Fig. 13. Forest park with a pond

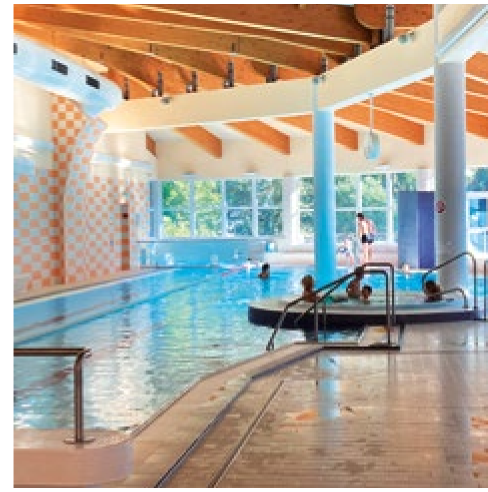


Fig. 14. Pool in Agricola

Fig. 15. Astoria Hotel


Fig. 16. Radium Palace


Fig. 17. Staircase on the hotel ground floor

elements of Viennese Secession (a form of Art Nouveau) was, at the time, the first spa institute of its kind in history. Kurhaus had a capacity of 40 bathing cabins, and a spa forest park was created around it, which to this day stands out for its meticulous landscaping and beautiful secluded spots (*Fig. 13*). Today, the Agricola building has been extended on both sides and serves as an aqua centre and mine themed sauna for the public (*Fig. 14*).


Fig. 18. Richly ornamented balustrades

## The pride of town called Radium Kurhaus

Frenzied construction activity continued, and Jáchymov began to transform into a spa town. Local entrepreneurs were also active, building additional guesthouses and hotels near the first spa building, the most famous of which remains the Astoria Hotel (*Fig. 15*). At the same time, a joint-stock company was established in Jáchymov, bringing together prominent figures from the high aristocracy and Viennese industry, headed by Arnošt Emanuel, Count Silva-Tarouca. In 1912, the grand hotel and sanatorium Radium Kurhaus (*now the Radium Palace, author's note; Fig. 16*) was officially opened, offering patients everything under one roof – accommodation, dining, and spa treatments. With its refined architecture and sensitive integration into the Ore Mountains landscape, it became the pride and symbol of Jáchymov and soon of the entire Ore Mountains region. Equipped with the most modern technical innovations of its time, it was from the outset aimed primarily at wealthier clientele and foreign guests (*Fig. 17*). The very first seasons after its opening promised that the return on investment would come within a few years. In the 1920s, the area in front of the building was redesigned, and an ornately decorated terrace with a colonnade and balustrades was added (*Fig. 18*). Nearby, tennis courts and a woodland café were established. Radium Kurhaus became one of the most luxurious hotels in Europe, attracting numerous world-renowned personalities. Among its guests were British King Edward VIII, Egyptian King Fuad I, German composer and conductor Richard Strauss, and writer Karl May, the creator of Winnetou. Notable Czechs who frequently stayed there included President T. G. Masaryk (after whom the main spa street is still named), Karel Čapek, and later President Václav Havel.

Fig. 19. Photo of Marie Curie-Sklodowska, unpublished in Czech media, taken in June 1925 in front of the Radium Palace Hotel
(a gift to the author from the archive of Ing. Jaroslav Ochec)

Fig. 20. Dr. Dana Drábová


Fig. 21. Ing. Martin Přibil

Fig. 24. Běhounek spa house


Fig. 22. MUDr. Jindřich Maršík, Chief Physician of Jáchymov Spa

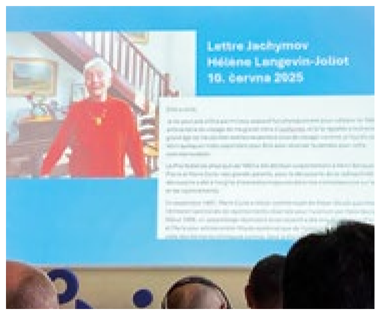


Fig. 23. A letter from the Curies' granddaughter

Fig. 25. Curie spa house

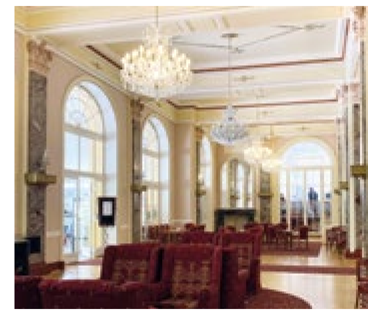


Fig. 26. Radium Palace lobby

However, one world visit is still remembered in Jáchymov today. In June 1925, Marie Curie Skłodowska, who literally stood at the cradle of radium, radioactivity and the unique treatment here, visited the town. After a brief stop in Prague and Lány, where she met President T. G. Masaryk, she arrived in Jáchymov and stayed at the Radium Palace Hotel (*Fig. 19*). She toured the spa and the radiology centre, descended into Svornost mine, and also visited Klínovec. This June marked exactly 100 years since that historic event, and to commemorate the anniversary, the aforementioned international conference was held in Jáchymov [5]. Among the speakers were, for example, Dr Dana Drábová, Chair of the State Office for Nuclear Safety (*Fig. 20*), Ing. Martin Přibil, Head of Svornost mine (*Fig. 21*), MUDr. Jindřich Maršík, MBA, Chief Physician of the Jáchymov Spa (*Fig. 22*), and many other distinguished guests. A letter from Hélène Langevin-Joliot, the 97-year-old granddaughter of Marie and Pierre Curie, was also read out during the conference (*Fig. 23*). Later that evening, a wooden bench engraved with Madame Curie's name was ceremoniously installed in front of the Radium Palace entrance, and two rose bushes bearing Marie's name were planted in the bed in front of the bench. How fitting – when she met President T. G. Masaryk in Lány, the media described their meeting as being "in the right place at the right time". It is as if, here in Jáchymov and at the Radium Palace hotel, the two-time Nobel laureate still lives on.

## New treatment houses

In October 1975 another treatment house was opened in Jáchymov. It was named Academician Běhounek Sanatorium (*now Běhounek, author's note; Fig. 24*) after František Běhounek, a prominent Czech physicist and chemist, who researched radiology and was Marie Curie-Skłodowska's guide during her trip to Jáchymov in June 1925. In July 1992, an institute bearing the telling name Curie was officially opened, significantly transforming the area around the spa crossroads (*Fig. 25*). Both buildings are very modern and also offer their clients everything under one roof – accommodation, dining, and treatments. However, the popularity of the Radium Palace hotel endures, and its interiors (*Fig. 26*) as well as its surroundings still offer the charm of the 'good old days' (*Fig. 27*).


Fig. 27. Part of the summer terrace floor is a chessboard

## Jáchymov radon therapy

What exactly does radon therapy involve? Shouldn't we be afraid of radon? According to the chief physician of Jáchymov Spa, MUDr. Jindřich Maršík, MBA [6], the most important factor is, of course, the dose. While high doses of radiation can have fatal consequences for humans, small doses can actually be beneficial. After all, the entire planet Earth and life on it originated under much higher levels of radiation than today. There are places, such as the geological substratum beneath Jáchymov, where the natural radiation background is higher. However, clients of the Jáchymov spas are not at risk because they typically stay for around two to four weeks. During that time, they receive only a very small dose of radiation, which has a demonstrably positive effect on them. Of course, a potential concern is for the permanent residents of Jáchymov and also for spa workers. Therefore, a very strict system of rules and regulations exists regarding high-quality air ventilation and other necessary measures that directly determine how much radiation dose a person can receive per year. These are followed by radiation protection measures set by the State Office for Nuclear Safety.

In Jáchymov, patients are irradiated only for non-cancerous conditions; cancerous diseases are, on the contrary, a contraindication here. As Chief Physician Maršík explains, "If I were to compare the doses of these two types of irradiation,

Fig. 28. Bathtub for radon bath

Fig. 29. Exercise in the pool

Fig. 30. Masseur Samuel Kolman

for cancer treatment the goal is to destroy the tumour tissue, not to cure it, so the radiation doses are up to sixty times higher than those we use here. Regarding client safety, the only form of radon water application is radon baths, and any negative effects from such small doses of radiation have never been proven. Only the skin may become slightly more sensitive after the baths, for example to sunlight exposure, but all of this disappears after the patients return home."

So how exactly does the treatment work, and what are its positive effects? "Regarding the benefits of our radon baths, numerous studies have clinically confirmed that changes occur from the molecular level to the cellular level to a systemic response in the form of an anti-inflammatory reaction and modulation of the immune response – all the way to the clinical response, where symptoms of the specific disease are alleviated. We now know that changes occur at the molecular level in the DNA, and that these changes are repairable, along with many other alterations that normally happen to DNA, for example, during inflammation or other metabolic processes. These common physiological processes, which we are often unaware of but are actually quite numerous, do not operate at full capacity. By supporting them, we increase their usable potential, and along with the effects we induce, the changes caused by inflammation begin to repair. This response is systemic because the radiation in the water is not localized to one specific tissue but affects the whole body – the so-called open radiator is the bath itself and the water within it. Within this response, there is an effect on the immune system, specifically involving T-lymphocytes and especially cytokines – substances that trigger a whole cascade of anti-inflammatory processes. One of these, frequently mentioned in connection with radon and shown to have increased activity, is TGF-β, which has a strong anti-inflammatory effect. Clinical studies have shown that the statistically significant effect persists for six to nine months after the end of treatment, and this applies to all four groups of our patients – including those with ankylosing spondylitis, rheumatoid arthritis, osteoarthritis, and clients with typical functional back pain. Simply put, our radon therapy has a strong anti-inflammatory effect as well as an analgesic effect, since it simultaneously triggers the release of endorphins," summarises Chief Physician Maršík [6].

Clients at Jáchymov spa receive between 18 and 24 radon baths, with 24 being the maximum allowed dose per year. The first bath lasts 15 minutes, and all subsequent ones last 20 minutes. Baths are conducted from Monday to Saturday in standard bath tubs (*Fig. 28*), with radon present in the form of gas dissolved in the water. The water is warmed to a temperature of 36 °C and must be filled from the bottom to prevent radon from escaping. The radon concentration in each bath is 4.5 kBq/l. To enhance the therapeutic effect, patients remain wrapped in a blanket for 10 minutes after the bath.

In addition to radon baths, patients usually receive bubble or additive baths, dry carbon dioxide baths, pool exercises (*Fig. 29*) and many other treatments depending on the type of illness. An integral part of the therapy are physiotherapy and massage, which, along with radon baths, is one of the finest treatments offered Jáchymov Spa has to offer (*Fig. 30*).

Finally, it is necessary to mention another Jáchymov unique feature, the so-called Jáchymov boxes, also known as brachytherapy (BRT). This involves irradiating the affected area (e.g., a joint, part of the spine, etc.) with ionizing radiation from close proximity. The radiation source used is radium-226. The treatment takes place in the Radiology Pavilion and results in significant pain relief. This therapeutic effect lasts for half a year to a year. Brachytherapy is carried out in only one place in the world – Jáchymov.

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## JAVORNÍK DURING A FLOOD

As part of an occasional series on mills and millraces in the Jeseník region, the current instalment focuses on Javorník, situated on the north-eastern foothills of the Golden Mountains in the Javorník Promontory, at the boundary between the geomorphological subunits of the Travná Highlands and the Vidnava Lowland. The first written mention of the town of Javorník dates back to the late 13th century, when it belonged to the Bishopric of Wrocław under the name *Jawornik*; however, it did not officially attain town status until 1549. The most important – and practically the only significant – watercourse within the built-up area of the town is the Javornický stream. It rises at an elevation of 712 metres in Travná. Historically, it has also been known as *Krautewalde Bach* or *Jauenig Bach*. On Polish territory, under the name *Jaworna*, it joins the Raczyna as a left-bank tributary. After passing through a system of flood-control dykes and canals, the Raczyna flows into the Nysa Kłodzka near the town of Otmuchów. Along the Javornický stream, within the built-up area of the town or in its immediate vicinity, there were four known mills: proceeding downstream, these were Upper Mill, Reinhold's Mill, Lower Mill (located in the immediate vicinity of the proposed site of the new station), and Kunert's Mill. More detailed descriptions and individual mill records can be found at www.vodnimlyny.cz. The photograph illustrates the creation of new channels during the September 2024 flood near the site of Upper Fořt Mill by the road between Javorník and Bernartice.

*Text and photo by doc. RNDr. Jan Unucka, Ph.D.*

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