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

VTEI/2026/3

60 years ago in VTEI

The article *Drinking Water from Sewage*, presented below, was published in VTEI No. 5 in 1966. It is a verbatim transcription of the original text.

The title may appear sensational, but it merely refers to replacing the existing indirect method of water reuse with a direct one. Experts from the United States Department of Health, Education and Welfare concluded that municipal wastewater treated by conventional methods contains 35 times less dissolved salts than seawater, which is in any case readily available at low cost only in coastal areas.

For this reason, pilot-scale experiments on the production of drinking water from sewage are being carried out in the town of Lebanon, Ohio (population 7,000). The capital cost of the experimental installation amounted to 150,000 dollars. A portion of the daily flow, approximately 4,000 m^3 of treated sewage, undergoes further treatment by diatomaceous earth filtration, adsorption on activated carbon, and electrodialysis. Although the water treated in this way is of drinking-water quality, it continues to be discharged into the river. In practice, this process is intended to be applied only in a larger city suffering from a shortage of drinking water, where approximately 40,000 m^3/day could be treated in this way. For such a case, the cost of producing drinking water from sewage is estimated at 0.106 dollars per m^3. The cost of supplying drinking water from conventional sources in the USA is about 0.04 dollars per m^3.

From TGM WRI archives

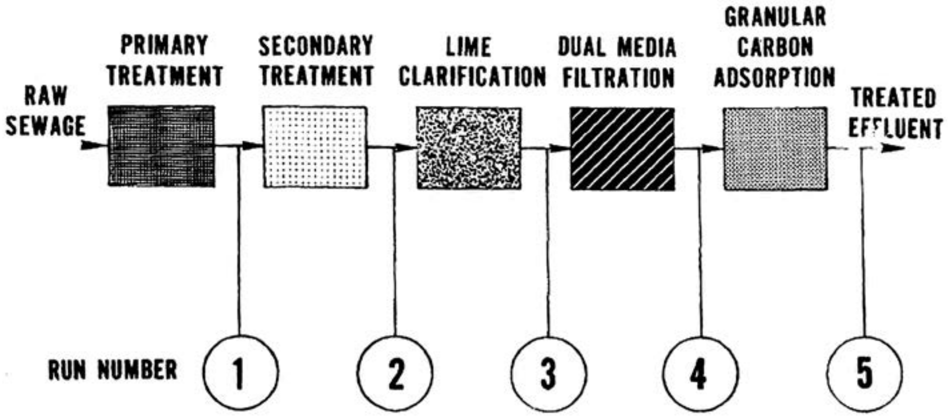

FIGURE 12

SCHEMATIC DIAGRAM OF WASTE STREAMS

LEBANON, OHIO

Content

Photo: J. Unucka

Dear Readers,

The June issue of VTEI is published at a time when water is coming to the forefront from several perspectives – from the landscape and drought to large river systems that connect countries, disciplines, and institutions. June is also associated with two important dates that are worth a brief reflection.

The first is the World Day to Combat Desertification and Drought (17 June), which has a very specific relevance for water management practice. It serves as a reminder that drought is not merely an episode of a hot summer, but also a long-term pressure on water resources, soil, and ecosystems. It also reminds us that true resilience arises from a combination of measures – from working with soil moisture and landscape retention, through the smart management of reservoirs, to realistic planning of abstractions and minimum flows.

The second is Danube Day (29 June), a traditional celebration of one of Europe's largest rivers. The Danube embodies a strong symbol of cooperation across borders and disciplines, while at the same time demonstrating that water regime and water quality are never addressed in isolation in practice. What happens in a catchment will sooner or later manifest itself downstream, whether in terms of precipitation, drought, pollution, or adaptation measures.

It is precisely this linking of connections – from detail to the broader context – that characterises our June issue of VTEI. In the scientific section, we present a diverse set of articles covering water quality, the history of extreme hydrological events, ecotoxicology, reservoir management, and the impacts of climate change.

We begin with a highly practical topic in the field of drinking water. The article by Dana Baudišová (National Institute of Public Health) and Karel Kolář (Pražské vodovody a kanalizace/Prague Waterworks and Sewerage) focuses on the species composition of enterococci in drinking water and on methods of their detection. The text goes to the heart of what constitutes one of the key microbiological indicators in the new legislation, while offering a balanced assessment of the suitability of different methods of determination and the risk of false results.

This is followed by an article by Jan Unucka et al. (CHMI), presenting a reconstruction of the July 1903 flood in the Opava River basin using GIS and hydrological models. It provides an instructive example of working with a heterogeneous mix of historical sources – from flood marks and historical maps to chronicles and eyewitness accounts – as well as of exploring ways to verify and meaningfully integrate them for present-day interpretation.

The third scientific article by Pavla Kovaláková (TGM WRI) bears the telling title Marketing vs. reality and focuses on the acute toxicity of environmentally friendly detergents assessed using a battery of bioassays. Its conclusions serve as a reminder that the label "ECO" does not automatically imply lower acute toxicity of the final mixture, and that experimental verification has an irreplaceable role in assessing real impacts.

Also highly topical is the article by Pavel Fošumpaur and Tereza Kováčová (CTU in Prague), which presents a methodology for the adaptive management of water reservoirs during hydrological drought. The emphasis is placed on combining modelling, climate scenarios, and the optimisation of rule curves so that it is possible to respond flexibly to the development of drought while at the same time minimising the risk of water supply disruptions and adverse impacts on water quality.

The foreign expert article by Imane Belkaf provides a systematic review of rainwater harvesting and floodwater management in rural areas. The paper summarises findings from recent years and demonstrates how important it is to design systems according to local conditions; at the same time, it does not overlook the practical barriers that determine their long-term functionality.

The scientific section of the June issue concludes with an article by Ivana Strnadová et al. (CZU Prague), which addresses the estimation of changes in design precipitation at selected ungauged locations using a geostatistical model of regional frequency analysis and climate projections. It provides important quantifications as well as insight into uncertainties – precisely what is essential for responsible design and the long-term performance of infrastructure.

In the information section, we highlight a topic that has received exceptional attention in recent years: microplastics in the aquatic environment. The article by Barbora Loskotová et al. (TGM WRI) presents the broader context and a significant milestone – the first accredited laboratory for microplastics in the Czech Republic at the TGM WRI.

The issue concludes with a short report by Barbora Sedlářová from the 28th conference *Radionuclides and Ionizing Radiation in Water Management*, held in České Budějovice in April 2026, which presented an overview of current topics in radionuclide monitoring, legislation, and research in the field of water management.

We thank the authors for their high-quality contributions, the reviewers for their time and professional diligence, and our readers for their continued support and feedback, which helps us to further develop VTEI. We wish you inspiring reading and a peaceful summer by the water, with just the right levels in the landscape and in our reservoirs.

For the VTEI Editorial Office
Ing. Josef Nistler

Species composition of enterococci in drinking water and detection methods

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Keywords: intestinal enterococci — drinking water — species composition — sensitivity to free chlorine

ABSTRACT

Intestinal enterococci are one of the two core microbiological parameters in the new drinking water legislation, used as indicators of faecal contamination. They must be detected in all analyses of drinking water. A total of 134 strains of enterococci (*Enterococcus* spp.) and 93 strains identified as background microflora, or as potentially false-positive strains, were examined from operational samples of treated (i.e. drinking) water. Untreated wells and boreholes, which are expected to carry a higher risk of faecal contamination, were not included. The most frequently detected *Enterococcus* species was *E. casseliflavus* (31 %), followed by *E. faecium* (25 %). The most frequent species not belonging to intestinal enterococci was *Aerococcus viridans* (n = 80); however, not all obtained strains survived the first passage. The lowest sensitivity to free chlorine was observed in *E. hirae* and also in the previously mentioned *A. viridans*. All strains were further tested using bile esculin azide medium (BEA test) after 2, 4 and 24 hours of incubation and for β-D-glucosidase (GLD) activity in a selective medium (Enterolert DW, IDEXX). A false-negative BEA test after 2 hours of incubation was recorded in 10 % of enterococci, most often in *E. gallinarum*, *E. casseliflavus*, and *E. durans*. Only 1 % of *Enterococcus* strains showed a false-negative results in the GLD test, but a further 7 strains (5.3 %) showed a weak reaction. A false-positive BEA test after 2 hours of incubation was recorded in 8 % of the background microflora strains, while a false-positive GLD test was observed in 14 % of the strains. The method according to the EN ISO 7899-2 standard is fully suitable for the detection of intestinal enterococci in drinking water. The use of alternative methods based on the determination of β-D-glucosidase activity is less appropriate, as it broadens the group of "intestinal enterococci" to include the entire *Enterococcus* genus, and the detection may therefore not clearly indicate faecal contamination.

INTRODUCTION

The detection of intestinal enterococci may appear straightforward at first glance, but it nevertheless has its pitfalls. On the one hand, intestinal enterococci are, in the new drinking water legislation, one of the two key microbiological indicators of faecal contamination, with the highest parametric value. On the other hand, alternative methods based on the detection of enterococci through β-D-glucosidase activity are gaining ground, extending the target group to all enterococci, i.e. *Enterococcus* spp. However, relatively little is known about the ecology of enterococci, particularly in drinking water, which complicates the interpretation of the results obtained. This study was therefore conducted, and the results were presented at the *Vodárenská biologie 2025 conference* [1]. A revised and extended version is presented here.

OVERVIEW OF THE ISSUE

Intestinal (faecal) enterococci are Gram-positive spherical or ovoid bacteria arranged in pairs or chains and belong to the genus *Enterococcus* (order Lactobacillales, phylum Firmicutes). Advances in molecular genetic methods in taxonomy have led to a continuous increase in the number of described enterococcal species; for example, only 19 species were known in 1995, whereas at present 60 species have been validly described [2]. With the now widely used MALDI-TOF method, individual species can be identified, allowing a more detailed interpretation of the results obtained. For example, among 101 isolates from various surface, technological, and drinking waters, the following species were identified: *E. faecalis* (26.7 %), *E. hirae* (20.8 %), *E. faecium* (18.8 %), *E. casseliflavus* (15.8 %), *E. durans* (11.8 %), and *E. mundtii* and *E. moraviensis* (both 2.3 %) [3].

Intestinal enterococci are regarded as indicators of faecal contamination, and their importance has increased in recent years – under the new legislation [4, 5], together with *Escherichia coli*, they represent a key indicator and must be determined in all types of analysis (both reduced and full). This is associated not only with an increased number of samples analysed, but also with a higher number of positive detections that need to be properly interpreted.

The frequency of detection in drinking water over the past five years in the Czech Republic, based on data from the National Institute of Public Health (Drinking Water Quality Report) [6], is presented in *Tab. 1*. At present, enterococci are the core parameter and its detection is included in all drinking water samples; consequently, the number of analyses, and thus the number of positive detections, is increasing (in *Tab. 1*, a marked difference can be seen particularly between 2023 and 2024). The higher numbers of detected enterococci are mainly associated with the increased number of tests performed. However, as the figures are still relatively low, it will be important to continue monitoring this situation.

There is a substantial body of scientific literature on intestinal enterococci; however, it predominantly consists of studies describing the sources from which particular species have been isolated or the description and characterisation of new species. Where environmental studies do exist, they are primarily focused on surface waters and bathing waters, as well as on sludge and sediments. Studies dealing with a more in-depth investigation of enterococci isolated from drinking water are lacking. Thus, although numerous studies [7, 8] address the question of "who isolated which enterococcus, when, and from where", relatively little is known about their actual ecology, particularly in relation to drinking water, drinking water treatment, and their survival and growth in biofilms.

Although all commonly identified enterococcal species occur in the intestines of humans or warm-blooded animals, a distinction is made between species that are typically faecal (*E. faecium*, *E. faecalis*, *E. hirae*, *E. durans*) and those

Tab. 1. Detection of intestinal enterococci in drinking water in the Czech Republic (categories: > 5 000 population supplied, < 5 000 population supplied, total number of samples analysed, number of positive samples, arithmetic mean and maximum value) in 2020–2024 (CFU = colony forming units)

Year	**> 5 000 population supplied**				**< 5 000 population supplied**			
	Samples analysed	Positive samples	Arithmetic mean [CFU/100 ml]	Max. [CFU/100 ml]	Samples analysed	Positive samples	Arithmetic mean [CFU /100 ml]	Max. [CFU/100 ml]]
2020	4,079	6	0.009	20	9,169	198	0.3	100
2021	4,377	5	0.009	25	9,605	170	0.236	> 150
2022	4,356	15	0.013	12	9,978	222	0.212	> 100
2023	5,778	10	0.024	> 100	10,242	216	0.312	> 100
2024	11,582	57	0.053	> 80	22,340	359	0.211	> 100

associated with possible proliferation on plant material (*E. mundtii*, *E. casseliflavus*) [3]. Enterococci are also frequently used as indicators in microbial source tracking (MST), and various methods for their elimination from the aquatic environment have been described. They are also considered significant carriers of antibiotic resistance (e.g. to vancomycin and ampicillin). In the environment, they often occur in a non-virulent VBNC (Viable But Non Culturable) state.

For the determination of intestinal enterococci in drinking water, the long-established method according to ČSN EN ISO 7899-2 [9] is used. This method includes membrane filtration of samples, incubation for 48 hours at 36 °C on Slanetz and Bartley agar, and confirmation for 2 hours at 44 °C on bile esculin azide agar (hereafter BEA). Intestinal enterococci are defined as red to maroon colonies (*Fig. 1*) that, after subculture on the confirmation medium, show blackening of the medium beneath the colony. This method is intended to detect predominantly enterococcal species of faecal origin (*E. faecalis*, *E. faecium*, *E. durans*, and *E. hirae*). This is also related to the reduction of the confirmation time from four to two hours in 2001, based on the assumption that typical faecal enterococci exhibit faster and more intense BEA activity. More recent methods, which aim to serve as alternatives, are often based on the activity of the enzyme β-D-glucosidase, which enables the detection of all enterococcal species (*Enterococcus* spp.) [10]. This does not appear to be appropriate, particularly because this parameter is not merely an indicator but a key parameter with a limit value (unsurpassable parametric value). On the contrary, a more appropriate approach for improving the interpretation of enterococci results would be to move in the opposite direction, namely towards the identification of individual species.

METHODOLOGY

This study included strains isolated from treated drinking water (but not from wells), obtained over a two-year period from operational hydroanalytical laboratories. The strains were purified, identified using the MALDI-TOF method (with

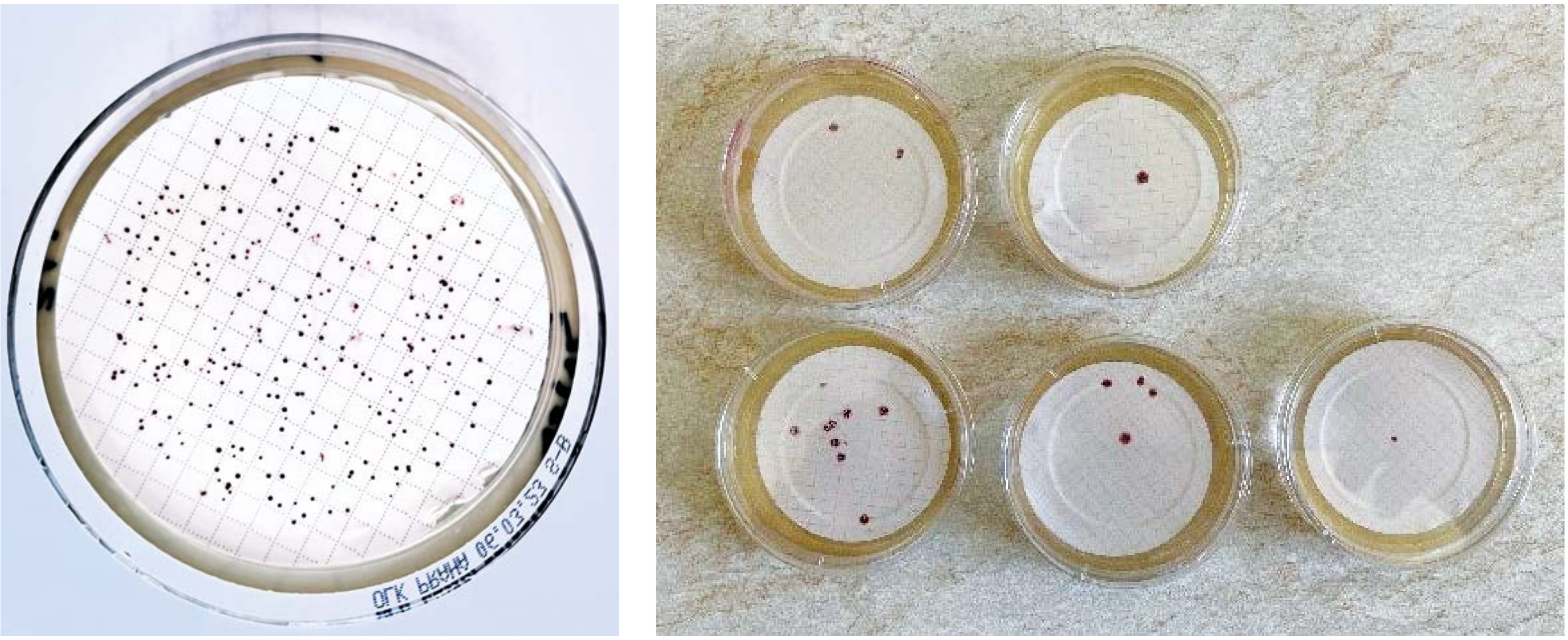

Fig. 1a, b. Left: *Aerococcus viridans*, forming very small (mostly non-blackening) colonies; right: detection of intestinal enterococci the application of formic acid), and the confirmation test was repeated, with results recorded after 2, 4, and 24 hours. In addition, the strains were tested for β-D-glucosidase activity in a selective medium (Enterolert DW, IDEXX; more recently also according to ISO 7899-3 [11]).

Finally, representatives of the most frequently isolated species were tested for sensitivity to free chlorine using a method modified according to Annex 4 of Decree No. 409/2005 Coll. [12]. A solution of sodium hypochlorite was added to a measured volume (1,000 ml) of settled tap water at laboratory temperature to achieve a free chlorine concentration in the range of 0.15–0.17 mg/L. The solution was then artificially inoculated with the tested strains of the genus *Enterococcus*. The initial concentration of the test strain was approximately 10^5 CFU/mL. Before the test, the contaminated water was thoroughly mixed (e.g. by shaking) to ensure uniform distribution of microorganisms. At test intervals of 1, 5, and 30 minutes, 0.5 ml of the prepared solution was inoculated onto the surface of a solid culture medium, and after incubation for 48 hours at (36 ± 2) °C, the colonies grown on the surface were counted. During the test period, the test solution in the flask was continuously mixed. Simultaneously, the original suspension was inoculated to determine the initial number of enterococci. All specified time intervals were tested; however, only the results after 1 minute were evaluated, as the results after 5 and 30 minutes were mostly negative. For each species, a strain isolated from treated drinking water and a strain isolated from the natural environment (bathing water) were tested in parallel, and all assays were performed in duplicate. After incubation, the relative reduction of the tested species (strain) after 1 minute of exposure to free chlorine was calculated in comparison with the control number.

RESULTS AND DISCUSSION

Identification of species

A total of 227 strains isolated in five water management laboratories from drinking (treated) water were processed; of these, 134 were subsequently identified as species belonging to the genus *Enterococcus* (a total of 10 species), while 93 belonged to other genera, with a clear predominance of *Aerococcus viridans*.

The species composition of enterococci and their relative distribution are shown in *Fig. 2*. The most frequently identified species was *E. casseliflavus* (31 %), followed by *E. faecium* (25 %), *E. hirae* (13 %), *E. faecalis* (10 %), and *E. mundtii* (9 %). Enterococcal species considered to be of faecal origin according to ČSN EN ISO 7899-2 [9] (*faecalis*, *faecium*, *hirae*, *durans*) accounted for only 54 %. For comparison, our earlier unpublished results from the identification of 612 enterococci from bathing waters showed that the most frequently identified species was *E. faecium* (25.2 %), followed by *E. faecalis* (21.1 %), *E. durans* (17.3 %), and *E. casseliflavus* (14.4 %). Such datasets can, of course, be compared only to a limited extent; nevertheless, it is evident that different matrices yield different results (unfortunately, the literature cited in the Introduction [3] analysed enterococci from a “mixture of matrices”). That bathing water represents a completely different matrix is also apparent from the composition of the accompanying microflora. According to our previous results, as well as the cited literature [3], the species most frequently interfering with the determination of intestinal enterococci in bathing waters was *Lactobacillus plantarum*, whereas in drinking water the most prevalent species of background microflora was *Aerococcus viridans*.

The high occurrence of *E. casseliflavus* in drinking water cannot yet be reliably interpreted; however, it should be noted that this was not a case of “many strains from a single sample”, as is often observed in bathing waters, but rather a more continuous occurrence. In previously cited studies, this species has often been associated with possible proliferation on plant material. In drinking water, the key question is how it behaves, for example, in biofilms or on sand filters, which is not yet known. In contrast to bathing water samples, where this species may proliferate, for example, on reeds and the membrane filter may then be covered with these (rather small) colonies, in this case overgrown filters were generally not observed. When membrane filters were covered with small colonies, these were exclusively *A. viridans*.

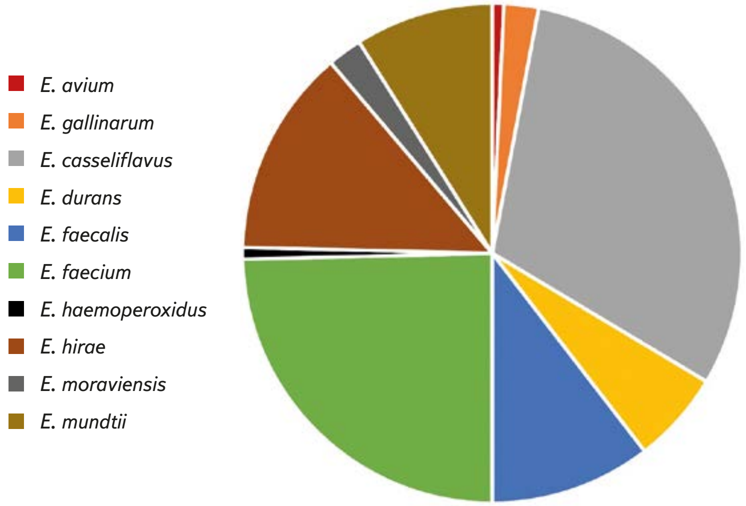

Fig. 2. Occurrence of individual species of intestinal enterococci isolated from drinking water

Confirmation and supplementary tests

The results of the confirmation and supplementary tests for individual species are presented in *Tab. 2*. In addition to the absolute number of positive reactions for strains of individual species, the table also shows the relative proportion of false-positive results (in background microflora) and false-negative results (in enterococci).

According to the current version of ČSN EN ISO 7899-2 [9], the duration of the BEA test is 2 hours, which was taken as the reference time. Additional times (the previously used 4 hours and 24 hours) were tested for the purpose of further discussion of the results. However, the difference between 2 and 4 hours was minimal. A false-negative BEA test (i.e. after 2 hours of incubation) was recorded in 10 % of enterococci, most frequently in *E. gallinarum*, *E. casseliflavus*, and *E. durans*. A false-negative result in the β-D-glucosidase test was observed in only 1 % of enterococcal strains, but a further seven strains (5.3 %) showed a weak reaction. Unfortunately, it is not precisely known how a positive GLD test should appear, as no comparator is available for the Enterolert DW test. A false-positive BEA test (after 2 hours of incubation) was recorded in 8 % of strains of the accompanying microflora; in some strains of *A. viridans*, the positive reaction faded during the subsequent 20 hours. A false-positive β-D-glucosidase test was observed in 14 % of strains.

Sensitivity of enterococci to free chlorine

The most frequently isolated enterococcal species and the most common background species, *A. viridans*, were selected for testing their sensitivity to free chlorine. It is generally accepted that enterococci are less sensitive to the effects of free chlorine than, for example, coliform bacteria, and this is also confirmed by the results of our operational testing of disinfectants (commercial, unpublished data). For each species, two strains were tested (three strains in the case of *E. faecalis*), with one strain always isolated from treated drinking water (and

Tab. 2. Results of additional tests for strains of individual species; the number of strains examined (n), positive results of the BEA test after 2, 4 and 24 hours, and positive results of the β-D-glucosidase (GLD) test. False results (false positives for backround microflora or false negatives in enterococci) for BEA test after 2 hours and for GLD are given separately [%]

		n	BEA 2 h	False results BEA 2 h [%]	BEA 4 h	BEA 24 h	GLD	False results GLD [%]
Aerococcus	*viridans*	80	7	9 %	8	5	12	15 %
Carnobacterium	*maltarum*	2	0	0 %	0	0	0	0 %
Enterococcus	*avium*	1	1	0 %	1	1	1	0 %
Enterococcus	*gallinarum*	3	1	67 %	1	1	2	33 %
Enterococcus	*casseliflavus*	41	34	17 %	34	41	41	0 %
Enterococcus	*durans*	8	6	25 %	8	8	8	0 %
Enterococcus	*faecalis*	14	14	0 %	14	14	14	0 %
Enterococcus	*faecium*	33	30	9 %	33	33	33	0 %
Enterococcus	*haemoperoxidus*	1	1	0 %	1	1	1	0 %
Enterococcus	*hirae*	18	18	0 %	18	18	18	0 %
Enterococcus	*moraviensis*	3	3	0 %	3	3	3	0 %
Enterococcus	*mundtii*	12	12	0 %	12	12	12	0 %
Lactobacillus	*lactis*	1	0	0 %	0	0	1	100 %
Lactobacillus	*plantarum*	1	0	0 %	0	0	0	0 %
Staphylococcus	*pasteuri*	1	0	0 %	0	0	0	0 %
Staphylococcus	*saprophyticus*	5	0	0 %	0	0	0	0 %
Staphylococcus	*warneri*	2	0	0 %	0	0	0	0 %
Streptococcus	*infantarius*	1	0	0 %	0	0	0	0 %

therefore potentially exposed to free chlorine) and the other from a typical natural environment (bathing water). According to legislative requirements [12], enterococci counts must be reduced by at least three orders of magnitude at a free chlorine concentration of 0.3 mg/L. The strains investigated in this study largely met this requirement even at half the concentration of free chlorine (0.15 mg/L). The results are illustrated in *Fig. 3*. The least sensitive species were *E. hirae*, *A. viridans*, and a strain of *E. mundtii* isolated from drinking water (rather than from bathing water), whereas the most sensitive species was *E. durans*. In 25 % of *E. durans* strains, a delayed BEA test reaction was observed (*Tab. 2*), which may be attributed to stress in strains originating from treated water. A certain degree of resistance to free chlorine in *E. hirae* may explain why this species ranked third among the identified strains, and a similar resistance in *A. viridans* may account for its frequent occurrence as accompanying microflora. The most resistant strain, *E. hirae*, is also prescribed for testing the bactericidal properties of disinfectants [13]. Until the final experiment, it appeared that strains from natural environments were more sensitive to the effects of free chlorine (possibly due to the absence of stress?) than strains isolated from drinking water; however, this was clearly not the case for *E. mundtii*, where the opposite was observed.

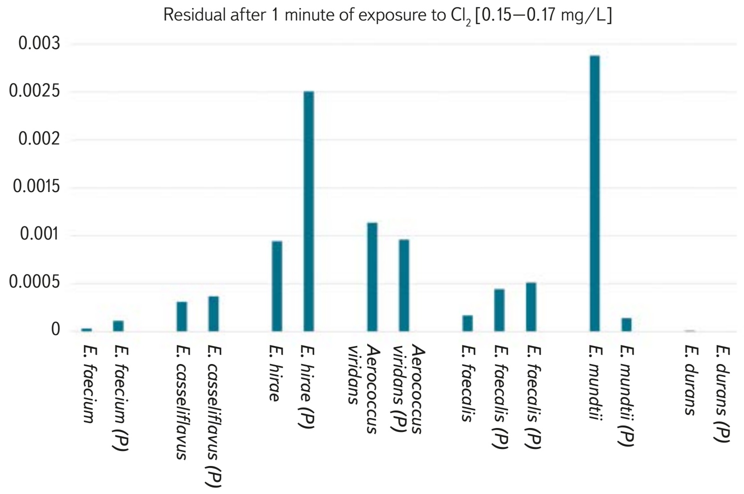

Fig. 3. Sensitivity of different enterococcal species to free chlorine; the strain marked (P) originates from the natural environment

CONCLUSION

Although the "collection of enterococci" lasted at least two years, the number of strains obtained was not particularly high (enterococci = 134 + accompanying microflora = 93). Nevertheless, valuable data were obtained. The most frequently isolated species from drinking water was *E. casseliflavus*, which is usually less abundant and occurs rather sporadically in natural waters. This occurrence cannot yet be fully interpreted; one possible explanation is its ability to survive in biofilms (?). This species has also been associated with the potential for proliferation on plant material. Among the accompanying microflora, the most frequently identified species was *A. viridans*, which, together with *E. hirae*, showed the lowest sensitivity to free chlorine. The method according to ČSN EN ISO 7899-2 is fully suitable for the determination of intestinal enterococci in drinking water. The use of alternative methods based on the determination of β-D-glucosidase (GLD) activity is not entirely appropriate, as it expands the group of "intestinal enterococci" to include *Enterococcus* spp., thereby extending detection to species with an uncertain faecal origin. Moreover, the interpretation of enterococci results would benefit from the opposite approach, namely the identification of strains and interpretation of their occurrence in the environment. In addition, the most frequently detected species of accompanying microflora, *A. viridans*, shows false-positive GLD results in 15 % of cases. Given that this is a key parameter with the highest parametric value, such an expansion of the "group" could lead to complications.

Acknowledgements

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Reconstruction of the July 1903 flood in the Opava River basin using GIS and hydrological models

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ABSTRACT

The 1903 flood was undoubtedly one of the most significant floods of the 20th century in Moravia and Silesia. Although systematic observations of water levels had already begun at many gauging sites during this period, it is difficult to convert historical water levels recorded at limnigraph stations into present-day equivalents due to historical territorial changes in terms of politics (Prussia versus the present-day Czech Republic), landscape structure (forest cover in the historical and present-day landscape), morphology (terrain and urban development in the affected areas), and water management conditions (the course of the Opava river channel and the condition of water flumes in 1903 and today). Useful (though not always entirely reliable) sources include historical flood marks, photographic documentation, historical maps and plans, reports in the contemporary press, family chronicles, and the recollections of millers, sawyers, and other craftsmen using water power. These sources form a rather heterogeneous body of evidence, and it is therefore necessary to find ways to verify and combine them. One possible approach is to use these data in GIS-based spatial analyses and subsequently as inputs for rainfall–runoff and hydraulic modelling. Since the team of the Czech Hydrometeorological Institute (CHMI), together with its partners, had already conducted similar analyses (e.g. during the reconstruction of the 1872 historical flood on Blšanka), they also attempted to apply this approach to the 1903 flood on the Opava river. The results, including a partial uncertainty analysis, are presented in this article.

INTRODUCTION

Reconstructions of historical floods are invariably associated with considerable uncertainty in the available data and, frequently, with the absence of discharge measurements or water-level records. If data on peak water levels can be identified in historical sources or in the field (e.g. flood marks), they represent a valuable – and often the only – source of information. Nevertheless, direct comparisons between peak water levels during historical floods and those recorded in recent decades remain subject to considerable uncertainty. In many cases, urban development and the morphology of floodplain areas have changed to such an extent that these water-level comparisons can only be regarded as approximate. On the other hand, the data and, in particular, the technologies currently available make it possible to reconstruct the course of historical floods. Using GIS-based spatial analyses and hydrological models (rainfall–runoff and hydrodynamic), the Czech Hydrometeorological Institute (CHMI) has already reconstructed the catastrophic historical flood on Blšanka in 1872. For this analysis of the historical flood, available archival materials were used, flood marks were resurveyed (some of which had been incorrectly identified as flood marks), and the possible course of the flood was subsequently reconstructed using rainfall–runoff and hydrodynamic models. One of the important factors is also the consideration of the historical runoff coefficient in the individual sub-catchments, because forest cover and land use in the landscape in 1872 undoubtedly differed from those of today, which also applies to the 1903 flood and others. On the other hand, during extreme rainfall events, the retention capacity of soils and the landscape becomes saturated, the proportion of surface runoff increases, and the influence of land use on runoff magnitude gradually decreases.

These factors were also taken into account in the reconstruction of the 1903 flood in the Opava River basin, with the main focus on the town of Opava. The 1903 flood ranks among the most significant flood events ever to affect the town, including in comparison with the extreme floods of 1997 and 2024. In addition to the Opava basin, floods and the associated damage were documented in virtually all catchments of the Jeseníky Mountains (Bělá, Vidnávka, Desná, etc.), as well as in the Beskydy part of the Odra basin (Ostravice and the right-bank tributaries of the Odra); see, for example, Brázdil, Kirchner et al. (2007) and Brosch (2005). In these analyses, the main objective was to reconstruct as accurately as possible the morphology of the built-up area of Opava and the river channel itself, together with the historical millraces, of which only remnants have survived to the present day. As part of the evaluation of the September 2024 flood, this extreme runoff event was also compared with previous floods. Following this assessment, greater attention was devoted to the 1903 flood as well, since it was among the events that initiated contemporary discussions and plans for Nové Heřminovy water reservoir. Another interesting aspect involved changes in the course of the Opava channel itself and the gradual disappearance of millraces within the built-up area of the town.

Objectives of the study, research questions, and hypotheses

The aim of this study is to quantitatively reconstruct the course of the July 1903 flood in the Opava River basin using a combination of historical sources, GIS-based spatial analyses, and hydrological and hydrodynamic modelling. The study focuses primarily on refining the estimate of the peak discharge of this event, which in the available literature is subject to considerable uncertainty and shows a substantial range of values depending on the methodology used.

A further objective is to verify the applicability of an integrated GIS–hydrological approach for the reconstruction of historical floods under conditions of limited availability of direct hydrological measurements. This approach consists in combining heterogeneous data sources (historical maps, flood marks, archival documents) and using them as inputs for rainfall–runoff and hydrodynamic models.

Another objective is to place the reconstructed event in the context of modern extreme floods in the Opava River basin, particularly the floods of 1997 and 2024, and to assess its relative extremity in terms of peak discharges, flood extent, and impacts on the built-up areas of settlements.

Based on the above objectives, the following research questions are formulated:

1. What was the realistic range of the peak discharge of the 1903 flood at the Opava profile?
2. To what extent is it possible to reconstruct the course of a historical flood with a sufficient degree of reliability by combining historical data with modern modelling tools?
3. To what extent are the modelling results consistent with preserved flood marks and qualitative descriptions of flood extent in historical sources?
4. How does the 1903 flood compare in magnitude and character with the floods of 1997 and 2024?
5. What influence do uncertainties in the input parameters (e.g. land use, infiltration characteristics, channel morphology, and floodplain morphology) have on the reconstruction results?

Based on existing knowledge and available source materials, the following initial hypotheses are formulated and subsequently tested within the study:

1. The peak discharge of the 1903 flood at the Opava profile was significantly higher than values derived using simpler historical calculation methods and lay approximately within the range corresponding to extreme discharges (hundreds of $m^3 \cdot s^{-1}$).
2. The combination of GIS-based spatial analyses, rainfall–runoff modelling, and hydrodynamic modelling (1D/2D) enables a more accurate and physically consistent reconstruction of historical floods than approaches based solely on empirical relationships or simplified hydraulic calculations.
3. The results of the hydrological and hydraulic modelling are broadly consistent with preserved flood marks and the documented extent of flooding and may therefore be regarded as a realistic approximation of the course of the flood.
4. The 1903 flood represented an extreme hydrological event comparable to – or locally even more severe than – the floods of 1997 and 2024 and exceeded commonly considered design discharges.
5. During extreme rainfall episodes and under conditions of high antecedent catchment saturation, meteorological forcing and the morphometric characteristics of the catchment play a dominant role, whereas the influence of differences in land use gradually decreases.
6. Uncertainties associated with the lack of input data can be quantified using stochastic approaches (e.g. Monte Carlo simulations), and these uncertainties significantly influence the resulting range of estimated peak discharges.

The formulated objectives, research questions, and hypotheses provide the framework for the subsequent application of modelling tools and the interpretation of the results of the reconstruction of the 1903 flood.

METEOROLOGICAL SITUATION

The high level of catchment saturation was an important factor in the development of the July 1903 flood. June 1903 had already been very wet in the Odra basin. For example, more than 60 mm of precipitation fell on average during the period from 11 to 16 June alone. As a result, catchment saturation was already considerable by 6 July. Between 6 and 8 July, a wavy cold front extended across Silesia and Moravia further southwards, separating cold air over western Europe from warm air over eastern Europe. In the Jeseníky region, a further approximately 35 mm of precipitation fell during these days, so that by the morning of 9 July the saturation of the local catchments was almost twice the normal level for that time of year.

A cyclone formed along this frontal boundary over northern Italy as early as 7 July and subsequently moved north-eastwards along the so-called Vb track in the following days. On 9 July 1903, it was situated over south-eastern Europe; along its eastern and northern margins, warm and humid air from the eastern Mediterranean flowed over Moravia and Silesia (*Fig. 1*). A northerly wind prevailed in the lower atmospheric layers and was intensified by the strong horizontal pressure gradient between the cyclone and an anticyclone centred over the British Isles. As a result, pronounced orographic enhancement of precipitation occurred, with the precipitation maximum located along the northern edge of Hrubý Jeseník; most of the area where totals exceeded 100 mm is drained into the Odra basin (particularly the Opava, Bělá, and Vidnávka catchments) within present-day Czech and Polish territory. A second anticyclone extending over eastern Europe also played a role by preventing the displacement of the precipitation-producing cyclone.

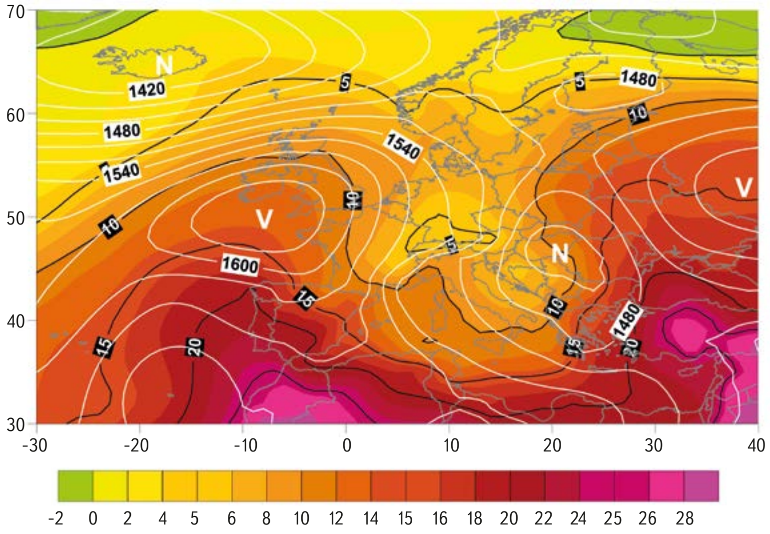

Fig. 1. Synoptic situation on 9 July 1903, expressed by the height of the isobaric level of 850 hPa in gpm (white isohypses) and the air temperature [°C] at this level (colour scale); the letters indicate the cyclone (N) and the anticyclone (V) (source: Wetterzentrale.de)

During this event, 240.2 mm of precipitation – i.e. 240.2 litres per m^2 – was measured at Nová Červená Voda station on 9 July, a total that was not exceeded during the 20th century until July 1997 at Studniční hora in Krkonoše. Until the flood of September 2024, this remained the daily precipitation record for Moravia, Bohemian Silesia, and Jeseníky. This exceptionally high daily precipitation total is remarkable given the low elevation of the station (310 m a.s.l.), which is nevertheless situated in the northern foreland of a mountain ridge whose highest peak, Studniční vrch, reaches 992 m a.s.l. In addition, precipitation totals of 200 mm or more were recorded that day at three other stations: 221.0 mm at Starý Rejvíz (757 m a.s.l.), 217.7 mm at the Šumný potok station (559 m a.s.l.), and 200 mm at Lázně Jeseník (625 m a.s.l.).

The extraordinary flooding was exceptionally destructive, particularly in Jeseníky, where the damage caused was regarded as the greatest in history until 1997. This may be illustrated by two contemporary reactions. "My heart bled at the sight of such a disaster," said the provincial governor, Count Heinrich Larisch-Mönnich, in an emotional opening address to that year's session of the Silesian parliament in Opava. A "view from below" was, among others, captured by the Silesian prose writer Ludmila Hořká (1892–1966) in her short story *Velká voda* [The Great Flood], which depicts the coexistence of villagers with the river: *"And Františka still remembers the great flood of 1903, when boats passed through our village (near Kravaře) as if it were Venice, when water flowed into cottages through the windows, and when two of them collapsed as though made of gingerbread. At that time even the authorities made an effort, sending soldiers to help, and firefighters also arrived from somewhere – but that is useful when there is a fire, and since there was no fire anywhere, they at least extinguished their thirst."*

The 1903 flood from a hydrological perspective in historical and other sources

The flood of 10–11 July 1903 in the Odra basin, which until the July 1997 flood had been the most destructive modern flood event in the region, represented a major natural disaster for this area. It was caused by extremely high two-day precipitation totals. On 9 July, the centre of the precipitation was located in the Hrubý Jeseník region, before shifting to Moravian-Silesian Beskydy on the following day.

Already in the same year, several authors described the situation in Jeseníky in detail, for example *Neu verbesserte Auflage der Hochwasser-Katastrophe am 10. und 11. Juli 1903 in politischen Bezirk Freiwaldau* (1903) [3], possibly [4] or *Landesanstalt für Gewässerkunde* (1904) [5]. The event was subsequently revisited by other authors, including Zeman (1961) [6], Polách and Gába (1998) [7], Štekl et al. (2001) [8], and Řezáčová et al. (2003) [9]. The 120th anniversary of the flood in Jeseníky was commemorated by Halásová (2023) [10].

In the Bělá basin and in the catchments of streams flowing into Kłodzko Nysa, flood marks comparable to those in Opava are not available. An exception is the statue of St Florian in Vidnava, on which flood marks from 1903, 1997, and 2024 can be found. The statue is on the right bank approximately 70 m from the watercourse and about 300 m from Vidnava hydrological station (Vidnávka), which is on the left bank further downstream. It is known that Vidnávka reached peak water levels of 370 cm on 7 July 1997 and 453 cm on 15 September 2024. The flood mark from 1903 is situated between them, indicating that Vidnávka most probably exceeded 400 cm. At that time, however, the river had not yet undergone significant channel regulation, which introduces additional uncertainty into the estimates. The situation is even more complicated on the Bělá, where flood marks documenting individual events are absent. According to the measured data, the Bělá at Mikulovice reached a peak water level of 475 cm on 15 September 2024 and 407 cm on 7 July 1997. For 1903, no measured data are available and it is therefore necessary to rely solely on descriptions of the event in historical sources. Zeman (1961) [6] states that a water level of 598 cm was recorded in Česká Ves at the toll bridge. Other sources refer to a level of just under 6 metres. The present-day hydrological station and the bridge are 8 km apart in a straight line and approximately 11 km apart along the river channel. The water level measured at the bridge may have been influenced by the bridge itself – specifically by its blockage and the resulting backwater effect. Furthermore, it is an indisputable fact that one of the narrowest sections of the Bělá river is located approximately 700 m upstream, which could have significantly affected the water level at the bridge. It is also documented that a breach occurred in the regulation embankment at Stařič, i.e. upstream of the bridge. In view of the above findings and the enormous material damage, it may be assumed that the Bělá river in Mikulovice most probably reached a peak water level exceeding 400 cm in 1903. Whether the level was even higher would require further and more detailed analysis.

If attention is focused on the town of Opava itself, the study by Kříž, Sochorec, and Kříž (1963) [11] probably provides the most detailed analysis of the 1903 flood. The authors focused primarily on hydrological and hydraulic evaluation based on the preserved data available at the time. Given the period in which the study was conducted, it is evident that GIS, mathematical models, and digital data could not yet be used.

Systematic observations of water levels on the Opava began in 1895. Until regulation of the Opava channel and the profile in 1912–1913, the water level on 11 July 1903 remained the highest on record, reaching 525 cm. Using the rating curve valid at the time for the surveyed Pilšťský Bridge profile, the Hydrological Department in Opava calculated a discharge of 454.5 $m^3 \cdot s^{-1}$. The authors of study [11], however, questioned this value and, using a formula for mean cross-sectional velocity with values of 1.7–1.8 $m \cdot s^{-1}$ and a flow area of 138 m^2, proposed a revised peak discharge of 235–248 $m^3 \cdot s^{-1}$. The authors themselves nevertheless emphasised that, at the time of the evaluation, they did not have data on flow areas and velocities for the left and right floodplains, which are essential parameters for the assessment of an extreme flood event. Likewise, in their subsequent calculations, the authors revised the value of the mean cross-sectional velocity during the flood peak from 1.8 $m \cdot s^{-1}$ and, using Manning's equation, proposed revised values in the range of 2.32–3.11 $m \cdot s^{-1}$. Using these values, they proposed a peak discharge in the range of 283–404 $m^3 \cdot s^{-1}$. The mean value of 343.5 $m^3 \cdot s^{-1}$ more or less corresponds to the peak discharge value of 360 $m^3 \cdot s^{-1}$ reported by Brosch [2]. For the 1903 flood, Brosch [2] reports peak discharges of 750 $m^3 \cdot s^{-1}$ for Ostravice / Moravská Ostrava profile, 400 $m^3 \cdot s^{-1}$ for Odra / Svinov profile, and 1,500 $m^3 \cdot s^{-1}$ for Odra / Bohumín profile, where sources describe the event as the greatest flood disaster in the history of the town [4]. In discussing the missing data, the authors also point out the absence of information on water-surface slope within the channel and floodplain areas, which can nowadays be successfully addressed using 1D and 2D hydraulic modelling. Study [8] also employed an approach based on the antecedent precipitation index (API), in which the maximum possible peak discharge derived using this method was estimated at 290 $m^3 \cdot s^{-1}$; however, from the perspective of simulations of this episode using rainfall–runoff models with an adequate API, this value appears to be substantially underestimated. Likewise, it does not correspond to the differences in water levels indicated by the preserved flood marks in Opava. To illustrate the wide range of estimated values, reference may also be made to the conclusions of the team led by Brázdil and Kirchner (2007) [1], as well as the earlier monograph by Brázdil et al. [12], in which the authors interpret the flood peak as corresponding approximately to a Q_{50} event. Such a return period, however, would not have caused the catastrophic damage reported in contemporary sources for the area between Opava and Děhylov.

The overall situation in the town of Opava is further illustrated by reports in the contemporary regional press, for example the newspaper *Grenzbote des nordwestlichen Mährens* [13] (translated from German): *"The situation in Opava was also extremely dangerous. First, Kateřinky (Katharein) was flooded, after which*

Fig. 2. Photo from the 1903 flood in the area of Pekařská street (source: Provincial Archives of Opava, archival number cz227205010//1062//1/2/1/1/2//23+43)

the local fire brigade and volunteer firefighters from Opava intervened. An hour later, the floodwaters also inundated Ratiboř suburb (Ratiborer Vorstadt). A company of the territorial defence force was called in and, together with firefighters, began evacuating residents from houses situated in lower-lying areas by the light of torches and lanterns. On Friday night (10 July), the water level in the Opava had already risen to the bridge, and it was expected at any moment that the river would overflow its banks. At that moment, two additional companies of imperial infantry arrived at the bridge. A third company was dispatched to the sugar refinery in Kateřinky, where the situation had become critical. Water had entered many houses and in some places even covered the ground-floor windows, making the rapid evacuation of endangered residents essential. Many refused to leave their homes and had to be evacuated by force." The newspaper *Deutsches Volksblatt für Mähren und Schlesien* (15 July 1903, No. 56, Vol. 27, p. 4) reported: *"The news from Opava is distressing. It was reported from there on the 12th of this month: Although the water has receded considerably, Ratiboř suburb and the neighbouring municipality of Kateřinky still resemble one vast lake, from which half-collapsed houses, tree trunks, and pieces of furniture protrude. With the assistance of an engineer company that had arrived late the previous evening from Kraków, it proved possible at dawn today to reach those parts of Ratiboř suburb that had until then been completely cut off from the outside world. Among them was Schwarzgasse (Black street), which presented a terrifying scene of suffering. The day before yesterday, water had entered the ground-floor dwellings there with such speed that the inhabitants barely escaped with their lives. Meanwhile, the military authorities organised supply convoys which transported bread, rolls, and milk by pontoon to houses affected by the flood. The first convoy was led by the provincial president, Count Thun-Hohenstein, who also personally participated in the distribution of food, at times standing chest-deep in water. During the course of the day, thirteen houses collapsed in Ratiboř suburb after their foundation pillars had been undermined by water, and many more houses were on the verge of collapse. A man whose identity has not yet been established was killed beneath the ruins of one of the collapsed houses. The greatest disaster currently causing concern is the shortage of water resulting from the flood, which has affected Opava since this morning. As already reported, the waterworks was forced to suspend operations yesterday as a result of the flooding, because its water supplies had been contaminated by infiltrating groundwater. Thus, since this morning the town has effectively been without water. The municipal park and the military shooting range are flooded, the waterworks is under water, and operations had to be suspended. In Kateřinky and Ratiboř suburb, the flood caused extensive damage. Cesspits in the houses were undermined and lifted by the water. Nákladní street (Lastenstrasse) and all the surrounding houses and gardens are completely flooded, while in Pekařská street (Bäckergasse) the water reached as far as 400 paces from Horní náměstí (Oberring). In Parkstraße (the area of present-day Sadová street), one house collapsed. The inhabitants were rescued in time. Many shops and offices had to operate with a greatly reduced number of employees because staff were unable to reach the town. For this reason, and also because the printing works was under water, the newspaper Freie schles. Presse could not be published."* *Lidové noviny* then provided more general information (12 July 1903, No. 157, Vol. 11): *"From Opava: Kateřinky was flooded yesterday. Two additional companies of troops were*

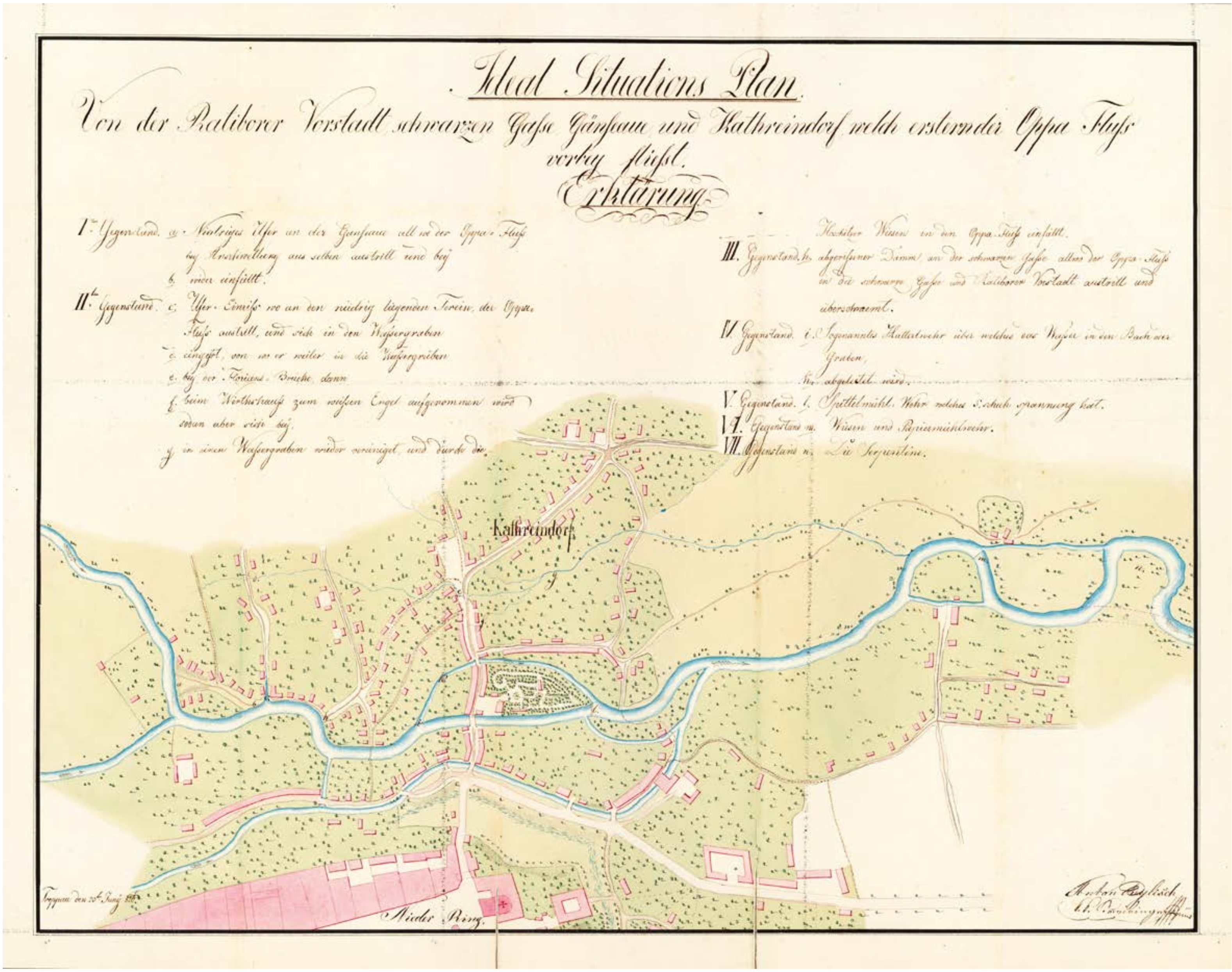

Fig. 3. Site plan of Kateřinky and Racibórz suburb from 1826 (source: Provincial Archives of Opava, archival number 688, inv. No. 50, signature 37/2)

yesterday dispatched to Krnov, which is under water and completely cut off from all railway connections, in order to provide assistance… Yesterday at 4 p.m., railway traffic between Opava and Krnov had to be suspended because the continually rising water had severely damaged the line. At 5 p.m., an attempt was made to dispatch a relief train carrying three battalions of troops to Krnov, but the train was forced to stop at Úvalno station, from where the soldiers had to continue on foot to Krnov. The military command in Opava requested the immediate deployment of engineering corps units from Kraków to the endangered districts. According to incoming reports, the flood had reached dimensions such as had never before been experienced in Silesia. The damage is enormous… 14 July 1903, No. 158, Vol. 159 … *All municipalities along the Northern Railway line from Opava to Svinov are flooded."*

Interesting sources of information are also provided by the recollections of eyewitnesses who were expelled to Germany after the Second World War. Two contributions dealing directly with the 1903 flood in Opava were published in *Troppauer Heimat-Chronik* in 1953 and 1963. According to Franz [14], the water level of the Opava river at the "large bridge" was approximately 1.7 m above normal level. This level was recorded at noon on Friday 10 July. The author lived directly at Ratibořská street No. 40 /Ratiborer Straße 40/ in Opava and, later that same afternoon /10 July/, the water had risen to the height of the shed roof. "*The water, however, was filthy and smelled terrible because it was mixed with the contents of cesspits and manure heaps.*" From the afternoon onwards, the family remained in the attic of the house. Crossing the bridge had already become impossible, since water was flowing across it like a wild river. Nevertheless, on the following morning /11 July/, firefighters were still working on the bridge, attempting to remove beams trapped in the bridge structure in order to clear the passage for the water. The water level inside the house reached a height of 167 cm /on the morning of 11 July/. "*We spent the night before Sunday, 12 July 1903, in relative peace, because the rain had stopped and the water had begun to recede slowly. On Sunday, the municipal building authority and volunteers erected temporary footbridges in the streets. By Sunday evening, the water had receded sufficiently for our*

Fig. 4. Extract from the Imperial Imprint of the Stable Cadastre for Kateřinky and Racibórz suburb (source: ČÚZK)

house to be free of flooding. Every room was covered in mud up to waist height." Franz further notes that the horrors of the floods, which frequently occurred throughout the history of Opava, are still recalled by the unofficial name of Ratiboř suburb: "Nasses Viertel" ("Wet Quarter"). The second eyewitness, Otto Schreiber, lived nearby at Ratibořská No. 30 /Ratiborer Straße 30/. Schreiber [15] describes how the water level rose to just 5 cm below the windows of his room and how his family had to live for several days on the first floor of a neighbour's house. He further notes that this flood, followed by the flood of September 1910, subsequently led to extensive regulation of the Opava river channel.

Historical plans, sketches, and maps constitute an important source of information, particularly regarding the topography of the study area. *Fig. 3* shows a site plan of part of the town of Opava, focusing on Ratiboř suburb and Kateřinky, dating from 1826 (Provincial Archives in Opava). In comparison with the Imperial Imprints of the Stable Cadastre (Moravia and Silesia were surveyed between 1826 and 1836), differences are apparent in the representation of the built-up area of Kateřinky at that time, see *Fig. 4*. Differences in the depiction of buildings are also visible in the Second Military Survey (Moravia and Silesia were surveyed between 1836 and 1840). It is also necessary to take into account the fact that Opava was affected by one of the more significant historical floods precisely in 1826, after which one of the historical regulations of the Opava channel was conducted; further floods subsequently occurred in 1829, 1831, and 1838 [1, 2].

Data and methods for hydrological reconstruction

As already mentioned in the introduction, the main tools used for the reconstruction of the flood were GIS software (ESRI ArcMap, ArcHydro, SAGA GIS, GRASS GIS), rainfall–runoff models (HEC-HMS), and hydrodynamic models (HEC-RAS, MIKE 11/21c). The Imperial Imprints of the Stable Cadastre and the Second Military Survey were the principal sources of information on historical topography and, to some extent, elevation data. Among the most important historical cartographic materials provided by the Provincial Archives in Opava were the *Site Plan of the Town of Opava* from 1826, the *Plan of the Drainage Situation of the Sugar Refinery in Opava* from 1854, and in particular the *Plan der Landeshauptstadt Troppau mit der neuen Wasserleitung und den Stadterweiterungsgründen* by Eduard Labitzke from 1876. After transformation into the S-JTSK coordinate system using control points, these materials were used for the digitisation of the drainage network, specifically the Opava channel itself and the historical millraces. Following digitisation in GIS, these features were converted into the schematic formats required for the DHI MIKE and HEC-RAS hydrodynamic models. The digital terrain model was subsequently incised along the historical course of the Opava channel using the ArcHydro toolset for the ESRI platform and the *r.carve* module in GRASS GIS. The historical millraces were likewise incised into the terrain model; however, readily usable geodetic data describing the channel parameters and diversion structures of these features are not available (parameters of the channels can also be derived from historical water registers; however, this represents a highly demanding

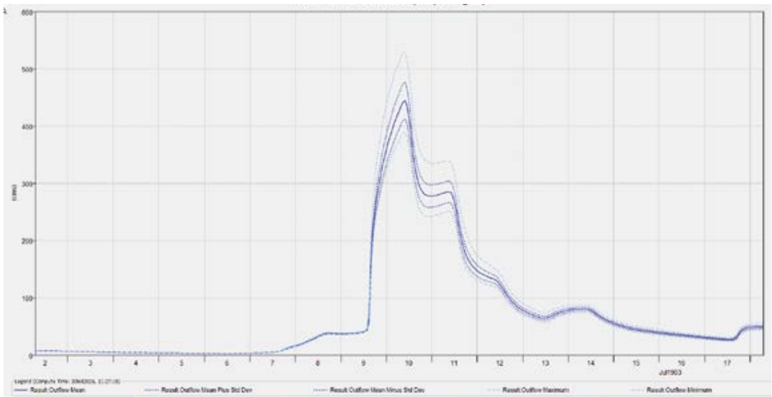

Fig. 5. Comparison of the simulated flood peak of the 1903 flood using the HEC-HMS model for the Opava profile with uncertainty analysis using the Markov chain Monte Carlo method

Fig. 6. Simulated water levels and flood extent in 1D and 2D hydraulic models (HEC-RAS and DHI MIKE) for the peak discharge of 438 $m^3 \cdot s^{-1}$. The red line is the Q_{100} boundary (388 $m^3 \cdot s^{-1}$) for the present-day riverbed and floodplain. The base map is Labitzky's 1876 plan of Opava

task in terms of both archival research and time, which is one of the reasons why this article emphasises the much more efficient possibilities offered by GIS tools). Nevertheless, during such an extreme flood event, the influence of these hydraulic structures on the extent of the inundated area was probably only marginal. Moreover, most of the millraces were situated in the right-bank zone, whereas the most severely affected area, Kateřinky, lies in the left-bank zone. The only exception was a millrace that approximately followed the route of the present-day streets Partyzánská, Holasická, and Na Potůčku.

Sensitivity analysis using the Markov Chain Monte Carlo method was conducted primarily within the HEC-HMS rainfall–runoff model, specifically for the possible ranges of infiltration values, Curve Number (CN) values, and concentration times, which depend both on catchment morphology and land use. In 1903, forest cover in the Opava basin was undoubtedly less extensive than today; therefore, CN values for the individual sub-catchments were set within the range from 65 (forest, HSG A) to 92 (arable land, HSG D), with 250 samples generated for the specified interval range. Because CN values are primarily derived for agricultural soils, values for forest soils in the upper parts of the catchment were derived using nomograms for forested areas; see, for example, Haan et al. [16] and Mishra and Singh [17]. The AMC (Antecedent Moisture Conditions) parameter was not modified because both precipitation totals and the antecedent precipitation index were known. At the same time, conversion equations between the SCS-CN method and the Green–Ampt method (see, for example, Mishra and Singh [17] and Bedient et al. [18]) were used to define the interval range for infiltration velocity.

The results of the HEC-HMS simulations with Markov Chain Monte Carlo sensitivity analysis are shown in *Fig. 5*. For the present-day Opava gauging profile, the peak discharge obtained using the SCS-CN method (and similarly for the Green–Ampt method) ranged from 389 $m^3 \cdot s^{-1}$ to 529 $m^3 \cdot s^{-1}$, with a mean peak discharge of 444 $m^3 \cdot s^{-1}$. This value corresponds relatively well to the peak discharge derived from the historical rating curve (454 $m^3 \cdot s^{-1}$).

The simulations performed in the HEC-HMS rainfall–runoff model were subsequently followed by simulations in the MIKE and HEC-RAS hydraulic models in both 1D (reconstructed course and condition of the channel according to preserved historical sources and maps) and 2D (state of the floodplain areas based on preserved maps and plans). Flood-mark elevations (Ratibořská street and the industrial area on Sadová street) and the extent of inundated areas in comparison with the Q_{100} flood and the floods of 1997 and 2024 were used for verification (*Fig. 6*). In terms of the flood-mark elevation on Ratibořská street, the simulated water level corresponding to a discharge of 438 $m^3 \cdot s^{-1}$ provided the best agreement (*Fig. 7*). If historical sources describing the situation in Kravaře and other settlements further downstream are also taken into account, this value may be regarded as realistic, including in comparison with the evaluated peak discharge of 670 $m^3 \cdot s^{-1}$ for the September 2024 flood (the difference between the flood-mark elevation and the 09/2024 flood level is 23 cm).

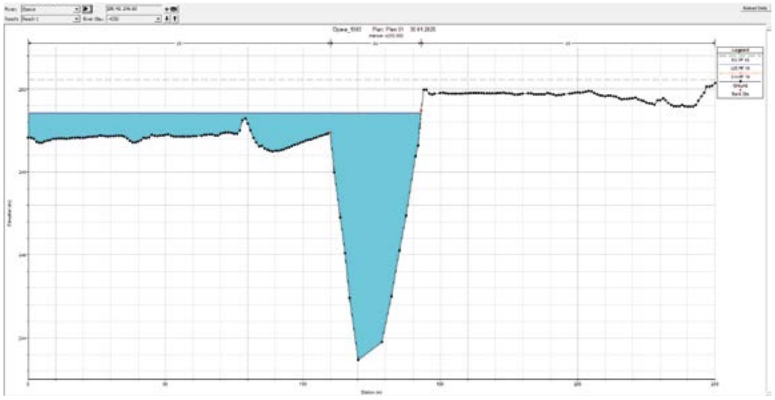

Fig. 7. Simulated water level in the HEC-RAS model for a peak discharge of 438 $m^3 \cdot s^{-1}$ in the area of Ratibořská street. The elevation of the flood mark on building No. 43 is 249.45 m above sea level (own geodetic measurements)

DISCUSSION

The reconstruction of the July 1903 flood in the Opava River basin is, naturally, subject to a range of uncertainties arising primarily from the limited availability of direct hydrological measurements, changes in the morphology of channels and floodplain areas, and substantial transformations in land use from the beginning of the 20th century to the present day. Nevertheless, based on the combination of historical sources, flood marks, contemporary testimonies, and later hydrological analyses, it may be concluded that this was an exceptionally extreme event whose impacts were comparable to – and in some profiles probably even more severe than – those of the floods of 1997 and 2024. The considerable variability in estimated peak discharges for the Opava river reported in the literature illustrates the limitations of traditional calculation approaches based on simplified hydraulic relationships and incomplete data. In particular, neglecting floodplain conveyance and uncertainties in the estimation of mean cross-sectional velocity and hydraulic water-surface slope may have led to underestimation of peak discharges in some studies. Estimates of flood peaks below the Q_{50} level (currently 312 $m^3 \cdot s^{-1}$) are inconsistent both with the documented extent of damage within the built-up area of Opava and in settlements further downstream as far as Děhylov profile, and with the preserved flood marks. Likewise, the peak discharge value of 290 $m^3 \cdot s^{-1}$ reported by Kříž et al. [11] as the minimum estimate within their range of values may also be regarded as underestimated. Modern hydrodynamic modelling tools, which make it possible to explicitly incorporate the morphological and hydraulic parameters of floodplain areas and the numerical solution of flow in 1D and 2D, represent a substantial advance in this respect and offer the possibility of refining historical estimates. Conversely, the combination of extreme precipitation totals, high antecedent catchment saturation, and the historical state of the river network indicates an event approaching extremes with a very low probability of occurrence.

An interesting aspect is the comparison of the 1903 flood with the floods of 1997 and 2024. Although the present-day landscape differs substantially from that of the Opava basin at the beginning of the 20th century – among other things in terms of forest cover, the higher proportion of built-up areas and technical river regulation works, and the presence of water reservoirs on Moravice – the influence of these historical differences gradually diminishes once the infiltration or retention capacity of the landscape is exceeded by extreme precipitation, and surface runoff becomes dominant. Under such conditions, it is more appropriate to focus on the fluvial component of flood dynamics and on the historical state of river channels, the influence of millraces and other historical hydraulic structures, and especially the morphology and transformation of built-up areas within floodplains, which may represent an interesting subject for further research. These factors also support the initial hypothesis that, during such extreme events, the dominant role is played primarily by meteorological forcing together with the morphometric and hydrological characteristics of the catchment.

The results of this discussion also underline the importance of historical floods for present-day water management planning. The 1903 flood played an important role in historical considerations of flood-protection measures, and its more detailed quantitative reconstruction may, among other things, contribute to a more objective assessment of the design parameters of water-management structures and measures, such as Nové Heřminovy reservoir, as well as to a better understanding of the actual flood risk in the Opava River basin.

CONCLUSION

The flood of July 1903 in the Odra and Opava basins undoubtedly represents an extreme hydrological event whose quantitative description is subject to considerable uncertainty arising from the absence of direct discharge measurements, incomplete information on hydraulic conditions, and substantial changes in the morphology of river channels and floodplain areas since the beginning of the 20th century. Nevertheless, the analysis of historical sources in combination with the results of rainfall–runoff and hydrodynamic modelling makes it possible to determine a realistic range of potential peak discharges and the course of the flood wave. The results of the rainfall–runoff simulations confirm the key role of extreme two-day precipitation totals and the degree of antecedent catchment saturation; under such conditions, the retention capacity of soils becomes rapidly saturated and the importance of differences in land use decreases. At the same time, the modelling results show that approaches based exclusively on simple antecedent precipitation indices or simplified empirical relationships frequently lead to errors in the estimation of peak discharges and flood-wave volumes. In this context, hydrodynamic modelling in 1D and 2D environments appears to be an essential tool for the reconstruction of historical floods, since it makes it possible to incorporate floodplain conveyance, the spatial variability of flow velocities, and the influence of local channel constrictions, bridge structures, and historical millraces. These factors may have had a crucial influence on water levels within the built-up areas of settlements during the 1903 flood (particularly in Opava and Kravaře) and help to explain the discrepancy between some earlier discharge estimates and the documented extent of inundation. The modelling scenarios also indicate that the 1903 flood probably exceeded the characteristics of commonly considered design events (e.g. Q_{50}) and approached extremes with a very low probability of occurrence (generally Q_{100} and above). These conclusions are consistent both with the preserved flood marks and with qualitative descriptions of the extent of damage contained in historical sources. Moreover, comparison with the floods of 1997 and 2024 shows that, during extreme precipitation events, catchments exhibit a typologically similar response regardless of differences in present-day land use (through the progressive increase in the proportion, ultimately leading to the complete dominance, of surface runoff within both direct and total catchment runoff), which represents another argument for the importance of hydrological modelling focused on extreme scenarios. In conclusion, it may be stated that the combination of historical data with GIS-based spatial analyses together with rainfall–runoff and hydrodynamic models represents an effective approach to improving the reconstruction of historical floods and to achieving a better understanding of their temporal and spatial characteristics. These findings are of direct relevance for present-day water management planning, particularly for the determination of design discharges, the calibration of extreme scenarios, and the professional assessment of the effectiveness of flood-protection measures in the Opava River basin.

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Marketing vs. reality: using a battery of bioassays to assess the acute toxicity of environmentally friendly detergents

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Keywords: acute toxicity — detergents — surfactants — EU Ecolabel — water flea *Daphnia magna* — bacterium *Vibrio fischeri* — green alga *Desmodesmus subspicatus* — battery of bioassays — environmental risk

ABSTRACT

Household detergents are an important source of complex mixtures of anthropogenic substances entering municipal wastewater systems and, subsequently, receiving waters. This study presents a comparative assessment of the acute ecotoxicity of conventional detergents and their environmentally certified counterparts (EU Ecolabel) using a battery of bioassays representing different trophic levels. The tests included the luminescent bacterium *Vibrio fischeri*, the water flea *Daphnia magna*, the green alga *Desmodesmus subspicatus*, and seeds of white mustard *Sinapis alba*.

The determined EC_{50} values and inhibition levels at a concentration of 100 mg/L revealed substantial variability in the toxic effects of the final formulations, which often did not correlate with the "eco" marketing label. The most notable finding was the high acute toxicity of an environmentally certified laundry gel to algae (72h EC_{50} 3.93 mg/L) and water flea (48h EC_{50} 5.49 mg/L), exceeding the toxicity of the conventional product by an order of magnitude. This effect can likely be explained by the high total surfactant content in the environmentally certified product (up to 50 %) and potential synergistic interactions with additional additives such as enzymes. In contrast, within the shampoo category, the eco-variant (EC_{50} > 100 mg/L) showed lower toxicity due to the replacement of aggressive sulphate surfactants with non-ionic surfactants based on coco-glucoside.

From a methodological perspective, the study confirmed that *Daphnia magna* and *Desmodesmus subspicatus* are the most sensitive bioindicators of detergent exposure, while *Sinapis alba* seeds exhibited considerably higher tolerance to acute exposure. The results highlight the importance of experimental testing of complete product formulations, as the regulatory criteria of the EU Ecolabel, primarily focused on biodegradability, do not necessarily guarantee lower acute toxicity of the mixture. Due to their widespread and continuous use, detergents may behave as pseudo-persistent pollutants in aquatic environments, maintaining a relatively constant toxic pressure on aquatic biota despite the theoretical biodegradability of their individual components.

INTRODUCTION

The use of household detergents represents a continuous source of anthropogenic chemical substances entering municipal wastewater systems and subsequently aquatic receiving environments [1, 2]. These products, including, for example, hand dishwashing detergents, laundry gels, dishwasher tablets, and shampoos, are defined as complex mixtures of intentionally added substances, by-products, and impurities [3, 4]. The dominant components of these formulations are surfactants, which account for approximately 15–40 % of the total mass of the detergent [2, 5]. In addition to surfactants, detergents contain a range of other additives, such as bleaching agents, enzymes, preservatives, and fragrances, which may exhibit their own toxic effects [6, 7].

Although modern wastewater treatment plants (WWTPs) remove common surfactants with high efficiency, often exceeding 90 %, some of these substances and their metabolites may still enter aquatic receiving environments [5, 8, 9]. As a result of the widespread and continuous use of detergents, these substances behave as so-called pseudo-persistent pollutants in the hydrosphere. Although the individual components are biodegradable, their concentrations in the environment remain relatively stable due to the continuous input from municipal wastewater. This phenomenon represents a long-term toxic pressure on aquatic organisms [9]. Exposure to detergents may induce adverse biological responses, particularly through disruption of cell membrane integrity and interference with the metabolic processes of organisms [5, 6, 8, 10].

The environmental risks associated with conventional detergents may be further increased by certain additives. These include, for example, phosphates and phosphonates contributing to the eutrophication of aquatic ecosystems [2, 7], persistent chelating agents such as EDTA, and preservatives belonging to the isothiazolinone group. Other potentially problematic components include enzymes such as subtilisin, which may exhibit high acute toxicity to aquatic organisms [3, 11–14].

In response to the environmental impacts of detergents, the EU Ecolabel certification scheme was introduced in the European Union (Regulation (EC) No 66/2010) [15]. The criteria of this certification are based on scientific principles and focus primarily on the biodegradability of components (both aerobic and anaerobic) and on reducing the overall toxic burden on the aquatic environment through the calculation of the Critical Dilution Volume (CDV). The criteria also include restrictions on or bans of substances of very high concern (SVHCs) and substances with high persistence or bioaccumulative potential.

Despite these regulatory requirements, which primarily focus on the environmental fate of individual components, the marketing label "ECO" may not always directly correlate with low acute toxicity of the final formulation across all trophic levels [5]. Within the EU Ecolabel criteria, substances classified as highly toxic to the aquatic environment are permitted, provided that they comply with the established limits and requirements regarding performance and biodegradability. Moreover, in the complex matrix of the final product, synergistic interactions between surfactants and other additives may occur, potentially modifying the resulting toxic effect beyond the level predicted from the properties of the individual components [5, 16, 17].

To objectively assess the actual impact of detergents on biota, a battery of bioassays representing different trophic levels of aquatic and terrestrial ecosystems was used in this study. The test battery included the luminescent bacterium *Vibrio fischeri*, which represents a standard indicator of microbial toxicity sensitive to a broad spectrum of pollutants. In addition, bacteria fulfil an important role as decomposers of organic matter in aquatic ecosystems. Another test organism used was the green alga *Desmodesmus subspicatus*, a unicellular primary producer sensitive to the lytic effects of detergents and simultaneously susceptible to growth stimulation in the presence of nutrients. Due to their position at the base of the food chain, algae represent a key trophic level in aquatic ecosystems. To assess toxicity at the consumer level, water fleas (*Daphnia magna*) were used, as they are among the most sensitive model organisms for surfactant testing. These planktonic crustaceans constitute an important component of zooplankton and form a significant link in the food chain of freshwater ecosystems. The test battery was complemented by a phytotoxicity test using seeds of white mustard (*Sinapis alba*), which serves as a model indicator of potential risks to terrestrial organisms, for example in the agricultural use of wastewater or sewage sludge.

The aim of the study was to verify to what extent the marketing declaration of environmental friendliness corresponds to the actual impact on aquatic biota. The study tests the hypothesis that certified detergents exhibit lower acute hazard than conventional products, taking into account the synergistic effects of all components present in the tested mixtures.

MATERIALS AND METHODS

Tested substances and sample preparation

Eight commercially available household detergents were tested in the study across four categories (hand dishwashing detergents, laundry gels, dishwasher tablets, and shampoos), each represented by a conventional and an environmentally certified variant. The characteristics of the samples, including pH and composition, are presented in *Tab. 1*. Stock solutions at a concentration of 1 g/L

Tab. 1. Characteristics of tested detergents and their declared composition

Product type	**Ecolabel**	**Composition**	**pH at a concentration of 1 g/L**	**Safety data sheet**
Environmentally certified laundry gel	EU Ecolabel	15–30 % non-ionic surfactants. 5–15 % anionic surfactants. Less than 5 % soap. Contains preservatives (phenoxyethanol), fragrances, and enzymes (subtilisin, amylase, cellulase, mannanase)	7.3	not available
Conventional laundry gel	Conventional	5–15 % anionic surfactants, < 5 % non-ionic surfactants, < 5 % phosphonates, fragrances (hexyl cinnamal), preservatives (2-bromo-2-nitropropane-1,3-diol, methylchloroisothiazolinone, methylisothiazolinone), enzymes	6.1	H319, H412
Environmentally certified dishwasher tablets	EU Ecolabel	5 % or more, but less than 15 %: oxygen-based bleaching agents, polycarboxylates; less than 5 %: non-ionic surfactants; enzymes	9.8	H319
Conventional dishwasher capsules	Conventional	15–30 % oxygen-based bleaching agents, 5–15 % non-ionic surfactants, < 5 % phosphonates, polycarboxylates, enzymes, fragrances, citronellol, limonene, linalool	10.2	H318
Environmentally certified hand dishwashing detergent	EU Ecolabel	5–15 % anionic surfactants; < 5 % non-ionic surfactants, amphoteric surfactants; phenoxyethanol; sodium benzoate; fragrances. Laurylamine dipropylenediamine, benzisothiazolinone, methylisothiazolinone (sodium laureth sulphate 10–25 %, cocamidopropyl betaine 1–3 %, alkyl C10–16 polyglucoside 0.1–1 %)	5	H319
Conventional hand dishwashing detergent	Conventional	contains less than 5 % anionic surfactants, preservatives (2-bromo-2-nitropropane-1,3-diol), fragrance, and colourant	5.5	H319
Environmentally certified shampoo	Certified natural cosmetics*	water, coco-glucoside, glycerin, sodium coco-sulphate, *Helianthus annuus* hybrid oil, xanthan gum, caffeine, inulin, hydrolysed corn protein, sodium PCA, lactic acid, hydrolysed wheat protein, hydrolysed soy protein, levulinate, levulin, sodium acid, sodium salt denat., *Lactobacillus* ferment, *Thymus vulgaris* leaf extract, menthol, sucrose, glucose, fructose, *Piper nigrum* fruit extract, fragrance, limonene, linalool, citral, geraniol, benzyl salicylate	6.1	not available
Conventional shampoo	Conventional	water, sodium laureth sulphate, sodium xylenesulfonate, cocamidopropyl betaine, sodium citrate, fragrance, sodium citrate, cocamide MEA, glycol distearate, piroctone olamine, dimethiconol, sodium chloride, guar hydroxypropyltrimonium chloride, dimethicone, sodium benzoate, TEA-dodecylbenzenesulfonate, sodium salicylate, hexyl cinnamal, linalool, tetrasodium EDTA, sodium hydroxide, trideceth-10, glycerin, niacinamide, panthenol, tocopheryl acetate, acetic acid, benzyl alcohol, triethylene glycol, propylene glycol, CI 42090, CI 17201	5.6	not available

* Natrue.org certification label. Does not contain synthetic fragrances, colourants or preservatives, mineral oil-based substances, genetically modified ingredients, or silicones. A total of 98 % of the ingredients are classified as biodegradable. H318 = Causes serious eye damage; H319 = Causes serious eye irritation; H412 – Harmful to aquatic life with long lasting effects

were prepared by dissolving an accurately weighed amount of the product in demineralised water and subsequently diluted to the required concentration. For the final tests, a logarithmic concentration series starting at 100 mg/L was used. In this study, this value was established as the upper testing limit, as products with EC_{50} values exceeding this threshold are no longer classified as acutely toxic to the aquatic environment according to the Globally Harmonized System (GHS) and the European CLP Regulation. Moreover, testing at higher concentrations lacks environmental relevance, since typical concentrations of surfactants (i.e. the active substances contained in detergents) in municipal wastewater generally reach only 1–10 mg/L and, after passing through WWTPs with high removal efficiency, are further substantially diluted in receiving waters [8, 18, 19].

The pH of the working solutions was adjusted as necessary using 0.1 M NaOH and HCl to a value of 7.5 ± 0.5 in accordance with the validity criteria of standardised test protocols. This step eliminated the influence of extreme acidity or alkalinity of the products, which could otherwise induce a non-specific toxic response independent of the effects of the substances present.

The bioassays were conducted in an accredited laboratory with an implemented quality control system, including regular determination of the toxicity of a reference substance (potassium dichromate) to verify the condition of the test organisms. The results of the reference tests confirmed that the sensitivity of the cultures used complied with the requirements of the relevant standards.

Luminescence inhibition test using *Vibrio fischeri*

Acute toxicity to marine luminescent bacteria was determined according to ISO 11348-2 using the strain *Vibrio fischeri* [20]. The test was performed using the LumiStox 300 measuring system (Dr Lange), comprising an incubation unit and a luminometer. The osmotic pressure of the samples was adjusted by the addition of NaCl to a final concentration of 2 %. Exposure was carried out at a stable temperature of 15 ± 0.2 °C and pH 7.0 for 15 and 30 minutes. The target parameter was the EC_{50} value, representing the concentration causing a 50% reduction in bacterial luminescence intensity compared with the control, calculated from six concentration points within the range of 1–200 mg/L.

Acute toxicity test using *Daphnia magna*

Determination of acute immobilisation of the freshwater crustacean *Daphnia magna* (Straus) was carried out in accordance with ČSN EN ISO 6341 [21]. A total of 20 individuals younger than 24 hours were used for testing. The tests were conducted under static conditions for 48 hours in vessels containing 50 mL of test solution without feeding or aeration. The temperature was maintained within the range of 18–20 °C under a photoperiod of 16 hours of light and 8 hours of darkness. The target parameters were the EC_{50} values after 24 h and 48 h, defined as the concentration of the product causing immobilisation in 50 % of exposed individuals. Five to six concentration levels ranging from 0.1 to 100 mg/L were used for the determination.

Growth inhibition test using *Desmodesmus subspicatus*

To evaluate effects on primary producers, a growth inhibition test using the freshwater alga *Desmodesmus subspicatus* was performed according to ČSN EN ISO 8692 [22]. Exposure was carried out in Erlenmeyer flasks with an initial density of 10,000 cells/mL in ISO culture medium for 72 hours. Cultivation was conducted at a temperature of 23 ± 1 °C under continuous illumination with an intensity of 9,000 ± 1,000 lux and constant stirring. The density of algal cells was measured after 72 hours using a counting chamber. The resulting parameter was the EC_{50} value, expressing 50% inhibition of the specific growth rate of the algal culture, calculated from five concentration levels within the range of 1–100 mg/L.

Phytotoxicity test using *Sinapis alba* seeds

The test using white mustard seeds was performed according to the Methodological Guideline of the Waste Department for the Determination of Waste Ecotoxicity [23]. Seeds (30 per concentration per Petri dish) were placed in duplicate on filter paper in Petri dishes and moistened with 5 mL of the tested solution at the required concentration. Incubation was carried out in a thermostat without access to light for 72 ± 2 hours at a temperature of 20 ± 2 °C. The monitored test parameter was the average root length of white mustard seedlings after 72 hours, from which growth inhibition was calculated.

Calculation of surfactant concentration in the samples

As the product compositions are reported in percentage ranges, the maximum theoretical surfactant load (i.e. a worst-case scenario) was calculated for the purposes of the discussion; however, this calculation represents only a theoretical estimate based on the declarations provided on the product packaging rather than an analytically determined value (*Tab. 1*).

The following equation was used to calculate the surfactant concentration in the tested sample ($C_{surfactant}$):

$$C_{surfactant}\ [mg/L] = EC_{50}\ (product)\ [mg/L] \times surfactant\ content\ [\%]/100$$

Statistical data analysis

The tests were performed in three independent replicates. Statistical analysis included the calculation of mean values and standard deviations. EC_{50} values were calculated using GraphPad Prism (GraphPad Software) by means of a four-parameter logistic curve based on nonlinear regression. The statistical significance of differences between the mean inhibition values of the tested solutions and the negative control was assessed at a significance level of $\alpha = 0.05$ ($p < 0.05$) using Student's t-test.

RESULTS

Validity of bioassays and overall ecotoxicological profile

The results of the EC_{50} determinations (*Tab. 2*) and inhibition at the limit concentration of 100 mg/L (*Tab. 3*) indicate that the sensitivity of the tested organisms to detergent exposure decreased in the following order: the water flea *Daphnia magna* > the alga *Desmodesmus subspicatus* > the bacterium *Vibrio fischeri* > white mustard *Sinapis alba*.

Within the applied battery of bioassays, white mustard (*Sinapis alba*) seeds exhibited the highest degree of tolerance to the tested products. In none of the eight evaluated samples was 50% root growth inhibition reached within the tested concentration range, and all EC_{50} values are therefore reported as > 100 mg/L. According to the GHS and CLP classification standards, the tested

Tab. 2. Results of acute ecotoxicity tests expressed as EC_{50} [mg/L] for selected bioindicators

	Environmentally certified laundry gel	**Conventional laundry gel**	**Environmentally certified dishwasher tablets**	**Conventional dishwasher capsules**	**Environmentally certified hand dishwashing detergent**	**Conventional hand dishwashing detergent**	**Environmentally certified shampoo**	**Conventional shampoo**
DS 72 h	3.93	25.3	73.3	> 100	> 100	> 100	> 100	17.3
DM 24 h	8.39	61.8	75.1	73.5	> 100	> 100	> 100	49.4
DM 48 h	5.49	20.1	76.5	52.3	> 100	> 100	59.5	19.8
SA 72 h	> 100	> 100	> 100	> 100	> 100	> 100	> 100	> 100
VF 30 min	21.5	79.6	>100	> 100	> 100	> 100	> 100	54.5

DS – alga *Desmodesmus subspicatus*, DM – water flea *Daphnia magna*, SA – germination of *Sinapis alba* seeds, VF – bacterium *Vibrio fischeri*.

Tab. 3. Results of acute ecotoxicity tests expressed as inhibitory effect [%] at a concentration of 100 mg/L (mean ± SD)

	Environmentally certified laundry gel	**Conventional laundry gel**	**Environmentally certified dishwasher tablets**	**Conventional dishwasher capsules**	**Environmentally certified hand dishwashing detergent**	**Conventional hand dishwashing detergent**	**Environmentally certified shampoo**	**Conventional shampoo**
DS 72 h	99.0 (±1.27)	93.2 (± 6.16)	89.6 (± 8.80)	14.7 (± 20.1)	24.6 (± 11.3)	4.68 (± 8.12)	-59.5 (± 59.5)	99.9 (± 0.09)
DM 24 h	100 (± 0.0)	70.0 (± 30.8)	100 (± 0.0)	75.0 (± 20.7)	40.0 (± 49.0)	6.7 (± 11.5)	43.3 (± 27.3)	100 (± 0.0)
DM 48 h	100 (± 0.0)	84.0 (± 15.2)	100 (± 0.0)	94.0 (± 8.94)	46.0 (± 50.8)	13.3 (± 23.1)	86.0 (± 11.4)	100 (± 0.0)
SA 72 h	-0.07 (± 4.91)	7.77 (± 3.29)	-12.8 (± 18.3)	-6.17 (± 12.2)	5.48 (± 9.02)	7.03 (± 14.0)	13.0 (± 25.4)	8.18 (± 9.08)
VF 30 min	89.1 (± 0.33)	55.0 (± 1.25)	16.1 (± 3.16)	10.1 (± 0.20)	11.6 (± 6.92)	9.10 (± 6.18)	12.6 (± 5.87)	78.5 (± 1.60)

DS – alga *Desmodesmus subspicatus*, DM – water flea *Daphnia magna*, SA – germination of *Sinapis alba* seeds, VF – bacterium *Vibrio fischeri*.

products therefore do not meet the criteria for classification as acutely hazardous to this indicator from the perspective of phytotoxicity.

At the highest tested concentration of 100 mg/L, a very low mean response was recorded, not exceeding 13 %. Statistical evaluation using Student's t-test demonstrated that the measured values did not differ significantly from the negative control ($p > 0.05$). This lack of statistical significance was primarily due to the higher variability of the measured data, as the standard deviation (SD) values frequently exceeded the mean inhibitory effect.

In half of the tested samples, negative inhibition, i.e. slight stimulation of root growth, was recorded at a concentration of 100 mg/L. The most pronounced stimulatory effect was observed for environmentally certified dishwasher tablets (–12.8 ± 18.3 %) and conventional dishwasher capsules (–6.17 ± 12.2 %). This response is probably related to the nutrient effect of certain components (e.g. phosphonates or plant proteins) at low concentrations, which, in more resistant organisms such as *S. alba*, obscures the difference compared with growth in the control medium.

The observed high tolerance and absence of adverse effects on the initial developmental stages are fully consistent with studies confirming that detergents at common concentrations do not affect seed germination [7, 24, 25]. A study by Uzma et al. (2018) on maize demonstrated that detergents in the range of 1–500 mg/L had no significant effect on germination. Similarly, Khan et al. reported that surfactant concentrations up to 100 mg/L did not affect the germination of lettuce or garden cress. According to the scientific literature, this resistance is attributed to the barrier function of the seed coat, which effectively protects the plant embryo from the penetration of toxic substances from the external environment [25].

Comparative evaluation of products

Laundry gels

The category of laundry gels yielded the most surprising results, with the environmentally certified product (environmentally certified laundry gel) exhibiting significantly higher toxicity than the conventional variant (conventional laundry gel). The environmentally certified laundry gel was classified as highly toxic to both algae (72h EC_{50} 3.93 mg/L) and water fleas (48h EC_{50} 5.49 mg/L), representing approximately a fourfold higher toxic pressure compared with the conventional gel, whose EC_{50} values ranged from 20.1 to 25.3 mg/L. At the limit concentration of 100 mg/L, the environmentally certified laundry gel caused complete immobilisation of water fleas (100 %) as well as inhibition of algal growth (99 %), which, together with the low EC_{50} values, demonstrates the high degree of acute hazard posed by this environmentally certified product.

Shampoos

In the shampoo category, the trend was reversed and confirmed the environmental friendliness of the certified cosmetic product. The environmentally certified shampoo exhibited low acute toxicity, with EC_{50} values above 100 mg/L for most organisms (except for water fleas, 48h EC_{50} 59.5 mg/L), whereas the conventional shampoo was toxic to both algae (EC_{50} 17.3 mg/L) and water fleas (48h EC_{50} 19.8 mg/L).

For the environmentally certified shampoo, growth stimulation of algae (-59.5 %) was observed at a concentration of 100 mg/L, indicating a nutrient effect of the contained plant extracts and proteins (e.g. hydrolysed corn, wheat, and soy proteins). In contrast, the conventional variant contained sodium laureth

Tab. 4. Calculation of theoretical maximum surfactant content in products and normalization of toxicity (EC_{50}) to active ingredient for D. magna

Product type	**Environmentally certified laundry gel**	**Conventional laundry gel**	**Environmentally certified dishwasher tablets**	**Conventional dishwasher capsules**	**Environmentally certified hand dishwashing detergent**	**Conventional hand dishwashing detergent**	**Environmentally certified shampoo**	**Conventional shampoo**
Anionic surfactants [%]	5–15	5–15	not specified	not specified	10–25 (SLES)	< 5	present*	present*
Non-ionic surfactants [%]	15–30	< 5	< 5	5–15	0.1–1 (alkyl polyglucosides)	not specified	present*	not specified
Other surfactants (soap, amphoteric) [%]	< 5 (soap)	not specified	not specified	not specified	1–3 (amphoteric)	not specified	not specified	present*
Total maximum surfactant content [%]	50	20	5	15	29	5	N/A**	N/A**
Concentration of pure surfactants at EC_{50} [mg/L] for *D. magna*	2.75	4.02	3.83	7.85	ND***	ND***	ND***	ND***

* Substances are listed in the ingredient list without percentage ranges. ** For cosmetic products (shampoos), legislation does not require the declaration of percentage ranges of surfactants on the packaging; therefore, the total surfactant content cannot be quantified. *** Cannot be determined.

sulphate (SLES), which contributes to the high inhibition of biota. The literature reports EC_{50} values of SLES for *Daphnia magna* in the range of 2–20 mg/L [26, 27]. The SLES content in the shampoo is unknown, as the legislation does not require the declaration of percentage ranges of surfactants on product packaging and no safety data sheet is available for this type of product (*Tab. 1*, *Tab. 4*).

Dishwasher detergents

Products intended for dishwashers exhibited a moderate degree of toxicity within the applied battery of bioassays, while significant differences in the sensitivity of individual organisms were identified. The most sensitive indicator for this category was the water flea *Daphnia magna*, for which the 48h EC_{50} values ranged from 52.3 mg/L (conventional dishwasher capsules) to 76.5 mg/L (environmentally certified dishwasher tablets). At the limit concentration of 100 mg/L, both products caused almost complete immobilisation of water fleas (94 % for conventional capsules and 100 % for environmentally certified tablets), indicating a high risk to aquatic invertebrates in the event of local overloading of the receiving environment.

A pronounced difference was observed in the effects on the alga *Desmodesmus subspicatus*. While the conventional capsules exhibited only mild inhibition at 100 mg/L (14.7 %), the environmentally certified variant caused strong growth suppression (89.6 %), corresponding to the measured EC_{50} value of 73.3 mg/L. This paradox is noteworthy, as the conventional product theoretically contains a higher load of surfactants (15 %) as well as bleaching agents (15–30 %) than the environmentally certified tablets (5 % surfactants and 5–15 % bleaching agents). The toxicity of the environmentally certified variant is probably influenced by other specific additives acting as stress factors for algae.

For the bacterium *Vibrio fischeri*, acute toxicity was negligible in both samples, with inhibition below 16 % at a concentration of 100 mg/L; consequently, the EC_{50} values were > 100 mg/L.

Hand dishwashing detergents

Hand dishwashing detergents were identified as the most environmentally benign category within the entire study. For all tested trophic levels, the determined EC_{50} values were consistently higher than 100 mg/L, which classifies these products, according to the criteria of the CLP Regulation, as substances with/lout acute hazard to the aquatic environment.

At the highest tested concentration of 100 mg/L, only low levels of inhibition were recorded: the conventional detergent caused only 13.3 % inhibition in water fleas, whereas the environmentally certified variant caused 46 % inhibition. The stronger effect of the environmentally certified detergent may be attributed to the higher declared content of the anionic surfactant SLES (up to 25 %) compared with the conventional sample (< 5 %).

The results obtained for bacteria and algae showed that inhibition ranged from 4.6 to 24.6 % for both product types, with the lowest response recorded for the bacterium *Vibrio fischeri* (9.1–11.6 %).

Statistical evaluation using Student's t-test confirmed that, for most organisms (with the exception of water fleas exposed to the environmentally certified variant), the measured effect at a concentration of 100 mg/L did not differ significantly from the negative control ($p > 0.05$). The results confirm that, despite the presence of substances such as SLES or preservatives (isothiazolinones), the final toxicity of these mixtures is very low owing to dilution in the working solutions.

DISCUSSION

The results of this study demonstrated pronounced differences in acute toxicity among the individual detergent categories, with the most marked effect observed for laundry gels. The environmentally certified laundry gel exhibited an order of magnitude higher toxicity towards the tested aquatic organisms than its conventional counterpart. However, the main factor underlying this increased toxicity was probably not the "ECO" nature of the formulation itself, but rather the high overall surfactant content, which in the environmentally certified variant reached a theoretical maximum of up to 50 %, compared with approximately 20 % in the conventional product (*Tab. 4*).

After recalculation of the EC_{50} values to the concentration of pure surfactants, the toxic profiles of both products became considerably more similar. For *Daphnia magna*, the surfactant concentration at the EC_{50} level reached approximately 2.75 mg/L for the environmentally certified gel and 4.02 mg/L for the conventional variant. This result suggests that surfactants represent the dominant factor determining the acute toxicity of the mixture in both types of formulation. At the same time, this finding confirms that even substances with relatively favourable biodegradability may exert significant toxic pressure on aquatic organisms when present at high concentrations in the final product. Moreover, the measured EC_{50} values approached environmentally relevant surfactant concentrations, which at WWTP effluents generally remain below 1 mg/L [8, 18, 31], although concentrations of anionic surfactants exceeding 8 mg/L have also been reported [18]. According to the literature, chronic toxic effects on aquatic biota may occur at surfactant concentrations as low as approximately 0.1 mg/L, indicating a realistic risk of both acute and chronic toxic effects even under conditions of moderate local overloading of the receiving environment.

Nevertheless, the results of toxicity normalisation to pure surfactant concentrations must be interpreted with awareness of the considerable uncertainty arising from the manufacturers' practice of declaring composition only within broad percentage ranges. The applied estimate (worst-case scenario), based on the maximum possible concentration, may lead to theoretical overestimation of the surfactant load. This lack of transparency regarding the composition of commercial mixtures, combined with the inability to quantify surfactant content in shampoos, confirms that, for water management practice, direct testing of final formulations as a whole represents a more valid approach, as it is the only method capable of capturing synergistic interactions among all additives.

The slightly higher toxicity of the environmentally certified gel, even after recalculation to surfactant content, can probably be attributed to the synergistic effects of additional additives, particularly enzymes. For example, the proteolytic enzyme subtilisin is classified as a substance highly toxic to aquatic organisms (H400), and the literature reports its ability to damage cellular structures even at relatively low concentrations [6]. These results support the assumption that the resulting toxicity of detergent formulations is determined not only by surfactant concentration, but also by complex interactions among the individual components of the mixture.

The necessity of testing final products as complete formulations, rather than only their isolated components, is further confirmed by the paradox observed in dishwasher detergents. In this case, the environmentally certified variant caused strong inhibition of algae (89.6 %), whereas the conventional capsules induced only mild inhibition (14.7 %), despite the fact that the conventional product contained a threefold higher surfactant load (15 % vs. 5 %). This demonstrates that synergistic interactions occur within complex mixtures and may amplify the resulting toxic effect beyond the level predicted from the properties of the individual components.

In the context of discussions on the environmental impacts of detergents, interpretation of the "ECO" label plays a crucial role, as consumers perceive it as a promise of lower toxicity and high biodegradability [5, 27]. Market surveys indicate that more than 50 % of customers are willing to pay extra for such products. Nevertheless, the literature expresses justified scepticism towards marketing claims not supported by independent certification, as the proprietary composition of products often prevents public scrutiny of all contained substances [5].

Despite the stringent regulatory requirements for the award of the EU Ecolabel, which primarily focus on the biodegradability and environmental fate of individual components, the results of this study confirm that environmental certification does not necessarily represent an absolute guarantee of lower acute toxicity of the final formulation across all trophic levels. This finding is fully consistent with the conclusions of Gray (2022), who also documented cases in which "ECO" products were more toxic to aquatic invertebrates than their conventional alternatives [5]. Similar conclusions were reported by Igos (2014), who stated that dishwasher tablets bearing an ecolabel did not exhibit a significant advantage over standard phosphate-free products, with their ecotoxic potential being nearly identical [28].

These findings underline the necessity of testing complete mixtures, as synergistic interactions among permitted additives (e.g. enzymes, fragrances, or preservatives) may modify the resulting toxicity beyond the level predicted from the individual components [6, 16].

The present study primarily focused on the acute ecotoxicity of final formulations, which represents an essential first step in the assessment of environmental risks, although with certain methodological limitations. The main limitation lies in the absence of data on chronic toxicity, which is particularly important for detergents as pseudo-persistent pollutants; long-term exposure to sublethal concentrations in receiving environments may affect the reproduction, growth, and physiological functions of biota in ways that short-term tests are unable to capture [9, 29]. Furthermore, the study did not address the assessment of genotoxicity and mutagenicity, although the scientific literature confirms that complex mixtures of surfactants and specific additives may induce DNA damage or increase micronucleus frequency even at concentrations that do not cause immediate mortality [6, 16, 30]. Additional limiting factors include the insufficiently explored potential for endocrine disruption [31, 32] and the absence of monitoring of the toxicity of biodegradation intermediates, which in some cases may exhibit greater hazard than the parent substances [11, 16]. It should also be noted that only a limited number of products within each category were tested, which may to some extent restrict the generalisability of the obtained results; the observed differences therefore cannot be unequivocally interpreted as a universally applicable trend. Expansion of the test battery to include the above-mentioned aspects will be the subject of a follow-up study, enabling a more comprehensive understanding of the long-term environmental impacts of modern detergents.

CONCLUSION

The results of this study indicate that, for water management practice and environmental risk assessment, it is essential to test final products as complete formulations rather than relying solely on theoretical calculations (e.g. Critical Dilution Volume – CDV) or marketing labels [16]. Experimental data confirm that the "ECO" label cannot automatically be equated with low acute toxicity, which is consistent with the findings of previous studies that also documented cases of higher toxicity of "green" products to aquatic organisms [5]. Although the EU Ecolabel certification guarantees improved biodegradability and restrictions on persistent substances, this benefit does not necessarily imply lower risk to biota in the event of accidental discharge of undiluted products into receiving waters. The main factor influencing toxicity remains the presence of highly concentrated formulations, in which the intrinsic hazard of the mixture is determined by the extreme surfactant load (up to 50 %) and the presence of specific additives that, through synergistic interactions, may damage cell membranes even at low concentrations. The study therefore underlines the critical necessity of using a battery of bioassays to validate manufacturers' environmental claims within regulatory processes, as only direct testing of complex mixtures can capture the actual toxic pressure exerted on aquatic ecosystems [16].

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Methodology for adaptive management of water reservoirs during hydrological drought

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Keywords: adaptive management — water reservoir — hydrological drought — climate change — rule curve — supply reliability

ABSTRACT

This article presents a methodology for the adaptive management of water reservoirs designed to ensure a reliable water supply under conditions of hydrological drought and climate change. The proposed approach combines hydrological modelling, climate change scenarios, and the optimisation of rule curves with regulation levels. The management system allows for flexible restrictions on water abstractions and the adjustment of minimum residual flows depending on the current state of the reservoir. A pilot application of the methodology was carried out on selected Czech reservoirs (Švihov, Klíčava, Žlutice, Obecnice, Pilská, Láz, Vrchlice) under current climate conditions and future scenarios for 2050 and 2100. Hydrological inputs were modelled using the GR4J and CemaNeige models, calibrated on historical data and adjusted for future climate scenarios. The results show that adaptive management significantly increases the reliability of water supply and minimises the risk of severe supply disruptions, while also reducing water level fluctuations in reservoirs, with beneficial effects on water quality. Compared to conventional control based on constant abstractions, this approach enables timely and gradual regulation of abstractions, thereby distributing the effects of drought over time and increasing the robustness of reservoir operation. The proposed framework represents a universally applicable non-structural measure, fully compatible with existing legislation, supporting long-term sustainable water resources management and providing a practical tool for adjusting reservoir management rules.

INTRODUCTION

Hydrological drought represents one of the most significant challenges for water management under Central European conditions. Hydrological drought is characterised by a long-term decrease in streamflow, a reduction in groundwater storage, and limited replenishment of accumulated water resources. Its impacts are particularly pronounced in water supply reservoirs, whose operation is based on the assumption of a relatively stable hydrological regime and long-term statistical stationarity of input series. However, this assumption has been systematically disrupted in recent decades by ongoing climate change.

Projections from regional climate models indicate a gradual increase in air temperature over the Czech Republic, along with changes in the seasonal distribution of precipitation and increased evapotranspiration. These changes are reflected in a decline in average summer streamflow, a more frequent occurrence of multi-year drought episodes, and increased variability in runoff. The extreme period of 2014–2020 demonstrated that even in regions traditionally considered stable in terms of water management, significant declines in water levels in water supply reservoirs may occur, potentially threatening the reliability of water abstractions. From a legislative perspective, the issue of drought adaptation is emphasised, for example, through the implementation of the Water Framework Directive, which highlights the principles of sustainable water resource management and the need for integrated river basin management. At the same time, national climate change adaptation strategies emphasise the need to strengthen the resilience of water management infrastructure to extreme hydrological events. In this context, not only the construction of new water infrastructure but, above all, the optimisation of the operation of existing reservoirs is gaining importance. Traditional operating rules for water supply reservoirs are typically based on fixed abstractions and predefined rule curves, the parameters of which are derived from historical data. Such an approach is relatively robust under stationary climate conditions; however, under a systematic decline in inflows, it may lead to increasing deficit volumes, failure to meet the required reliability of water abstractions, and significant fluctuations in water levels. Pronounced drops in water levels have secondary impacts not only on water supply use but also on the morphology of the littoral zone, the thermal and oxygen regime of the reservoir, and eutrophication processes. Fluctuations in water levels may therefore adversely affect raw water quality and increase the demands placed on its treatment.

The motivation for the present research is the need to develop a methodological framework that enables a flexible response to changing hydrological conditions without the need for costly structural interventions. Adaptive reservoir management represents a promising non-structural measure based on the gradual regulation of abstractions and, where appropriate, the adjustment of minimum residual flows depending on the current state of storage and the expected development of inflows. In addition to increasing the reliability of water abstractions, this approach also has the potential to stabilise water level fluctuations in the reservoir. Gradual and timely restriction of abstractions can prevent deep declines in water levels towards the end of dry periods, thereby limiting the development of undesirable physico-chemical and biological processes affecting water quality. The aim of this research is to develop and validate a methodology for the adaptive management of water supply reservoirs during hydrological drought, based on a combination of hydrological modelling, climate change scenarios, and the optimisation of operating rules. The specific objectives are: (1) to quantify the impacts of future climate scenarios on the reliability of water abstractions; (2) to design a system of regulation levels and rule curves enabling the gradual restriction of abstractions; and (3) to compare the effectiveness of conventional and adaptive operational regimes in terms of both supply reliability and water level stability. The expected outcome is a methodological tool applicable to various types of water supply reservoirs, supporting long-term sustainable water resources management under conditions of intensifying hydrological drought and contributing to the stabilisation of the internal environment of reservoirs in terms of water quality.

CURRENT STATE OF KNOWLEDGE

Adaptive reservoir management is addressed in the scientific literature as a response to increasing hydrological uncertainty driven by climate change, variable streamflow, and the growing frequency of multi-year drought periods. Traditional approaches to reservoir operation, which maintain constant operating rules derived from historical hydrological series, provide good water management stability under conditions of a relatively stationary climate. However, as early as the 1980s and 1990s, the first methodological studies began to consider, in a water management context, greater operational flexibility and rules for restricting abstractions during drought periods in order to distribute water deficits more evenly over time. These concepts were derived from economic theories and subsequently applied to the evaluation of reservoir operation strategies under climatically variable conditions [1]. Management rules are often designed to optimise a loss function representing the total financial losses incurred by water users due to water supply deficits. As early as 1982, Hashimoto et al. [2] demonstrated that, with a non-linear loss function, early restriction of abstractions is advantageous, as a single severe water deficit causes greater damage than several smaller deficits distributed over time, even if they amount to the same total shortage [3]. In the Czech Republic, models of adaptive reservoir management and water management systems were first studied at the Faculty of Civil Engineering, Czech Technical University in Prague, through the work of Nacházel and Patera [4, 5].

The study by Ahmadi, Haddad, and Loáiciga [6] represents one of the first comprehensive models of adaptive reservoir operation rules with respect to the impacts of climate change. The authors used climate projections for the mid- and late 21st century and subsequently optimised rule curves to increase reliability and reduce the vulnerability of water supply reservoir operation during prolonged drought periods. The principle of adaptation was also applied to the strategic management of water management systems by Marton et al. [7, 8].

At present, adaptive management has attracted increasing attention, particularly in the context of combining climate scenarios, hydrological modelling, and optimisation methods. Research applies various approaches, including heuristic algorithms, model predictive control, and optimisation techniques aimed at ensuring the reliability of storage function performance under future hydrological conditions [9]. Studies show that adaptive operating rules can significantly improve the reliability of water supply during drought while simultaneously reducing extreme fluctuations in storage levels [10].

Another important direction is the research of optimisation strategies for the management of multi-purpose reservoirs. For example, study [11] demonstrates how operating rules can be modified using regulation levels in response to multi-year drought periods, thereby improving the operational efficiency of the system. Modern approaches are also increasingly turning to the use of machine learning models for reservoir management decision-making, reflecting the complex interactions between hydrological inputs and operational constraints [12].

In the Czech Republic, the implementation of adaptive reservoir management is supported by legislative and strategic documents. The legal framework is primarily based on the Water Act No. 254/2001 Coll., which sets out the principles of water management and the operating rules for water structures, including the requirement to minimise the adverse impacts of drought and water scarcity. In addition, Drought Management Plans are developed at both regional and national levels, complementing river basin management plans through operational measures in accordance with the requirements of the EU Water Framework Directive 2000/60/EC.

These regulations support adaptive approaches that can be implemented within operating rules and the planning of minimum residual flows, with an emphasis on drinking water supply as a priority function. Such approaches are already being tested or applied in practice by river basin authorities in the Czech Republic. An example is the adaptive reservoir management system in the Oder River Basin, based on study [13].

METHODOLOGY

The fundamental principle of adaptive reservoir management is the replacement of rigid operation with constant abstractions by a flexible management system that continuously responds to the development of hydrological conditions. A key element of this approach is the optimisation of rule curves, which define regulation levels of storage for individual calendar months. As storage volume decreases below defined thresholds, abstractions are gradually restricted according to predefined priorities of individual users, while minimum residual flows downstream of the reservoirs are adjusted in a controlled manner. This flexible regime enables a timely response to the onset of drought and distributes the impacts of water scarcity over time, thereby preventing sudden and severe disruptions in water supply.

As part of the research, a system of rule curves and regulation levels was developed to define optimal abstractions and minimum residual flows for individual months and climate conditions. The methodology was pilot-tested on selected water supply reservoirs in the Czech Republic, namely Švihov, Klíčava, Žlutice, Obecnice, Pilská, Láz, and Vrchlice.

Climatic conditions

The verification of the proposed adaptive reservoir management approach was carried out for current climatic conditions and for future conditions corresponding to time horizons around 2050 and 2100. For Švihov reservoir, optimisation of adaptive management was based on the so-called Medium Climate Change Scenario for Water Management in the Czech Republic, developed by the TGM WRI in 2019 [14]. For the other reservoirs, climate data are derived from the latest results of the "Water Centre" project. Within this project, the publicly available HYMOD database [15] was developed, providing detailed results of hydrological modelling and analyses of the hydrological balance of catchments (water bodies) under current and future climatic conditions. The database is available via a web application (https://shiny.vuv.cz/HYMOD-KZ/) and provides a comprehensive set of climatic and hydrological characteristics derived from multiple climate models. Based on a detailed analysis of the climate scenarios included in the HYMOD database, changes in key meteorological variables, particularly air temperature and precipitation totals, were determined for individual catchments of interest for future time horizons up to the end of the 21st century. The database includes results from a wide range of global and regional climate models, including MEAN (the average of all models), CMCC-ESM2, EC-EARTH3, GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, TAIESM1, and the regional climate model ALADIN-CLIMATE/CZ, representing a broad spectrum of possible future climate development.

For the purposes of verifying adaptive reservoir management, a single representative climate scenario was selected for methodological reasons. The regional climate model ALADIN-CLIMATE/CZ under the SSP5-8.5 scenario was chosen as the most suitable basis. For the Czech Republic, this scenario projects a gradual increase in mean annual air temperature of approximately 1.0 to 1.4 °C by 2050 and approximately 3.1 to 3.8 °C by 2085 (or 2100). These values are also broadly consistent with the long-term warming trend observed since the 1980s. In contrast, projected changes in annual precipitation totals remain within a relatively narrow range across most models and, compared to temperature changes, are not considered a dominant factor in terms of the overall water balance.

The selection of a single climate scenario was motivated by the fact that the aim of the research was not to project future climate or to assess uncertainties in climate models, but rather to test the robustness of the proposed adaptive reservoir management system under systematically worsening hydrological conditions. The selected scenario makes it possible to evaluate the effect of warming on the hydrological response of catchments, to ensure consistent inputs for water management simulations, and to clearly interpret the behaviour of reservoir operating and regulation rules. By contrast, the use of an ensemble of multiple global climate models would lead to a substantial increase in uncertainty and would complicate the evaluation of the effectiveness of specific measures in the management of reservoir storage functions.

The defined climate scenario was subsequently used to adjust input hydrological series and to simulate the operation of selected water supply reservoirs under both current and future climatic conditions. The results of these simulations provided a consistent basis for assessing the effectiveness of adaptive management as a non-structural measure for mitigating the impacts of climate change on the reliability of water resources.

Hydrological model

To simulate hydrological conditions in the catchments of the selected water supply reservoirs, a hydrological model capable of representing the key processes of runoff and water storage within the catchment, including the influence of snow cover, was used. The main tool was the application of the GR4J hydrological model [16], supplemented by the CemaNeige module [17], which enables the simulation of snow storage and its gradual melt. The GR4J model is a conceptual model of the hydrological cycle that transforms daily precipitation and potential evapotranspiration into catchment runoff using four main parameters. These parameters represent water retention within the catchment as well as both the fast and slow components of runoff, thereby enabling a realistic simulation of daily flows at the reservoir dam profile. The CemaNeige module is used to represent snow accumulation and melt, which significantly influences spring flows. The catchments were divided into five elevation zones according to altitude in order to account for differences in snow accumulation and melting conditions between higher and lower elevations. For each day, excess precipitation and snowmelt were calculated for individual zones, with the resulting inflow to the reservoir being the sum of contributions from the respective elevation zones.

Model calibration was carried out using natural flow series derived at a monthly time step from measured flows at the dam profile of each reservoir. These series were corrected for the effects of controlled abstractions, releases, and operational water management, using detailed operational records, primarily for the period 1981–2024. Daily precipitation and air temperature data were used as input meteorological variables, with runoff also simulated at a daily time step. For calibration purposes, daily runoff values were aggregated to a monthly time step in order to minimise daily variability and enable comparison with aggregated monthly flow series. The quality of calibration was evaluated using a combination of standard criteria, namely Kling–Gupta Efficiency (KGE), Nash–Sutcliffe Efficiency (NSE), and PBIAS, which assess the agreement between simulated and observed flow values, the variability of the time series, and systematic deviations. The values of these criteria for individual reservoirs are presented in *Tab. 1* and confirm good agreement between simulated and reference flows.

For calibration, the KGE criterion was used, confirming very good model performance with values ranging from 80.1 % to 89.5 %. NSE values range from 60.0 % to 80.2 %. The PBIAS criterion falls within the range of very good performance for all catchments. These values, specifically from -0.4 % to 1.6 %,

Tab. 1. Performance criteria for hydrological model calibration for the catchments of the selected reservoirs

Reservoir	**Klíčava**	**Žlutice**	**Obecnice, Pilská, Láz**	**Vrchlice**
Period	01. 11. 1980 – 31. 10. 2024	01. 11. 1980 – 31. 10. 2020	01. 11. 1981 – 31. 10. 2024	01. 11. 1985 – 31. 10. 2024
Evaluation criteria				
NSE [%]	65.9	80.2	60.0	70.9
KGE [%]	82.9	89.5	80.1	85.2
PBIAS [%]	-0.1	1.6	-0.4	0.6

Tab. 2. Conditions for defining rule curves

Rule curve	**Climate**	**Water supply abstraction (Op)**	**Minimum residual flow (MRF)**	**Required reliability by duration**
DG1	Current climate	Op1 – according to the water use permit	MRF1 – according to the water use permit	98.5 % or 99.5 %, depending on reservoir importance
DG2	Climate 2050	Op2	MRF2	
DG3	Climate 2100	Op3 – actual abstraction over the last 5 years	MRF3	

indicate that the model does not exhibit a significant tendency to overestimate or underestimate the total flow volume. It can therefore be concluded that the optimised parameters are reliable and suitable for subsequent application.

After calibration, the simulated series for the 2050 and 2100 time horizons were corrected for systematic errors using a multiplicative method, which adjusts runoff series proportionally to reflect historical differences between modelled and observed flows. This approach ensures that the simulated series retain a realistic flow dynamics while enabling the testing of adaptive reservoir management under scenarios of progressively worsening hydrological conditions derived from the climate model. The resulting hydrological series form a consistent input for simulations of the operation of selected reservoirs with the application of adaptive management, enabling a comprehensive evaluation of the effectiveness of the proposed regulation rules under both current climatic conditions and future conditions corresponding to the years 2050 and 2100. This approach ensures that the testing of adaptive management is based on realistic, climate- and operation-informed scenarios, while maintaining a clear interpretation of the results and enabling unambiguous quantification of the benefits of individual regulatory measures.

Methodology of adaptive management

The first and fundamental step in adaptive management is the development of rule curves. A rule curve represents a key tool for controlling reservoir outflow, as it defines the relationship between regulated outflow and the current storage level of the reservoir over the course of the year. Within the storage zone of the selected reservoirs, three rule curves (DG1, DG2, and DG3) were defined, together with three regulation levels that vertically divide this zone, as shown in *Fig. 1*, into:

- regulation level RS1 – bounded above by the full storage capacity and below by the rule curve DG2,
- regulation level RS2 – bounded above by the rule curve DG2 and below by the rule curve DG3,
- regulation level RS3 – bounded above by the rule curve DG3 and below by the dead storage level.

The rule curves were defined to ensure the required reliability of water supply abstractions (Op) and the minimum residual flow (MRF) downstream of the dam, under different climate change time horizons, as shown in *Tab. 2*.

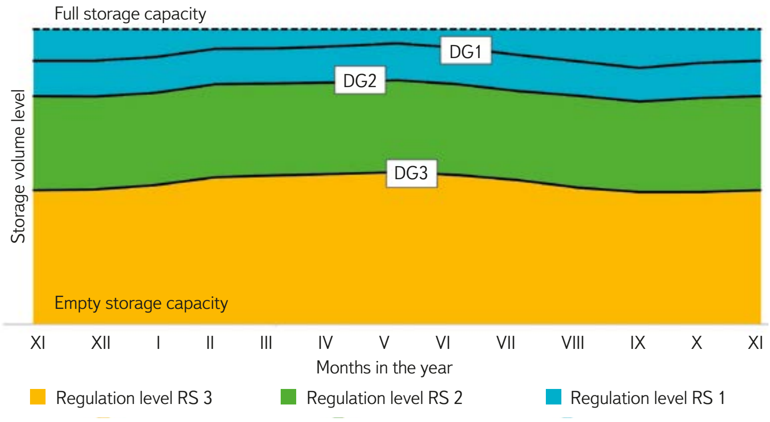

Fig. 1. Diagram of rule curves and operation levels for reducing water supply withdrawals and minimum residual flow

As follows from *Fig. 1* and the description above, rule curve DG1 in this configuration does not serve as an active control element for transitions between individual regulation levels. In practice, when the reservoir level is above DG1, controlled pre-release of storage down to the DG1 level can be implemented without compromising the reliability of the storage function, for example to enhance flood protection or to optimise hydropower use.

To derive the rule curves, a function based on an iterative search for minimum reservoir levels was developed. Its objective is to determine the lowest safe reservoir level for each month of the year while ensuring that the required reliability is maintained. For each climate scenario, the algorithm generates a separate rule curve based on the specified target values for abstractions (Op) and minimum residual flow (MRF).

The essence of adaptive management in this algorithm lies in its dynamic response to the current reservoir storage level. Whereas conventional management assumes fixed abstractions, this model actively adjusts its targets according to the prevailing conditions. Based on a comparison of the current storage volume with the rule curves, the water supply abstraction (Op) is immediately switched between three operating modes:

- full operation – when sufficient water is available, i.e. when the current storage volume is within the first regulation level, the maximum abstraction Op1 and MRF1 are applied in accordance with the valid water use permit,
- restricted operation – when the storage level falls into the second regulation level, abstraction requirements are automatically reduced to Op2 and MRF2,
- minimum operation – when the storage level falls into the third regulation level, abstraction requirements are automatically reduced to Op3 and MRF3, ensuring that the reservoir is not completely depleted and can maintain at least a minimal supply over a longer period.

For each of the analysed reservoirs, the threshold values Op1 to Op3 were defined within a range from the permitted abstraction specified in the valid water use permit down to the level of the actual abstractions. This approach made it possible to test the adaptive response of the system across the realistic range of operational demands of the given hydraulic structure. A similar approach was applied to MRF values, with an effort to maintain the first and second levels at their full values. Reduction to lower values occurred only when the storage level fell into the third regulation level, thereby maximising the protection of the remaining water reserves in the reservoir under critical conditions.

Evaluation of the effectiveness of adaptive management

The proposed methodological approach is demonstrated in detail for the management of Klíčava reservoir. Klíčava reservoir is located in the Vltava River basin on the Klíčava stream, a left-bank tributary of the Berounka River. The dam of the hydraulic structure is situated at river kilometre 3.1 in the cadastral area of the municipality of Zbečno in the Central Bohemian Region. The division of storage zones of Klíčava reservoir is presented in *Tab. 3*.

Tab. 3. Division of storage zones in Klíčava reservoir

Storage zone	**From [m a.s.l.]**	**To [m a.s.l.]**	**Volume [10^6 m^3]**
Dead zone	259.60	267.60	0.119
Active storage	267.60	293.70	7.860
Controlled flood storage	293.70	294.60	0.537
Uncontrolled flood storage	294.60	296.91	1.598
Total	259.60	296.91	10.150

Klíčava reservoir serves the following functions, listed in order of priority:

1. The primary purpose is the storage of water for the Klíčava water treatment plant, operated by Středočeské vodárny, a.s. The average permitted abstraction is 110 L · s^{-1}, with a maximum of 140 L · s^{-1}. Water abstraction is carried out using a multi-level intake structure, with flow regulated by a local valve within the water treatment plant.
2. Provision of the MRF downstream of the dam, corresponding to Q_{364}d = 12 L · s^{-1}. According to long-term observations, tributaries in the Klíčava catchment frequently dry out completely, with dry periods lasting from several days to weeks, and exceptionally even months.
3. Improvement of water quality conditions in the river downstream of the dam through operational measures.
4. Reduction of flood flows using the retention storage. The non-damaging discharge downstream of the dam is set at 6 m^3 s^{-1}.

The reservoir supplies drinking water to fewer than 50,000 inhabitants and ensures the MRF downstream of the dam. According to ČSN 75 2405 [18], Klíčava reservoir is classified as category B in terms of importance, and the required reliability must be ensured with a duration of at least $p_t \geq 98.5\%$.

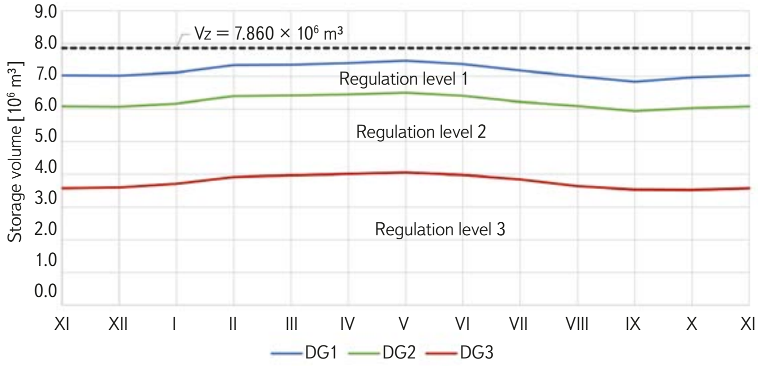

Fig. 2. Rule curves (DG) and operation levels for Klíčava reservoir

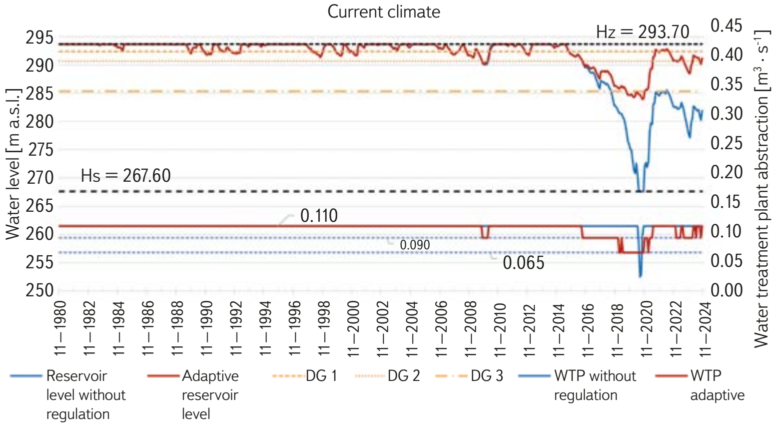

Fig. 3. Comparison of water levels and water supply to the treatment plant under constant withdrawal and adaptive reservoir management of Klíčava reservoir under current climate conditions

For Klíčava reservoir, the rules for individual regulation levels were defined (*Tab. 4*) such that the first level ensures abstractions in accordance with the water use permit, while the third level limits abstraction for the water treatment plant to the actual average value over the last five years of operation. The second level is defined as a transitional stage. In the first and second levels, the MRF is maintained at its full value, while in the third regulation level it is reduced to half. The resulting configuration of rule curves and regulation levels is shown in *Fig. 2*.

Tab. 4. Operating levels with restrictions on water supply withdrawals (Op) and minimum residual flow (MZP)

Regulation level	**Op [L · s^{-1}]**	**MZP [L · s^{-1}]**
RS 1	110	12
RS 2	90	12
RS 3	65	6

For clarity, graphs showing the variation of reservoir water levels and water supply abstractions were included for both constant abstraction and MRF without restriction (in accordance with the water use permit) and for adaptive

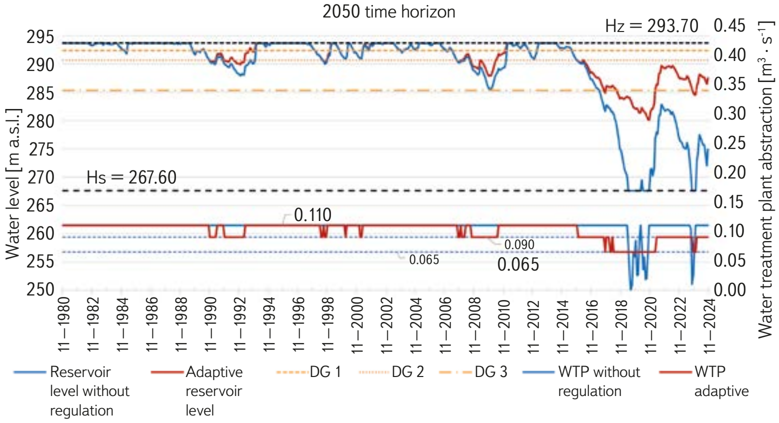

Fig. 4. Comparison of water levels and water supply to the treatment plant under constant withdrawal and adaptive reservoir management of Klíčava reservoir under 2050 climate conditions

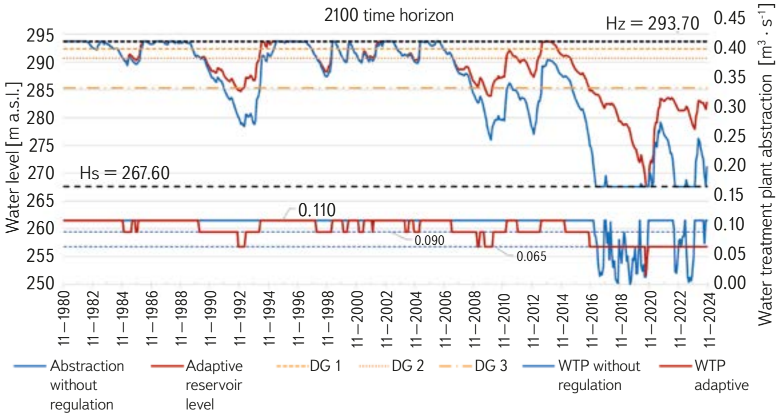

Fig. 5. Comparison of water levels and water supply to the treatment plant under constant withdrawal and adaptive reservoir management of Klíčava reservoir under 2100 climate conditions

Tab. 5. Comparison of water supply reliability under constant withdrawal and minimum residual flow according to water use permits and under adaptive management for the studied reservoirs

Reliability pt [%] of water supply abstraction		**Current climate**		**Climate 2050**		**Climate 2100**	
Reservoir	**Management**	**Permitted abstraction**	**Actual abstraction**	**Permitted abstraction**	**Actual abstraction**	**Permitted abstraction**	**Actual abstraction**
Klíčava	Conventional	99.1	99.5	96.1	97.4	88.9	91.7
	Adaptive	85.3	99.9	68.8	99.9	48.8	99.5
Obecnice	Conventional	99.1	99.7	97.7	99.5	93.9	98.3
	Adaptive	93.7	99.9	89.2	99.9	79.5	99.7
Láz	Conventional	99.9	99.9	99.9	99.9	99.5	99.5
	Adaptive	99.9	99.9	99.5	99.9	98.3	99.9
Pilská	Conventional	99.9	99.9	99.7	99.9	96.6	97.2
	Adaptive	99.9	99.9	98.5	99.9	87.1	99.5
Vrchlice	Conventional	92.2	94.5	88.1	90.9	81.5	86.6
	Adaptive	65.9	99.9	60.1	99.9	48.2	99.6
Švihov	Conventional	99.3	99.6	97.1	97.8		
	Adaptive	97.0	100.0	90.6	99.5		

management. The graphs are presented in *Fig. 3* for current climatic conditions, in *Fig. 4* for the 2050 time horizon, and in *Fig. 5* for the 2100 time horizon. The water level and abstraction time series show that adaptive management significantly reduces water level fluctuations, while the actual abstraction for the water treatment plant (65 L · s^{-1}) remains secured up to 2100. By contrast, under conventional management, it can be observed that in several cases the water supply dropped well below current demand levels, particularly for more distant climate change time horizons.

The differences between management based on constant abstraction according to the water use permit and adaptive management are also quantified in *Tab. 5*. The table presents reliability values (p_t) for Klíčava reservoir and for other analysed reservoirs: Obecnice, Láz, Pilská, Vrchlice, and Švihov. Cells in which the required reliability of abstraction is achieved are highlighted. In the case of Švihov reservoir, adaptive management was designed using two regulation levels based on the so-called Medium Climate Change Scenario for Water Management in the Czech Republic [14]. The management design was developed as part of study [19], and the derived rules for adaptive restriction of abstractions were incorporated into the reservoir operating rules. For the optimisation of rule curve storage levels, generated synthetic series with a length of 1,000 years were also used, derived for current climate conditions and for the 2041–2060 time horizon according to [14]. For the 2100 time horizon, adaptive management rules were not included in the analysis, as their future revision is anticipated.

The results summarised in *Tab. 5* demonstrate the effectiveness of the proposed adaptive management, which was tested on a set of selected water supply reservoirs. In all cases, timely restriction of abstractions makes it possible to ensure the required reliability of water supply abstractions for all considered climate change horizons. The simulations further show that the benefits of adaptive management increase with longer climate change horizons. While differences between conventional and adaptive management are relatively small under current hydrological conditions, under scenarios for 2050 and especially 2100, the adaptive approach becomes a key tool for maintaining an acceptable level of reliability of water supply abstractions. This trend confirms that the importance of non-structural measures will likely increase in the future. It should be emphasised, however, that the simulation results are subject to certain uncertainties arising from the climate and hydrological models used. In this study, a single representative climate scenario was applied for methodological reasons, enabling a consistent interpretation of the behaviour of the proposed management system. In the future, it would be appropriate to consider a broader set of climate scenarios and to carry out a robustness analysis of the proposed rules with respect to uncertainties in future climate development.

CONCLUSION

The results obtained indicate that adaptive management represents a key and essential tool for the future operation of water supply reservoirs under climate change conditions. It enables the identification of an operationally acceptable compromise between user demands and the actual capacity of water resources, enhances the operational safety of hydraulic structures, and contributes to the long-term sustainability of water management. At the same time, adaptive management has a positive impact on water quality in reservoirs, as limiting deep and prolonged declines in water levels contributes to more stable thermal and quality conditions within the reservoir. This reduces the risk of eutrophication processes and deterioration of raw water quality, which are expected to occur more frequently under a warming climate. The proposed approach can also be regarded as an effective non-structural adaptation measure that is fully compatible with existing legislative frameworks and provides a practical basis for the modification of reservoir operating rules in the Czech Republic. At the same time, it is necessary to prepare new reservoirs and expand storage capacities, particularly in deficit areas, in order to ensure a sufficient long-term water supply for future abstractions and increased variability of hydrological conditions resulting from climate change.

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Rainwater harvesting systems and flood water management in rural areas: A systematic review

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ABSTRACT

In a climate marked by prolonged drought, observed mainly in arid and semi-arid areas, the installation of hydraulic systems for rainwater collection and storage in rural and isolated areas is becoming a necessity to preserve livestock and ensure water security for the local population. For this purpose, this review synthesizes recent studies on the various hydraulic systems used for rainwater harvesting (RWH) in rural areas to support agriculture, livestock, and households. This review examines 66 relevant studies published in journals indexed in ScienceDirect and Scopus over a period of five years (January 2021 – December 2025). It emphasizes the importance of design based on the specific characteristics of each location or country, the criteria for selecting implementation sites, the impact of RWH systems on agriculture, livestock, and rural households, existing challenges, and proposes some guidelines for sustainable rainwater management and flood reduction.

INTRODUCTION

Pressure on water and natural resources in the world, exacerbated by climate change, is threatening agriculture, livestock and increasing poverty in arid and semi-arid areas, especially in rural, isolated localities. It is in this context that rainwater harvesting (RWH) systems have gained importance internationally as a sustainable rainwater management solution.

RWH is the process of collecting raindrops or runoff and storing them in tanks, reservoirs, or other storage systems. The harvested rainwater can subsequently be utilized for various on-site purposes due to its limited captured volume. Rainfall can be collected from different sources. RWH systems (RWHS) are designed to collect surface runoff from steep and sparsely forested mountain slopes to agricultural areas [1]. As a result, these systems serve a dual purpose: providing water supply and managing floodwater, which makes them both distinctive and exceptional [2]. Okello et al. [3] claimed that in addition to increasing the availability of water, RWH helps restore nearby groundwater sources and generates employment opportunities in the local communities. Consequently, the widespread adoption of RWH as a strategic solution to water scarcity has contributed to a reduction in groundwater extraction. RWH has been employed not only to address the growing imbalance between water supply and demand but also to promote social, environmental, and economic development, ultimately enhancing the quality of life in arid and semi-arid areas [4–7].

Over the past few decades, numerous researchers have shown their interest in RWH technologies and practices, and also several countries worldwide have been using RWHS as an alternative measure to provide water for domestic and agricultural uses in dry and isolated areas. However, these RWHS differ from one location to another according to multiple criteria such as: the geographical situation, land configuration, hydrographic network, purpose of rainwater usage, socio-economic situation, local population preferences, and environmental contexts. Consequently, researchers try to combine all these criteria to design and implement an adapted RWHS for a specific location.

Current review studies primarily focus on the benefits of RWHS in addressing water scarcity in drought-prone areas [8, 9], the modernization of traditional RWHS [10, 11], their potential applications in agriculture and livestock activities [12, 13], and the integration of new technologies to maximize RWHS performance [14, 15]. Nonetheless, these reviews have adopted diverse methodological approaches, and often include sources with varying levels of scientific rigor, such as professional reports and book chapters. Furthermore, some focus narrowly on a specific aspect of RWH or are limited to particular regions, such as the Middle East and North Africa (MENA) or low-and middle-income countries (LMICs). This disjointed perspective hampers a comprehensive understanding of the global importance and diverse applications of RWHS across multiple sectors. To address these gaps, this study conducts a systematic literature review based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, exclusively considering peer-reviewed articles published in Scopus and ScienceDirect from January 2021 to December 2025. This structured and transparent methodology enhances reproducibility and offers a thorough synthesis of worldwide research. Distinct from earlier reviews on RWHS (e.g., [7, 16–19]), this study is organized to facilitate understanding of the complex structure of RWHS, directed by crucial questions aimed at identifying the scholarly advancements of RWH, analyzing different research contributions in RWH, and determining the challenges of rain and flood water management policies. Throughout this scholarly pursuit, this study offers a detailed synthesis of the main principal RWH techniques, applications, and practices that exist worldwide. It emphasizes recent advancements and future perspectives for sustainable water resources management.

This paper is organized as follows: The first section presents the methodology of this study, highlighting the criteria used for selecting sources and studies using the PRISMA-based systematic literature review. The second part consists of a literature review that summarizes the results of all the reviewed articles. This section is organized into several parts: first, an overview of historical and traditional RWH techniques in arid and semi-arid areas; followed by a technical review of RWHS, including types, design considerations, implementation sites, and maintenance practices. The next section discusses the impacts of RWH on agriculture, livestock, and livelihoods in rural areas, as well as its role in managing food and water erosion. Finally, the concluding section examines water management policies and institutional support mechanisms.

METHODS

To conduct this review, the methodology of systematic literature review was used to collect, analyze, and evaluate a certain number of scientific papers on RWH in the world. For this purpose, the guidelines of the PRISMA were employed to guarantee an organized and credible selection process. Moher et al. [20] introduced the PRISMA statement as a set of directives aiming to enhance the transparency and comprehensiveness of reporting in systematic reviews through a defined set of steps, containing article identification, screening, eligibility, and final inclusion.

Eligibility criteria

RWH has become a popular topic since the early 2000s, with an increase in the number of publications over the years [16]. Considering this extensive volume of publications, the studies included in the present review were carefully selected according to predefined eligibility criteria to ensure relevance and coherence. These eligibility criteria included peer-reviewed journal articles written in English, published between January 2021 and December 2025, indexed in Scopus and available in ScienceDirect and Scopus, and related to rural RWH.

Search strategy

The bibliographic databases used in the article search: ScienceDirect and Scopus. Particular keywords and terms related to rural RWH were utilized in this search (*Fig. 1*). The query was structured as follows: ("rainwater" OR "stormwater" OR "surface water") AND ("harvesting" OR "collecting" OR "storing" OR "management" OR "conservation" OR "water erosion") AND ("rural" OR "mountain" OR "arid" OR "semi-arid" OR "dry area") AND ("agriculture" OR "livestock" OR "fields") AND ("techniques" OR "design" OR "hydraulic system" OR "construction materials" OR "implementation site" OR "efficiency"). Using this search strategy, an initial dataset of 1,854 publications was obtained.

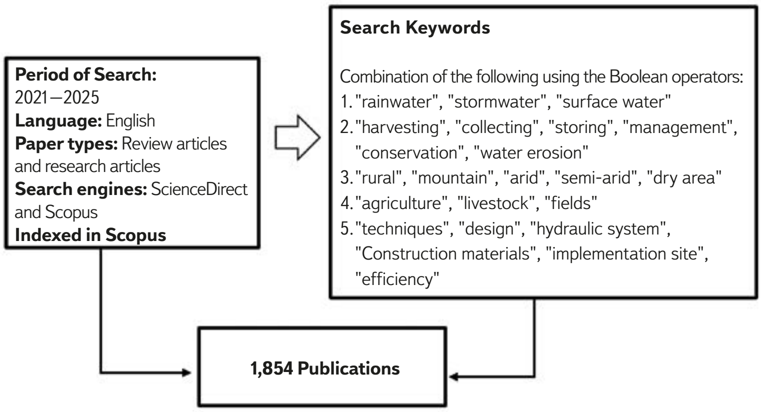

Fig. 1. Strategy used in the search of bibliographic databases

Screening and selection process

Management of the references

All the retrieved publications from the searches were imported into Zotero, which is a reference management software [21] to identify and remove all the duplicated publications. At this level, 79 papers were removed from the dataset for being duplicates (*Fig. 2*).

Selection process

After removing all the duplicated records, a second filter was applied on the remaining 1,775 records based on the article titles to ensure the inclusion of relevant content. Accordingly, articles that did not contain the predefined keywords (*Fig. 1*) in the title were excluded from the database. Thus, 1,579 articles were removed, and the number of records at this stage decreased to 196. To further refine this dataset, a third manual filter was applied using the article abstracts, aiming to include only articles that align with these three main topics:

- RWH practices and technologies in agriculture, livestock preservation, and rural households;
- Floodwater and water erosion management in rural areas;
- Water government policy.

Both authors conducted this process, and unclear cases were analyzed in more detail and discussed until a consensus decision was reached.

At the end of this process, 96 articles were excluded after reading the abstract, and 100 articles were selected for additional analysis (*Fig. 2*).

Inclusion/exclusion criteria

After an in-depth reading of the full-text articles meeting the initial screening criteria, clear inclusion and exclusion criteria were established to confirm the alignment with the research main themes (*Tab. 1*). As a result of this process, 89 articles were selected for further evaluation. The entire screening process was documented using Zotero and Excel spreadsheets, including relevant notes for each article.

Tab. 1. Inclusion and exclusion criteria

Inclusion criteria
Included articles treating:
RWHS in rural locations: design; implementation sites; practices and technologies;
RWHS used to improve the quality of agriculture, livestock, and life in rural households;
Floodwater and erosion management in rural areas by installing RWHS;
Water government policy related to RWH.
Exclusion criteria
Excluded articles are about:
Urban RWHS;
RWH for groundwater recharge management;
Rainwater quality;
The combined systems: RWH and solar energy.

Data collection process

All data relating to the 89 selected articles were meticulously extracted and organized into an Excel spreadsheet. This retrieved dataset includes key information, specifically authors' names, articles' titles, years of publication, study locations, main topics, abstracts, research methodologies, and results. This structured approach simplified the analysis and guaranteed easy access to articles details for comparison and review.

Quality assessment

The methodological quality of all the included articles was evaluated based on two main criteria:

— The clarity of the research methodology;
— The pertinence and validity of results.

This assessment was conducted manually by both authors, and notes on the limitations of each article were recorded in Excel spreadsheets. According to these specified criteria, 8 articles were excluded due to weak methodology, and 15 articles were excluded due to the absence of relevance and validity of findings. Following this assessment, 66 articles satisfied the criteria and were selected for final inclusion.

Bias assessment

Following the quality assessment, a bias assessment was conducted on the remaining 66 articles using the Critical Appraisal Skills Program (CASP) checklist. This evaluation focused on the clarity of the research process, the presence of references, empirical data, and the validity of findings. Unlike the previous quality assessment, no articles were excluded at this stage based on bias considerations, indicating that all the included studies demonstrated an acceptable level of bias control and transparency.

Data synthesis

The definitive dataset containing 66 articles was analyzed using a qualitative synthesis approach, enabling the identification, organization, and examination of each article's findings and results. During this process, outcomes of the studies were summarized, compared, and heterogeneities were evaluated. Consequently, the articles were categorized according to their focus areas into main sub-topics, including RWH in ancient and modern structures, RWH applications in rural settings, floodwater and water erosion management, and water governance policies. This classification provided a systematic overview of the existing literature.

The PRISMA flow diagram

At the conclusion of this process, a PRISMA flow diagram (*Fig. 2*) was constructed manually to illustrate the entire selection workflow, starting with the initial identification of records and ending with the final inclusion.

This structured method ensures transparency and enhances the reproducibility of the review.

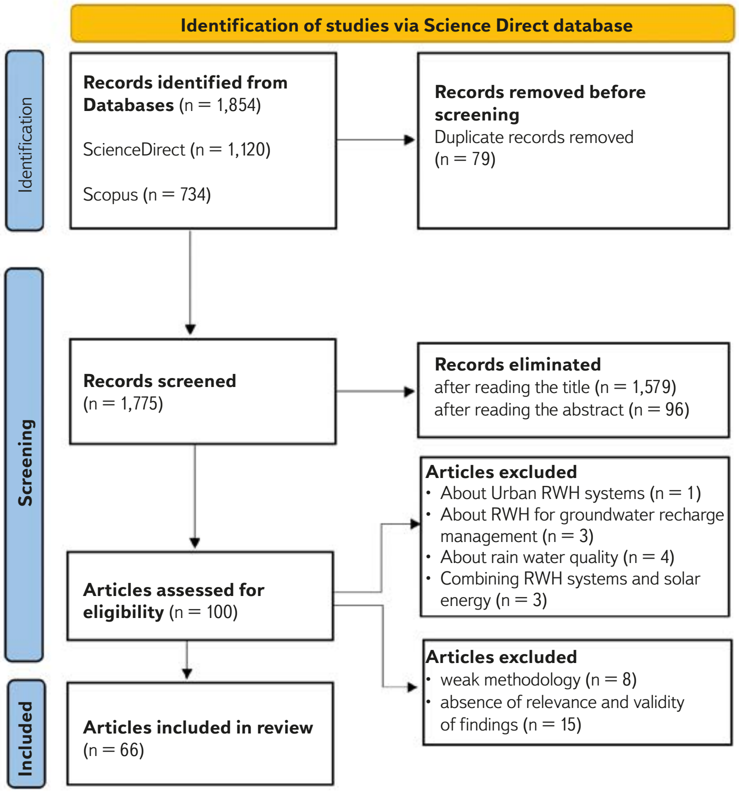

Fig. 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram

RESULTS AND DISCUSSION

The findings synthesize information from the selected literature and highlight representative examples from diverse regions. Due to the heterogeneity in geographical contexts and methodological approaches, the strength of evidence among the reviewed studies is variable, which may influence the generalizability of the conclusions. Consequently, the overall confidence in the body of evidence can be considered moderate. Therefore, the results should be interpreted with caution, taking into account the inherent limitations of the available evidence.

To facilitate a comprehensive analysis, the articles from the final inclusion were classified and organized into five sub-topics using Zotero:

— historical and traditional RWH techniques in arid and semi-arid regions;
— main characteristics of RWHS;
— impact of RWHS on agriculture, livestock, and life in rural households;
— floodwater and erosion management in rural areas;
— water government policy related to RWH and floodwater management.

Historical and traditional RWH techniques in arid and semi-arid regions

RWH has long served as a foundation stone of water management in arid and semi-arid regions, reflecting the cleverness and cultural resilience of communities challenging water scarcity. This part synthesizes recent studies that collectively highlight the importance and the diversity of these traditional RWH practices and their cultural significance across the Middle East, Asia, North Africa, and Sub-Saharan Africa.

Subterranean channels

Subterranean channel is one of the most advanced traditional RWH practices in the MENA region, designed in a way to reduce evaporation and increase efficiency. These underground water systems present differences from one country to another in techniques and nomenclature: qanats, falaj or aflaj, or foggaras [5]. These systems use gravity to transport water from higher elevation aquifers to lower elevation farmlands. This technique not only provides water to areas with limited surface water accessibility but also reduces water evaporation. On the other hand, Weerahewa et al. [22] introduced aflaj as a hydraulic system inspired by local traditions and Islamic principles of equity insuring fair water distribution in the Arabian Peninsula.

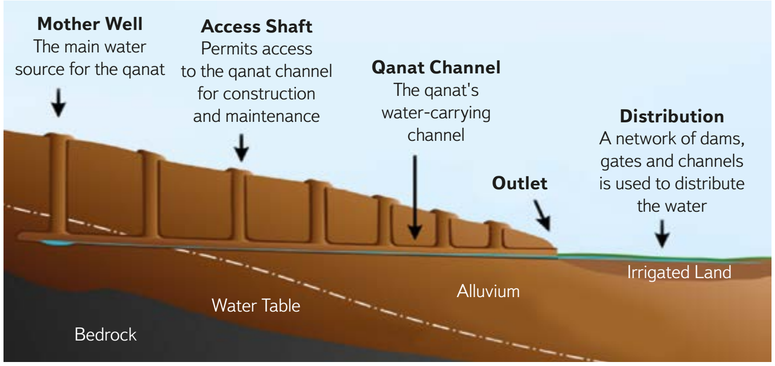

Fig. 3. Cross-section of qanat system (source: [5])

Cisterns

These water storage systems permit water harvesting in wet seasons to provide water during the prolonged periods of drought. Cisterns vary from one location to another, given their typology, construction materials, and they can also be open reservoirs, as observed in Sela in the Southern Transjordan Plateau [23] or underground like **sarnıç,** known as traditional cisterns implanted in Bozcaada (Türkiye) to ensure water scarcity in this island [24].

Fig. 4. Ancient Cistern in central Morocco (source: authors)

Surface water harvesting traditional techniques

Surface water harvesting can also refer to RWH and floodwater harvesting. This method is based on collecting and storing rainwater or floodwater in soil, natural reservoirs, or underground for later use. According to Ben Hassen et al. [5], this ancient technique is largely practiced in many arid and semi-arid regions around the world:

— In Tunisia, **jessour** are utilized as traditional water collection structures made of earthen small dams installed across valley floors to catch rainwater. The main role of jessour is to harvest rainwater from rare events and to transfer it through a terracing system, facilitating the cultivation of crops like olive and almond trees in dry environments.

Fig. 5. The jessour system in Tunisia (source: [5])

— In Yemen, **spate irrigation (e.g., Wadis)** is commonly used as an ancient and traditional water management method. It is designed using earthen structures to redirect floodwaters by gravity from mountainous catchments to agricultural fields to rapidly irrigate them [5].

Fig. 6. Spate irrigation system in Yemen (source: [5])

— In Kenya and Tanzania, **sand dams** are used to store rainwater in sand in wet seasons to reduce evaporation and to increase groundwater recharge [3].

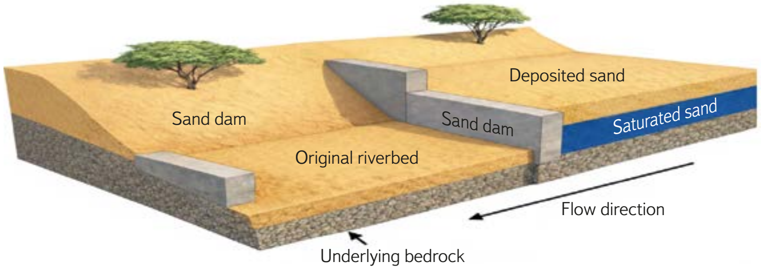

Fig. 7. Cross-section of a sand dam system (source: authors)

Main characteristics of RWHS: innovation, design, implementation, and sustainability

Modernization of traditional RWHS

RWHS have been used for centuries to manage water resources, demonstrating the ingenuity and wisdom of rural ancient populations. Based on this, contemporary researchers are increasingly interested in modernizing traditional RWHS by integrating new technologies and advancements to develop sustainable solutions for water deficiency.

Although the European approach considers rainwater as wastewater, Madomguia et al. [11] underscore that rainwater is a sustainable water resource, distinct from surface or underground water. A recent study by Madomguia et al. [11] highlights the important role of RWH in the Mandra Mountains of Cameroon. In this region, ancient RWHS called the **biefs** are revitalized by residents to serve as small dams. Additionally, stone terraced systems are maintained through the implementation of green bamboo walls. These methods not only enhance crop yields in terrace farming but also help to mitigate flood risks and provide food and water security in this mountainous area.

Similarly, Carrion-Mero et al. [25] emphasize the use of hydrogeological and geomorphological analysis through Geographic Information Systems (GIS) to more effectively identify hydraulic structures and drainage areas on the slopes of the Chimborazo Volcano in Ecuador. The research advocates for the modernization of the traditional RWHS "**Camellones**" to increase its efficiency and promote sustainable water management.

In Tunisia, the **tabias** system serves as an indigenous RWH structure to control flooding. These hydraulic systems consist of stone barriers integrated into terraced farms (e.g., jessour) to catch runoff in order to safeguard farms from flooding and to provide irrigation water. Considering its vital role in agriculture and flood management, the Tunisian government demolished many traditional tabias and reconstructed a significant number of these structures using modern construction tools and techniques [10].

RWHS types, designs, and suitable sites determination

RWHS are characterized by their variety of types and designs according to their geographical locations, hydrological conditions, socio-cultural environment of users, and their purposes of use. Consequently, numerous studies have been conducted in recent years to investigate these systems and to accurately determine their optimal future sites.

- **Suitable site selection methods:** Selecting appropriate sites for implementing RWHS is a crucial step to ensure long-term sustainability and efficiency of these hydraulic structures [26]. The process of potential site selection typically involves the following steps:
- **Study area identification and data collection:** Define the study area, and gather relevant spatial and non-spatial datasets, including topographical maps, geological and hydrological data, meteorological records, Landsat 8 remote sensing (RS) imagery, and socio-economic data [4, 27–30].
- **Criteria identification and data processing**: Determine key criteria based on literature review, field experiences, and the harvested water potential usage. The collected data and criteria are processed and transformed into thematic layers within GIS. Common layers include slope, stream order, drainage density, rainfall, soil type, land use/land cover (LULC), and road networks. These thematic layers are reclassified [26, 28] and standardized using fuzzy membership functions for numerical data and step-wise functions for categorical data [29]. The processed layers serve as GIS inputs for generating a final suitability map.
- **Hydrological modeling:** To refine the site suitability map, hydrological models such as the Soil and Water Assessment Tool (SWAT) model [27] or the Soil Conservation Service Curve Number (SCS-CN) method [28, 29] can be employed to simulate runoff, infiltration, and sediment yield. Although hydrological modeling is recommended by many researchers, it remains optional to determine the suitable implementation sites for RWHS.
- **Criteria weighting and Multi-Criteria Decision Analysis (MCDA)**: Assign weights to each criteria using methods such as the Analytic Hierarchy Process (AHP) [27] or fuzzy AHP [29]. To enhance robustness of results, some studies incorporate MCDA techniques combined with statistical analysis of spatial associations like Weight of Evidence (WOE) [28] or employ the VlseKriterijumska Optimizacija (VIKOR) method to rank alternatives based on subjective decisions of field experts [29].
- **Suitability map generation and visualization:** Integrate weighted criteria within GIS to produce a suitability map, classifying the study area into categories such as very high, high, moderate, low, and very low suitability [1, 4, 9, 27–29, 31, 32].
- **Validation and policy alignment:** Validate the suitability results by linking them to Sustainable Development Goals (SDGs) and examining their alignment with local governmental policies in the study area [27, 29]. Various modeling tools have been employed to develop RWH suitability maps. These include a GIS-based SWAT model for assessing the sub-daily hydrological influence of RWH on landscape irrigation [33]; GIS-based AHP; machine learning algorithms [28]; and a Markov chain model estimating the transition probabilities between hydrological states to optimize RWH site selection [34]. Collectively, these tools aim to assist policymakers and stakeholders in establishing sustainable water management frameworks.
- **RWH types and their design approaches**: RWHS exhibit a wide variety of designs, shaped by their implementation in different, diverse cultural and spatial contexts. The table below (*Tab. 2*), compiled from a review of numerous studies published globally between 2021 and 2025, summarizes the design approaches associated with each existing RWH type. Notably, innovative RWH structures and methods are primarily developed in China, such as Bioinspired one-dimensional (1D) structures [15] and road-based RWH technologies [35, 36]. Conversely, recent research in India emphasizes RWHS that prioritize minimal water contamination, exemplified by designs like the rain saucer [37].

In arid and semi-arid rural regions in Pakistan, Sri Lanka, and Djibouti, traditional RWHS such as ponds, percolation tanks, and small tanks are common. These structures serve as small water surface reservoirs for local uses like irrigation and livestock watering, and they also facilitate groundwater recharge. Their designs are generally simple, reflecting the low construction material requirements. These RWHS are typically located on gentle slopes, generally less than 5 %, with soil conditions tailored to their function: clayey or loamy soils for ponds to minimize seepage, and permeable soils like sandy or fractured rock formations for percolation tanks to allow water infiltration into the aquifers, ensuring groundwater recharge [28, 29]. Small tanks are often interconnected in cascade systems to maximize water distribution and reduce evaporation losses [32].

In Middle Eastern countries, dams and check dams are considered the ultimate solutions to water scarcity. Their design and construction are heavily influenced by local site conditions, particularly local geology and hydrology, to determine optimal shape, storage capacity, and construction materials, which are typically locally sourced, like gravel, clay, and limestone rocks; to reduce construction costs and enhance durability. The primary purpose of these structures also guides their design; check dams are mainly intended for erosion control and RWH, whereas dams serve multiple functions, including flood management, water storage for agricultural, domestic, and industrial use, and power generators [1, 4, 9, 27, 28, 31].

These integrated design methods, combining traditional approaches with modern modeling tools, assist policymakers and investors in identifying appropriate locations for RWHS installation and selecting suitable RWH designs for each site, thereby improving the effectiveness and sustainability of RWH ingenuities [28, 29, 32].

Tab. 2. RWH types and their design approaches

Type of RWHS	Design approach	Country	References
Dams and check Dams	A complex hydraulic structure featuring diverse shapes and storage capacities. Its construction strongly advocates the use of locally available materials. The design is customized to suit site conditions and intended functions.	Iraq; Egypt; Morocco; Pakistan; India	[1, 4, 9, 27, 28, 31]
Ponds, percolation tanks, and small tanks	A simple hydraulic structure with various shapes, designed to enhance groundwater recharge and serve as a water reservoir for agriculture and livestock. Its design and dimensions are closely tailored to site-specific features such as slope, soil types, and stream locations.	Pakistan; Sri Lanka; Djibouti	[28, 29, 32]
Rain saucer	A roofless RWH technique consists of installing a sheet made of a food-grade polypropylene to directly catch the rainwater without any contact with impurities.	India	[37]
Road-based RWH technologies	Consists of constructing concrete cisterns along mountainous roads to allow rainwater to be transported by gravity and fill the cisterns.	China	[35, 36]
Bioinspired 1D structure	Inspired by the natural water harvesting mechanisms, like in wheat awn, the surface of spider silk, araucaria leaf, Cactus spine.	China	[15]

Additionally, Membrane technologies were introduced as a complement to RWHS. They are generally installed downstream of the RWH structures as a rainwater treatment to ensure water quality before its reuse for domestic and agricultural purposes. This method consists of filtering rainwater using different types of membranes (surface membrane, gravity-driven membrane processes, and membrane bio-reactor process) [14].

Considerations for maintenance and sustainability

The durability of RWHS is highly desirable, especially given their positive impacts on multiple levels. Sustainability in RWH concerns the following aspects:

- **Full and lasting engagement of all actors**
  The success of a RWH project ultimately depends on the commitment of all water sector actors, including government agencies, investors, farmers, and the rural population as a whole. This collaboration would simplify the construction, preservation, and maintenance operations of RWH structures [38]. These contributors are instrumental in bringing the project to life, from its inception to installation and operationalization. In addition, Pala et al. [18] emphasize the importance of education and awareness among rural communities regarding RWHS conservation and advocate for the enforcement of laws and amendments to preserve these hydraulic structures.
- **Maintenance of the RWH structures**
  Given the high initial costs of modern RWH structures, their maintenance expenses and considerations during the operational phase should be factored in from the feasibility and conceptual stages to ensure their long-term durability [7, 39]. Regular maintenance is crucial to ensure the longevity of RWHS [40]. This includes cleaning water storage tanks, ponds, cisterns, and catchment areas; monitoring odor, color, and chemical qualities of stored water; treating stagnant water before use; and repairing the defective parts of the RWHS [17]. Adequate and periodic maintenance helps preserve the functionality of the structures and ensures the continuity of their positive impacts.
- **Environmental sustainability**
  RWH projects have demonstrated positive environmental impacts by contributing to reducing energy consumption, recharging groundwater, mitigating floods, and thereby restoring some aspects of the natural water cycle [19]. This involves encouraging the sustainable use of water resources and preserving local ecosystems.
- **Socio-economic and environmental assessment of RWHS**
  While the fundamental principle of the RWH technique is simple: collecting, storing, and providing water, the selection of suitable RWHS implementation sites remains a challenging decision for researchers and decision-makers, as it depends on socio-economic and environmental parameters.

Socio-economic hardships are the main challenges for indigenous peoples in affording water or investing in water structures [6]. Therefore, RWHS offer deprived communities indisputable social and economic benefits [41]. Accordingly, Rodrigues de Sá Silva et al. [7] emphasize the positive socio-economic impacts of using RWHS in agriculture and households in arid and semi-arid regions on the Loess Plateau in China, noting an annual water saving of 75.8 m3 per household and an annual energy saving of 138.6 kWh per household. A similar study conducted by Richards et al. [42] in India found that installing RWHS in rural public schools could save about 25 % of the water used for non-drinking purposes. Additionally, Khanal et al. [43] underscore the importance of RWH users' awareness of sustainable water management practices and recommend integrating rainwater-related courses into university programs to expand knowledge in this field. However, Xue et al. [44] point out that the economic advantages of RWH and utilization differ considerably depending on the climatic conditions of a region.

Socio-environmental variables such as topographical, climatological, hydrological, agricultural, geological, pedological, and human factors are essential in successfully selecting RWHS potential sites on large-scale regions [45]. In this context, Teston et al. [19] proposed an analysis of the prospective location of RWHS that considers environmental impacts generated by such systems using Life Cycle Assessment (LCA) and water balance modeling tools.

RWHS USED TO IMPROVE THE QUALITY OF AGRICULTURE, LIVESTOCK, AND LIFE IN RURAL HOUSEHOLDS

Impact of RWH on agriculture in rural areas

Rural agriculture is menaced by water scarcity that is due to climate change and over-extraction of groundwater [13]. This situation is exacerbated by irregular precipitation patterns and inefficient irrigation structures, particularly in arid and semi-arid regions. To mitigate this issue, RWH appeared as the eventual solution to increase water efficiency and enhance the resilience of rural agricultural systems. RWH is crucial for ensuring adequate water for crop production, which enhances rural economics [12, 30]. In the following, concrete examples of RWH benefits on crop yields were identified based on the reviewed articles.

In arid and semi-arid regions of China, several studies were led on the cultivation of alfalfa in ridge-furrow RWH in combination with biochar by Wang et al. [46] and with chopped straw by Zhao et al. [47]. These studies demonstrated a significant positive impact on crop productivity and an optimized water supply. Consequently, this proves the resilience of high-value crops to drought. Similarly, Chen et al. [48] highlighted the meaningful increase of maize yields in farms relying on ridge-furrow RWHS, which enhances livelihoods of local farmers.

In marginal areas of Zimbabwe, a recent study conducted by Kubiku et al. [49] on two varieties of sorghum as the main food crop in Southern Africa showed that field-edge RWHS are promising low-cost water and nutrient management in sorghum's rainfed farms, boosting crop productivity and enhancing food security.

In Turkey's semi-humid Black Sea region, Yildirim et al. [50] led research on the effects of ridge-furrow RWHS on the growth, yield, and quality of red pepper. The findings indicate that RWHS improved red pepper production and contributed to the achievement of sustainable red pepper net income for farmers in the region.

In arid degraded areas of Jordan, two RWHS (the Vallerani and the Marab) were implanted in the Badia region to collect rainwater and support vegetation growth. The study emphasizes the important role of RWHS in enhancing land rehabilitation and sustainable agriculture [51].

In India, [52] recommended using RWH in on-farm reservoirs as a strategic approach to increase second-crop yields and improve water management in small-scale farming communities.

Impact of RWH on livestock and the quality of their products

Water scarcity highly impacts livestock productivity, particularly in dryland regions where the water shortage is a main stressor for cattle. In fact, animals facing water stress often conserve their body water by decreasing feed intake, which negatively affects their health, reproductive performance, growth rates, and product quality [53]. Therefore, sheep are directly affected by water restrictions, losing between 1.2 and 21.5 % of their body weight, as confirmed by Chikwanha et al. [53], influencing meat quality and quantity. Likewise, Halimani et al. [54] found that smallholder sheep farmers in South Africa's arid areas notice water deficiency as a major risk, pushing them to implement various water management strategies (e.g., RWHS) to alleviate stress on their livestock.

RWH installations become a necessity in arid and semi-arid areas to enhance cattle's quality by offering additional water supply during dry periods. According to Chikwanha et al. [53] and Halimani et al. [54] access to RWH has a positive impact on livestock productivity and, consequently, on smallholder sheep farmers by enhancing water security and being able to maintain production levels even in drought periods. RWHS allows farmers, particularly underground groups, to invest in supplementary feeding and use adapted breeds to improve animals' growth, health, and meat quality. Meanwhile, Muhirirwe et al. [55] emphasize the importance of RWHS on dairy production, increasing milk yield and quality by reducing dependency on seasonal water sources and supporting livestock survival. Thus, RWHS guarantee consistent water supply for both animals and crop cultivation, thereby enhancing the nutritional and economic value of livestock products.

RWH and the quality of life in rural households

RWH has shown a significant contributionin converting rural households by mitigating water scarcity, boosting agricultural productivity, and enhancing livelihood resilience in water-scarce regions. From this perspective, a recent study by Waqas et al. [40] revealed that the use of RWH structures to offer additional irrigation in fields increased the food security in Potohar Plateau (Pakistan). Similarly, Gebru et al. [56] highlight the crucial role of RWH technologies in guaranteeing food security for households in Ethiopia's arid and semi-arid regions. These technologies allow the use of rainwater to cultivate crops during dry seasons and help diversify agricultural production.

In localities where households are exposed to flooding and poor drainages like in Asuncion (Paraguay), RWHS is considered an ultimate solution for managing the risks associated with this natural phenomenon [57].

Domestic clean water supply in rural arid and semi-arid areas is gradually being provided by RHWS. García-Avila et al. [17] reviewed RWH and storing systems and their potential to offer safe drinkable water in rural households, and emphasized the importance of monitoring the stored water quality parameters, such as pH, turbidity, and E. coli, to protect public health. In another study, Osayemwenre & Osibote [58] provided an overview of the health hazards related to RWH from various rooftops (e.g., green, conventional, and photovoltaic rooftops). The research identified potential contaminants like microbes and heavy metals, which may negatively affect the rural population's health if they are not properly managed. Therefore, García-Avila et al. [17] highlighted the major role of careful selection of materials, regular disinfestation, and maintenance of RWHS to ensure the safe use of these systems.

Despite its benefits for agriculture, livestock, and life in rural households, the adaptation of RWHS faces numerous challenges. Muhirirwe et al. [55] noticed the prohibitive initial cost of RWH innovative structures, although its long-term advantages. Also, Chikwanha et al. [53] and Halimani et al. [54] pointed out that the main obstacles to RWHS installation by small-scale farmers are the limited resources, lack of technical knowledge, and insufficient policy support.

FLOODWATER AND EROSION MANAGEMENT IN RURAL AREAS

RWH and water erosion management

Water erosion is considered the main threat to agricultural lands around the globe. It affects the sustainability of agricultural farms and grazing areas. According to Firoozi & Firoozi [59], water erosion occurs through hydrodynamic forces, where rainwater flows or infiltrates through the soil, thereby removing and transporting soil particles. This process gradually alters the landscape and leads to the loss of cultivable land. To control water erosion Yu et al. [60] insist on studying precipitation regimes because rainfall intensity is considered the primary factor of soil detachment. Therefore, Haddad et al. [61] present RWH as an eventual solution to collect and store runoff, reducing erosion effects and supporting the growth of local plants in the rangeland of Jordan. Analogously, RWH by tied ridges slows down the erosive runoff during extreme rainfall events and harvests water during light rainfall events in Tanzania [62].

RWH and flood water management

Following the climate changes marked by consecutive drought years, irregular precipitation, and unpredictable flood events, the sustainable management of these risks has become increasingly essential, particularly in arid and semi-arid regions. In this context, RWH appears as a dual solution to mitigate flood impacts while storing overflowing water for reuse in rural activities such as crop irrigation, livestock watering, and domestic use. Ansari et al. [63] provide a concrete example of the positive impact of implementing RWH structures in Pakistan, specifically the Mangla Dam. Since its commissioning, the dam has been able to reduce the intensity of flooding in the Upper Jhelum Basin by 20 %, despite its primary objectives being water storage for irrigation and power generation. Similarly, Raoufi & Tsubaki [2] propose an innovative RWHS that transforms floods into a mitigating solution for drought in the Southwestern provinces of Iran. This approach involves renovating traditional RWHS (e.g., qanat, Ab-Anbar) to effectively manage and store excess floodwater for use during drought periods. Meanwhile, farmers in the Jordanian desert use floodwater to support agriculture through a method known as “floodwater farming”. This technique relies on ancient RWHS like wall-and-channel networks to introduce, alleviate, store, and irrigate crops with floodwater [64]. In the same vein, Ndayiragije et al. [39] highlight the important role of floodwater harvesting and reuse in promoting socio-economic development. This practice significantly reduces the energy required for pumping underground water while providing sustainable water for agricultural activities.

Overall, the reviewed studies demonstrate that RWH functions as an effective land and water management strategy, simultaneously mitigating erosion and reducing flood risks. RWHS enhance water infiltration and help protect agricultural land from degradation. Furthermore, the harvested floodwater can be used for non-potable purposes such as irrigation and livestock activities, thereby strengthening resilience in arid and semi-arid regions. Collectively, the literature advocates for the adoption of RWH techniques to promote sustainable agriculture and improve rural livelihoods.

Water government policy related to RWH and floodwater management

Given the current global situation marked by successive drought years and irregular rainfall patterns, especially in arid and semi-arid regions, exacerbated by phenomena such as water erosion and flooding, integrating RWH in its diverse forms into water resource management policies has become an obligation for countries. This integration aims to ensure sustainable water management in agriculture and to better handle risks related to water erosion and floods.

Saudi Arabia suffers from severe water scarcity due to high evaporation and low rainfall, and the significant water use in agriculture (87 % of the kingdom’s water). Consequently, the Saudi Arabian government has been prompted to adopt advanced strategies in the agricultural sector, such as integrating precision irrigation, encouraging less water-intensive crops, and enhancing RWH structures and fog water collection [65]. In the same vein, Egypt is affected by serious water scarcity problems like flash floods and the salinization of groundwater. These challenges highlight the necessity of identifying suitable RWH sites and combining this technology with hydrological modeling to decrease flash flood risks and enhance aquifer recharge, thus supporting agricultural and domestic water needs [38]. Similarly, community engagement and strengthening of RWHS are considered as strategic policies to handle risks related to excessive rainfall and floods in India [66]. Meanwhile, Tunisia established a hydro-social strategy based on investments in soil and water infrastructure to improve the collection and reuse of stormwater [67]. Also, Bangladesh confronts extreme meteorological conditions and uncontrolled water usage, which make is necessary to implement community-based RWHS (CBRWHS) and promote government financial and technical support to boost RWH installations in coastal locations [68]. Moreover, including RWHS in water management strategies and empowering local governance to design and maintain these hydraulic structures in LMICs will reduce the negative impact of flooding, drought, and unpredictable water availability in these regions [8]. Additionally, adopting natural-based solutions to rehabilitate degraded water infrastructure and engaging local communities in water management policies in Africa’s arid and semi-arid lands will reduce land degradation and enhance water supply for agriculture and domestic usage [3]. Despite differences in governance, climate conditions, and technologies across regions, the literature recommends that integrating RWHS into broader climate adaptation and water security strategies can effectively support sustainable development in water-scarce areas. However, the success of such initiatives largely depends on the active participation of all actors, including policymakers, researchers, investors, and local communities, in the planning, implementation, and management of these hydraulic structures.

CONCLUSION

The current paper presents a systematic review of RWHS studies using the PRISMA approach. The review includes publications from January 2021 to December 2025, sourced from ScienceDirect and Scopus databases, with a focus on articles indexed in Scopus.

A comprehensive analysis of 66 selected articles has been conducted to develop an in-depth literature review that highlights various aspects of RWHS, emphasizing their vital role in water resource management, particularly in arid and semi-arid areas experiencing severe droughts and water scarcity.

The study synthesizes ancestral RWH practices and explores their cultural significance across the Middle East, Asia, North Africa, and Sub-Saharan Africa. It also gives insights into their modernization efforts, especially the integration of new technologies and advancements in developing sustainable solutions for water shortage and flood control.

This review underscores the importance of innovative methods employed worldwide to identify potential sites of RWH structures, considering the diversity of types, designs, and socio-economic and environmental parameters. Such an approach assists decision-makers and investors in identifying suitable locations for implementing various types of RWHS.

Despite the dual benefits of RWHS in providing water to enhance agriculture, cattle, and rural livelihoods, as well as mitigating floods and water erosion, these systems are yet to be fully integrated into water management policies of several water-scarce countries. Challenges for sustainable water resource management using RWHS include raising consciousness and education among rural communities regarding the use and conservation of these hydraulic structures, as well as establishing strong institutional support mechanisms.

In conclusion, future research should focus on evaluating governmental and institutional frameworks to expand the adoption of RWHS in arid and semi-arid regions, promoting their role as a sustainable technique to mitigate water deficiency.

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Estimation of changes in design precipitation at ungauged locations using a geostatistical model of regional frequency analysis with climate projections

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Keywords: extreme precipitation — IDF, GEV, RFA — ensemble spread — climate change — CORDEX

ABSTRACT

The study quantifies changes in the 100-year design quantile of short-duration precipitation at ungauged locations in the Czech Republic and analyses the uncertainty structure of these estimates under climate change conditions. Reference IDF curves were derived using regional frequency analysis based on the index-flood concept, employing the GEV distribution with parameter estimation using the method of L-moments. Future changes were determined from a multi-model ensemble of CORDEX regional climate projections for the RCP2.6, RCP4.5, and RCP8.5 scenarios for the periods 2035–2065 and 2070–2100.

Under the RCP8.5 scenario (2070–2100), the mean relative change in the 100-year hourly quantile is approximately 52 %, with the 5th–95th percentile range spanning from –7 % to +126 %. In the period 2035–2065, differences among emission scenarios are smaller than the internal variability of the models, whereas in the second half of the century the emission trajectory becomes the dominant source of projection divergence. Relative amplification is greater for shorter durations, indicating a disproportionate sensitivity of short-term extremes.

The analysis shows that uncertainty at high return periods is strongly influenced by the estimation of the GEV shape parameter, where small differences lead to nonlinear growth in extrapolated quantiles. The detected intensification of extreme precipitation is consistent with the expected thermodynamic amplification of the hydrological cycle; however, the ensemble spread highlights substantial structural uncertainty in regional climate models.

The results indicate that the use of historical IDF curves without accounting for climate change may lead to a systematic underestimation of design values, particularly for infrastructure with a long service life.

INTRODUCTION

Extreme precipitation events are of the most significant hydrometeorological phenomena affecting public safety, the functioning of technical infrastructure, and the economic stability of regions [1]. Under Central European conditions, flash floods and local inundation have long been associated primarily with short-duration intense rainfall events, the impacts of which are intensified by urbanisation and changes in land use. The increasing proportion of impervious surfaces, river channel modifications, and the concentration of built-up areas accelerate the runoff response of catchments and increase the sensitivity of the landscape to extreme precipitation episodes.

The design of technical measures such as sewer systems, retention reservoirs, dry polders, and blue-green infrastructure elements is therefore based on the statistical description of extreme precipitation [2]. In practice, design quantiles expressed through intensity–duration–frequency (IDF) curves are used as the principal tool for the dimensioning of water management structures [3, 4]. These curves are usually derived from historical precipitation time series and implicitly assume a stationary climate regime [3].

The assumption of stationarity, however, is no longer defensible in the context of ongoing climate change [1]. Increasing concentrations of greenhouse gases lead to atmospheric warming, which is associated with changes in the hydrological cycle [5]. Climate models as well as observed trends indicate an intensification of extreme precipitation in many regions of the world [1, 6]. The physical basis of this intensification is linked to the Clausius–Clapeyron relationship, according to which the maximum water vapour content of the atmosphere increases by approximately 7 % per 1 K of warming [5, 6]. A higher water vapour content creates the potential for more intense precipitation events, particularly those of a convective nature [6].

Although the physical mechanism responsible for the intensification of extreme precipitation is relatively well understood, its quantification at the regional and local levels is subject to considerable uncertainty [1]. This uncertainty arises from several sources, namely structural differences among climate models, uncertainty associated with emission scenarios, and internal climate variability [7]. From the perspective of water management practice, however, not only the mean change in the design quantile is important, but above all its upper bound, which represents the potential risk of infrastructure underdesign.

Another significant problem is the limited availability of long-term high-quality precipitation measurements. In many locations, sufficiently long time series enabling reliable estimation of high return periods are not available. The extrapolation of a 100-year or 200-year quantile from a short time series is statistically unstable and sensitive to individual extreme events [2, 8]. Regional frequency analysis (RFA) represents a methodological approach that mitigates this problem through the sharing of information among climatically similar locations [9]. By separating the regional shape of the distribution from the local

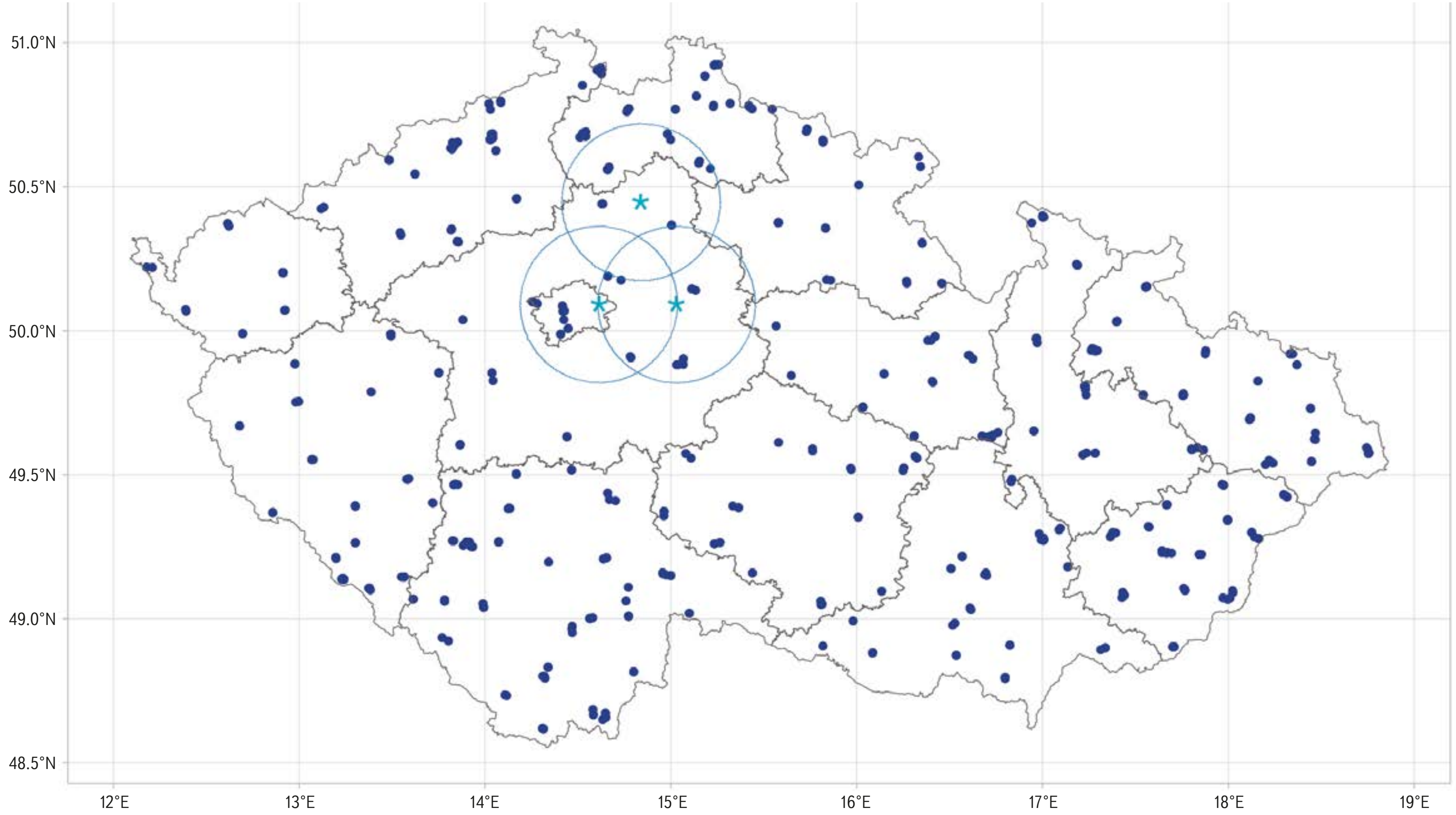

Fig. 1. Selection of stations for RFA – locations marked with a star indicate pilot sites, points marked with a dot represent rain gauge stations CHMI, and circles denote the 30km buffer

scale, it enables a more robust estimation of extreme quantiles even in areas without direct measurements or with limited data availability [9].

The literature contains numerous studies addressing changes in extreme precipitation in the context of climate change; however, fewer studies systematically combine regional frequency analysis with a multi-model ensemble of climate projections and explicitly quantify the uncertainty associated with high return periods [3, 10, 11]. In particular, insufficient attention has been paid to the question of how large the uncertainty of the 100-year design quantile is and how its structure changes depending on the time horizon and emission scenario [7].

The present study aims to partially fill this gap. The methodology described below was applied to three pilot locations (Bukovno, Pečky, and Běchovice). The main research questions can be formulated as follows:

- What is the magnitude of the change in the 100-year design precipitation under future climate conditions?
- What is the spread of the climate projection ensemble, and how does it evolve over time?
- Is the observed intensification of extreme precipitation consistent with the theoretical Clausius–Clapeyron scaling?

Answers to these questions are of direct relevance to the dimensioning of water management infrastructure as well as to the strategic planning of adaptation measures. The study therefore combines regional frequency analysis with a multi-model ensemble of regional climate projections and focuses not only on the estimation of future IDF curves, but especially on the systematic quantification of their uncertainty [7, 10, 11].

DATA

Observed precipitation data

Observed data on short-duration precipitation totals from the network of stations operated by the Czech Hydrometeorological Institute (CHMI) were used for the construction of reference IDF curves for the three pilot locations [12, 13]. Only stations with time series exceeding 30 years in length were included in the analysis, representing the minimum duration required for a more robust estimation of high return periods within the framework of block maxima analysis [2, 8]. The selection of stations was further restricted to locations with sufficient measurement continuity and a minimal proportion of missing data.

The primary criterion for station selection was their spatial proximity to the analysed locations, defined as a circular buffer with a radius of 30 km. Only stations located within this radius and simultaneously meeting the requirement of a time series of annual maxima of at least 30 years were included in the regional analysis. The minimum record length was selected with regard to the stability of the estimation of the parameters of the GEV (General Extreme Value) distribution and to the limitation of uncertainty associated with the extrapolation of high return periods. This approach assumes that stations meeting both criteria exhibit sufficient climatic similarity and statistical robustness for the application of regional frequency analysis. The stations used are shown and described in *Fig. 1* and *Tab. 1*.

Tab. 1. Meteorological stations used for RFA, their distances to the pilot locations, and the length of the annual maxima time series

Location	Station ID	Distance [m]	Number of years	First year	Last year
Bukovno	P2CDUB01	27,831	48	1957	2022
	P2SEMC01	14,603	35	1986	2022
	P2TURN01	27,367	49	1951	2022
	U2DOKY01	18,074	60	1963	2022
Pečky	H3PODE01	8,629	37	1951	2022
	P2BRAN01	28,639	36	1986	2022
	P2NVES01	23,383	33	1986	2022
Běchovice	P1PBRA01	14,740	45	1961	2008
	P1PKAR01	13,792	61	1961	2022
	P1PKLE01	14,024	55	1961	2022
	P1PLIB01	15,041	51	1972	2022
	P1PRUZ01	24,845	37	1986	2022
	P2BRAN01	11,440	36	1986	2022
	P2NVES01	12,665	33	1986	2022
	P3ONDR01	23,791	37	1986	2022

The block maxima method was used for the application of extreme value theory [2, 8]. For each duration (5 minutes to 24 hours), annual maxima were extracted from the time series. This approach is consistent with the classical formulation of EVT (Extreme Value Theory) and allows the direct application of the GEV distribution [8]. The resulting set of annual maxima constituted the input for the regional frequency analysis and for the estimation of the parameters of the GEV distribution in the reference period [8, 9].

CORDEX climate projections

Future changes in design precipitation were derived from regional climate projections of the CORDEX (Coordinated Regional Climate Downscaling Experiment) initiative [14]. Models from the European EUR-11 (horizontal resolution of approximately 11 km) and EUR-22 (resolution of approximately 22 km) domains were used [15]. The higher spatial resolution allows a more detailed representation of orography and regional circulation processes influencing extreme precipitation.

The ensemble included multiple combinations of global climate models (GCMs) and regional climate models (RCMs). This multi-model approach makes it possible to capture structural uncertainty arising from differences in the dynamical cores of the models, the parameterisation of cloud processes and convection, and atmosphere–surface interactions [7, 16]. Each GCM–RCM combination represents one realisation of future climate, while the complete set of realisations constitutes the ensemble. An overview of the ensemble combinations used is presented in *Tab. 2*.

Tab. 2. Composition of the ensemble of projections used (number of unique GCM–RCM combinations) by RCP scenario and domain

RCP	EUR-11 (11 km)	EUR-22 (22 km)
RCP2.6	4	2
RCP4.5	5	0
RCP8.5	23	3

Three time periods were evaluated:

- the reference historical period (model simulation corresponding to past climate conditions),
- the near-future period 2035–2065,
- the distant-future period 2070–2100.

For future projections, the RCP2.6, RCP4.5, and RCP8.5 emission scenarios were analysed, representing different trajectories of greenhouse gas concentration development [17, 18]. The RCP2.6 scenario assumes rapid stabilisation of emissions, RCP4.5 an intermediate stabilisation trajectory, and RCP8.5 a scenario of continuing emission growth [18].

Hourly precipitation data from climate models, expressed in units of $kg \cdot m^{-2} \cdot s^{-1}$, were used and converted to precipitation totals before being aggregated to the required durations. For each grid point corresponding to the analysed pilot sites, a time series of annual maxima was extracted from the regional models using a procedure analogous to that applied to the observed data [8].

To reduce the influence of systematic model biases, the future change in the design quantile was expressed in relative form [3]:

$$\Delta = \frac{Q_{\text{future}} - Q_{\text{historical}}}{Q_{\text{historical}}} \tag{1}$$

This approach assumes that the systematic model bias is largely consistent between the historical and future periods, thereby allowing the analysis to focus on the relative change in extremes rather than on their absolute values [16]. The relative changes were subsequently applied to the reference IDF curves derived from observed data, yielding future design values for the individual emission scenarios for both projection periods [12, 13]. This procedure made it possible to link the local statistical behaviour of extreme values derived from observed data with future climate projections, while simultaneously systematically quantifying the ensemble spread as a measure of model uncertainty [7].

Theoretical framework

Extreme value theory

Extreme value theory (EVT) represents a statistical approach based on the asymptotic properties of extremes, intended for modelling the behaviour of maxima of random variables [2, 8]. Whereas the classical central limit theorem describes the limiting behaviour of sums, EVT focuses on the limiting properties of extremes. For independent and identically distributed random variables $X_1, \dots, X_n$, it holds that for suitably normalised maxima $M_n = \max(X_1, \dots, X_n)$, the corresponding distribution function converges to the Generalised Extreme Value (GEV) distribution [8].

The distribution function of the GEV distribution is given by the following equation:

$$F(x) = \exp\left\{-\left[1 + \kappa\left(\frac{x - \xi}{\alpha}\right)\right]^{-\frac{1}{\kappa}}\right\} \tag{2}$$

where:

ξ is the location parameter
$\alpha > 0$ the scale parameter
κ the shape parameter [8]

The shape parameter determines the thickness of the right tail of the distribution. For κ > 0, the distribution has a heavy tail (Fréchet type); for κ = 0, it reduces to the Gumbel type; and for κ < 0, it has a finite upper bound (Weibull type) [8]. Estimation of this parameter is crucial for the extrapolation of high quantiles, because small changes in κ may lead to substantial differences in the estimation of 100-year or 200-year extremes [2, 8].

Quantiles of the GEV distribution can be expressed by inversion of the distribution function:

$$Q(T) = \xi + \frac{\alpha}{\kappa}\left[\left(-\ln\left(1 - \frac{1}{T}\right)\right)^{-\kappa} - 1\right] \tag{3}$$

where:

T is the return period [8].

This explicit formulation allows the direct calculation of design values following parameter estimation.

Regional frequency analysis

Regional frequency analysis (RFA) is a methodology developed to increase the robustness of the estimation of extreme quantiles in situations with limited time-series length [9]. The basic idea is the sharing of information among stations exhibiting similar statistical behaviour of extremes [9].

The index-flood concept assumes:

$$Q_i(F) = \mu_i q(F) \tag{4}$$

where:

$Q_i(F)$ is the quantile at location
μ_i the local scaling factor
$q(F)$ the dimensionless regional growth curve common to the entire region [9]

The scaling factor μ_i is typically defined as the first L-moment (analogous to the sample mean) of annual maxima [9, 19]. For the pilot locations without direct measurements, the scaling factor was estimated using the IDW (Inverse Distance Weighting) method. This method allows the interpolation of quantile values from surrounding gauged stations on the basis of a weighted average of the values, where the weight assigned to each station is inversely proportional to the distance from the analysed location. The distances of the individual stations used for the three pilot locations are presented in *Tab. 1*. By normalising the data from individual stations by their local scale, a dimensionless dataset is obtained, from which the regional shape of the distribution is subsequently estimated [9].

Homogeneity of the region was evaluated within the framework of regional frequency analysis based on L-moments according to [9]. For each duration, the L-moment ratios of individual stations were first calculated, and the expected variability of a homogeneous region of the same size was subsequently estimated using Monte Carlo simulations (1,000 realisations). On this basis, H-statistics (H_1, H_2, H_3) were determined (a summary is provided in *Tab. 3*) quantifying the deviation of the observed inter-station variability from the variability of the simulated homogeneous region.

According to the interpretation criteria of [9], $H < 1$ indicates a homogeneous region, $1 \leq H < 2$ weak heterogeneity, and $H \geq 2$ a heterogeneous region.

To identify potentially inconsistent stations, the discordancy measure was applied. Its values remained, in most cases, below the critical threshold (1.33 for the three-member subregion and 2.33 for the broader region), indicating no pronounced outliers in the L-moment space. Overall, the region can be considered sufficiently homogeneous for the application of regional frequency analysis, while acknowledging slightly increased variability for longer durations.

Tab. 3. Summary of regional statistics for the Bukovno, Pečky, and Běchovice regions; ranges of heterogeneity metrics are reported

Statistic	**Běchovice**	**Pečky**	**Bukovno**
Discordancy (D)	<0.02; 2.48>	<0.06; 1.33>	<0.02; 1.33>
H_1	<-1.32; 2.13>	<-1.19; 0.66>	<-0.91; 2.47>
H_2	<-1.62; 2.82>	<-0.60; 1.93>	<-1.24; 1.41>
H_3	<-1.33; 2.56>	<-1.05; 2.04>	<-1.12; 2.00>

The overall assessment indicates that the Bukovno area is predominantly homogeneous from the perspective of regional frequency analysis, although with locally increased heterogeneity, particularly according to the statistic H_1 and marginally also H_3. The Pečky area appears to be the most homogeneous of the three locations, with no exceedance of the critical discordancy threshold and only indications of weak to moderate heterogeneity in H_2 and H_3. In contrast, Běchovice exhibits the highest degree of spatial heterogeneity, reflected both by isolated exceedances of the critical discordancy threshold and by elevated values of the H_2 and H_3 statistics.

RESULTS

The theoretical framework based on the GEV distribution and regional frequency analysis made it possible to translate climate projections into changes in the design quantiles of extreme precipitation. The following section therefore presents a quantification of these changes, focusing on the magnitude of the 100-year quantile and on the structure of uncertainty arising from the multi-model ensemble.

Change in the 100-year hourly quantile

The relative change in the 100-year hourly quantile Q_{100} exhibits a systematic dependence on both the emission scenario and the time horizon. In the period 2035–2065, differences among the RCP scenarios are smaller than the internal variability among individual realisations within the same scenario. In the distant period 2070–2100, a pronounced divergence among the scenarios becomes apparent.

Under the RCP8.5 scenario (2070–2100), the mean relative change in Q_{100} amounts to 52 % with a standard deviation of 41 %. The interval between the 5th and 95th percentiles ranges from –7 % to +126 %. The median change is approximately 47 %. Approximately 80 % of the realisations exhibit a positive change.

For the RCP2.6 scenario (2070–2100), the mean change is approximately 19 %, and the uncertainty interval is substantially narrower. The difference between the mean changes under the RCP8.5 and RCP2.6 scenarios in the second half of the century exceeds 30 percentage points.

Values exceeding 100 % are generated by a limited number of realisations and correspond to cases with a positive shape parameter κ, implying a heavy right tail of the GEV distribution. The distribution of changes across scenarios and periods is shown in *Fig. 2*, which illustrates the pronounced widening of the ensemble spread under the RCP8.5 scenario (2070–2100).

Dependence on duration

The relative change in extreme precipitation exhibits a decreasing trend with increasing duration. Under the RCP8.5 scenario, representing a high-emission scenario used primarily to illustrate the upper bound of climate impacts (2070–2100), the mean change is approximately:

- 1 h: 52 %,
- 6 h: 39 %,
- 24 h: 28 %,
- 48 h: 28 %.

This gradient is also evident from the IDF curves for the same scenario variant shown in *Fig. 3*, where the intensification is more pronounced for shorter durations.

The range between the 5th and 95th percentiles is wider for shorter durations. Relative uncertainty therefore increases with the intensity of the extreme event.

Influence of the shape parameter κ

The sensitivity of high quantiles to the shape parameter increases with the return period *T*. It follows from the GEV quantile function (3) that $\partial Q / \partial \kappa$ increases with *T*. Small differences in the estimation of κ therefore lead to substantial differences at high return periods.

Realisations with $\kappa > 0$ generate more rapid growth of *Q(T)* and explain the upper part of the ensemble spread. This effect represents a structural

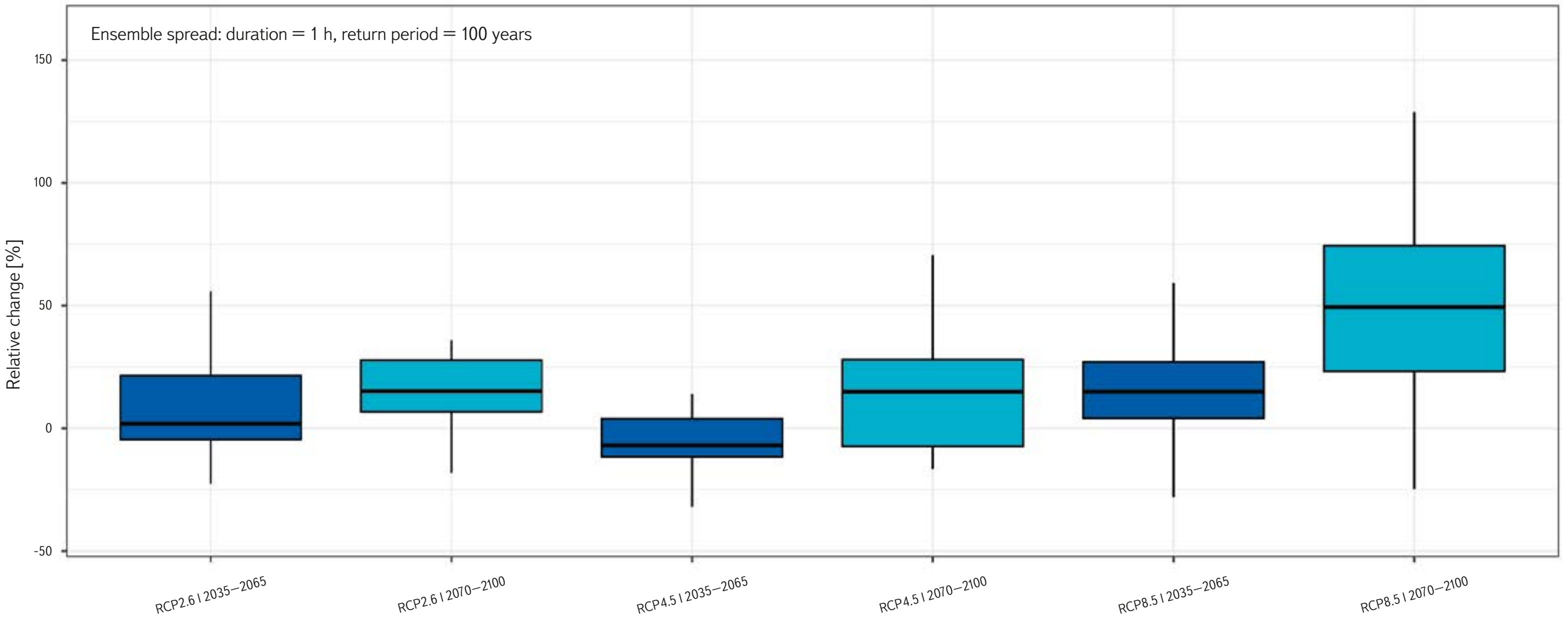

Fig. 2. Relative change in the 100-year hourly quantile (Q_{100}, 1 h) across RCP scenarios and time horizons for three pilot areas. Box plots represent individual GCM–RCM realizations (37 in total) within the 5th–95th percentile range; the box indicates the interquartile range and the black line denotes the median. Time horizons are distinguished by colour – dark blue (2035–2065) and light blue (2070–2100). The ensemble spread is substantially wider under the RCP8.5 scenario (2070–2100), where the upper bound exceeds 100 %

source of extrapolation uncertainty. The increase in relative uncertainty with return period is documented in *Fig. 4*, where the spread of projections systematically increases with increasing return period.

DISCUSSION

Dominant sources of uncertainty

The nature of uncertainty differs depending on the time horizon. In the near-future period, structural model variability is dominant, whereas in the distant-future period the divergence among emission scenarios becomes increasingly important. This result is consistent with the general conclusions of climate projection studies.

It should be emphasised that the presented spread includes only the variability among model realisations. Uncertainty associated with the estimation of the GEV parameters (e.g. confidence intervals of κ) is not explicitly quantified here and may further increase the overall uncertainty.

Interpretation of high relative changes

Relative changes exceeding 100 % represent the upper part of the projection distribution and are not representative of the centre of the ensemble. Their

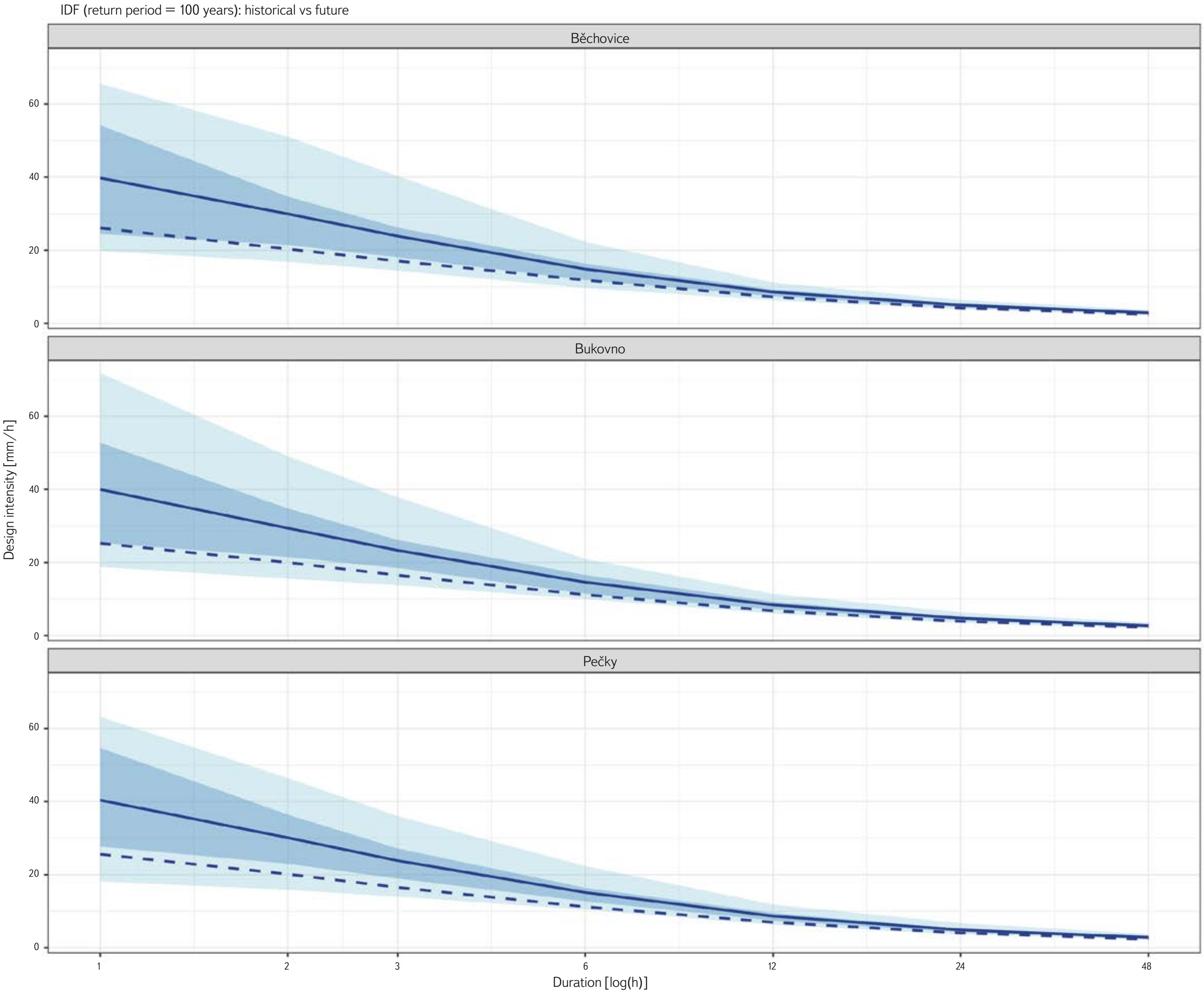

Fig. 3. Comparison of historical and future IDF curves ($T = 100$ years) for the pilot locations Bukovno, Pečky, and Běchovice. The solid line represents the median of the RCP8.5 (2070–2100) projections, while the dashed line corresponds to the reference period. The lighter blue area indicates the 5th–95th percentile range of the ensemble, and the darker blue area shows the 25th–75th percentile range

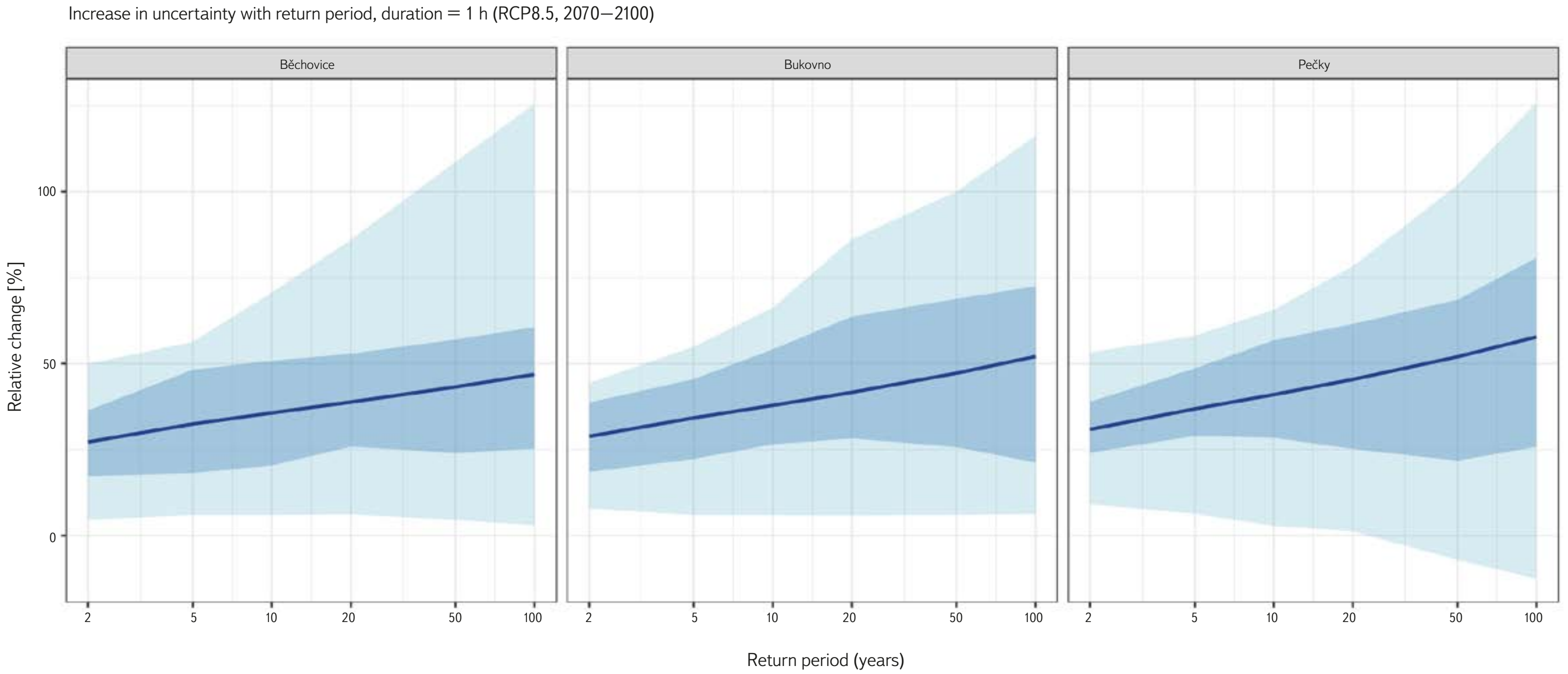

Fig. 4. Dependence of the relative change in the design quantile on return period (logarithmic scale) for a 1-hour duration under the RCP8.5 scenario (2070–2100). Solid lines represent the mean change, the light blue area indicates the 5th–95th percentile range of the ensemble, and the darker blue area shows the 25th–75th percentile range. The spread among realizations increases with return period, reflecting the sensitivity of the extrapolation to the shape parameter κ

occurrence is associated with a combination of a strong climate signal and positive κ.

From a purely thermodynamic perspective, Clausius–Clapeyron scaling would imply an intensification of approximately 28 % for a warming of about 4 K [5, 6]. The mean value of 52 % under the RCP8.5 scenario (2070–2100) exceeds this simple scaling, suggesting that, in addition to thermodynamic intensification, dynamic changes in circulation, changes in convective organisation, or nonlinear responses of extremes may also play a role.

Since the study does not perform an explicit analysis of the underlying dynamical mechanisms, this interpretation should be regarded as a hypothesis consistent with the literature rather than as direct evidence.

Implications for infrastructure design

The use of historical IDF curves without accounting for climate change leads, under higher-emission scenarios, to a systematic underestimation of extreme precipitation volumes.

At the same time, the ensemble mean cannot be regarded as a sufficient representation of risk. Design values should reflect the full range of projections and should be assessed in the context of the acceptable level of risk and the service life of the infrastructure.

Application framework of the study

The methodology and the selection of pilot locations are directly linked to the objectives of the project *Adaptation of Urbanised Areas to Flash Floods and Drought* (SrUrb, No. SS06010386), funded by the Technology Agency of the Czech Republic under the Environment for Life programme. The aim of the project is to support decision-making processes related to the adaptation of urbanised areas to extreme hydrometeorological events, which determined the selection of locations with a high degree of urbanisation and direct practical relevance for the design of adaptation measures.

The selected 30km spatial buffer and the regional frequency approach were therefore conceived primarily as a tool for the application-oriented estimation of design values in specific project areas, rather than as a general climatological regionalisation at the national level. This application framework explains both the pragmatic choice of spatial criteria and the focus on the 100-year design quantile, which is of key importance for the dimensioning of urban infrastructure.

Limitations of the methodological approach

Although the study provides a systematic quantification of changes in IDF curves, several limitations must be emphasised. The study is based on hourly outputs from regional climate models, which do not allow the explicit representation of sub-hourly extremes. Short-duration intense precipitation events with durations below one hour may therefore be underestimated or omitted in the model projections. The GEV model was applied in a stationary manner to individual time periods, without implementing an explicit non-stationary parameterisation with time-varying parameters. In addition, no formal decomposition of variance into model, scenario, and internal variability components was performed. These aspects represent limitations of the study and at the same time indicate potential directions for further methodological development.

It should also be noted that regional climate models are affected by systematic biases [16]. Although relative change with respect to the historical model simulation was used, structural errors in the representation of extreme processes cannot be excluded [16]. At the same time, regional frequency analysis assumes regional homogeneity [9]. Although homogeneity was statistically tested, the actual climate field may exhibit spatial gradients that partially violate this assumption [9].

The results should therefore be interpreted primarily as support for decision-making in project areas and as an illustration of the possible range of changes in extreme precipitation, rather than as a spatially comprehensive climatic characterisation of the entire Czech Republic. Despite these limitations, the study provides a robust framework for the quantification of changes in design precipitation and the associated uncertainty.

CONCLUSION

The aim of the present study was to quantify changes in design precipitation at ungauged locations and to systematically evaluate the uncertainty of the 100-year design quantile under climate change conditions. The combination of regional frequency analysis and a multi-model ensemble of regional climate projections made it possible to link the local statistical estimation of extremes with the global and regional climate context [9, 14, 15].

The results indicate an intensification of extreme precipitation across most realisations and evaluated scenarios, while the magnitude of change generally increases with both the emission trajectory and the time horizon [1, 18]. Under the RCP8.5 scenario, the mean relative change in the 100-year hourly quantile reaches approximately 30–50 % by the end of the century, whereas the upper bound of the ensemble spread may indicate more than a doubling of the extreme event. At the same time, the uncertainty interval also includes realisations with smaller or only marginal changes, reflecting the persistent model variability associated with emission scenarios. These results have important implications for the dimensioning of long-life infrastructure, particularly for decision-making under conditions of substantial uncertainty [7].

The uncertainty analysis showed that, in the near-future horizon (2035–2065) model variability among individual regional climate models is dominant [7]. In the more distant horizon (2070–2100) however, the divergence among emission scenarios becomes increasingly significant [7, 18]. This implies that decision-making regarding adaptation measures must take into account not only the mean projection, but also the range of possible developments and the associated emission trajectory.

The detected intensification of extremes is physically consistent with the expected Clausius–Clapeyron scaling of approximately 7 % per 1 K of warming [5, 6]. The slightly stronger intensification under the RCP8.5 scenario may reflect a combination of thermodynamic and dynamical changes in atmospheric circulation and convection [1, 6].

From the perspective of water management practice, the results suggest that the use of historical IDF curves without accounting for climate change may lead to systematic underdesign of infrastructure [1, 3]. At the same time, the ensemble spread indicates that a design based solely on the mean projection may not be sufficient from the perspective of risk management [7]. A future adaptive approach should therefore work with a range of possible changes and explicitly take uncertainty into account.

The study presents a methodological framework that can also be applied to other regions with limited measurement density. Further research should focus on the use of non-stationary extreme value models, the application of convection-permitting climate models with higher temporal resolution, and a deeper integration of climate projections into decision-making processes in the field of stormwater management [6, 20].

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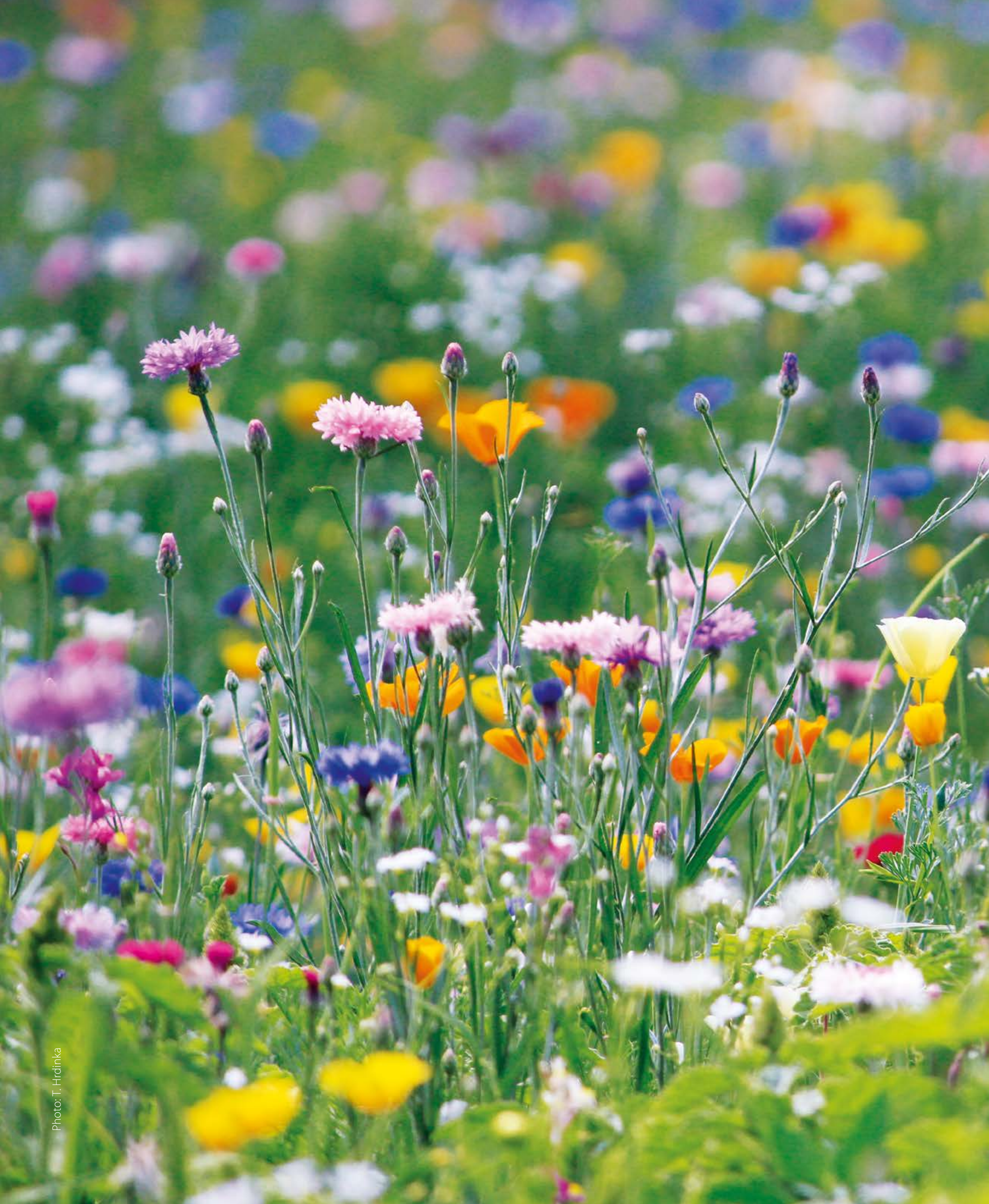

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Microplastics in waters: The first accredited laboratory in the Czech Republic at the TGM WRI

Microplastics, defined as particles of synthetic polymers smaller than 5 mm, represent one of the most intensively studied environmental issues of the present day (*Fig. 1*). These ubiquitous particles, arising primarily from mechanical abrasion, fragmentation, or industrial processing of plastics, are released into the environment in large quantities. While early research focused on seas and oceans, attention is now shifting to freshwater ecosystems and drinking water, where they pose significant environmental and health risks [1, 2]. The effects of microplastics on organisms are complex – they act as vectors for contaminants sorbed from the environment, release chemical additives intentionally incorporated into plastics (such as plasticisers and flame retardants) and may mechanically disrupt tissues and cause chronic inflammation [3]. As a result of their slow degradation, they readily enter food chains and accumulate in biota at all trophic levels [4].

The increasing research interest in microplastics is also reflected in the legislative sphere. European legislation requires the implementation of microplastics monitoring in drinking water through an amendment to the EU Directive on the quality of water intended for human consumption (Commission Decision 2024/1441). Similar requirements are expected soon for surface waters following the adoption of the relevant Directive of the European Parliament and of the Council amending Directive 2000/60/EC (Water Framework Directive). In response to this context, and with the aim of providing a reliable analytical background, a specialised Laboratory for Microplastics Analysis was established at the Brno branch of the TGM Water Research Institute (TGM WRI), which has been intensively engaged in this field since 2023.

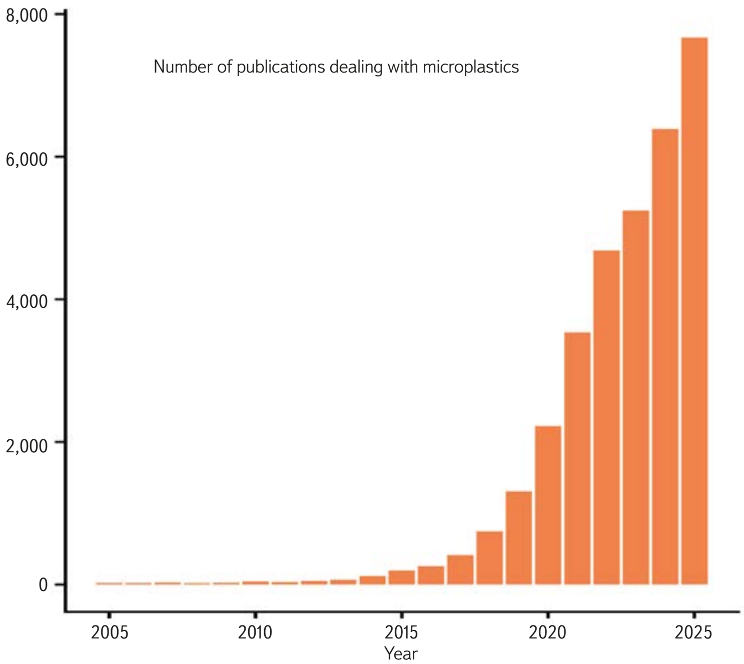

Fig. 1. Cumulative number of scientific publications in the Scopus database containing the keyword *microplastic*

In the field of microplastics analysis, two main groups of methods are key, differing primarily in detection limits and output. Vibrational spectroscopy, in particular Fourier transform infrared spectroscopy (FTIR), and Raman spectroscopy are widely used non-destructive methods for the analysis of microplastic samples. By surface scanning of a prepared sample, a so-called chemical map can be obtained, providing precise information on the number, size, shape, and chemical composition of the detected particles (*Fig. 2*). The FTIR method is suitable for the quantification and identification of particles from a size of 5 µm [5], whereas Raman spectroscopy can detect particles down to approximately 300 nm [6], thereby enabling the detection of nanoplastics. Another possible method for determining the presence of microplastics is pyrolysis coupled with gas chromatography and mass spectrometry, which, however, leads to the destruction of the analysed sample and provides information only on the total mass of individual polymer types in a given sample [7].

Information on size distribution and shape obtained by spectroscopic methods is also essential for assessing risks to organisms and is therefore crucial for meeting legislative requirements. At the Laboratory for Microplastics Analysis at TGM WRI, FTIR spectroscopy was selected as the detection method. The laboratory has been equipped with a µFTIR spectroscope LUMOS II by Bruker Corp. (*Fig. 3*). This instrument enables fully automated analysis of entire areas (typically a filter with a diameter of 25 mm) and the creation of a chemical map of the analysed surface. From the resulting map, computational methods can automatically identify plastic particles, their shape and size, and, most importantly, their chemical composition, that is, the type of polymer.

The analysis itself is preceded by a relatively complex sampling process – in the case of water, using a cascade of filters and, where appropriate, a pump (*Fig. 4*) – followed by sample preparation. Sample preparation for analysis involves oxidative digestion processes aimed at removing organic residues from samples originating from environmental matrices (see, for example, [8, 9]), complemented by density separation to eliminate the remaining inorganic fraction [10].

The entire process of sample preparation and analysis has been standardised and optimised, and in 2025 the laboratory first obtained certification

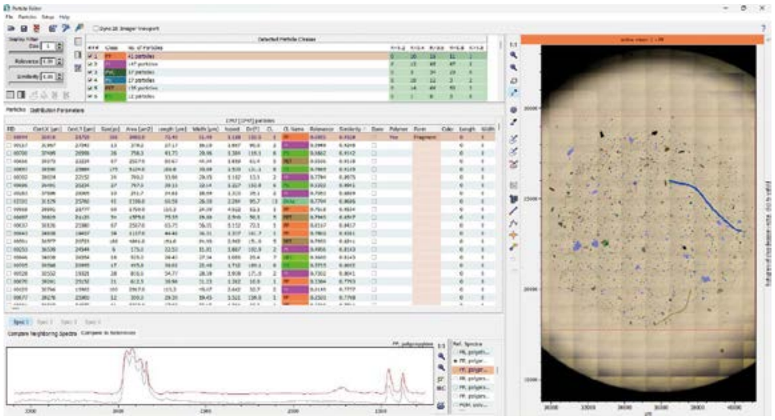

Fig. 2. Chemical map of the analysed microplastics sample visualised using the Microplastic Finder software (Purency)

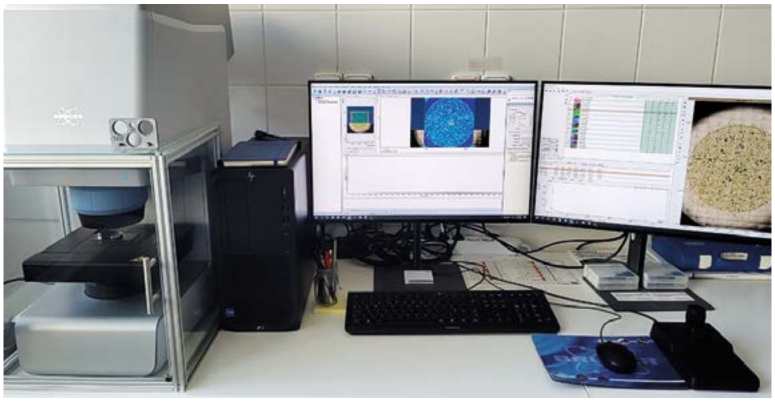

Fig. 3. From left: sample being analysed in the μFTIR spectroscope LUMOS II; processing in the OPUS software; evaluation of the content and type of microplastics using the Microplastic Finder software

from the Centre for Assessment of Laboratories (ASLAB), followed by accreditation from the Czech Accreditation Institute (CAI). Both certifications apply to the determination of microplastics in water using Fourier transform infrared spectroscopy and to the sampling of water for the purpose of determining microplastic content. TGM WRI laboratory currently operates the first and, to date, only laboratory in the Czech Republic accredited by CAI and assessed by ASLAB for the sampling and analysis of the quantity, size, and chemical composition of microplastics specifically in drinking water samples. At the same time, the laboratory information system (LIS) LABSYSTÉM was adapted for sample intake and result recording. Experience gained from national and international projects in which the laboratory is currently actively involved was directly utilised in the accreditation process (see Info box).

The Brno branch of TGM WRI offers analytical services to a wide range of clients, including research organisations, laboratories, operators of water supply systems and wastewater treatment plants, public authorities, and the general public within the framework of commercial services. Thanks to our experience from international and national projects and our certified quality standards, we provide comprehensive services ranging from sample collection and analysis to the interpretation of results.

Systematic monitoring of microplastics in the aquatic environment is an essential prerequisite for identifying their pathways of entry, assessing ecological risks, and developing strategies to reduce their presence in the environment. Our laboratory is prepared to provide qualified support in this important area of water resource and human health protection.

Fig. 4. Pumping and filtration of water from a stream for microplastics analysis (left); detail of the filtration apparatus (right)

Overview of ongoing projects at the Brno branch of TGM WRI focused on the detection of microplastics in environmental samples

Project *Mikroplast-IKA*; Funding: Technology Agency of the Czech Republic (TA CR), Environment for Life II Programme, No. SS07010295

The aim of the project is to quantify microplastics in surface waters and to identify their main pathways of transport into watercourses. The initial phase focuses on the development and standardisation of methodologies for sampling and sample processing from complex matrices, specifically water, sediments, and biota. Subsequent monitoring is targeted at critical sources of contamination, such as effluents from wastewater treatment plants and combined sewer overflows, as well as at retention areas such as reservoirs. The project outputs will provide a robust basis for assessing the anthropogenic load of microplastics in surface waters and will enable the effective targeting of mitigation measures at critical points within catchments.

Project *MicroDrink*; Funding: Interreg Danube Programme, No. DRP0200442

The main objective of the project is to strengthen institutional capacities and governance processes for the prevention of microplastic contamination of drinking water sources in the Danube region. The project brings together the scientific community, decision-making bodies, and operators of water infrastructure with the aim of standardising procedures for monitoring and risk mitigation. A key output is the sharing and practical evaluation of knowledge in the field of sampling and analysis of microparticles in drinking water. The results will support strategic decision-making and the implementation of preventive measures at the transnational level, thereby contributing to the protection of water resources across eight participating countries.

Project *Joint Danube Survey 5*; Funding: Technology Agency of the Czech Republic (TA CR), Long-term Environmental and Climate Perspectives (Centre Water), No. SS02030027

The fifth Joint Danube Survey (JDS5) represents a unique scientific expedition focused on a comprehensive assessment of water quality and biodiversity across 14 countries in the Danube basin and its major tributaries.
The main objective is to obtain comparable data on priority pollutants and emerging contaminants that are not included in standard national monitoring programmes. An innovation of JDS5 lies in the integration of advanced methods, such as environmental DNA (eDNA) analysis and the systematic monitoring of microplastics along the entire watercourse. The results of the survey contribute to the harmonisation of methodologies in line with the Water Framework Directive and provide a scientific basis for updating the Danube River Basin Management Plan.

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XXVIII conference on *Radionuclides and ionising radiation in water management*

The latest edition of the annual conference Radionuclides and ionising radiation in water management took place on 21–22 April 2026 at the Clarion Hotel in České Budějovice. The scientific coordinators of the conference were Ing. Barbora Sedlářová, Ing. Eva Juranová, Ph.D., and RNDr. Diana Marešová, Ph.D. (TGM WRI), while the organisational coordinator was Jan Kříž (ČVTVHS). The conference was attended by 63 experts, with 59 participants from the Czech Republic and four from the Slovak Republic.

The conference offered a diverse scientific programme focused on current research, monitoring, and legislative aspects related to the occurrence of radionuclides in the environment, particularly in water.

The conference programme covered a broad range of topics, from monitoring of the radiation situation and legislative changes in the field of atomic law to applied research focused on the behaviour of radionuclides in the hydrosphere. Considerable attention was devoted, for example, to the issue of tritium in water, which was discussed both from the perspective of analytical methods and in the context of current legislation.

Some scientific contributions focused on the hydrogeological and hydrochemical monitoring of selected sites intended for a deep geological repository for radioactive waste in the Czech Republic, including the assessment of radionuclide migration and transport in these environments. The conference also presented research results concerning mine water at the flooded Rožná uranium deposit, as well as issues related to the management of materials with elevated concentrations of natural radionuclides during the construction of the D11 motorway.

Another block of presentations was devoted to laboratory and experimental studies, including radionuclide sorption on nanosorbents, the leachability of natural radionuclides from waste materials, and the optimisation of analytical methods for the determination of selected radionuclides in complex matrices. Presentations were also given on the determination of radionuclides in the hydrosphere in the vicinity of nuclear facilities.

The conference included a poster section presenting, for example, statistical analyses of radionuclide concentrations in drinking water, monitoring of radionuclides in the vicinity of nuclear power plants, and new approaches to the determination of isotopes in air and water.

The conference once again confirmed its importance as a platform for sharing the latest knowledge, discussing current issues, and establishing professional cooperation between institutions from the Czech Republic and abroad. The broad range of presented topics and the high scientific standard of the contributions contributed to professional discussion and the exchange of experience in the field of radionuclide monitoring and radiation protection in water management.


Fig. 2. From the excursion to the historic centre of České Budějovice (Photo: T. Bouda)

The conference proceedings are available at: https://www.vuv.cz/wp-content/uploads/2026/04/SBORNIK_Radionuklidy2026.pdf

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An informative article that is not subject to peer review.


Fig. 2. Lecture session from the conference on Radionuclides and ionising radiation in water management (photo: E. Juranová)

VTEI/2026/**3**

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ROLNIČKY (SOUTH BOHEMIA, SUMMER 2016)

I enjoy travelling to South Bohemia, and not only for photography. The landscape has a particular charm, with beautiful, secluded spots where civilisation still feels like an unwelcome guest. And when the fog sets in, it is so dense it feels as though it could be cut with a knife. Out of the mist, small jewels emerge, as if waiting to be captured by the camera. It is a striking contrast – in the macro world everything is full of colour, while the surrounding world remains grey and almost opaque. I lie on a damp sleeping mat, and cold, wet fingers slowly creep down the back of my neck, yet through the lens a window opens into a world where tiny bells softly chime and every droplet is like a child's room full of colours. I spend a long time searching for the right angle and the right light. Most of the time, I move the lens at a distance of just two to eight centimetres from the subject, so I have to be very careful not to touch the surrounding blades and fibres with an incautious movement; a single touch – and the whole constellation of droplets slides down. When I get up after an hour of photographing, I am stiff and soaked, yet I move straight on a metre further, because this dew-covered world holds thousands more surprises. The morning is still young, and a meadow filled with mist and dew is simply a gift for macro photography.

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

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