VODOHOSPODÁŘSKÉ TECHNICKO-EKONOMICKÉ INFORMACE

(WATER MANAGEMENT TECHNICAL AND ECONOMIC INFORMATION)

VTEI/2026/4

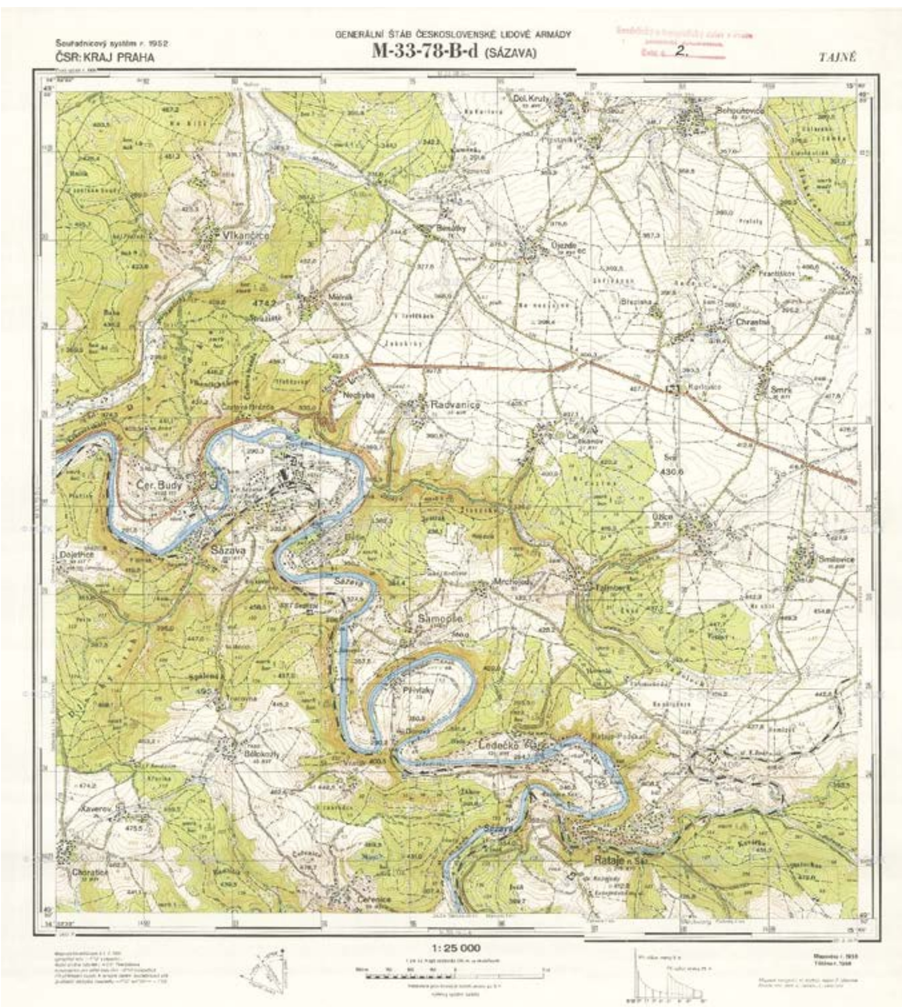
60 years ago in VTEI

In Issue 3 of VTEI in 1966, an article entitled "Weirs on the Sázava river" was published. It was written by Ing. Zdeněk Teplý of KVRIS Prague.

Fifty years ago, timber rafting on the Sázava river was gradually coming to an end. From that time onwards, the weirs served mainly to power watermills. More recently, however, the mills have been closed, and no one has taken responsibility for maintaining the weirs. Although property law formally attaches the maintenance obligation to the relevant property, the new tenants of the former mill buildings, who use them as grain stores, feed-grinding facilities, or residential premises, have no interest in harnessing water power and in keeping the weirs in good condition. As a result, the weirs have long been left without maintenance. They no longer impound water and, from a hydraulic engineering perspective, no longer function even as drop structures capable of maintaining a stable water level.

The deterioration of the weirs results in irreversible damage. As the riverbed is progressively scoured, the riprap subsides into deepened sections near the banks and no longer provides adequate support for the bank protection. The groundwater level falls, and the adjacent land loses its productivity as it is effectively drained. Water levels in wells also decline, making it necessary to deepen them. The impounded reaches behind the weirs are left without water. The above clearly demonstrates the importance and necessity of maintaining weirs, and greater attention should be paid to their upkeep in the future.

From TGM WRI archives



Topographic map S-1952 from 1956, Archive application (https://ags.cuzk.gov.cz/archiv/)

Content

Photo: 123rf.com

Dear Readers,

At the end of the summer holidays, the water management community, together with the wider professional public, will mark World Lake Day, observed annually on 27 August. This new international observance, proclaimed by the United Nations General Assembly in December 2024, highlights the importance of lakes, reservoirs, and associated aquatic ecosystems for water supply, as well as for biodiversity, landscape resilience, recreation, and economic development. At the same time, lakes and reservoirs are highly sensitive to climate change, pollution, land-use changes, and growing pressure on water resources. Their management therefore requires an integrated approach that brings together hydrology, limnology, water quality management, spatial planning, engineering measures, and long-term landscape management.

This broad spectrum of water management topics is also clearly reflected in the current issue of VTEI, which opens with an article by Petr Šercl and co-authors focusing on improving the estimation of flash flood risk in the Flash Flood Indicator application used by the Czech Hydrometeorological Institute. The proposed methodological enhancements incorporate the degree of urbanisation and critical concentrated runoff points, enabling a more accurate assessment of the risk of local flooding, particularly within built-up areas.

The second expert article, by Petr Vyskoč and his colleagues, presents a nationwide assessment of the reliability of water abstractions and minimum flows up to 2050 under the combined effects of climate change and projected socio-economic development. The results indicate potential risks to a number of reservoirs and groundwater bodies, underscoring the importance of long-term planning to secure future water resources.

The following article, by a team of authors led by Hana Prchalová, focuses on assessing trends in the status of surface waters and the progress made towards achieving good status. Using a discrepancy index, it evaluates changes in selected water quality indicators and shows that while the status of some substances has improved, other indicators have remained unchanged over the long term or have improved only very slowly.

Silvie Semerádová's article focuses on the relationship between flow conditions and the concentrations of selected water quality indicators. It demonstrates that statistical analysis of long-term data can help distinguish different types of relationships between discharge and pollutant concentrations, improve the identification of the key drivers within a catchment, and support more targeted monitoring strategies.

The international contribution by Nassima Lekouaghet and her colleagues presents the application of modern machine learning methods to predict BOD_5 concentrations in wastewater treatment plant effluent. The article demonstrates data-driven approaches and artificial intelligence tools that are increasingly being applied in water management practice, particularly to improve the evaluation of operational data and support decision-making.

The August issue concludes with an interview with Jiří Jílek, offering readers a more personal perspective on water management and landscape practice. The interview explores river and landscape restoration, water management in public spaces, the importance of attention to detail, and the experience gained from implementing specific projects. It serves as a reminder that successful water management solutions depend not only on calculations and technical design, but also on an understanding of the site, the materials used, the surrounding landscape, and the people who live in and use it.

I believe this August issue of VTEI offers readers a diverse perspective on current water management topics – from hydrological extremes and climate change to water quality, modern data-driven methods, and practical experience from the field. We hope you will find inspiration for your own professional work, further discussion, and broader reflection on the role of water in the landscape and in society.

On behalf of the VTEI Editorial Office
Ing. Josef Nistler

Linking critical points to the Flash Flood Indicator

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Keywords: flash floods — flood risk — Flash Flood Indication (FFI) — critical points — urban areas — nowcasting

ABSTRACT

This paper addresses the issue of refining the estimation of flash flood hazard by modifying the Flash Flood Indicator (FFI) application, which is used by the flood forecasting service of the Czech Hydrometeorological Institute (CHMI). The existing FFI approach was based primarily on hazard assessment determined by comparing the runoff response with threshold values derived from theoretical discharge rates with a given return period, while exposure and vulnerability were considered only implicitly. The article proposes extending the methodology by explicit consideration of these factors by means of two main approaches: (i) adjusting the threshold values for hazardous runoff depending on the degree of urbanisation of the area, and (ii) incorporating critical points (locations where concentrated runoff may enter urban areas) and their contributing catchment areas in the FFI calculations.

Based on analysis of selected rainfall events from 2023–2024, it was found that lowering the threshold values in urban areas leads to a more realistic estimate of the risk of localised flooding, particularly within built-up areas of municipalities. At the same time, it was shown that the inclusion of critical points – defined as locations of concentrated runoff at the interface between built-up and non-built-up areas – significantly improves the identification of locations with an increased risk that are not adequately captured by the 3 × 3 km polygon grid. The results also confirm the crucial influence of the quality of meteorological data input – particularly radar precipitation estimates – on the accuracy of the resulting risk assessment. The proposed modifications represent a shift from assessing the hazard itself to a more comprehensive expression of actual risk, which takes into account the spatial variability of exposure and vulnerability. The article also identifies the main limitations of the current approach and gives recommendations for further development of the FFI system, particularly in terms of refining meteorological input and adaptive setting of threshold values.

INTRODUCTION

Flash floods can cause significant material damage and loss of life. They occur as a result of rapid water runoff triggered by intense rainfall, usually confined to a small area. Precipitation over an area typically up to a few km^2, lasting a matter of minutes, does not usually trigger a flash flood, but merely leads to rapidly forming surface runoff from the surrounding land. This can cause localised flooding of low-lying areas and buildings. However, if torrential rainfall persists for a longer period and affects a larger area, surface runoff concentrates in the valleys of permanent watercourses; and if several catchment areas of smaller watercourses are affected simultaneously, this leads to flash flooding at their confluence, which may also affect settlements situated further downstream.

The media has been focusing on the occurrence of flash floods in various parts of the world and their catastrophic consequences. In Europe, notable examples include the floods of July 2021 in Germany on the River Ahr (180 fatalities) and those of October 2024 near Valencia in Spain in the Turia river basin (232 fatalities). The high death toll of the flooding in Germany was due to local underestimation of the situation: despite the weather forecasts being more or less accurate, the hydrological response was not adequately assessed, which resulted in a lack of essential warnings of extreme flooding [1]. In Spain, the main problem arose from late warnings by local authorities and, more generally, the overall lack of preparedness of the emergency response system, infrastructure and the population [2].

In the Czech Republic (CR), torrential flooding of significant geographical extent and severity has also recently occurred, for example on the evening of 7th June 2020 in the Uničov region and parts of the Šumperk region [3], and on the evening of 29th June 2022 in the Pošumaví region in the Blanice catchment area on the Zlatý potok watercourse [4]. The peak flows of both floods reached a return period of approximately 50 years.

Early warning of flash flooding is often very difficult. Neither the resolution of meteorological models, nor the complex physics of the atmosphere during convective storms allow for a precise determination of the location of rainfall of hazardous intensity. The probability of a successful forecast is higher for extreme rainfall over a larger geographical area. However, meteorological models predict levels for certain parameters (e.g. CAPE – convective available potential energy), from which it is possible to deduce a general risk of torrential rainfall occurring in a given (larger) area. Forecast uncertainty often persists even on the day of the expected event. The variability of individual outputs from forecast models is high, which complicates spatial precision of meteorological or hydrological warnings. Soil saturation from previous rainfall is one of the key factors affecting runoff; i.e. higher levels of soil saturation lower the threshold for potentially hazardous intensity of rainfall.

For a more accurate prediction of flash flooding, it is therefore necessary to use data from meteorological radars. Based on the current development of water-bearing clouds in time and space, the propagation of these clouds is calculated over a time frame of approximately 30 minutes to an hour. This short-term forecast, which calculates the subsequent position of these rain clouds within a given time based on their movement and upper-air flow over the most recent time interval, is known as nowcasting. The nowcasting method currently used by the CHMI projects the movement of water-bearing clouds forward in time without any change to their structure (rain intensity), which is currently the greatest limitation of this short-term forecasting method.

Information on current soil moisture levels and the latest developments in water-bearing cloud cover is utilised by the Flash Flood Indicator (FFI), which is used for short-term prediction of the risk of localised flooding and the occurrence of flash floods. This tool has been in use within the CHMI forecasting service for several years and has undergone significant development since 2017 [5]. Experience gained from the operation of the FFI in 2022, and to some extent in 2023, is analysed and discussed in this article [4].

Until now, the hazard of flash floods and localised flooding has not been closely linked to 'risk' within the FFI system, which, in addition to hazard, also includes elements of exposure and vulnerability. One of the objectives of the research project, on which this article is based, was to incorporate elements of exposure and vulnerability in the FFI system, in particular by utilising the location of newly identified "critical points" and their contributing areas throughout the Czech Republic. Critical points (CP), defined as intersections of concentrated runoff paths and boundaries of built-up areas, represent locations where the effects of hazard posed by torrential rainfall are concentrated. At the same time, we can speak of risk (damage, loss of life and harm to population health) within urban areas.

This article demonstrates the current capabilities of the FFI system in predicting torrential flooding, using selected flood events as examples. In the case of localised flooding, the article examines options for adjusting parameters to determine critical thresholds for hazardous runoff and the use of critical points to emphasize factors of vulnerability and exposure within FFI calculations. Through re-simulation of selected events, the inclusion of adjusted critical runoff thresholds and a layer of critical points is evaluated.

METHODOLOGY

Risk estimation in the Flash Flood Indicator

Risk is most commonly expressed as the probability of an undesirable event occurring, and of adverse impact on life, health, property or the environment. Generally, such risk arises from the interaction of hazard, vulnerability and exposure, i.e. the duration for which the hazard is present.

$$R = f\,(\text{Hazard, Vulnerability, Exposure}) \qquad (1)$$

The longer the duration of exposure – that is, the longer the period during which an object is exposed to a hazard and the greater its vulnerability – the greater the overall risk.

From a perspective of probability, risk is defined as an n-tuple of vectors [6]:

$$R_i \equiv (Sc_i, P_i, D_i),\ i = 1, \ldots, n \qquad (2)$$

where:

Sc	is	hazard scenario
P		the probability of the hazard scenario occurring
D	are	the consequences (damage, loss), expressed in appropriate units

All these quantities are time-dependent, as the hazard scenario, the probability of its occurrence and the damage may all change over time. In accordance with the general definition given above, risk can be defined as a continuous function according to the following equation:

$$R(D) = \int_0^\infty (D(u|O) \cdot g(u) \cdot du) \qquad (3)$$

where:

D(u|*O*)	is	the risk function
u		an event quantifier dependent on the vector of measures and decisions
O		the height of the protective embankment along the watercourse, the capacity of the spillway, timely evacuation, etc., which influence the consequences of an extreme event.

The function *g(u)* represents the probability density of the occurrence of an event (hazard scenario) with consequences.

A simple conceptual model based on the equation described above (1) was applied to express risk within the tool – the Flash Flood Indicator. In the context of flash floods and to enhance the clarity of the text, individual components of risk are defined as follows:

— **Hazard**: a condition (threat or phenomenon) with the potential to cause undesirable consequences. In the context under consideration, this refers to flash floods or localised flooding resulting primarily from very heavy rainfall, or the breach of a reservoir dam (exceptional floods). These phenomena can cause flooding, damage buildings and infrastructure, and endanger lives.

The Flash Flood Index (FFI) calculates the probable runoff response to past, current or expected precipitation, namely:
- within a system of catchment areas and river sections, where, in each sub-catchment area, the temporal progression of the runoff response is derived at the location of the outlet profile; the output is an estimate of hazard characteristics, i.e. flash floods, for so-called "obce s rozšířenou působností" – ORPs (= municipalities with extended competence),
- in a regular 3 × 3 km polygon grid, where the magnitude of the maximum specific runoff in a given polygon is derived; the output is an estimate of the hazard characteristics of localised flooding for ORPs.

By combining the characteristics of both hazard components – localised flooding and flash floods – the extent of so-called 'aggregate' flash flood hazard is derived.

The peak discharge or maximum specific runoff is compared with the theoretical value of the discharge (specific runoff) corresponding to a 100-year return period, and, based on established threshold values, the hazard level of flash-flooding (within the catchment system) and localised flooding (within the polygon grid) is determined. The hazard level is classified according to the theoretical return period of the given event, regardless of the location where it occurs. The result is an expression of the event's hazard level on a four-point scale {0, 1, 2, 3}.

— **Exposure**: describes the extent to which (or for how long) people, infrastructure, property or other valuable assets are exposed to hazard. This includes residents, buildings, roads, infrastructure or agricultural land located in areas exposed to flash flood inundation or localised flooding. For example, buildings near watercourses where there are insufficient flood defences, or low-lying areas in settlements without adequate drainage systems, are more exposed to such a hazard.

— **Vulnerability**: refers to conditions determined by physical, social, economic and environmental factors or processes that increase the susceptibility of individuals, communities, physical assets or systems to the impact of a hazard. In the case of floods, vulnerability may mean:
- buildings that are not sufficiently resistant to the effects of (flowing) water,
- a lack of, or inadequate, flood prevention plans or measures,

— inadequate function of drainage systems in built-up areas, e.g. low capacity of bridges, culverts or sewers,
— insufficient awareness among residents of potential threats or current risks.

Within the Flash Flood Indicator tool, the characteristics of the area determined by exposure and vulnerability are key to distinguishing between built-up and non-built-up areas. For both exposure classification and vulnerability, a two-tier scale is applied [0, 1], based on the following logic:

Exposure: *Built-up areas* {1}
Non-built-up areas {0}
(4)
Vulnerability: *Built-up areas* {1}
Non-built-up areas {0}

Built-up areas (intravilan) are therefore classified at the highest level in the FFI system. Risk thus becomes a function of the hazard itself, with exposure and vulnerability being treated as (non-zero) constants. In this case, the following therefore applies:

$$R = f\,(\text{Hazard}) \tag{5}$$

The hazard level, and thus the risk, increases with the return period of the event; for example, a flood with a return period of 100 years poses a greater hazard than a flood with N = 10 years. However, it has become apparent that the hazard level must be assessed differently in built-up and non-built-up areas. In areas with a higher proportion of urbanised land, the volume of runoff from precipitation increases proportionally; that is, potentially hazardous runoff occurs with greater frequency. At the same time, the probability of greater exposure and vulnerability increases significantly, and therefore the potential hazard posed by a 100-year flood in rural areas, occurs with greater frequency in built-up areas.

It is clear from the above that there remains a need to refine vulnerability or exposure for specific locations in sufficient detail to enable all parameters to be set precisely for each specific catchment, river section or polygon within the FFI system. A simple principle has therefore been proposed for the assessment of risk of localised flooding, which takes into account the proportion of urban areas in determining the level of risk, by setting lower threshold values in relation to the magnitude of specific runoff:

$$T_u = T_{100} + (T_0 - T_{100}) \cdot (1 - u_p)^2 \tag{6}$$

where:

u_p is the proportion of urban area
T_{100} the threshold value relative to the 100-year specific runoff within the built-up area
T_0 the threshold value relative to the 100-year specific runoff outside built-up areas

By applying this principle, the hazard classification – and thus the flood risk value – is adjusted; see *Equation (5)*.

Critical points and the Flash Flood Indicator

Critical points – in relation to flood hazard – are locations at the boundary between built-up and non-built-up areas where, during torrential rainfall, concentrated runoff may occur from what is known as the contributing area, i.e. rural land. The contributing area is the watershed which ends at the profile of the critical point. Concentrated runoff therefore poses an immediate danger to the municipality in question and, under certain circumstances, a significant risk to the property and lives of the municipality's inhabitants. Determination of critical points is based on a modified methodology [7], in which, in addition to the size of the respective contributing area, the key parameters include the average slope, the proportion of arable land and the value of the CN parameter (runoff curve number), which is used to express the overall characteristics of the so-called critical conditions index (F).

Within the assessment of risk arising from localised flooding or flash floods for the FFI, the original intention was to include the contributing catchment areas in the calculation of the flash flood risk estimate; in other words, to calculate the risk within a system of interconnected catchments and river sections. However, from the perspective of actual assessment of the hazard arising from the potential occurrence of torrential rainfall in the catchments of critical points, it was decided to incorporate the catchments associated with critical points (CPs) in the assessment of the localised flooding hazard, as the nature of runoff response is more like a pluvial flood than a fluvial (river) flood. The contributing layers of CPs therefore function within the FFI system as a separate GIS input layer with calculated physical-geographical characteristics and specified threshold values to assess the level of localised flooding risk.

The integration of critical points and their characteristics in the FFI system was tested using data derived from a previous project in 2009 (a total of 9,261 CPs and their contributing areas). The system is gradually being adjusted to layers of critical points updated in 2026. The classification of critical point catchments for risk assessment was based on a modified approach (see Section Risk estimation in the Flash Flood Indicator), which, in addition to the hazard level increasing proportionally with the increasing return period of the peak discharge, also assumes that exposure and vulnerability will increase proportionally with an increasing degree of urbanisation within the catchment area. Given that critical points, such as outlet profiles of contributing catchment areas, lie on the boundaries of built-up areas, the threshold values for determining the hazard level were considered for a degree of urbanisation corresponding to 100 per cent.

The FFI calculation procedure, used to derive the hazard (and risk) level of local flooding caused by torrential rainfall, has been modified so that, in addition to determining runoff within a 3 × 3 km grid, the risk of hazardous runoff from the catchment to critical points is also calculated. The affiliation of individual catchment areas of critical points to an ORP is determined by the catchment's outlet profile and its position relative to the ORP. The resulting risk level arising from local flooding is considered as the less favourable of the two calculations: over the 3 × 3 km grid and for the catchment areas leading to critical points.

RESULTS

Adjustment of threshold values for hazardous runoff

The *Equation (6)* was tested on selected significant rainfall events between 2023–2024 which had caused localised flooding, primarily within urban areas. In addition to rainfall data, the selection of episodes was based on fire brigade call-out data, which the CHMI holds for internal use, as well as photographs and videos from the affected areas.

In some cases, lowering the threshold values logically led to estimates of a higher degree of risk of localised flooding in polygons where the actual risk, based on actual consequences, was greater than the risk estimate based on the original threshold values (*Tab. 1*).

Tab. 1. Selected tested events with occurrence of torrential rainfall

Date of calculation	Tested ORP	Original maximum risk	New maximum risk
16th August 2023, 18:50	Prague	1	2
13th September 2023, 22:20	Opava	1	1
6th June 2024, 20:05	Brno	0	0
19th June 2024, 21:35	Ostrava	0	1
18th August 2024, 17:35	Prague	2	3

Three selected episodes are described in more detail below, in which changes to the threshold settings succeeded in bringing the FFI outputs closer to reality in the affected areas. These are the dates 16th August 2023, 19th June 2024 and 18th August 2024. In the remaining two cases, in Opava and Brno, changing the parameters did not alter the calculated risk level. The figure on the left shows the location of water-related fire brigade call-outs (black dots) and the highest risk values for individual ORPs, where the colour coding corresponds to risk levels 0–3, as shown in *Tab. 1*. The figure on the right shows the distribution and amount of rainfall during selected episodes.

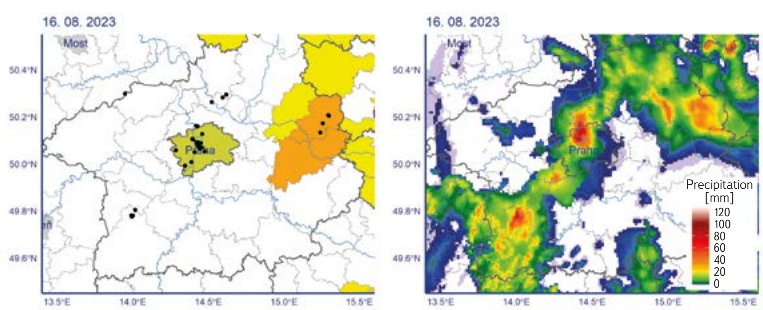

Fig. 1 a, b. General flash flood risk and precipitation total (MERGE) from 16th August 2023

On 16th August 2023, localised and very intense rainfall moved over the centre of Prague from the north and progressed very slowly (*Fig. 1b*). It therefore remained in a single location for an extended period, with 40 to 50 mm falling in approximately one hour (e.g. 44.5 mm at the Praha-Střešovice station). Judging by the high number of fire brigade call-outs, reports directly from the field and the volume of photos and videos on social media, relatively large parts of central Prague were affected. Although normal traffic and business were almost brought to a standstill for a short time, two consecutive FFI calculations in the early evening identified only the lowest risk of localised flooding (*Tab. 1*), which also corresponded to the lowest level of aggregate risk (*Fig. 1a*). Following changes to the threshold settings according to the *Equation (6)* and a subsequent re-simulation, the second level of local flooding risk was calculated for the centre of Prague, which represents at least an approximation of the actual impact of this situation on the centre of Prague.

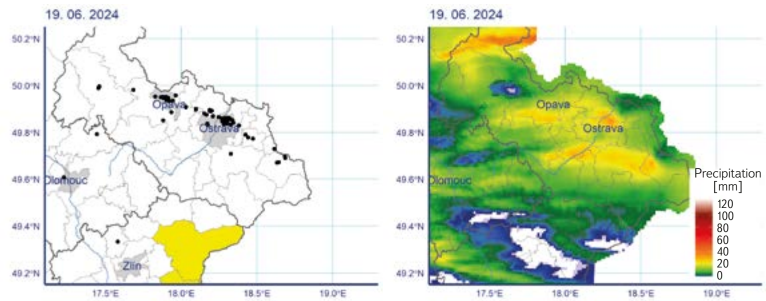

Fig. 2 a, b. General flash flood risk and precipitation total (MERGE) from 19th June 2024

From the FFI's perspective, the rainfall event in the Ostrava region on 19th June 2024 (*Fig. 2*) was a relatively complex situation, as the passage of intense rainfall over Ostrava was very rapid, while the FFI compares potential high-risk rainfall with actual rainfall over a period of at least one hour. In Ostrava, approximately 30 mm of rainfall occurred in some places over roughly 30 minutes, or even a shorter period, and radar estimates of rainfall tended to underestimate the actual amounts. In this case, the FFI was unable to respond adequately, and not even the lowest risk level was calculated. After a change to the parameters and a re-simulation, at least the lowest risk level for localised flooding was calculated for some parts of Ostrava.

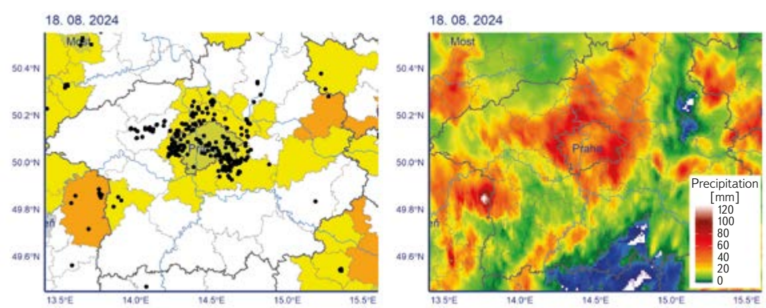

Fig. 3 a, b. General flash flood risk and precipitation total (MERGE) from 18th August 2024

The last episode tested was that of 18th August 2024, when Prague and the surrounding area were hit by very intense rainfall (*Fig. 3b*). At Prague-Ruzyně Airport, where rainfall was nearly 70 mm/hour, operations at the international airport had to be suspended because the runways (among other areas) were flooded. In many other places in and around Prague, the rainfall was so intense that it led to localised flooding or rapid runoff from the surrounding area. The FFI's operational calculations generated a Level 1 aggregate risk (shown in yellow in *Fig. 3a*), and only in exceptional cases was the risk of localised flooding at Level 2 (*Tab. 1*). Following changes to the threshold settings and a subsequent re-simulation, the highest level of localised flooding hazard was calculated for the Ruzyně Airport area, and in several locations localised flooding hazard was at the medium level 2.

Incorporation of critical points in the Flash Flood Indicator

The modified FFI procedures (see Section Critical points and the Flash Flood Indicator) were tested against past rainfall-runoff events from previous years, prioritising three selected flood events. Specifically, these were the flash flood of 2nd June 2024 in Štěnovice in the Plzeň region and the flash floods of 27th June 2024 in Blížejov in the Domažlice region and in Šišma near Lipník nad Bečvou.

Fig. 4 shows an example from the testing of a flash flood in Blížejov in the Domažlice region on 27th June 2024, specifically from the simulation run at 12:20 UTC, when significant localised flooding caused by torrential rainfall was recorded in the village of Blížejov. The upper part of the figure shows the distribution of rainfall (combined radar estimate – MERGE) and indicates the direction of inflow into the village of Blížejov. It is evident that two contributing areas of critical points were affected. The figure at the bottom left (*4b*) shows the original version of the calculation without critical points, while the figure on the right (*4c*) shows the result with CPs included. The heaviest rainfall occurred precisely on the catchment area with the defined critical points to the northwest of the village, which significantly influenced the estimate of actual risk of local flooding in the village of Blížejov. While calculations for the 3 × 3 km grid cell alone indicated only a low to medium risk (yellow), a very high risk (red) was recorded in the catchment area around the critical points. Furthermore, the unnamed watercourse in the village is culverted, and further downstream the channel leads into a railway culvert with limited capacity, which also contributed to the worsening of the drainage situation in the village.

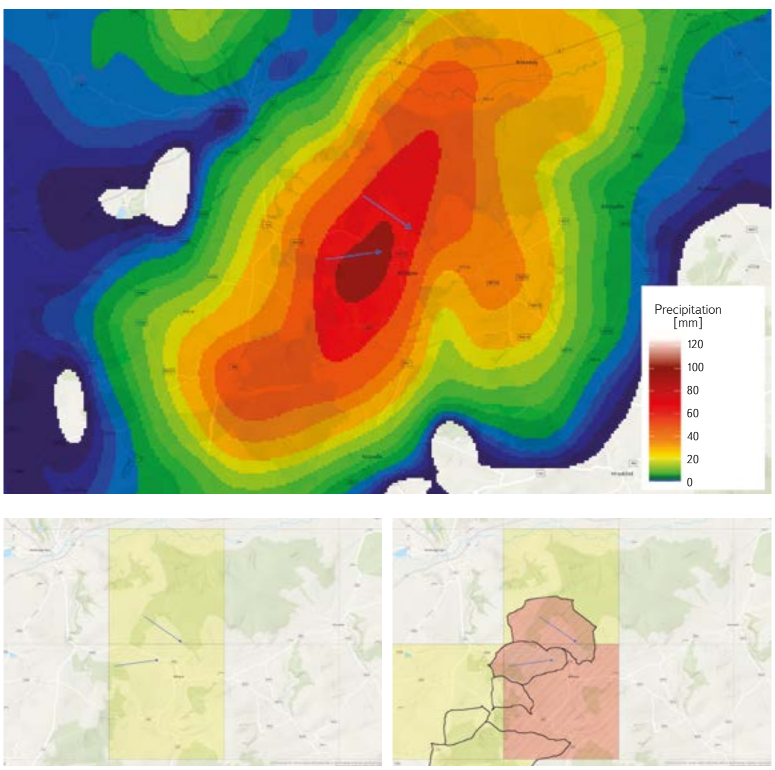

Fig. 4 a, b, c. Testing of calculations for the flash flood situation in Blížejov in the Domažlice region on 27th June 2024, 12:20 UTC. The upper image shows 24-hour precipitation total up to 28th June 2024, 06:00 UTC. On the left is the FFI calculation version without critical points; on the right is the new FFI calculation version including them

Fig. 5 shows the situation in the vicinity of the village of Štěnovice in the Plzeň region on 2nd June 2024, when a major flash flood occurred, causing considerable damage to property and posing a threat to residents. The Losinský stream, where torrential rainfall occurred, is a right-side tributary to the river Úhlava which flows through Štěnovice. Downstream of the confluence, there is a gauging station on the Úhlava, which recorded the flood on the Losinský stream in the form of a distinct flow peak (*Fig. 6*). Based on the recorded hydrograph of the flood on the Úhlava, it can be deduced that an estimated 40–45 $m^3 \cdot s^{-1}$ ($Q_{100} \cong 20\ m^3 \cdot s^{-1}$) was flowing into the Úhlava river from the Losinský stream (11.6 km^2) at the peak of the flood.

Findings from amateur rainfall observations in Štěnovice and the village of Losiná conclude that there was relatively significant underestimation of radar rainfall estimates combined with rain gauges (using the MERGE method), which resulted in the FFI detecting only the lowest risk level (yellow) for the Losinský stream catchment. When considering the catchment area in relation to critical points, a level two (orange) risk was estimated north of Štěnovice, presumably due to slightly higher rainfall estimates that were, most likely, closer to reality.

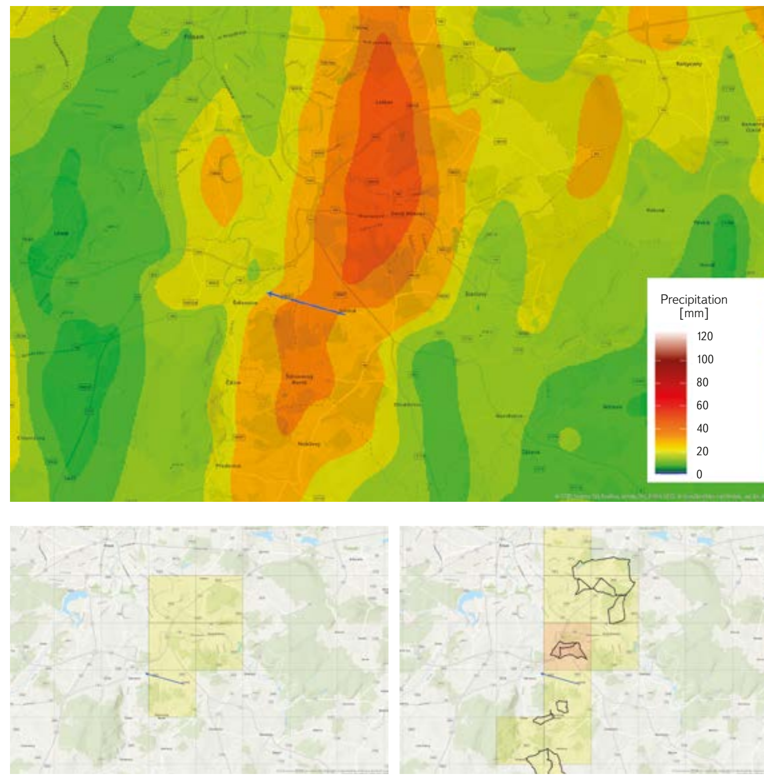

Fig. 5 a, b, c. Testing calculations for the flash flood situation in Štěnovice in the Plzeň region on 2nd June 2024 at 10:50 UTC. The upper image shows 24-hour precipitation total up to 3rd June 2024, 06:00 UTC. On the left is the FFI calculation version without critical points; on the right is the new FFI calculation version already including them

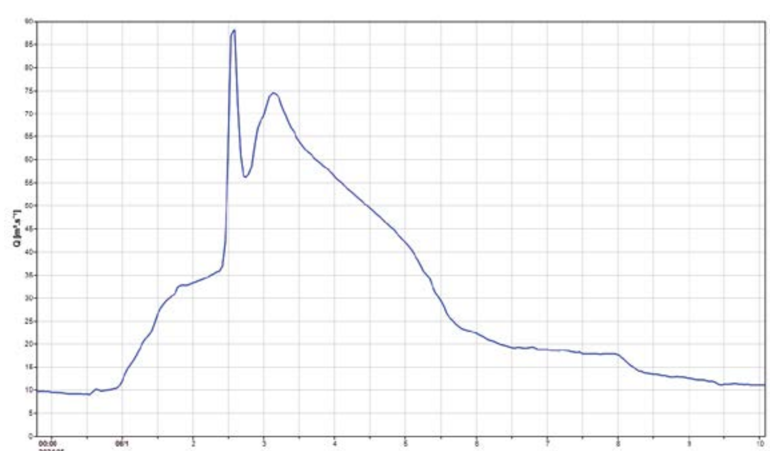

Fig. 6. Flood wave on the Úhlava river in Štěnovice at the beginning June 2024

The third event under consideration is the extreme flash flood of 27th June 2024 on the Šišemka (a tributary of the Moštěnka) in the Přerov region, where Šišma was the worst-affected village, although other villages were also affected. Flow conditions in Šišma were adversely affected by numerous footbridges over the Šišemka stream to individual properties. The peak flow rate in the villages of Šišma and Hradčany is estimated to have exceeded 30 $m^3 \cdot s^{-1}$ (more than Q_{100}), while in Prusy on the Moštěnka, the flow wave – which was apparently flatter, i.e. transformed – peaked at 18–20 $m^3 \cdot s^{-1}$.

Fig. 7 shows the situation around the village of Šišma and the combined radar precipitation estimates (MERGE), which were, unfortunately, significantly underestimated. An amateur rain gauge in the village of Šišma recorded more than 50 mm in roughly 30–40 minutes, yet the radar precipitation estimates for that location were only 10 mm. For this reason, the FFI also recorded the risk at only the lowest level (yellow), even when taking into account the catchment area contributing to critical points.

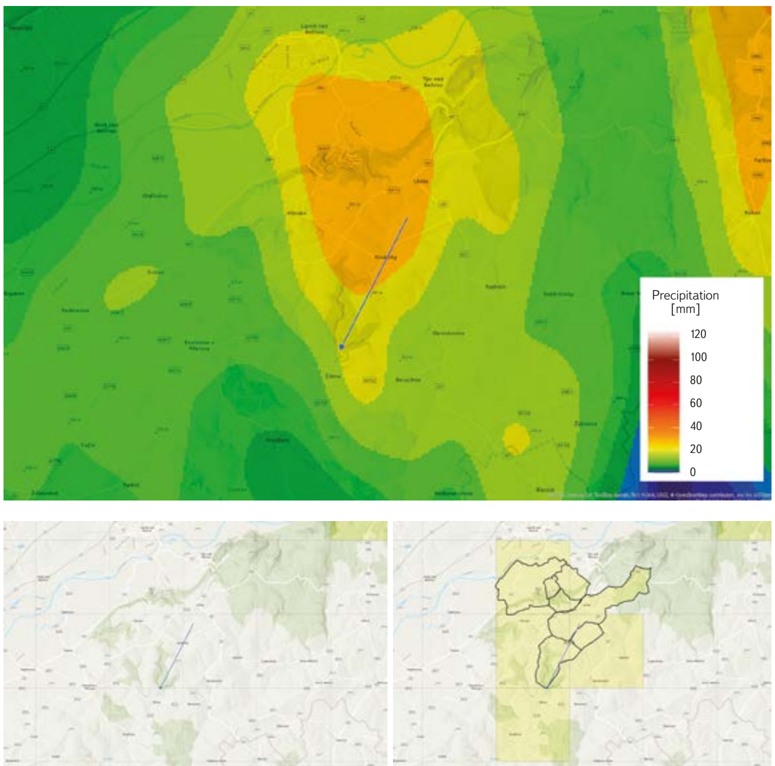

Fig. 7 a, b, c. Testing of calculations for the flash flood situation in Šišma near Lipník nad Bečvou on 27th June 2024, 15:35 UTC. The upper image shows the 24-hour precipitation total up to 28th June 2024, 06:00 UTC. On the left is the FFI calculation version without critical points; on the right is the new FFI calculation version including them

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Predicting flash floods remains one of the most complex tasks in the hydrometeorological forecasting service. The main reason for this difficulty lies in the significant spatial and temporal variability of convective precipitation, which fundamentally limits the reliability of the forecast. Numerical weather models, including those with high spatial resolution, generally provide only information on the increased probability of hazardous rainfall occurring in wider areas, but not on its precise location and intensity. Nowcasting enables short-term forecast refinement, the main benefit of which lies in extrapolating the current movement of precipitation. However, this approach is as yet largely unable to reliably capture rapid changes in the structure and intensity of convective cells, which are key to the development of flash floods. Furthermore, the resulting accuracy of flash flood predictions is significantly influenced by hydrological inputs, primarily the estimate of current soil saturation, as well as uncertainties in the estimation of both actual and forecast precipitation.

In the context of flash floods, the classification of areas as either built-up or non-built-up zones is essential. In urban areas, the catchment's runoff response is much faster and the volume of surface runoff increases, resulting in more frequent occurrence and higher intensity of local flooding, even during rainfall events with shorter return periods. The assessment of risk level in the FFI is linked to threshold values for hazardous runoff, which are derived from the discharge volume with a 100-year return period and remain the same regardless of the area's classification. However, values determined in this way may not reflect the actual level of hazard and risk in built-up and non-built-up areas.

A key element of exposure and vulnerability is critical points, defined as locations where concentrated surface runoff from the agricultural landscape enters the built-up area of a municipality. It is these locations that often represent the initiation points of flood damage during torrential rainfall. Including the catchment areas of these critical points in the FFI calculation significantly improves the accuracy of hazard and risk estimates [8], particularly in cases where the standard 3 × 3 km polygon grid is unable to adequately capture local runoff response and its impact on populated areas.

Despite these adjustments to the method of determining hazard and risk levels, the reliability of the input precipitation data remains a key source of uncertainty. An analysis of selected cases of significant downpours and floods, for example in Štěnovice on 2nd June 2024 and in Šišma on 27th June 2024, revealed a significant underestimation of radar precipitation forecast compared with the totals measured by amateur observers. This shortcoming had a direct impact on the FFI's ability to adequately assess the level of risk, even though the calculations included all available data on precipitation totals, intensity and critical points. These examples, along with other cases from previous years, emphasise that further improvements in the prediction and assessment of flash floods will necessarily depend not only on refining the FFI methodology, but also on further development and validation of radar precipitation products, which are undergoing gradual development [9].

Based on the modified approaches tested on real flood events, the following conclusions can be drawn:

The flood events tested demonstrated that adjusting the threshold values for hazardous runoff based on the proportion of urban areas within the calculation polygons allows for a more realistic estimate of the risk level within built-up areas. This leads to a better distinction between situations that may result in actual impacts within built-up areas and cases where increased runoff has less significant consequences. At the same time, however, it is important to bear in mind that reducing runoff thresholds may lead to an increase in the number of false alarms.

The inclusion of critical points in the FFI calculation represents a significant contribution to local risk assessment. Taking the catchment areas of critical points into account makes it possible to capture local runoff peaks which would otherwise be suppressed or completely overlooked within a standard polygon grid. This approach contributes in particular to a more accurate risk assessment in smaller settlements and in areas where concentrated surface runoff enters built-up areas and represents the main mechanism causing flood damage.

At the same time, it is confirmed that the successful prediction of flash floods is fundamentally dependent on the quality of meteorological inputs. Uncertainties in radar precipitation estimates and in short-term precipitation forecasts are directly reflected in the overall uncertainty of the FFI results and may lead to an underestimation of risk, even in cases where critical points and the degree of urbanisation of the area are taken into account. Despite these limitations, however, it can be stated that the FFI is gradually shifting from assessing the hazard level itself towards a more realistic estimate of flood risk.

Nevertheless, analysis of flood events continues to show that model estimates require further refinement, particularly in urban environments. Local terrain morphology, technical infrastructure and land use have a fundamental influence on the resulting level of risk and present a significant challenge for the further development of methodological approaches to the assessment and prediction of flash floods.

Based on the above conclusions, it is possible to formulate recommendations for the further development of the FFI, including towards more effective management of the risks associated with flash floods. These recommendations relate both to the technical development of FFI itself and to its practical integration into crisis management and directions for further research.

Further improvements to the processing of radar precipitation estimates appear to be key. Regular validation of radar data against a network of professional rain gauges should be a standard part of operations. In addition, the use of local rain gauges operated by local authorities or volunteers could also be considered [10]. Despite the awareness of possible systematic or random errors in these measurements, such data can provide valuable information on local extremes that radar estimates cannot always reliably capture. Another important step towards reducing the uncertainties in forecasts of convective precipitation—which is crucial for the development of flash floods—is to strengthen nowcasting methods, particularly by incorporating algorithms capable of modelling the development of convective cells over time, including changes in their structure and intensity. At the same time, the introduction of adaptive hazard and risk thresholds, differentiated according to the type of settlement, appears to be a promising approach. Urban, suburban and rural areas differ significantly in their runoff response, and uniform thresholds may therefore not correspond to the actual level of risk in a given area.

Alongside technical developments, it is essential to focus on better integration of risk assessment into the crisis management system. Critical points identified across the whole of the Czech Republic should be systematically utilised, for example, when updating local flood management plans. At the same time, it is advisable to improve communication of the risk to local residents, particularly in relation to areas where there is an increased concentration of surface runoff and localised flooding caused by inadequate drainage within the municipality. Raising awareness of these 'blind spots' can help to reduce damage and improve residents' preparedness. A further step could be to integrate the FFI indicator with municipalities' automated warning systems, such as smart sirens, SMS alerts or notifications via mobile apps. Such integration would enable faster and more targeted warnings in situations where the risk of localised flooding is rapidly increasing.

Acknowledgements

This article was produced with the support of research project No. SS06010059, Enhancing the preparedness of urban areas in the Czech Republic by linking the critical points method with the Flash Flood Indicator.

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This paper has been peer-reviewed.

DOI: 10.46555/VTEI.2026.05.001

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Forecast of water resource security in the Czech Republic by 2050

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Keywords: climate change — water resources — water scarcity — water supply — water balance

ABSTRACT

This article presents the methods and results of an assessment of the security of water abstraction and minimum flows for 2050, taking into account the potential impacts of climate change on water resources and projected water demand based on socioeconomic development forecasts. The study covered the entire Czech Republic. The smallest spatial scale used was that of water bodies used in water management planning. The study employed simulation modelling methods (for assessing surface water resources), water balance methods, and procedures for assessing the quantitative status of groundwater bodies. The potential impacts of climate change on water resources were considered using combinations of eight climate models (CMCC-ESM2, EC-EARTH3, GFDL-ESM4, MPI-ESM1-2-HR, MPI-ESM2-0, TAIESM1, HADGEM2-ES, and ALADIN-CLIMATE/CZ) and five emission scenarios (SSP126, SSP245, SSP370, SSP585, and RCP4.5). Existing reservoirs and water transfer infrastructure, including their capacities, were taken into account. The assessment of surface water resources identified 33 reservoirs (out of 82 assessed) as potentially at risk; these reservoirs secure water abstraction and/or ensure minimum flows in watercourses. Groundwater resources were assessed for 838 groundwater body assessment units (out of 1,220 in the Czech Republic). High risk was identified for 106 units (covering 12.7 % of the country), medium risk for 43 units (6.1 %) and low risk in 689 units (66.3 %).

INTRODUCTION

The availability of water resources and the security of water use requirements (particularly water abstractions) under the potential impacts of climate change have been the subject of numerous studies conducted at various spatial scales over the past two decades. Between 2020 and 2025, these issues were also addressed within Work Package 1 (WP1), *Forecasting Water Resource Security in the Czech Republic up to 2050 at the Regional Level under Climate Change*, of Project No. SS02030027, *Water Systems and Water Management in the Czech Republic under Climate Change* (hereinafter referred to as *Water Centre* project). The objective was to assess water resource security for the year 2050, taking into account the impacts of climate change on water resource capacity and scenarios of future water demand across individual sectors based on projected socio-economic development. The principal outcome is the identification of potentially vulnerable areas. The assessment was carried out at the national scale. The WP1 workflow is illustrated in *Fig. 1*.

It can be divided into three consecutive stages:

A. development of water demand scenarios, particularly the forecasting of water abstraction requirements,

B. development of climate change impact scenarios for hydrological characteristics and identification of areas with water deficits,

C. assessment of the balance between water demands and water resources, taking into account the existing infrastructure (reservoirs, water transfers, and their capacities), followed by an assessment of water resource security and the identification of potentially vulnerable areas.

The development of water demand scenarios is described in [1], while the impacts of climate change on hydrological characteristics are presented in [2]. This article focuses on the final stage of the assessment: evaluating the security

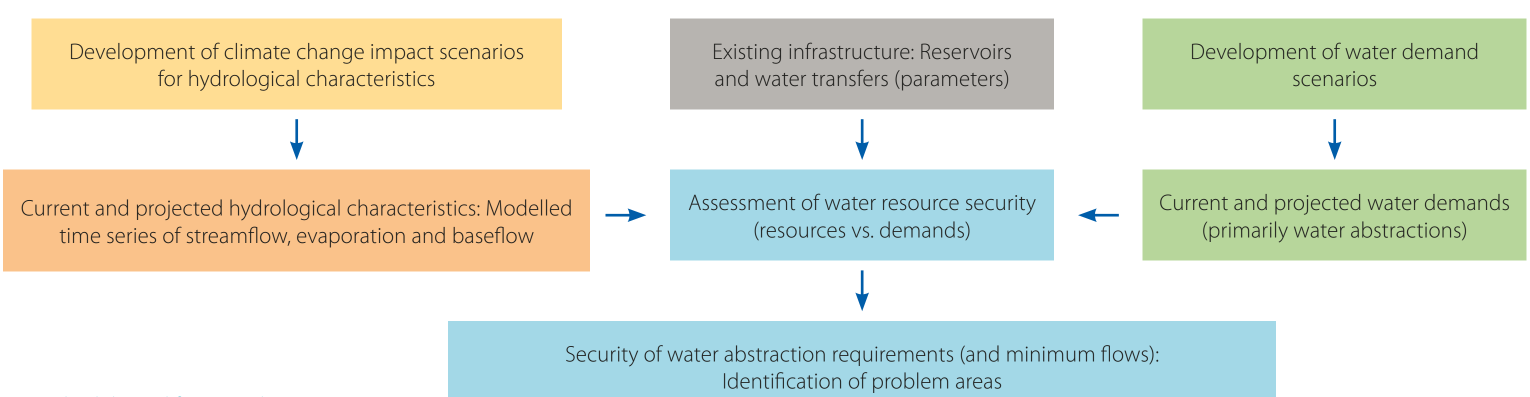

Fig. 1. Methodological framework

of water abstraction requirements and identifying locations that may be at risk of water scarcity in the future. A detailed description of this stage of the assessment is provided in the corresponding research report [3]. A number of organisations collaborated on WP1, particularly in the area of forecasting water demand: the TGM WRI (public water supply and energy sector abstractions; impacts of climate change on hydrological characteristics and identification of water-deficit areas; assessment of water resource security; and identification of potentially vulnerable locations); the University of Chemistry and Technology, Prague (industrial water demand); the Institute of Geology of the Czech Academy of Sciences (water demand for irrigation under climate change impact scenarios); the Czech Technical University in Prague (irrigation); the Czech University of Life Sciences Prague (irrigation and livestock production); and the Czech Hydrometeorological Institute (CHMI, the effects of abstractions and discharges on streamflow). The WP1 activities within the *Water Centre* project build to some extent on Security Research Project No. VI20192022159, *Water Management and Water Supply Systems and Preventive Measures to Reduce Risks in Drinking Water Supply*, carried out by the TGM WRI between 2019 and 2022. Unlike WP1 of the *Water Centre* project, this project was limited to issues related to public water supply systems [4, 5]. Owing to the similarity of the methodologies applied, selected outputs from this project have also been incorporated into the risk assessment results presented in this paper. Detailed descriptions and the results of both projects are available on their respective websites [6] and [7].

METHODOLOGY AND DATA

The forecasting of water resource security focused on assessing the risk of future failure to meet water abstraction requirements and, to a certain extent, minimum flow requirements. The smallest spatial unit adopted for the assessment was the water body, or part thereof, as defined for the purposes of water management planning (a total of 1,118 surface water bodies and 1,220 groundwater body assessment units are defined in the Czech Republic). The methodology and level of detail of the assessment were largely determined by the availability of data. The principal inputs to the water resources–water demands balance assessment were projected water abstraction requirements and projected values of hydrological characteristics affected by climate change. These input data were developed directly within WP1 of the *Water Centre* project [1, 2] and the Security Research Project [4, 5].

Input data

The following datasets were used in the assessment:

- Projected water abstractions for 2050, disaggregated by calendar month. Source: TGM WRI, University of Chemistry and Technology, Prague; Czech Technical University in Prague; and Czech University of Life Sciences Prague [1].
- Time series of modelled irrigation water demand projected for 2050. Source: Institute of Geology of the Czech Academy of Sciences [1].
- Data on water abstractions, discharges, water storage, and reservoir parameters (active storage volume and minimum outflow) recorded in accordance with Decree No. 431/2001 Coll. Source: River Basin Authorities and TGM WRI [8].
- Data on the proportion of stormwater in discharges to surface waters from the Water Supply and Sewerage Assets and Operations Register (sewer network and wastewater treatment plant sections), maintained in accordance with Decree No. 428/2001 Coll. Source: Ministry of Agriculture [9].
- Time series of modelled monthly streamflow, evaporation, and baseflow from the catchments of gauging stations and the inter-catchment areas of surface water bodies. Source: TGM WRI [2, 4].
- Long-term and annual baseflow values for the hydrogeological zones of the Czech Republic. Source: CHMI.
- Reassessment of groundwater resources. Source: Czech Geological Survey [10].
- Hydrogeological zoning. Project of the Government Council of the Czech Republic for Research and Development No. VaV/650/4/02, Final Summary Report for the 2002–2005 project period. Source: TGM WRI [11].

Hydrological conditions

Given the uncertainties associated with predicting the impacts of climate change on hydrological characteristics, the assessment of water resource availability for 2050 was carried out using multiple scenarios. The hydrological scenarios were defined by combinations of climate models and emission scenarios [2, 4]. An overview of the climate models and emission scenarios considered is provided in *Tab. 1*. The HADGEM2-ES climate model and the hydrological conditions corresponding to a 2 °C increase in temperature were assessed within the Security Research Project, and their impacts were evaluated only for public water supply abstractions [4]. The remaining climate models and emission scenarios were evaluated as part of WP1 of the *Water Centre* project [2]. Each combination of a climate model and an emission scenario represents an alternative projection of future climatic conditions. This approach makes it possible to better capture the uncertainties associated with future climate development and to assess the robustness of the results under different climate scenarios.

Tab. 1. Evaluated climate models and emission scenarios

Climate model	Emission scenario	Note
CMCC-ESM2	SSP126, SSP245, SSP370, SSP585	-
EC-EARTH3	SSP126, SSP245, SSP370, SSP585	-
GFDL-ESM4	SSP126, SSP245, SSP370, SSP585	-
MPI-ESM1-2-HR	SSP126, SSP245, SSP370, SSP585	-
MPI-ESM2-0	SSP126, SSP245, SSP370, SSP585	-
TAIESM1	SSP126, SSP245, SSP370, SSP585	-
ALADIN-CLIMATE/CZ	SSP245, SSP585	-
HADGEM2-ES	RCP4.5	Public water supply abstraction
Current climate + 2 °C	-	Public water supply abstraction

The SSP585 emission scenario is widely interpreted in the current scientific literature as a high-emissions scenario representing the upper bound of potential future climate change. Although some experts no longer regard it as the most likely trajectory of future socioeconomic development, it remains an appropriate scenario for risk assessment and for evaluating the sensitivity of water resources to potentially adverse climate change. Accordingly, in the present study, the SSP585 scenario was not interpreted as the most likely future scenario, but rather as one of several scenarios used to assess the range of potential impacts of climate change on water resource availability.

Water abstraction requirements and minimum flows

In 2021, a total of 5,602 water abstraction points were registered in accordance with [8], with a total annual abstraction of approximately 1,400 million $m^3 \cdot year^{-1}$ (excluding abstractions for water transfers). These comprised 883 surface water abstraction points, with a total annual abstraction of approximately 1,030 million $m^3 \cdot year^{-1}$ (about 74 % of the total volume abstracted), and 4,719 groundwater abstraction points, with a total annual abstraction of approximately 370 million $m^3 \cdot year^{-1}$ (about 26 % of the total volume abstracted). Whereas surface water abstractions are used extensively for public water supply, industry, energy production, and agriculture, groundwater abstractions are used primarily for public water supply.

Water abstraction requirements were considered under two scenarios: current water demand and projected water demand for 2050 [1].

Current water demand was determined as follows:

- Public water supply, energy production, and industrial abstractions were based on recorded monthly water abstraction data for the period 2015–2021. Monthly water demand was calculated as the arithmetic mean of the recorded abstractions for all economic sectors except agriculture.
- Agricultural abstractions were determined as the maximum monthly values recorded during the same period (abstractions for irrigation increase substantially during dry periods).

Projected water demand (the high scenario) was determined as follows:

- Public water supply abstractions were based on the average monthly abstractions for the period 2016–2021, adjusted according to the high demographic development scenario.
- Energy sector abstractions were projected for 2050 based on the supporting documents for the national energy strategy.
- Industrial abstractions were determined as the maximum recorded annual abstraction during the period 2009–2021, distributed evenly throughout the year.
- Agricultural abstractions were determined as the maximum abstractions recorded for each calendar month during the period 2015–2021.
- Irrigation demand was represented by time series of monthly irrigation water demand for the inter-catchment areas of surface water bodies for the individual climate models and emission scenarios, using the following variants:
  - prevention of drought stress,
  - optimisation of crop production.

The security of minimum flows was assessed on the basis of the current minimum reservoir outflow requirements and the active augmentation of minimum flows at downstream control points.

Methodology for assessing surface water resources

The security of surface water abstractions and minimum flows in watercourses was assessed using water balance methods and simulation modelling of the storage function of water management systems. The modelling approach is described in detail in [12]. The model simulates the behaviour of the water management system as a chronological sequence of discrete time steps (a monthly time step was adopted in this study). The simulation is based on time series of natural streamflow (i.e. unaffected by regulation or water abstractions/discharges), water use requirements (water abstractions in this study), minimum flow requirements, the technical parameters of the system components (here, the active storage volumes of reservoirs and the capacities of water transfers), and the operating rules incorporated into the model for regulating outflows (i.e. reservoir operating rules governing releases from active storage). The model outputs time series of simulated variables, including streamflow, reservoir surface evaporation, water abstractions, reservoir outflows, and water volumes and water levels within the active storage zone of reservoirs. These time series are subsequently subjected to statistical analysis. The primary indicator used to express the security of water abstractions is the duration-based security index (P_t), defined in [13] (in simplified terms, it expresses the percentage of the total assessment period during which water abstraction requirements or minimum flow requirements are fully met). Water management simulations were carried out using the "Simulation Model of the Storage Function of a Water Management System" [14], developed by TGM WRI.

In the reference year 2021, the water abstraction register maintained in accordance with [8] included 82 reservoirs and 14 water transfers relevant to the provision of storage capacity, as well as 883 surface water abstraction points. For the assessment, abstraction points with an annual abstraction exceeding 500 thousand $m^3 \cdot year^{-1}$ were selected. A total of 132 abstraction points met this criterion. These abstraction points accounted for approximately 90 % of the total volume of surface water abstracted. The selected abstraction points are shown in *Fig. 2*. The effects of the remaining (smaller) water abstractions were incorporated into the assessment in aggregated form at the nearest water management system point. Similarly, the effects of all groundwater abstractions (by projecting the abstraction points onto the river network) and water discharges were also incorporated in aggregated form. The water management system also included 16 control points at which the active augmentation of minimum flows by reservoirs was assessed, together with 222 outlet points of surface water bodies, where the potential to meet irrigation demand within the corresponding inter-catchment areas was evaluated.

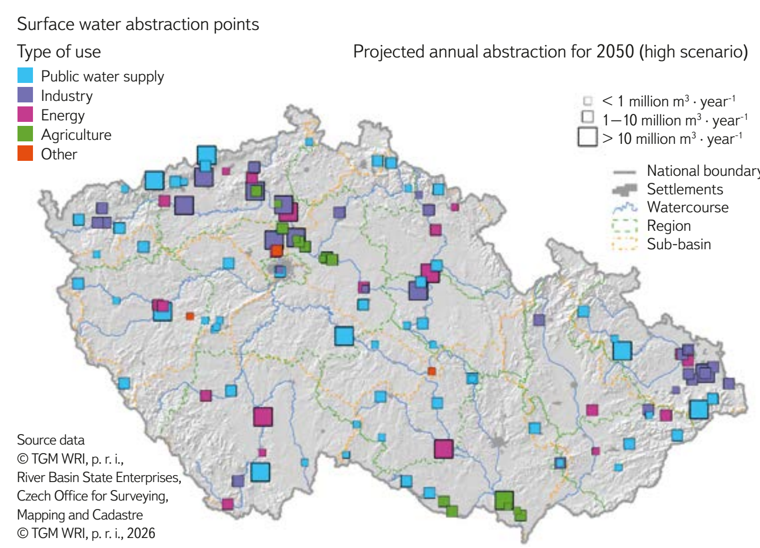

Fig. 2. Locations of significant surface water abstraction

The storage function was simulated for each assessment scenario using a monthly time step and a chronological hydrological dataset comprising time series of modelled natural mean monthly streamflow and evaporation over a period of 30 years (or 60 years in the Security Research Project). For each water abstraction and minimum flow requirement considered, the simulation model then calculated the corresponding security level and compared it with the security level recommended by Czech Standard ČSN 75 2405 [13].

Tab. 2. Water reservoirs at risk of failing to meet surface water abstraction requirements and/or minimum flow rates by 2050

Reservoir	Watercourse	Water abstraction	Projected water abstraction [thousand $m^3 \cdot year^{-1}$]	Maximum security P_t [%]	Minimum security P_t [%]	Risk
Březová	Teplá	-	-	98.8	84.4	High
České Údolí	Radbuza	-	-	99.1	84.9	High
Dalešice	Jihlava	Other	54,697	99.9	98.2	Medium
Hamry	Chrudimka	Public water supply	328	99.9	90.5	Medium
Hracholusky	Mže	-	-	99.9	99.1	Medium
Hubenov	Maršovský stream	Public water supply	3,812	99.9	95.8	Medium
Husinec	Blanice	-	-	99.9	94.9	Medium
Jesenice	Odrava	-	-	99.9	87.8	Medium
Karhov and Zhejral	Studenský stream	Public water supply	217	99.9	95.9	Medium
Klabava	Klabava	-	-	93.8	78.8	High
Klíčava	Klíčava	Public water supply	2,858	99.9	74.4	Medium
Koryčany	Kyjovka	Public water supply	705	99.9	95.2	Medium
Les Království	Labe	-	-	99.9	98.8	Medium
Lučina	Mže	Public water supply	1,324	99.9	95.2	Medium
Ludkovice	Ludkovický stream	Public water supply	434	99.9	99.8	Medium
Luhačovice	Luhačovický stream	-	-	99.9	98.8	Medium
Myslivny	Černá	Public water supply	303	99.9	98.8	Medium
Nová Říše	Řečice (Olšanský stream)	Public water supply	980	99.9	79.4	Medium
Obecnice	Obecnický stream	Public water supply	771	99.6	69.4	High
Olešná	Olešná	Other	3,961	99.9	89.4	Medium
Opatovice	Malá Haná	Public water supply	2,039	99.9	96.7	Medium
Pilská	Pilský stream	Public water supply	970	99.9	91.6	Medium
Pilská u Žďáru	Sázava	-	-	99.9	95.5	Medium
Podhora and Mariánské Lázně	Teplá	Public water supply	585	99.9	97.8	Medium
Římov	Malše	Public water supply	16,605	99.9	99.5	Medium
Slušovice	Dřevnice	Public water supply	4,907	99.9	99.1	Medium
Stanovice	Lomnický stream	Public water supply	5,318	99.9	96.0	Medium
Staviště	Staviště	-	-	99.9	97.1	Medium
Tatrovice	Tatrovický stream	Other	3,519	99.9	96.3	Medium
Vranov	Dyje	Public water supply	2,273	99.9	98.2	Medium
Vrchlice	Vrchlice	Public water supply	3,813	99.9	92.2	Medium
Znojmo	Dyje	Public water supply	2,377	99.9	98.1	Medium
Žlutice	Střela	Public water supply	2,561	99.9	98.0	Medium

Methodology for assessing groundwater resources

The adequacy of groundwater resources was assessed using water balance methods for evaluating the current and projected status of groundwater quantity [15], together with procedures for assessing the quantitative status of groundwater bodies [16]. A limitation of applying these established nationwide methods was the availability of input data on natural groundwater resources, which were compiled only at the scale of hydrogeological zones (152 in total), with areas of up to 5,800 km². Consequently, the final results could, in practice, represent only part of the assessed area. A new stage of quantitative groundwater status assessment is currently being completed, in which the water balance is calculated directly at the scale of groundwater bodies (174 in total). However, this is based only on the redistribution of natural groundwater resources according to the proportion of each groundwater body's area relative to that of the corresponding hydrogeological zone. The only exception is the quaternary upper-layer groundwater bodies, for which the methodology for assessing quantitative status has been completely revised. The first project to apply a more sophisticated approach to assessing natural groundwater resources at a finer spatial resolution over a large part of the Czech Republic was the Security Research Project [5], carried out between 2019 and 2022. In this project, the current status and projected changes in baseflow were calculated at the scale of the inter-catchment areas of surface water bodies (1,118 in total), providing data for 825 groundwater body assessment units (out of 1,220) under Variant II. In the *Water Centre* project, the risk of future inadequacy of groundwater resources for groundwater abstractions was likewise assessed at the level of groundwater working units.

On the groundwater resource side, long-term estimates of natural groundwater resources were taken from the Groundwater Resource Reassessment [10] (covering natural resources with 50 % and 80 % security, as well as exploitable groundwater resources), from data provided by the CHMI (natural resources with 50 % and 80 % security), and, as supplementary information, from the Hydrogeological Zoning 2005 project [11] (equivalent to natural resources with 50 % security). All these values were subsequently downscaled to the smaller groundwater body assessment units using the outputs of the current-state hydrological balance model.

In assessing the risk of insufficient groundwater resources for groundwater abstractions, the impacts of all climate models and emission scenarios on changes in baseflow were first evaluated using spatial analysis. Subsequently, the combination of the ALADIN-CLIMATE/CZ climate model and the SSP585 emission scenario for 2050 (within the *Water Centre* project), and the HADGEM2-ES climate model and the RCP4.5 emission scenario for the 2041–2060 period (within the Security Research Project), were selected as the representative scenarios.

On the demand side, the groundwater resource balance is based on groundwater abstraction data converted to $L \cdot s^{-1}$. For the *Water Centre* project, the following values were determined:

- total annual abstractions for the period 2016–2021 for hydrogeological zones and groundwater body assessment units,
- average annual abstractions for the period 2016–2021 for hydrogeological zones and groundwater body assessment units,
- projected abstractions for 2050, calculated using the methodology developed for the *Water Centre* project (high scenario).

The *Water Centre* project included only groundwater abstractions recorded in 2021, expressed as average annual values for the period 2016–2021, whereas the Security Research Project used data for the period 2013–2018. Abstractions for drinking water supply amounted to approximately 308 million $m^3 \cdot year^{-1}$, representing about 82 % of the total volume of groundwater abstracted (from 64 % of the registered abstraction points), while other abstractions totalled approximately 65 million $m^3 \cdot year^{-1}$, accounting for about 18 % of the abstracted volume (from the remaining 36 % of registered groundwater abstraction points). Projected abstractions comprised unchanged non-potable water abstractions together with drinking water abstractions for each water balance unit, adjusted according to the projected demographic development up to 2050. The projected groundwater abstraction requirements based on the expected demographic development to 2050 are shown in *Fig. 3*.

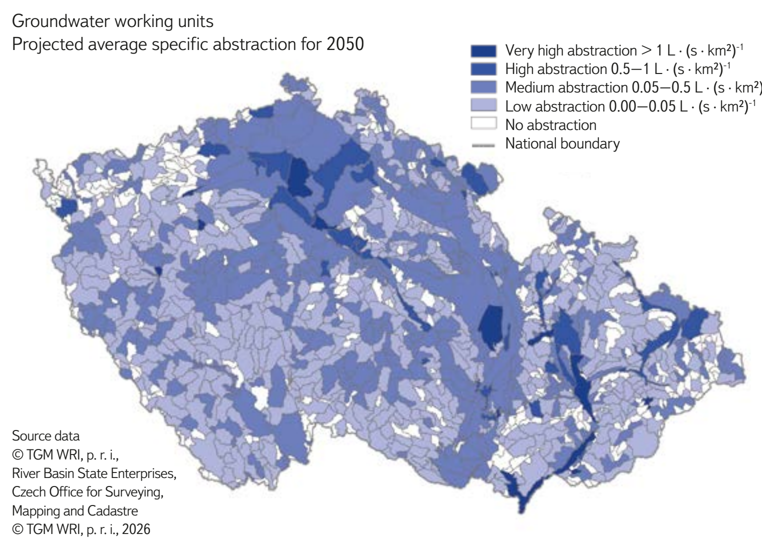

Fig. 3. Projected groundwater abstraction requirements by 2050

Only 271 of the 1,220 groundwater body assessment units, namely those with annual groundwater abstractions of at least $5\ L \cdot s^{-1}$ in 2021, were included in the water balance comparison of groundwater abstractions and natural groundwater resources. The remaining 949 assessment units were not evaluated in the *Water Centre* project, just as 395 assessment units had been excluded from the future projections in the Security Research Project. This is because water balance assessments involving very small abstraction volumes are subject to considerable uncertainty.

RESULTS

The procedures described above resulted in an assessment of the adequacy of water resources in relation to water abstraction and minimum flow requirements. Because of the large number of scenarios assessed and the corresponding volume of data, the detailed results are presented in the relevant specialised public database (see below). The results presented here are therefore provided in summary form.

Surface water resources

The assessment of the security of surface water abstractions and minimum flows downstream of reservoirs was carried out for more than 50 scenarios combining the hydrological conditions considered (climate models and emission scenarios) with the required water abstraction volumes.

The risk of failing to meet surface water abstraction or minimum flow requirements by 2050 is expressed for each assessment point, across all scenarios considered, using the following classification:

- High risk: The requirement is not fully met under any scenario, and in at least one scenario fails to achieve the level of security recommended by the standard [13].

— Low risk: The requirement is fully met under all scenarios.
— Medium risk: All other cases.

The results are illustrated in *Fig. 4*. The reservoirs identified as being at risk, together with the minimum and maximum duration-based security (P_t) achieved for the water abstractions and/or minimum flows they support under the 2050 scenarios, are presented in *Tab. 2*.

The Obecnice public water supply reservoir, together with the Březová, České Údolí, and Klabava reservoirs, was identified as being at high risk. A further 29 reservoirs, including 19 public water supply reservoirs, were classified as presenting a medium risk.

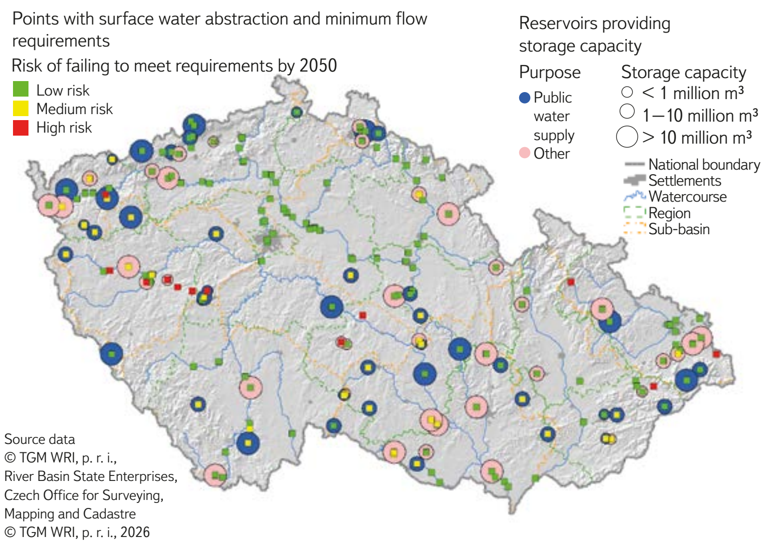

Fig. 4. Risk of failing to meet surface water abstraction requirements and minimum flow rates by 2050

Groundwater resources

For the assessment, the critical threshold values for the ratio of groundwater abstractions to natural groundwater resources were adopted from the procedures used to assess quantitative groundwater status, namely 0.4 for natural groundwater resources with 50 % security and 0.5 for natural groundwater resources with 80 % security. For the comparison of groundwater abstractions with exploitable groundwater resources, water balance ratios were not calculated. Instead, the average annual abstractions for the period 2016–2021 were subtracted from the exploitable groundwater resources, and the proportion of the remaining (unutilised) resources relative to the total exploitable groundwater resources was compared with the critical threshold of 20 % (i.e. the result was considered unsatisfactory if the proportion of unutilised resources was less than 0.2).

In addition to assessment units with very small groundwater abstractions, hydrogeological zone 3110 Pavlovské vrchy was also excluded from the water balance assessment because natural groundwater resources have not been quantified for this region by any method, and it does not contain any significant groundwater abstractions.

The synthesis of the individual water balance comparisons between groundwater abstractions and natural groundwater resources (six comparisons for the current state and six for the projected state) gave slightly greater weight, as a precautionary measure, to unfavourable results based on the ratio to natural groundwater resources with 50 % security. The results of the comparisons with natural groundwater resources having 80 % security, and of the comparisons with exploitable groundwater resources, were considered less reliable. Zero abstractions did not, logically, worsen the final status classification, whereas zero natural groundwater resources did. The final synthesis was also adversely affected by the number of water balance comparisons that could not be performed because of the absence of data on natural groundwater resources in assessment units where at least one comparison had produced an unfavourable result.

The water balance assessment resulted in an evaluation of both the current and the projected status (the results for 2050 are shown in *Fig. 5*). Using the ALADIN-CLIMATE/CZ climate model, the SSP585 emission scenario for natural groundwater resources, and the projected demographic development, relatively few groundwater body assessment units were identified as being at risk. Of the assessment units evaluated, 47 were classified as high risk (covering 6.6 % of the area), 16 as medium risk (1.5 % of the area), and 208 as low risk (39.7 % of the area). The remaining 949 assessment units (52.2 % of the area) were not evaluated because groundwater abstractions were very small (less than 5 L · s^{-1}), resulting in an unacceptably high level of uncertainty.

For hydrogeological zones in which at least one groundwater body assessment unit was identified as being at risk under the projected conditions, summary statistics were compiled based on the percentage of the region's area represented by the individual assessment units (see *Fig. 6*). The proportion of the area that could not be evaluated reached as much as 84.4 % in some hydrogeological zones. Nevertheless, the results clearly showed that the risk assessment can vary considerably within individual hydrogeological zones, demonstrating that assessing future conditions at a finer spatial resolution is worthwhile despite the inherent uncertainties of future projections.

For the ALADIN-CLIMATE/CZ climate model and the SSP585 emission scenario, the total average annual groundwater abstraction during the assessment period 2016–2021 was 11,627 L · s^{-1}, while the total projected abstraction for 2050 was 11,665 L · s^{-1}. Of the total projected groundwater abstraction for 2050, 29.2 % (3,410 L · s^{-1}) was associated with groundwater body assessment units classified as high risk, 5.8 % (681 L · s^{-1}) with medium-risk units, 56.3 % (6,567 L · s^{-1}) with low-risk units, and 8.6 % (1,007 L · s^{-1}) with assessment units that were not evaluated.

Within the Security Research Project, 825 of the 1,220 groundwater body assessment units were evaluated using the HADGEM2-ES climate model and the RCP4.5 emission scenario for the 2050 projection. Of these, 91 assessment units, covering 11.1 % of the Czech Republic, were classified as high risk, 37 units (6.1 % of the country's area) as medium risk, and 697 units (67.1 % of the country's area) as low risk (*Fig. 6*). The remaining assessment units were not evaluated because groundwater abstractions were too small.

Finally, the results from the *Water Centre* project and the Security Research Project were synthesised by adopting the more adverse classification from the two assessments for each groundwater body assessment unit. In total, 838 of the 1,220 groundwater body assessment units were evaluated, of which 106 units, covering 12.7 % of the Czech Republic, were classified as high risk, 43 units (6.1 % of the country's area) as medium risk, and 689 units (66.3 % of the country's area) as low risk (*Figs. 6* and *7*). The remaining 382 assessment units (14.9 % of the country's area) were not evaluated.

Groundwater body assessment units identified as being at risk are shown in the overview map in *Fig. 7*.

Fig. 5. Proportion of work units (PRJ) at risk of groundwater abstraction shortages by 2050 in hydrogeological zones

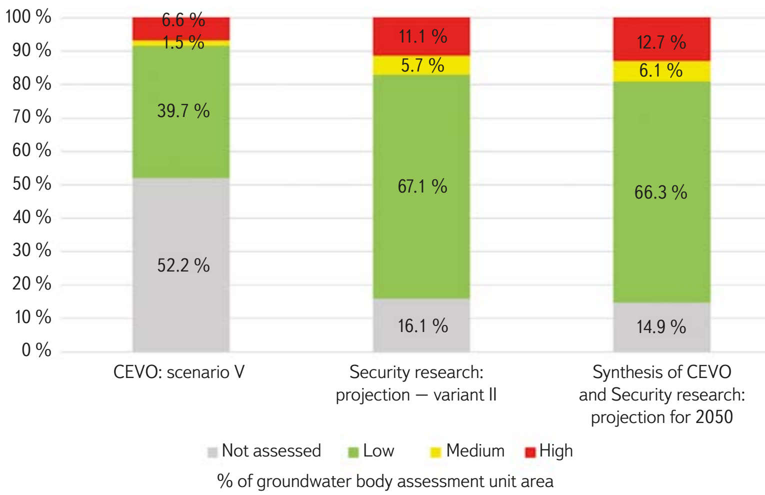

Fig. 6. Comparison of risk assessment results for the ALADIN-CLIMATE/CZ climate model under the SSP585 scenario (*Water Centre* – CEVO) and the HADGEM2-ES climate model under the RCP4.5 emissions scenario (Security research)

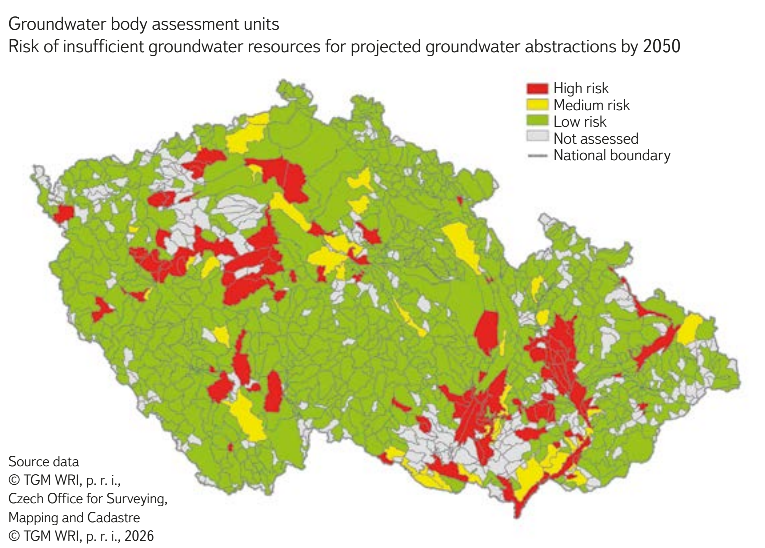

Fig. 7. The risk of insufficient groundwater resources for abstraction by 2050

Public specialised database

The detailed results of the water resource security assessment have been incorporated into the specialised public databases developed within the two projects [17, 7]. The data are available through web-based map services in the form of interactive maps and linked tables. The user interface is shown in *Figs. 8* and *9*

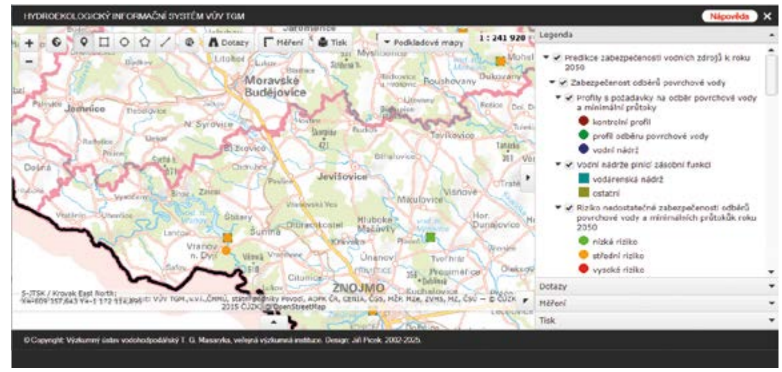

Fig. 8. Browser Service User Interface: Map section

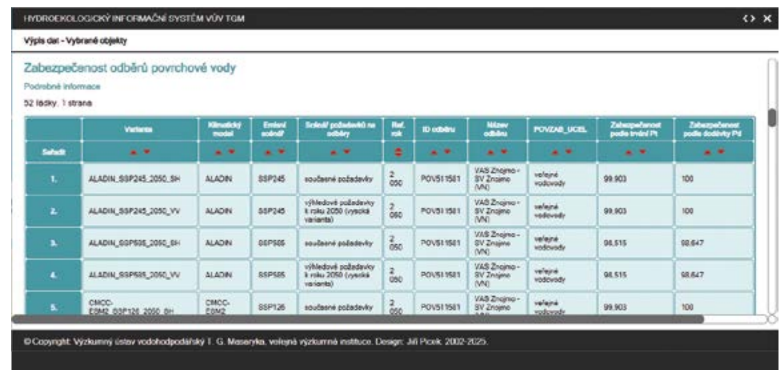

Fig. 9. Browser Service User Interface: Table view

DISCUSSION

Assessing future water resource security is a complex undertaking. Its modelling at the scale of the entire Czech Republic requires a number of necessary simplifications and is subject to considerable uncertainty. The principal sources of uncertainty include the following. The time horizon of 2050 was selected in accordance with the objectives of the *Water Centre* project and, at the same time, represents a period for which not only the evolution of climatic conditions, but also future water abstraction requirements and the state of water management infrastructure, can still be projected with a reasonable degree of confidence. Extending the projection to 2100 would substantially increase the uncertainties associated not only with climate models, but also with demographic, economic, and technological developments. For this reason, the results should primarily be regarded as a basis for the medium-term planning of climate adaptation measures over the coming decades. They should not be interpreted as a definitive prediction of future conditions, but rather as an assessment of the range of possible future developments under different combinations of climatic and socioeconomic assumptions.

A major source of uncertainty in the assessment results is the prediction of the impacts of climate change on hydrological characteristics and, to a lesser extent, the projection of future water abstraction requirements. This uncertainty is reflected in the use of multiple assessment scenarios. Consequently, the assessed level of water resource security also exhibited a degree of variability (e.g. for the Klíčava, Obecnice, Stanovice, and Hamry reservoirs), with many locations being identified as at risk only under some of the less favourable scenarios. The highest levels of identified risk generally occurred for combinations of climate models with the SSP585 emission scenario, which should be regarded primarily as representing the upper bound of the potential impacts of climate change. This scenario was not interpreted in the present study as the most likely future development, but rather as one of the scenarios used to assess the range of potential future risks to water resources. The assessment of groundwater resources is subject to uncertainties arising from the current estimates of groundwater resources, the heterogeneity of natural groundwater resources within hydrogeological zones, and the approximation of natural groundwater resources under future conditions.

Water abstractions are constrained by the need to preserve the ecological functioning of watercourses. At present, this requirement is addressed by maintaining so-called minimum residual flows. A Government Regulation is currently being prepared that is intended to bring the method for determining minimum residual flows more closely into line with the requirements of the EU Water Framework Directive. In this study, the assessment of minimum flow security was limited to flows actively maintained by reservoirs (i.e. the minimum reservoir outflow and, where applicable, the active augmentation of minimum flows at downstream control points). For the remaining assessment points, no projected minimum flow was determined and, consequently, its level of security was not classified.

Water abstraction requirements are based primarily on an analysis of recorded water abstractions. However, actual water abstractions may not accurately represent current water abstraction requirements, as the volume abstracted can vary in response to a range of factors, such as industrial operating conditions (e.g. plant shutdowns) or drought (e.g. abstraction restrictions resulting from insufficient water resources or increased irrigation demand due to soil moisture deficits). Difficulties in determining water abstraction requirements and the corresponding water sources may also arise in public water supply systems, where water may be abstracted from multiple sources (watercourses or reservoirs), and the volume abstracted from a particular source may vary depending on other operational factors. In addition, the permitted abstraction volume often differs substantially from the volume actually abstracted and, in many cases, is considerably higher.

CONCLUSION

The aim of the assessment described above was to evaluate the security of water abstractions and minimum flows supplied by surface water and groundwater resources under projected conditions for 2050, and to identify potentially vulnerable locations. Water abstraction security was assessed using simulation modelling (for surface water resources), water balance methods, and procedures for assessing the quantitative status of groundwater bodies. The assessment was carried out at the national scale. The principal input data comprised time series of modelled streamflow, evaporation, and baseflow from the catchments of gauging stations and the inter-catchment areas of surface water bodies under projected climate change conditions, together with projected water abstraction requirements. Existing reservoir and water transfer infrastructure, including their capacities, was taken into account. The uncertainties associated with projecting future developments were addressed by considering multiple assessment scenarios. Water abstraction requirements were evaluated for both current recorded abstractions and projected future abstractions. The potential impacts of climate change on water resources were considered using combinations of climate models and emission scenarios. Sources of uncertainty in the assessment include the determination of water abstraction requirements (e.g. the long-term discrepancies between permitted and actual abstraction volumes), the treatment of minimum residual flows, and the interaction between surface water and groundwater. The assessment of surface water resources identified 33 reservoirs (out of the 82 assessed) as potentially being at risk. Groundwater resources were evaluated for 838 groundwater body assessment units (out of the 1,220 in the Czech Republic), of which 106 units, covering 12.7 % of the country's area, were classified as high risk, 43 units (6.1 % of the area) as medium risk, and 689 units (66.3 % of the area) as low risk. The remaining 382 assessment units (14.9 % of the country's area) were excluded from the projected assessment because groundwater abstractions were too small (less than 5 $L \cdot s^{-1}$), resulting in an unacceptable level of uncertainty. For the ALADIN-CLIMATE/CZ climate model and the SSP585 emission scenario, groundwater body assessment units classified as high risk accounted for 29.2 % of the total projected groundwater abstraction for 2050 (3,410 $L \cdot s^{-1}$ out of a national total of 11,665 $L \cdot s^{-1}$), while medium-risk units accounted for 5.8 % (681 $L \cdot s^{-1}$), low-risk units for 56.3 % (6,567 $L \cdot s^{-1}$), and assessment units not included in the evaluation for 8.6 % (1,007 $L \cdot s^{-1}$).

The assessment results have been incorporated into the relevant specialised public databases. Despite the uncertainties and necessary simplifications associated with conducting the assessment at the national scale, the identification of surface water and groundwater resources that may be at risk in the future provides a valuable basis for more detailed investigations and the timely preparation of measures to reduce these risks.

Acknowledgements

This article is based on research carried out within Project No. SS02030027, Water Systems and Water Management in the Czech Republic under Climate Change, funded by the Technology Agency of the Czech Republic under Subprogramme 3 – Long-term Environmental and Climate Perspectives of the SS Programme – Programme for Applied Research, Experimental Development and Innovation in the Environment – Environment for Life, and Project No. VI20192022159, Water Management and Water Supply Systems and Preventive Measures to Reduce Risks in Drinking Water Supply, funded by the Ministry of the Interior of the Czech Republic under Programme BV III/1-VS.

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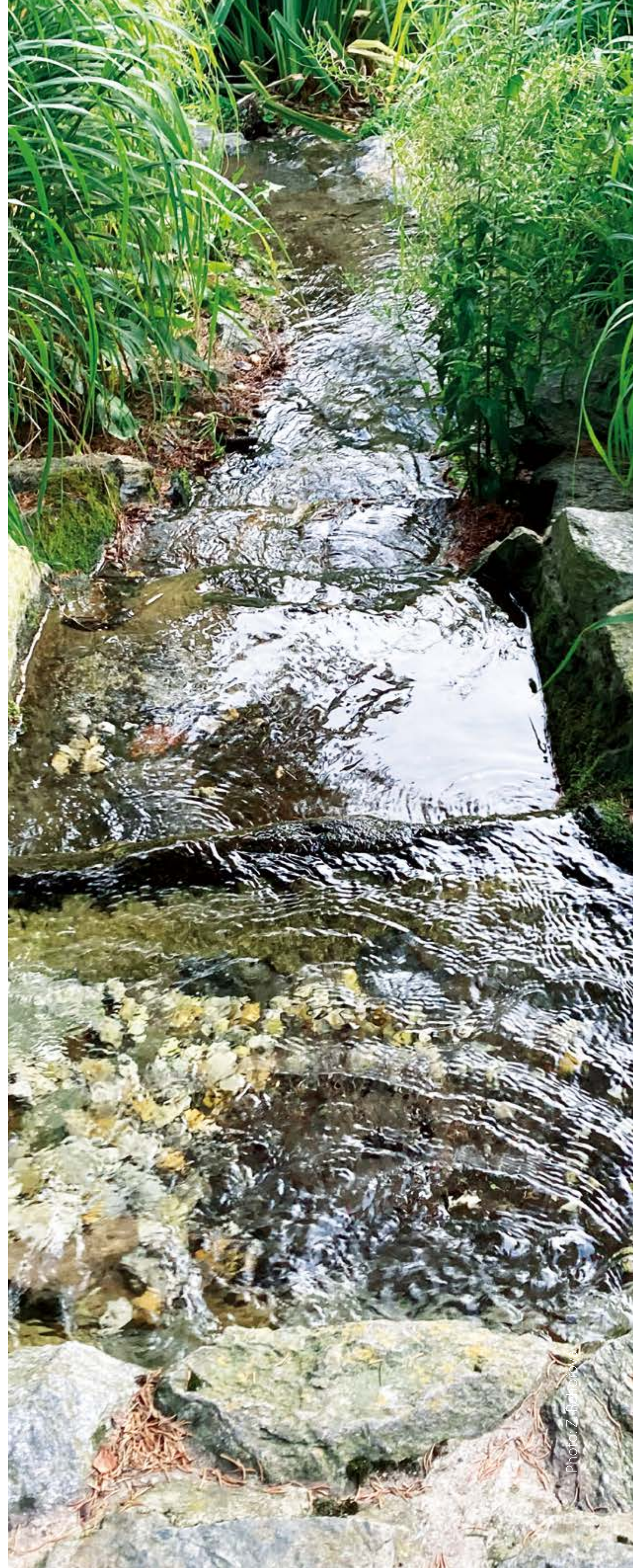
The Czech version of this article was peer-reviewed, the English version was translated from the Czech original by Environmental Translation Ltd.

DOI: 10.46555/VTEI.2026.05.005

ISSN 0322-8916 (print), ISSN 1805-6555 (on-line).



Changes in the status of surface water bodies based on chemical and physicochemical indicators

HANA PRCHALOVÁ, PETR VYSKOČ, MARIE KOZLOVÁ

Keywords: chemical status of water — ecological status of water — water quality indicators — progress toward achieving good status for water bodies

ABSTRACT

This article presents proposed approaches for assessing changes in the status of surface waters, i.e. progress towards achieving good status as a result of the measures implemented. The approaches are based on newly recalculated assessments for individual profiles, indicators and three-year periods, using the most recently approved characteristic values and limits. In addition to the overall result (good/non-compliant status), each profile, indicator, and three-year period is assigned a non-compliance index, which is the ratio of the characteristic value to the good status limit. The next step is to classify the non-compliance index into categories that represent either the extent to which the limit is exceeded or, conversely (for good status categories), proximity to the limit. When comparing results for individual three-year periods, it is necessary to select only those profiles with measurements for the entire assessment period to ensure the comparison is reliable.

The approach was also applied to ten of the most problematic indicators of ecological and chemical status/potential (with the exception of biological quality elements, which were not addressed by the project).

The results showed that concentrations of nitrate and ammoniacal nitrogen, fluoranthene, alachlor metabolites and AOX are decreasing and that good status is being achieved more frequently; concentrations are also decreasing in profiles where the non-compliance index is high. Concentrations of BOD_5, metolachlor and its metabolites, and EDTA are generally stable; concentrations of total phosphorus and phosphate phosphorus are stable or even slowly increasing, while high concentrations show no improvement either.

INTRODUCTION

An important component of River Basin Management Plans (RBMP) under the Water Framework Directive (WFD) [1] is the assessment of the status of water bodies. The objective of RBMPs is to achieve good ecological status (or good ecological potential, where applicable) and good chemical status of surface waters. For the purposes of RBMPs, the status of surface waters is assessed once every six years. However, pursuant to Section 4 of Czech Decree No. 98/2011 Coll., on the method for assessing the status of surface water bodies, the method for assessing the ecological potential of heavily modified and artificial surface water bodies, and the requirements for programmes for the monitoring and assessment of the status of surface waters, as amended [2], the status of surface water bodies is evaluated every three years. For the purposes of RBMPs, the results from the later of these two three-year assessment periods are used. Thus, during the third RBMP cycle, surface water status was evaluated for both the 2013–2015 and 2016–2018 assessment periods, with the RBMP being based primarily on the results for 2016–2018.

Although chemical status and ecological status/potential each comprise multiple quality elements or pollutants, for which the "one out, all out" principle applies (i.e. the overall status is determined by the lowest classification), the results are generally presented in aggregated form as a single ecological or chemical status for each water body. Since status assessments have been carried out since 2010, many changes have occurred over the past 16 years at both the European and national levels. These include changes in the delineation of water bodies, the selection of indicators, good status limits, assessment methodologies, and the indicators monitored. At the same time, measures to improve water status have also been implemented. As a result, it is very difficult to determine from the aggregated assessment results alone whether the situation is improving. The implementation of these measures is also very costly, making it essential to evaluate their effectiveness. This is important both for the institutions responsible for designing and implementing the measures and for the wider public. At the European level, there is now a consensus that, in order to assess progress towards achieving good status, ecological status assessments should be broken down at least into the individual quality elements: biological, hydromorphological, chemical (specific pollutants), and physicochemical. Similarly, chemical status assessments should distinguish between so-called ubiquitous substances and all other substances. For chemical status, the European Commission requires results to be reported using this classification to ensure comparability. However, experience has shown that even this level of classification is not sufficiently detailed.

Discussions at the European level have shown that it is very difficult to develop a single approach to assessing progress towards achieving good status that is suitable for all Member States. This is because both the frequency and timing of monitoring for individual indicators or pollutants, as well as the methods used to assess status, differ between countries. For example, some countries assess the status of selected chemical status indicators every year and use the most recent assessment. In contrast, other countries assess these indicators only in selected years. In the Czech Republic, chemical status is generally monitored annually, with the overall status being determined by the worst result recorded during the preceding three-year period. For general physicochemical indicators (e.g. nutrients, temperature, and oxygen), the assessment is based on the results for a three-year period. In the Czech Republic, this is usually the median value calculated from the previous three years (with maximum values

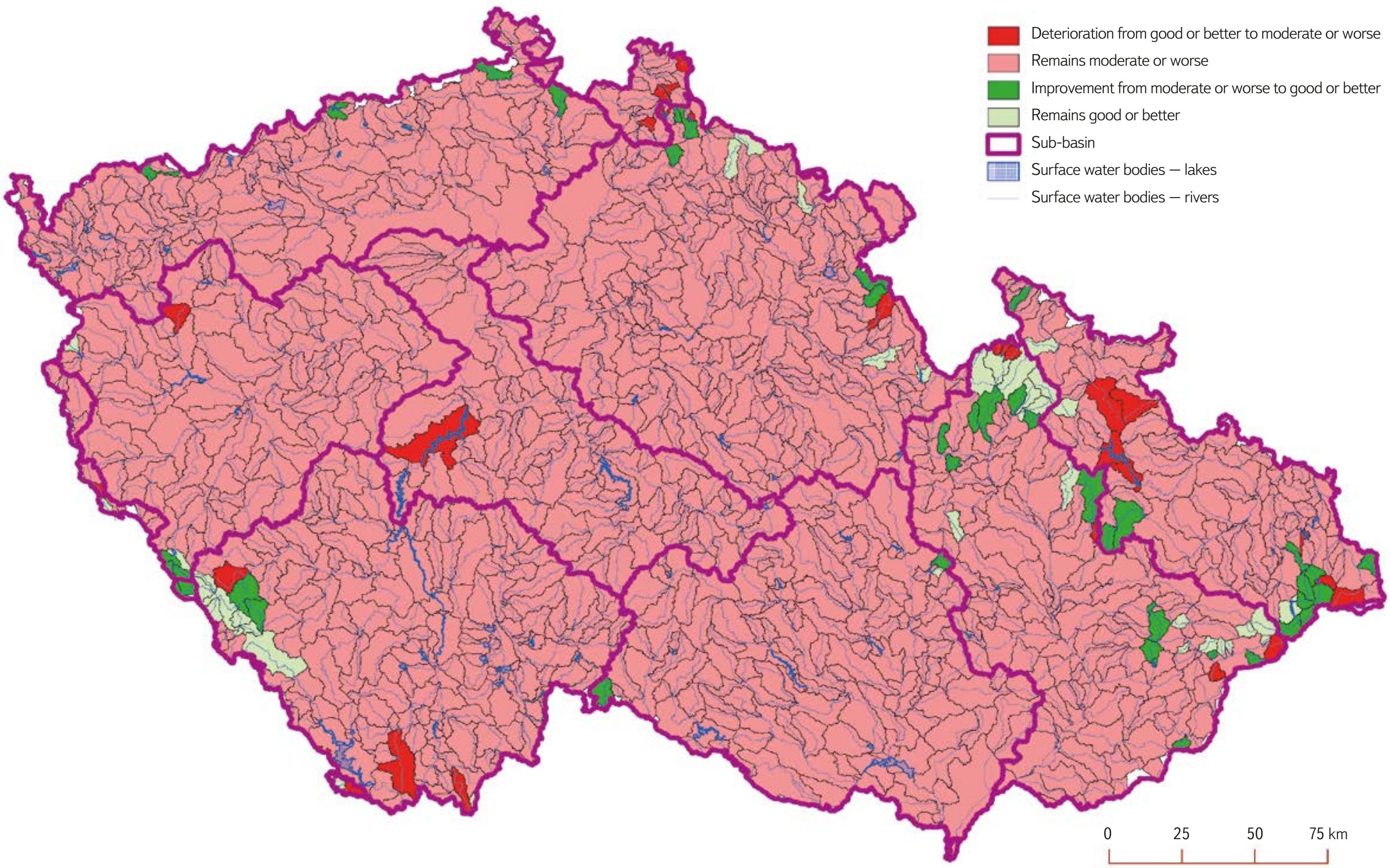


Fig. 1. Changes in the ecological status or ecological potential of surface water bodies between the periods 2016–2018 and 2022–2024

also used for nitrate nitrogen and temperature). However, the assessment methods differ between individual countries. For example, both Austria and the Czech Republic assess nitrogen in surface waters as nitrate nitrogen, and the boundary between good and moderate ecological status is defined according to river type. The threshold values generally range from 3.0 to 4.0 mg/L (compared with 2.3–3.8 mg/L in the Czech Republic). However, in Austria, the assessment is based on the 90th percentile of data collected over the entire calendar year, with the final status corresponding to the worst annual result recorded during the entire six-year assessment period [3]. In Hungary, total inorganic nitrogen is assessed, with annual arithmetic mean threshold values ranging from 1.4 to 5.0 mg/L. However, if the phytobenthos or phytoplankton is classified as being in good status, the result for total inorganic nitrogen is disregarded. For status reporting, a six-year arithmetic mean is calculated from all annual mean values. However, if nitrogen concentrations show a clear upward trend during the last three years of the assessment cycle, only data from those three years are used [4]. In France, nitrates are assessed, with a single good status threshold of 50 mg/L (ca. 11.3 mg/L nitrate nitrogen) applying to all surface waters. As in Austria, the annual 90th percentile is used. However, as in the Czech Republic, the final status is based on the results from the last three years of the monitoring cycle, calculated as the 90th percentile [5]. This brief overview clearly demonstrates that assessment methodologies vary considerably. Consequently, attempts to establish a common European methodology have generally resulted in the adoption of the lowest common denominator [6]. Although this approach may facilitate comparisons between countries, its value for assessing progress is considerably limited.

For these reasons, the methodology presented in this paper was developed to assess progress towards achieving good surface water status. The methodology was developed as part of Research Project No. SS02030027, *Water Systems and Water Management in the Czech Republic under Climate Change*. Although it is based on the fundamental European principles [6], it has been adapted to the data and assessment procedures used in the Czech Republic.

METHODOLOGY AND DATA USED

Before the most appropriate methodology was selected, different approaches were tested over a relatively long period. The most common approach was to compare water bodies achieving good status with those failing to achieve good status (*Fig. 1*), with the map showing changes in ecological status/potential between two RBMP cycles [7].

Ecological status/potential was selected for this comparison because it is the simplest parameter to compare. Both three-year assessment periods were evaluated using the same methodology, and the ecological status of almost all water bodies was assessed (i.e. there were very few unassessed water bodies). The map clearly shows that only a small number of changes in ecological status/potential occurred, including both improvements (green water bodies) and deteriorations (red water bodies). During the 2022–2024 assessment period, the status of 18.3 % of water bodies improved. However, an improvement did not necessarily mean that good status had been achieved, as improvements

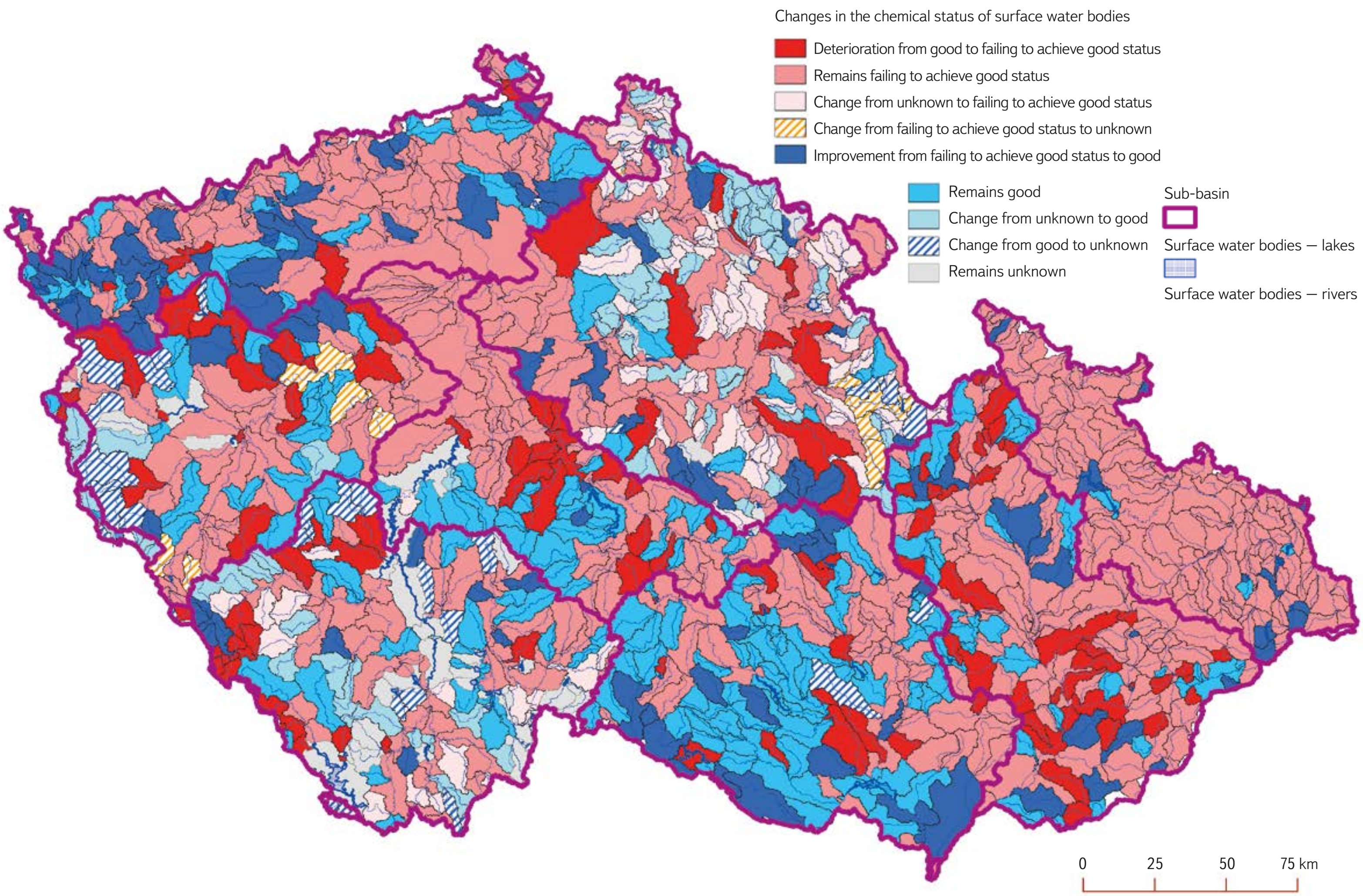


Fig. 2. Changes in the chemical status of surface water bodies between the periods 2016–2018 and 2022–2024
Note: Minor final changes for 2022–2024 are not included in the maps or percentages.

also included changes from bad to poor status and from poor to moderate status. By contrast, the status of 14.7 % of water bodies deteriorated, while 3.4 % remained in good status and 63.6 % remained in less than good status. However, this method of comparison provides no information on the reasons for the observed changes in status.

Changes in chemical status were illustrated in the same way (*Fig. 2*). Since some water bodies were not monitored during one or both three-year assessment periods (or because too few measurements were available), considerably more status categories were required. These additional categories cannot simply be ignored. Alternatively, they could all be grouped together as unknown, but this would not accurately reflect the underlying data. Consequently, the overall results are both less informative and more difficult to interpret. An improvement to good status was recorded for 10.6 % of water bodies, while 10.8 % deteriorated. A further 18.5 % remained in good status, 37.3 % continued to fail to achieve good status, and 22.8 % could not be assessed during at least one of the two three-year assessment periods (most recently in 2022–2024).

To assess changes in ecological and chemical status, it is necessary to examine the individual indicators and, where appropriate, the individual quality elements. The first question is which indicators and quality elements should be considered. Excluding the hydromorphological quality element, which serves only as a supporting element, there are 5 biological quality elements, 10 general physicochemical indicators, and 137 specific and priority pollutants. However, not all quality elements and indicators are equally important in terms of failing to achieve good status. This article does not examine the biological quality elements, although they are highly significant and were responsible for 76.3 % of water bodies failing to achieve good ecological status or ecological potential during the 2022–2024 assessment period. An even higher proportion (88.7 %) was attributable to the general physicochemical indicators. Ecological status also includes specific pollutants, which were responsible for 42 % of water bodies failing to achieve good status.

However, when individual indicators are considered, the number of those that are truly significant is much smaller (*Tab. 1*).

To assess trends in individual indicators, it is appropriate to compare successive three-year assessment periods. Assessment results are available for a total of five such periods, ranging from 2010–2012 to the most recent period, 2022–2024. The use of three-year periods reduces the influence of fluctuations in concentrations, which are mainly caused by changing hydrological conditions, including short-term droughts and, conversely, flood events. However, as already mentioned, the first three assessment periods were accompanied by substantial changes in the assessment methodology, such as the re-delineation of surface water bodies, changes to the assessment procedures (including the definition of the boundaries between good and moderate ecological status and between good and failing to achieve good chemical status), and the gradual inclusion of additional priority substances and matrices in the assessment

Tab. 1. Indicators that most often fail to achieve a good status in the three-year assessment 2022–2024

Indicator	Percentage of non-compliant water bodies
General physicochemical quality element	
Total phosphorus	65.2
Phosphate phosphorus	51.1
Oxygen saturation	41.7
Nitrate nitrogen	40.9
BOD_5	32.6
Ammonia nitrogen	20.8
Water temperature	19.1
pH	10.3
Specific pollutants	
Alachlor metabolites	11.0
AOX	9.0
EDTA	8.9
Metolachlor and its metabolites	7.9
Iron	7.6
Priority substances	
Benzo[a]pyrene	34.8
Fluoranthene	33.5
Benzo[ghi]perylene	23.9
Benzo[b]fluoranthene	15.7
Benzo[k]fluoranthene	7.3

of chemical status. These factors, which prevent direct comparison of status assessment results, were recognised at the European level some time ago. However, another equally important change has still not received sufficient attention: the gradual expansion of the range of monitored indicators.

The progressive expansion of monitoring can be illustrated by ethylenediaminetetraacetic acid (EDTA), which is classified as a specific pollutant in the Czech Republic and was monitored and assessed at 165 monitoring sites during the first three-year assessment period and at 376 sites during the most recent period (*Fig. 3*).

However, when assessing trends in individual indicators in terms of progress towards achieving good status – and thus the effectiveness of the measures implemented – it is necessary to consider more than the status assessment results alone. Several key principles should therefore be followed:

- the assessment period should be as long as possible,
- results should be based on three-year assessment periods,
- the assessment should be based on the established methodologies and good status thresholds,
- only monitoring sites for which analytical data are available for the assessment periods should be included,
- the assessment should focus not only on the achievement of good status, but also on trends in decreasing or increasing concentrations.

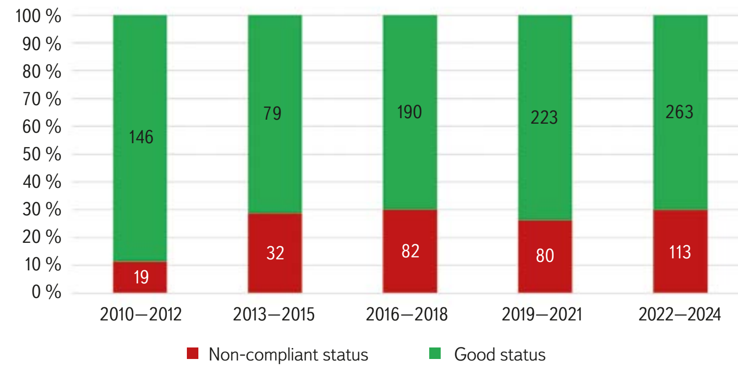


Fig. 3. Assessment of ethylenediaminetetraacetic acid (EDTA) in individual three-year periods based on good status limits (numbers in the graph represent the number of water bodies)

Notes

The assessment period should begin only after the introduction of RBMPs. Otherwise, the analysis would measure general improvements in water quality rather than the effectiveness of measures implemented under the RBMPs. If data from the 1990s were used (provided they were of sufficient quality), the apparent improvement – at least for the conventional indicators – would naturally be much greater. However, such improvements would not be attributable to measures implemented under the RBMPs.

The current assessment methodologies and good status thresholds should be used. Where these thresholds have changed over time, the currently applicable thresholds should be applied, as they are generally more stringent. Nevertheless, a single approach cannot be applied to all indicators. For specific pollutants and priority substances, where annual mean concentrations are used and the status is determined by the worst annual result, the annual means are recalculated from the primary data for each three-year assessment period, and the resulting three-year mean values are compared. Where both a median and a maximum value, or a mean and a maximum value, are used for status classification, only the median or mean is suitable for comparing trends. Although we attempted to assess trends in maximum values, we found no method that produced meaningful and reliable results. Consequently, many priority substances cannot be assessed because they are classified solely on the basis of maximum values. This makes it necessary to use the primary data rather than relying solely on the status assessment results. Initially, only the first and the most recent three-year assessment periods were compared. However, it was ultimately found to be more appropriate to include all five three-year assessment periods.

Only monitoring sites for which water quality data are available throughout the entire assessment period can be used to assess trends. This addresses both changes in the delineation of water bodies (by including only monitoring sites that consistently represented a water body throughout the assessment period) and changes in the range of monitored indicators. Although this reduces the number of monitoring sites that can be assessed compared with the present day, it ensures that the results are comparable.

The final principle is equally important. Particularly for indicators with a high proportion of non-compliant results, it is important to assess not only whether good status has been achieved, but also whether concentrations are generally decreasing, remaining stable, or increasing. Calculating trends for individual monitoring sites is labour-intensive and, when based on linear trend analysis, is also relatively unreliable [8]. A simpler approach was therefore adopted by classifying the results according to the so-called non-compliance index, calculated as the ratio of the relevant characteristic value to the good status threshold. For all indicators, the following categories were used: ≤ 0.8; 0.8–1 (both representing good status); 1–1.5; 1.5–2; and > 2. Where a large number of monitoring sites failed to achieve good status and the non-compliance indices were also high, additional categories with higher non-compliance index thresholds (2, 3, and 4, or 2, 4, and 7) were introduced.

The following indicators were ultimately excluded from *Tab. 1*: oxygen saturation, water temperature, pH, iron, benzo[a]pyrene, benzo[ghi]perylene, benzo[b]fluoranthene, and benzo[k]fluoranthene. In most cases, the reason was that status assessment is based solely on maximum values. The exceptions were water temperature (for which the thresholds will probably need to be revised in response to climate change), iron (because it is not possible to distinguish reliably between naturally elevated concentrations and anthropogenic pollution), and benzo[a]pyrene, for which the environmental quality standard (the good status threshold) was, until recently, lower than the limit of quantification.

For the remaining indicators, the individual non-compliance index categories were calculated and compared across all three-year assessment periods. For the general physicochemical indicators, the analysis covered the period from 2010–2012 onwards; for fluoranthene and the specific pollutants, from 2013–2015 onwards (because substantially fewer monitoring sites were included in the first three-year assessment period); and for ethylenediaminetetraacetic acid (EDTA), from the third assessment period (2016–2018) onwards. The analysis included all representative monitoring sites of surface water bodies in the Czech Republic. The number of monitoring sites meeting the selection criteria varied considerably: 793–850 for the general physicochemical indicators, 310–343 for fluoranthene and the specific pollutants, and only 203 for ethylenediaminetetraacetic acid (EDTA).

RESULTS AND DISCUSSION

General physicochemical indicators

The results for the general physicochemical indicators differ considerably. For both nitrate nitrogen and ammoniacal nitrogen (*Figs. 4–8*), the concentrations show a declining trend, both across the individual non-compliance index categories and in terms of achieving good status. For nitrate nitrogen, the difference between the first and the most recent three-year assessment periods was 7.8 percentage points (*Fig. 5*), compared with 7.3 percentage points for ammoniacal nitrogen (*Fig. 6*). Ammoniacal nitrogen also showed a marked reduction in high concentrations, both in terms of the number of monitoring sites and their proportion (*Fig. 7*).

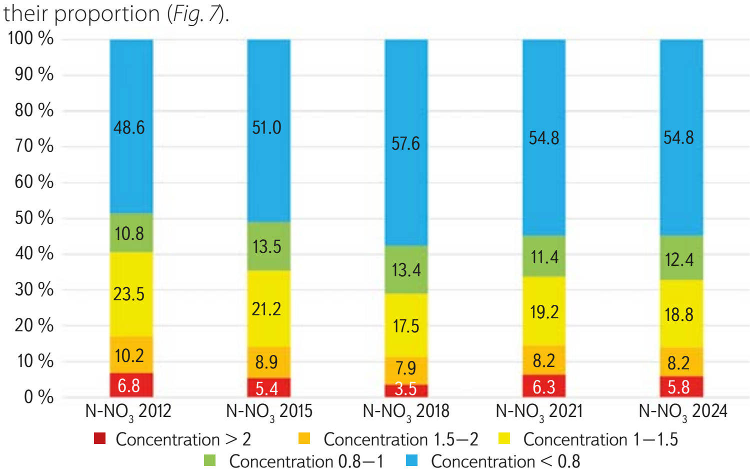


Fig. 4. Proportion of profiles by multiples of nitrate nitrogen concentrations relative to the limit in each three-year period
Note: The three-year periods are designated by their final year.

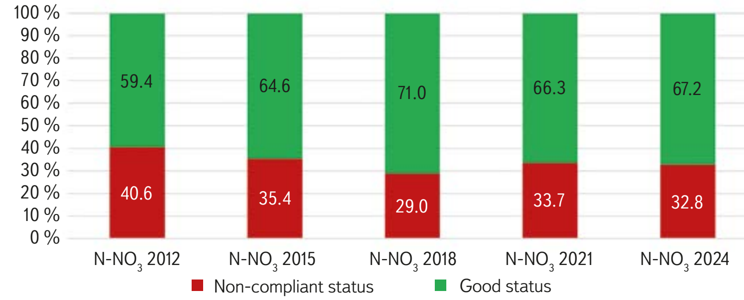


Fig. 5. Proportion of profiles by nitrate nitrogen limits in each three-year period

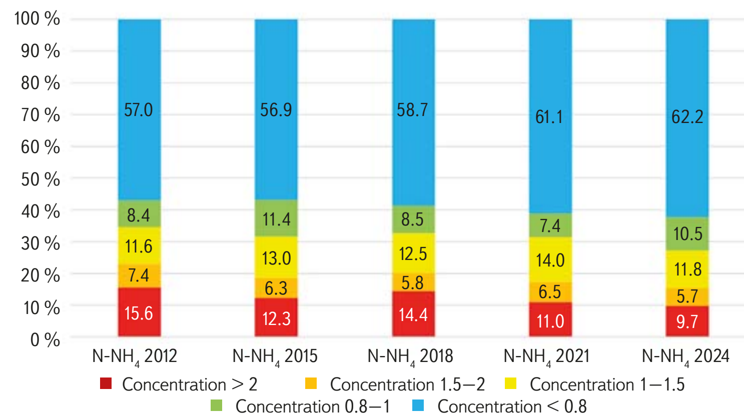


Fig. 6. Proportion of profiles by multiples of the ammoniacal nitrogen concentrations relative to the limit in each three-year period

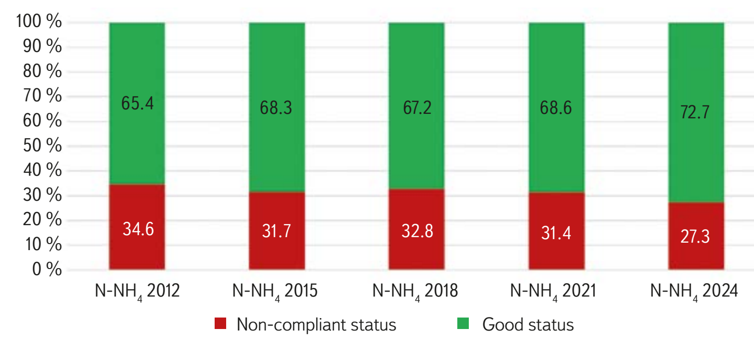


Fig. 7. Proportion of profiles by ammoniacal nitrogen limits in each three-year period

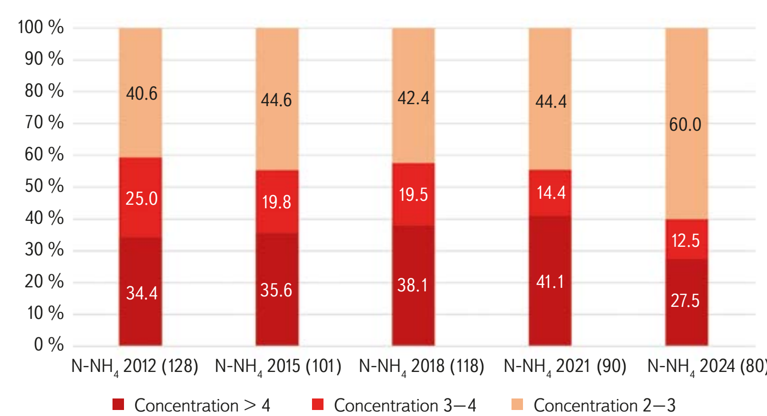


Fig. 8. Proportion of profiles by multiples of the ammoniacal nitrogen concentration relative to the limit in each three-year period – high concentrations (numbers in the graph in brackets represent the number of profiles)

The main difference between the two indicators lies in their trends across the individual three-year assessment periods. Nitrate nitrogen concentrations were lowest during the 2016–2018 assessment period, when the effects of a prolonged drought were apparent. Concentrations increased slightly during the following three-year period before declining again. This was probably because the principal source of nitrate nitrogen is diffuse agricultural pollution. During dry periods, nitrogen is not leached from the soil, although it is also taken up less readily by plants. It is released into surface waters only after precipitation increases again. Differences between the individual three-year assessment periods were less pronounced for ammoniacal nitrogen, which can probably be explained by the fact that its principal source is municipal wastewater rather than agriculture.

Although biochemical oxygen demand (BOD_5) showed a smaller improvement in status than the nitrogen forms (*Fig. 10*), it exhibited equally marked reductions in high concentrations (*Fig. 9*). It should be noted that the greatest reductions in BOD_5 concentrations occurred during the period 1990–2010, and that improvements have been more gradual since then.

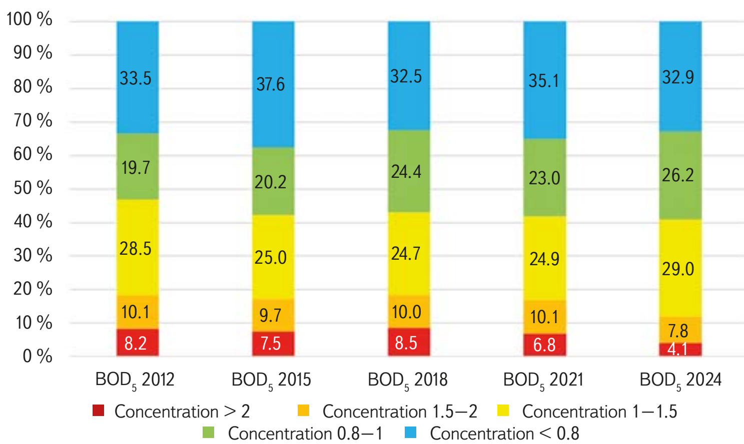


Fig. 9. Proportion of profiles by multiples of the biochemical oxygen demand concentrations relative to the limit in each three-year period

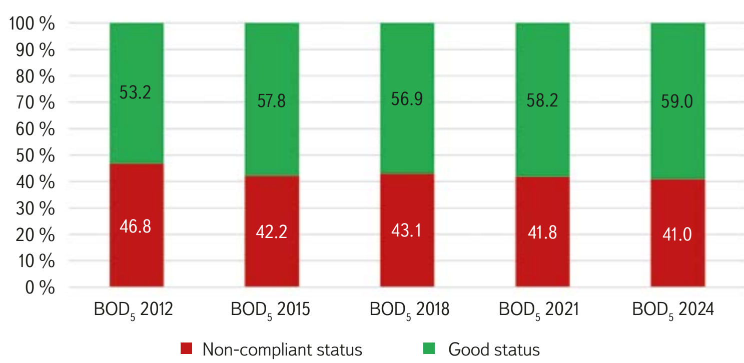


Fig. 10. Proportion of profiles by biochemical oxygen demand limits in each three-year period

The remaining general physicochemical indicators are total phosphorus and orthophosphate phosphorus (*Figs. 11–13*). Unfortunately, unlike the previous indicators, they show virtually no improvement, with only minimal differences between the individual three-year assessment periods. Compared with total phosphorus, phosphate phosphorus exhibits only slightly lower non-compliance indices (*Fig. 13*) and a somewhat higher proportion of monitoring sites achieving good status.

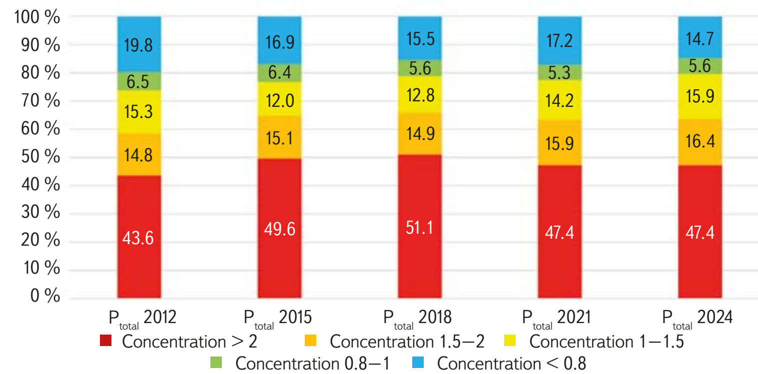


Fig. 11. Proportion of profiles by multiples of the total phosphorus concentrations relative to the limit in each three-year period

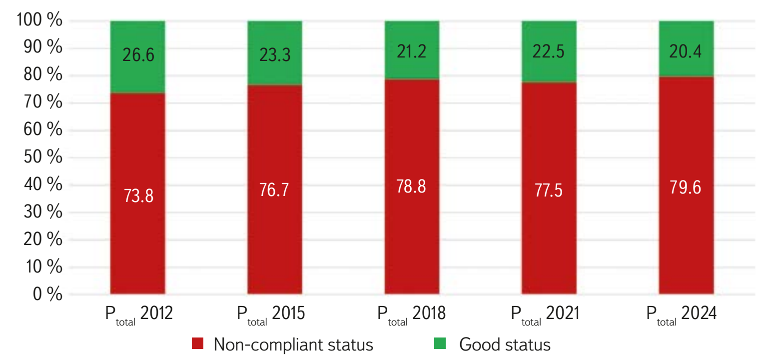


Fig. 12. Proportion of profiles by total phosphorus limits in each three-year period

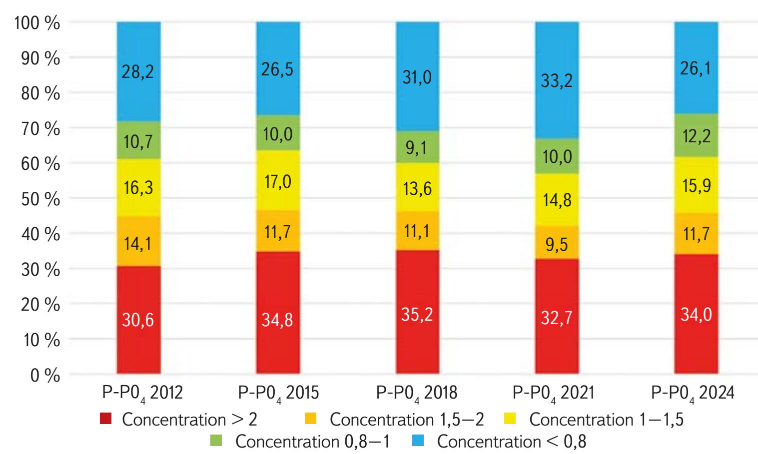


Fig. 13. Proportion of profiles by multiples of the phosphate phosphorus concentrations relative to the limit in each three-year period

Fluoranthene and specific pollutants

Unlike the general physicochemical indicators, for which gradual improvement was observed only for nitrate nitrogen and ammoniacal nitrogen, fluoranthene, alachlor metabolites, and adsorbable organically bound halogens (AOX) showed marked improvement. For fluoranthene, substantial reductions in concentrations can be observed in all three types of graphs (*Figs. 14–16*). The proportion of monitoring sites achieving good status increased by 13.4 percentage points (*Fig. 15*), while the proportion with concentrations exceeding a non-compliance index of 7 decreased markedly from 5.5 % of all monitored sites to just 1.5 % (*Fig. 16*). In addition, the decline was gradual, with no evidence of pronounced fluctuations.

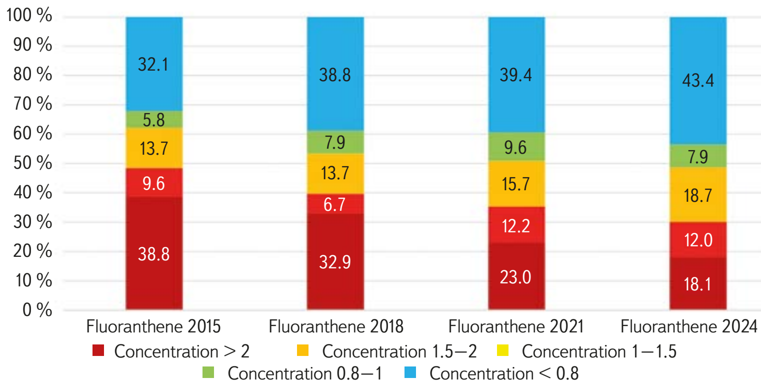


Fig. 14. Proportion of profiles by multiples of fluoranthene concentrations relative to the limit in each three-year period

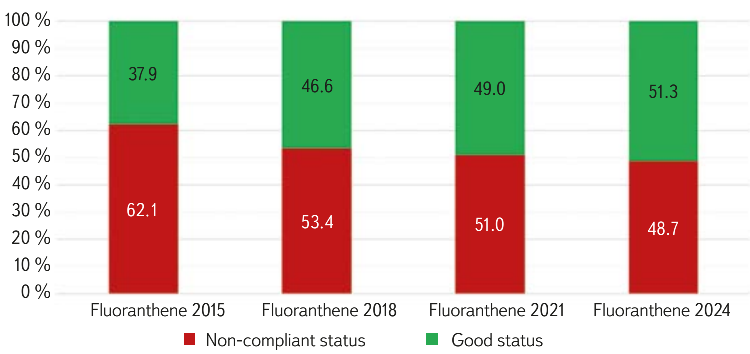


Fig. 15. Proportion of profiles by fluoranthene limits in each three-year period

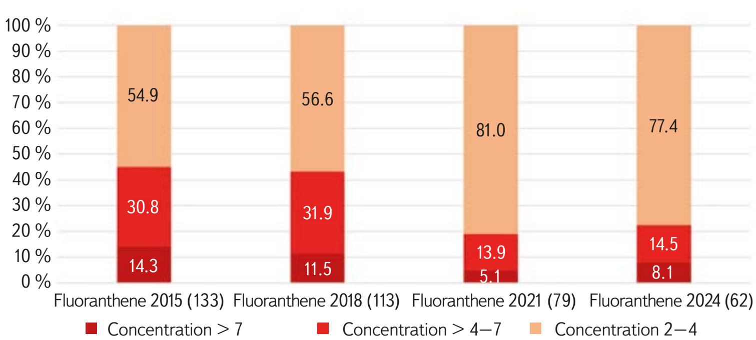


Fig. 16. Proportion of profiles by multiples of fluoranthene concentrations relative to the limit in each three-year period – high concentrations (numbers in the graph in brackets represent the number of profiles)

A similar pattern was observed for alachlor metabolites. The proportion of monitoring sites achieving good status increased by 10.6 percentage points (*Fig. 17*), while the proportion with concentrations exceeding a non-compliance index of 4 declined markedly from 4.8 % of all monitored sites to just 0.3 % (*Fig. 18*). However, the decline in concentrations appears to have levelled off during the last two three-year assessment periods. This may be explained by the fact that alachlor was banned as early as 2006.

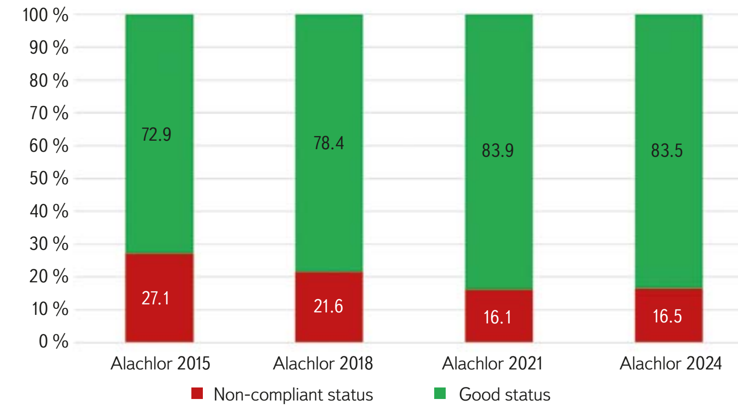


Fig. 17. Proportion of profiles by alachlor metabolite limits in each three-year period

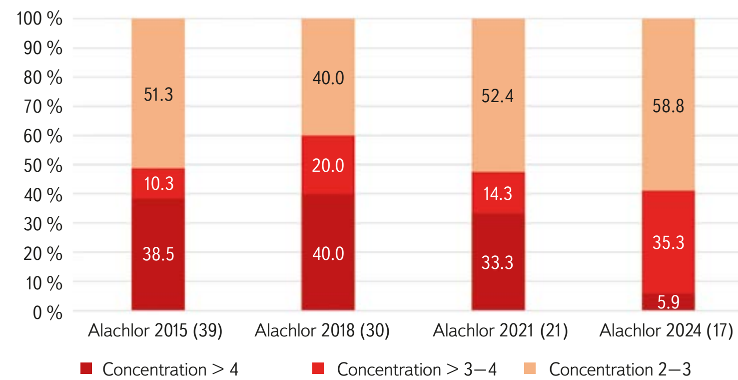


Fig. 18. Proportion of profiles by multiples of the alachlor metabolites concentrations relative to the limit in each three-year period – high concentrations (numbers in the graph in brackets represent the number of profiles)

Adsorbable organically bound halogens (AOX) also showed a pattern similar to that of fluoranthene (*Fig. 19*). Concentrations declined steadily, the proportion of monitoring sites achieving good status increased by as much as 17.3 percentage points, and in the most recent three-year assessment period no monitoring site had a non-compliance index greater than 2.

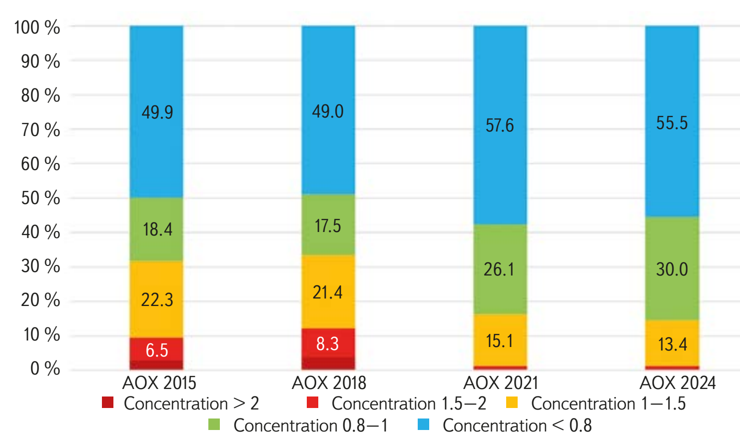


Fig. 19. Proportion of profiles by multiples of the AOX concentrations relative to the limit in each three-year period

The situation is somewhat different for metolachlor and its metabolites (*Fig. 20*). Although contamination of surface waters is less widespread than for alachlor metabolites (during the 2022–2024 assessment period, only 7.9 % of water bodies in the Czech Republic failed to achieve good status because of metolachlor), the proportion of water bodies failing to achieve good status has remained more or less unchanged. The use of S-metolachlor was also banned in 2024, although this could not yet have been reflected in the assessment period analysed. Nevertheless, metolachlor metabolites can be expected to persist in soils and surface waters for a considerable time.

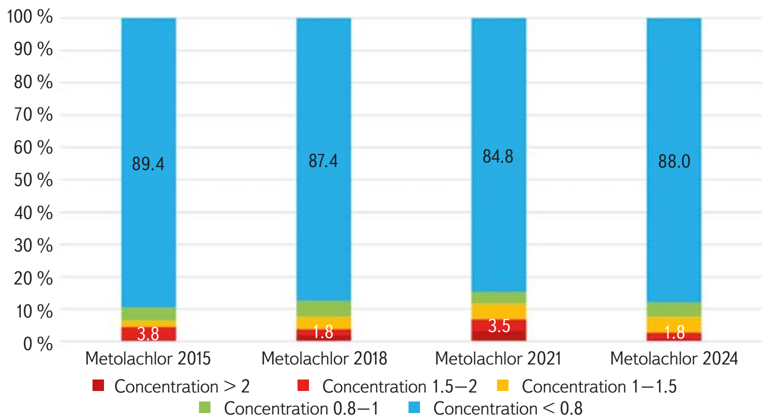


Fig. 20. Proportion of profiles by multiples of metolachlor and its metabolites concentrations relative to the limit in each three-year period

The final specific pollutant assessed was ethylenediaminetetraacetic acid (EDTA). No clear trend in concentrations can be observed, and the difference of 3.5 percentage points is not significant (*Fig. 21*). However, the highest concentrations, with non-compliance indices exceeding 7, appear to have declined gradually, from 4.9 % of all monitoring sites to 2.5 % (*Fig. 22*). However, because EDTA has been monitored more extensively only since the 2016–2018 assessment period and the comparison is based on just 203 monitoring sites, this conclusion is not sufficiently supported by the available data.

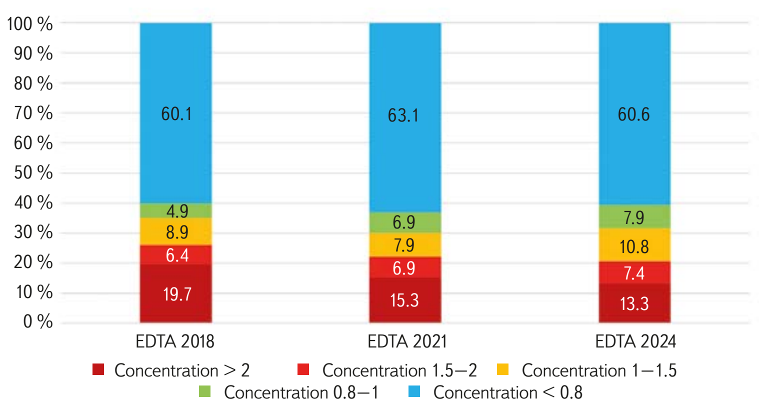


Fig. 21. Proportion of profiles by multiples of the EDTA concentrations relative to the limit in each three-year period

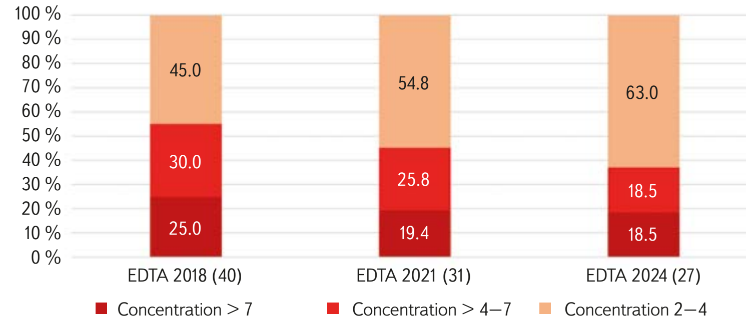


Fig. 22. Proportion of profiles by multiples of the EDTA concentrations relative to the limit in each three-year period – high concentrations (numbers in the graph in brackets represent the number of profiles)

CONCLUSION

To assess trends in the status of surface waters, it is necessary to focus on individual indicators. Three-year assessment periods provide the most appropriate basis for this analysis. They are consistent with the assessment of surface water status and, at the same time, reduce the influence of hydrological extremes, particularly short-term droughts and periods of high flow, on the measured concentrations. Only monitoring sites that were monitored throughout the entire assessment period should be included. The methodology should correspond as closely as possible to the procedures used for classifying chemical and ecological status, using mean values or medians (this approach cannot be applied to maximum or minimum values) and the same good status thresholds (environmental quality standards). Where the assessment methodologies have changed over time, the most recently applicable methodology should be used. This means that status must be recalculated from the primary data. Although it is possible simply to compare the first and the most recent three-year assessment periods, using all five assessment periods provides a much clearer picture of the trends. The methodology is best suited to larger geographical areas. However, once the behaviour of an indicator has been characterised across a large number of water bodies or monitoring sites, differences between individual water bodies or sites can also be investigated. The methodology presented here was developed using data for the whole of the Czech Republic covering the period 2010–2024, i.e. five three-year assessment periods. However, it is not sufficient simply to determine the number of monitoring sites achieving good status. A more suitable approach is to classify the results according to non-compliance index categories (i.e. the ratio of the relevant characteristic value to the good status threshold). For this purpose, non-compliance index categories of 0.8, 1, 1.5 and 2 proved appropriate, with additional categories of 2, 3 and 4, or 2, 4 and 7, where a high proportion of non-compliant results occurred.

The methodology was applied to five general physicochemical indicators (nitrate nitrogen, ammoniacal nitrogen, BOD_5, total phosphorus, and phosphate phosphorus), one priority substance (fluoranthene), and four specific pollutants. All five three-year assessment periods were evaluated for the general physicochemical indicators. For the remaining indicators, data could be used only from the second assessment period onwards because too few monitoring sites were included in the first three-year assessment period, while for EDTA the analysis could begin only with the third assessment period for the same reason.

The analysis showed that nitrate nitrogen and ammoniacal nitrogen concentrations have been declining gradually, while significant improvements were demonstrated for fluoranthene, alachlor metabolites, and AOX. By contrast, concentrations of BOD_5, metolachlor and its metabolites, and EDTA have remained stable, whereas total phosphorus and orthophosphate phosphorus have shown stagnation or even a gradual deterioration. In terms of the effectiveness of the measures implemented, wastewater treatment appears to have been successful in reducing ammoniacal nitrogen concentrations and, probably, industrial wastewater pollution represented by AOX. Diffuse agricultural pollution also appears to have declined, probably owing to a combination of factors, including high fertiliser prices and effective advisory services. Although no measures have been implemented specifically to reduce fluoranthene pollution, concentrations have declined significantly, probably as a result of the gradual closure of some industrial facilities and the continuing reduction in coal mining and combustion. The ban on the use of alachlor in 2006 also contributed to the decline in alachlor metabolites. Nevertheless, water pollution continued to decrease only until the 2019–2021 assessment period and has since levelled off. A similar trend can be expected for metolachlor and its metabolites. However, as their use was not banned until 2024, any improvement is likely to take considerably longer. On the other hand, contamination of surface waters is much less widespread, with only 7.9 % of water bodies failing to achieve good status during the 2022–2024 assessment period.

Although BOD_5 concentrations have remained stable, municipal wastewater treatment can be assumed to be operating effectively, and the remaining elevated concentrations are more likely to originate from other sources. The least progress has been made in reducing total phosphorus and phosphate phosphorus concentrations, probably owing to the high proportion of combined sewer overflows, households not connected to the sewerage system, and soil erosion.

It should be emphasised that the methodology presented here is not intended to replace the assessment of surface water status. The reported values and percentages indicate only how the results change over time; they do not represent the proportions of water bodies achieving or failing to achieve good status, because not all assessment results can be used for comparison. The greater the number of monitoring sites included in the assessment of progress towards achieving good status, the more closely the results reflect the situation for the Czech Republic as a whole. This applies, for example, to nitrate nitrogen and ammoniacal nitrogen, although the status assessment for nitrate nitrogen also includes maximum values in addition to the median, resulting in less favourable status classification results. The assessment of EDTA may be particularly biased because it is based on only 203 monitoring sites.

The Water Framework Directive also prohibits deterioration in status. However, analysis of real-world data confirms that changes in flow conditions can cause concentrations of some indicators to fluctuate, resulting in movement between classification categories. For status assessment, this mainly affects monitoring sites with non-compliance indices in the ranges 0.8–1 and 1–1.5. As a result, water bodies may move from "good status" to "failing to achieve good status", even though no genuine deterioration has occurred.

Acknowledgements

This article was prepared as part of research carried out within Project No. SS02030027, Water Systems and Water Management in the Czech Republic under Climate Change, funded by the Technology Agency of the Czech Republic under Subprogramme 3 – Long-term Environmental and Climate Perspectives of Programme SS – Programme for Applied Research, Experimental Development and Innovation in the Environment – Environment for Life. The authors also wish to thank the Vltava River Water Authority, Elbe River Water Authority, Ohře River Water Authority, Morava River Water Authority, and Oder River Water Authority for providing the data used in this study.

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The Czech version of this article was peer-reviewed, the English version was translated from the Czech original by Environmental Translation Ltd.

DOI: 10.46555/VTEI.2026.05.002

ISSN 0322-8916 (print), ISSN 1805-6555 (on-line).

Photo: Z. Řehořová

The impact of hydrological situation on water quality – assessment options

SILVIE SEMERÁDOVÁ

Keywords: surface water – water quality – water quantity – concentration – discharge relationship – statistical methods

ABSTRACT

Changing climatic and hydrological conditions affect the quality of water in streams and reservoirs. A number of studies have been published on this topic, mostly focussing on specific areas and conditions. However, sufficiently long and detailed time series of flow and water quality data are available in the Czech Republic to enable detailed analysis; this can identify the types of relationships that prevail under different catchment characteristics and pollution sources.

Selected methods were applied to a test dataset comprising water quality data for 2010–2019, supplemented by hydrological characteristics derived from long-term flow time series. For this study, long-term water quality monitoring profiles were selected for which reasonably accurate flow data at the time of sampling, as well as general catchment characteristics, were available.

Measured concentrations of the monitored determinants were compared with hydrological conditions, quantified using the flow percentile on the sampling date based on the long-term flow time series. Concentration-discharge (C–Q) relationships for selected substances can be divided into three categories: chemostasis, where concentrations remain constant or vary independently of discharge; enrichment, where concentrations increase with increasing flow; and dilution, where concentrations decrease with increasing discharge. Which of these relationships prevails, or whether several relationships occur in combination, depends on both the properties of the substances and catchment characteristics. In some cases, the observed relationship can be used to identify the predominant source of pollution in a catchment.

The aim of this article is to highlight the potential of statistical methods for optimizing monitoring campaigns and identifying the key factors and catchment characteristics that influence C–Q relationships.

INTRODUCTION

Climate change in recent decades has affected the hydrological characteristics of watercourses, as demonstrated by long-term monitoring in the Czech Republic [1]. In addition to declining mean flows, drought episodes are becoming more frequent and prolonged, while extreme runoff events are also occurring more frequently. These changes have consequences for water quality, potentially causing serious problems given that many water bodies already fail to meet the requirements for good chemical and ecological status. Despite numerous measures, improvement is slow or non-existent and, in some cases, conditions are deteriorating [2].

A number of studies have examined on the relationships between the quantitative and qualitative characteristics of watercourses in different types of catchments and under different hydrological conditions. Most studies focus on natural catchment chemistry [3, 4] and nutrients [5, 6], with less attention paid to other substances such as pharmaceuticals or pesticides. The relationship between concentration and flow (C–Q) is used as a metric for this purpose and is strongly influenced by both catchment characteristics [7] and predominant pollution sources, including legacy pollution [8]. The relationship manifests itself differently in longer time series based on less frequent monitoring than in high-resolution time series, in which relationships typical of rainfall–runoff events can be identified [9]. The factors determining the behaviour of substances in a catchment may also act in combination, as demonstrated by the model for nitrates developed by Minaudo et al. [10], which incorporates both seasonal patterns and individual events with largely opposing effects.

Understanding these relationships can help identify pollution sources, model responses to climate change or, conversely, to proposed mitigation measures, and improve estimates of constituent loads exported from catchments. Data preparation methods were therefore tested on a selected dataset, and selected results are illustrated in a series of graphs.

The purpose of this study was to compile a sufficiently robust dataset for the Czech Republic combining hydrological and water quality characteristics of watercourses, while testing which data and methods could be used for this purpose and identifying their limitations. A further aim was to analyse the data to determine whether findings reported in the literature also apply under conditions in the Czech Republic and to establish the extent to which methods used for general chemical parameters can be applied to other, less frequently monitored substances. A series of simple graphs generated using a consistent procedure is intended to illustrate the methods and general patterns and help identify the parameters, relationships and types of watercourses that warrant more detailed investigation.

METHODOLOGY

The relationship between water quality and quantity is most commonly determined using paired measurements of concentration and discharge at the time of sampling. Both simple statistical approaches and advanced modelling methods are used to analyse these relationships, including linear and nonlinear regression, correlation analysis and multivariate statistical methods [3, 7].

Linear regression is used when an approximately linear relationship between variables is assumed, although its application is constrained by the requirement for normally distributed residuals. This is particularly problematic for hydrological data, as concentrations and flows typically have strongly skewed distributions. For this reason, one or both variables are often log-transformed, which stabilizes variability in the data and allows the linear relationship to be better approximated in the transformed space [4, 7].

Tab. 1. Number of available values

Parameter – name	Number of profiles with measurements	Number of values	Number of values below the detection limit	Abbreviation (in graphs)
Acetochlor	127	9,299	8,846	ACETOCHLOR
Acetochlor metabolites	132	9,411	9,063	ACETOCHLOR-MB
Aluminium	126	10,532	1,527	AL
Alachlor	132	10,197	10,091	ALACHLOR
Alachlor-ESA	120	5,856	2,666	ALACHLOR-ESA
Alachlor metabolites	122	6,594	6,578	ALACHLOR-MB
Alachlor-OA	120	5,856	5,661	ALACHLOR-OA
AMPA	126	6,803	2,122	AMPA
Adsorbable organically bound halogens	134	14,457	122	AOX
Arsenic	133	14,384	4,146	AS
Benzo[a]pyrene	133	9,832	3,794	B-A-PYRENE
Benzo[b]fluoranthene	133	9,833	3,077	B-B-FLUORANTHENE
Benzo[g,h,i]perylene	133	9,831	3,476	B-GHI-PERYLENE
Brominated diphenyl ether	114	6,534	5,432	BROMDIPHENYL ETHER
Five-day biochemical oxygen demand	138	16,135	19	BOD_5
Calcium	138	15,726	0	CA
Cadmium	131	11,456	7,349	CD
Cadmium – dissolved	137	18,262	13,497	CD-D
Iron – total	132	13,585	142	FE-TOTAL
Fluoranthene	133	9,839	343	FLUORANTHENE
Metazachlor	128	9,522	8,051	METAZACHLOR
Metolachlor	127	9,507	7,950	METOLACHLOR
Metolachlor metabolites	132	9,643	8,381	METOLACHLOR-MB
Naphthalene	133	9,666	2,557	NAPHTHALENE
Ammoniacal nitrogen	138	16,158	1,903	$N\text{-}NH_4$
Nitrate nitrogen	138	16,053	62	$N\text{-}NO_3$
Total nitrogen	138	14,047	8	N-TOTAL
Lead	131	11,485	4,310	PB
Lead – dissolved	137	18,268	10,696	PB-D
Phosphate phosphorus	138	15,363	864	$P\text{-}PO_4$
Total phosphorus	138	16,034	25	P-TOTAL

Correlation coefficients, particularly Pearson's and Spearman's, are also used to assess the relationship between concentration and flow. Spearman's rank correlation coefficient is preferred when the data do not meet the assumption of normality or when the relationship is nonlinear or monotonic [9].

More advanced approaches include regression and semiparametric models, such as generalized linear models (GLMs), generalized additive models (GAMs), and mixed-effects models with random effects. Specialized approaches for estimating constituent transport are also frequently used in hydrology, including WRTDS (Weighted Regressions on Time, Discharge, and Season), which can better capture seasonality and long-term trends in the data.

When several explanatory variables are available, multivariate statistical methods such as factor analysis, cluster analysis, or principal component analysis can be used to help identify the dominant processes affecting the export of constituents from catchments [6].

Relating concentrations to flow percentiles is useful for identifying system behaviour under extreme conditions, such as high or low flows. This approach is often used to interpret concentration–discharge (C–Q) relationships [3, 7]. The advantages of this method are its simplicity and interpretability, and the fact that it can be applied even when data are limited or include values below the detection limit.

For this study, mean concentrations were compared across flow percentiles, primarily because of the method's simplicity, clarity, and ability to illustrate the basic principles underlying the relationship between hydrological conditions and constituent transport. However, it should be emphasized that any analysis of this type is highly dependent on appropriate data preprocessing, which is essential for reliable interpretation of the results.

Selection of monitoring sites

To make the statistical analysis as robust as possible, the dataset needs to be as complete as possible. The limiting factors in selecting monitoring profiles were temporal coverage, the availability of data for the broadest possible range of parameters, and the possibility of obtaining flow data for the time of sampling. For this study, profiles were selected where water quality had been monitored monthly for ten years, measurements were available not only for general parameters relating to oxygen conditions and nutrients but also for other substances, and a suitable hydrological gauging station could be assigned. To obtain hydrological data, each water quality monitoring profile was matched with the nearest hydrological gauging station upstream or downstream. Gauged flows were adjusted according to the ratio of catchment areas. Profiles with a catchment area ratio greater than 4 or less than 0.2 were excluded.

Parameter selection

Parameter selection was based primarily on data availability. Particular emphasis was placed on parameters responsible for failure to achieve good status under the Water Framework Directive [11], and preference was given to monitoring profiles for which a broader range of parameters was available. Operational monitoring data from 2010–2019 were used, and parameters for which insufficient measurement data were available were excluded; the parameters included in the analysis and the abbreviations used in the graphs are listed in *Tab. 1*.

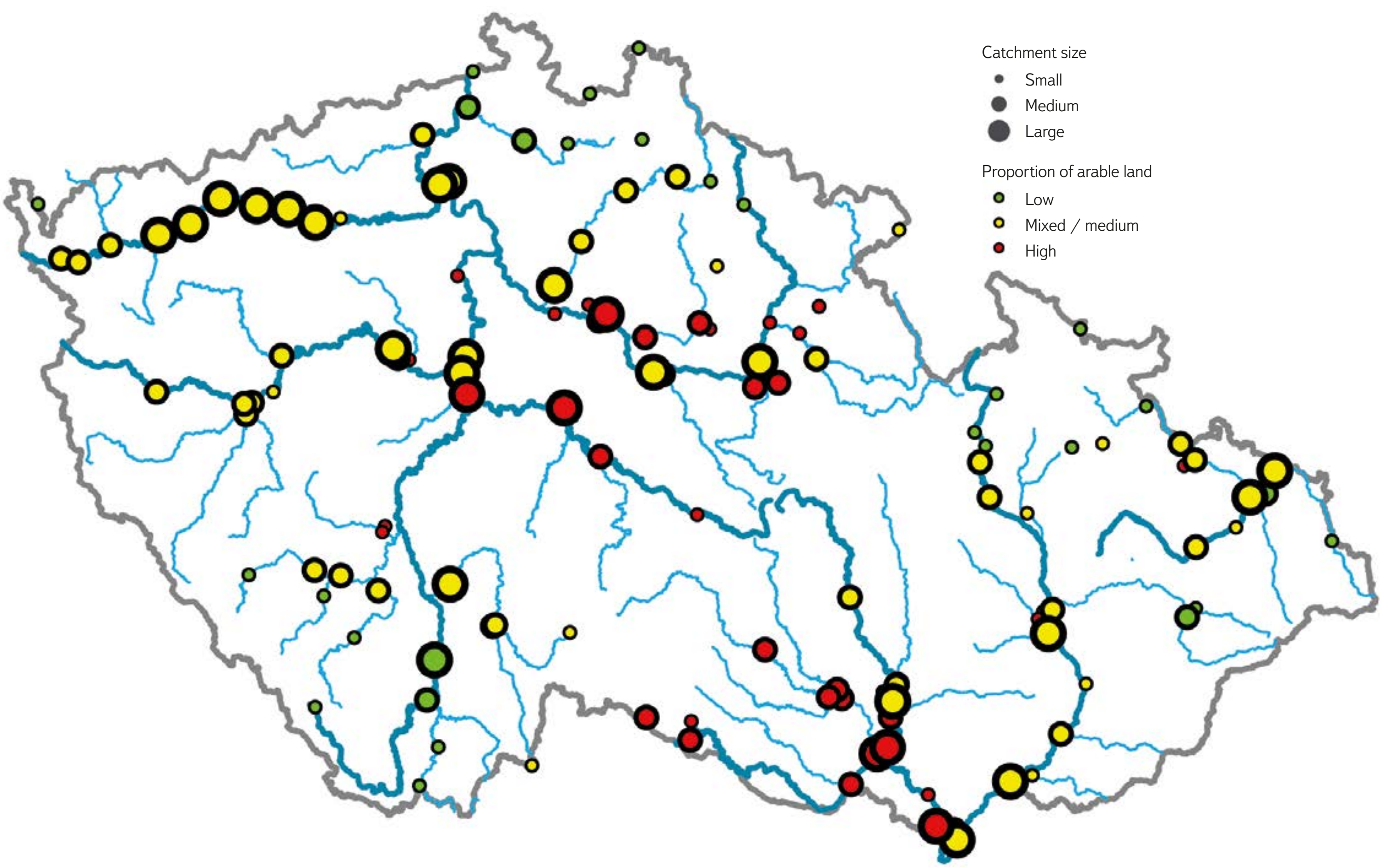

Fig. 1. Location and type of profiles (dot size indicates small, medium and large catchments; green, yellow and red indicate a small, medium and large share of arable land, respectively)

Method for assessing hydrological conditions

Daily flows from continuously monitored hydrological gauging stations were used to assess hydrological conditions. Flow percentiles were determined for each profile based on long-term daily flow series for 1980–2019; in a few cases, only shorter series were available, but these covered at least the period 2002–2019. The adjusted flow at the time of water quality sampling was compared with the corresponding adjusted percentile and assigned to the appropriate group. This made it possible to determine whether flow at the time of sampling was significantly higher or lower than usual.

Catchment characteristics

For each water quality monitoring profile, the catchment area and the proportions of arable land and urban development within the catchment were determined. The catchments were then classified as small (< 500 km²), medium-sized (500–2,000 km²), or large; as having a high (> 60%), medium (20–60%), or low proportion of arable land; and as having a high (> 5%), medium (1–5%), or low proportion of urban development (≤ 1%). The purpose of this classification was to determine which factors influence the relationships between water quality and hydrology – for example, whether small watercourses are more sensitive to periods of drought or, conversely, to extreme rainfall–runoff events, and whether the likely dominant influence of different types of pollution can be distinguished on the basis of the type of relationship. The number of profiles in each group is shown in *Tab. 2*. To allow conditions in large and small catchments to be compared, profiles in the lower reaches of watercourses were retained in the dataset even where their catchments overlapped with those of upstream profiles.

This resulted in 138 partially overlapping catchments varying in their characteristics (*Fig. 1*).

Tab. 2. Number of profiles

	Small	Medium	Large
High proportion of arable land, high proportion of urban land	6	3	1
High proportion of arable land, medium proportion of urban land	10	13	5
High proportion of arable land, low proportion of urban land	2	1	0
Medium proportion of arable land, high proportion of urban land	5	6	4
Medium proportion of arable land, medium proportion of urban land	7	17	17
Medium proportion of arable land, low proportion of urban land	1	7	0
Low proportion of arable land, high proportion of urban land	7	1	0
Low proportion of arable land, medium proportion of urban land	10	3	0
Low proportion of arable land, low proportion of urban land	10	1	1

RESULTS

Trends

Although the selected catchments cannot be considered representative for assessing hydrological conditions across the Czech Republic, they nevertheless show a slight downward trend in mean flows since the 1980s, as well as the dry period in the second half of the 2010s. *Fig. 2* shows the mean flow across all monitored catchments. The fitted linear trend is downward, although this may be distorted by several dry years at the end of the study period.

The water quality data cannot be considered representative either; nevertheless, trends at the selected profiles are consistent with those previously reported. *Fig. 3* shows trends in the average annual concentrations of selected indicators at the monitored profiles. To allow comparison between indicators, changes in concentration are expressed not in the original units but as a percentage of concentrations at the beginning of monitoring. Most indicators show a very slight decline or remain stable, while phosphate phosphorus shows an increase.

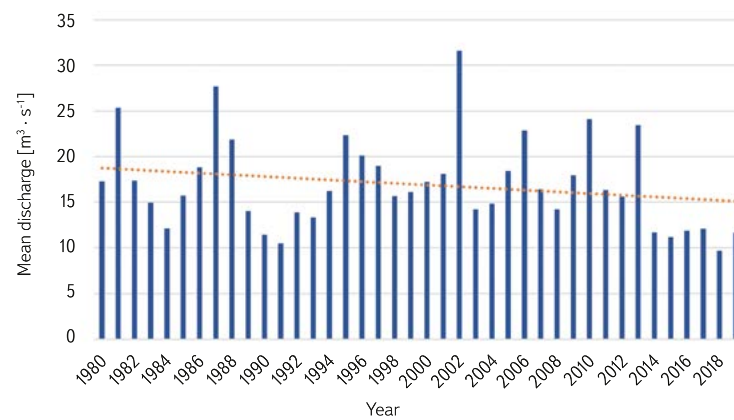

Fig. 2. Average flow rate of the test dataset (m³/s)

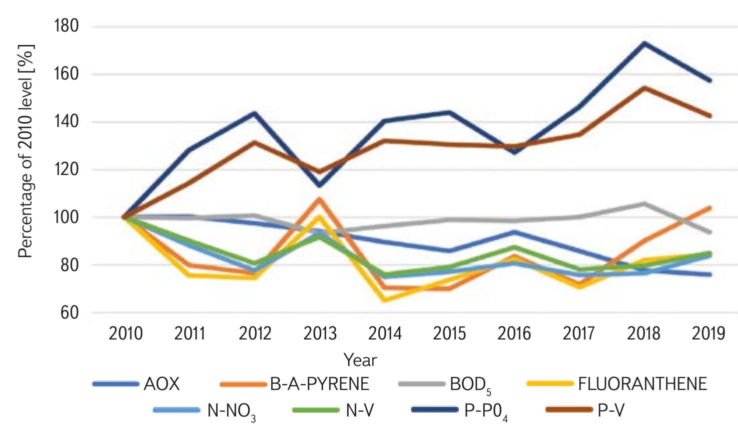

Fig. 3. Development of average annual concentrations of selected indicators in tested profiles (as a percentage of 2010 levels)

Seasonality

An important factor that needs to be taken into account is seasonal variation in both flow and water quality. Low flows are generally more frequent during the summer months, while high flows regularly occur in March and April. This is also reflected in the monthly distribution of samples among flow percentiles.

Fig. 4 shows the number of samples collected at different flow percentiles. *Figs. 5* and *6* show the distribution of samples among flow percentiles by month and year, respectively. Samples collected during the summer months were clearly more likely to coincide with the lowest flows.

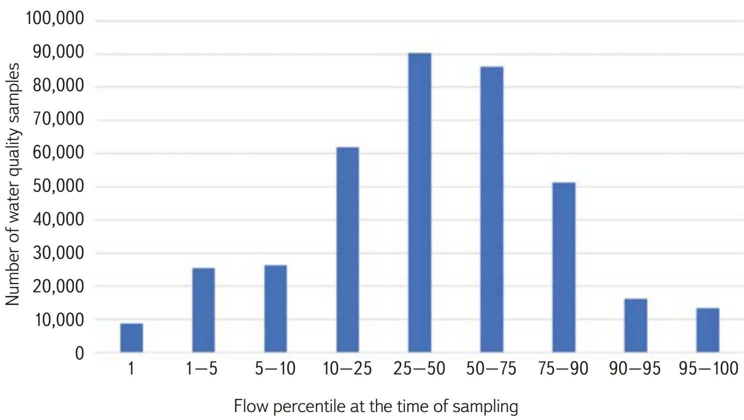

Fig. 4. Number of samples by flow percentile at the time of sampling

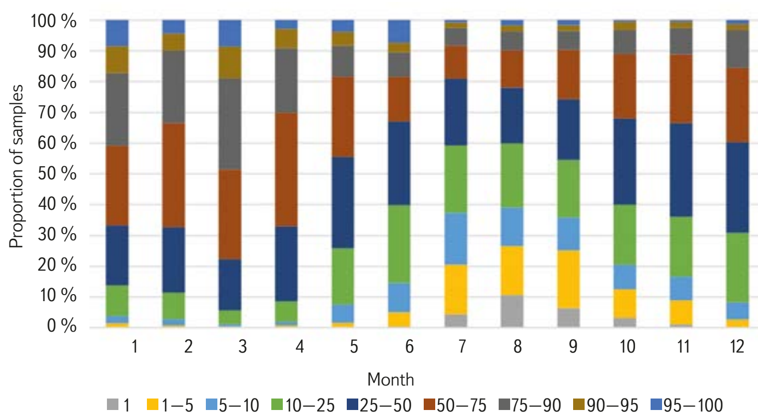

Fig. 5. Number of samples by flow percentile at the time of sampling in each month

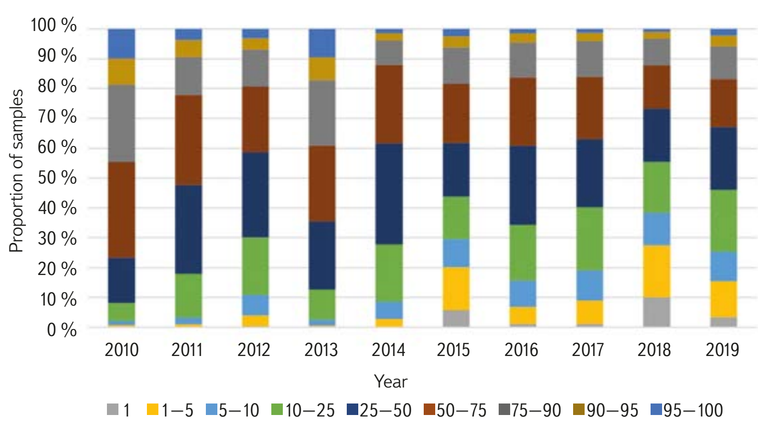

Fig. 6. Number of samples by flow percentile at the time of sampling in each year

Seasonal variation also affects the monitored water quality parameters. Higher nitrogen concentrations in winter and phosphorus concentrations in summer were confirmed. The occurrence of pesticides and some of their metabolites is also seasonal, as clearly demonstrated in *Figs. 7–9*. These figures show the occurrence of metabolites of alachlor (banned in 2008) and metolachlor (authorized during the data collection period). Although these substances were analysed regularly, measurable concentrations were detected in only some samples, making it necessary to include results below the limit of quantification (LOQ). Comparison of the two parameters shows the seasonal occurrence of the substance still in use, in contrast to the constant occurrence of metabolites of the banned substance, both in terms of detection frequency and measured concentrations.

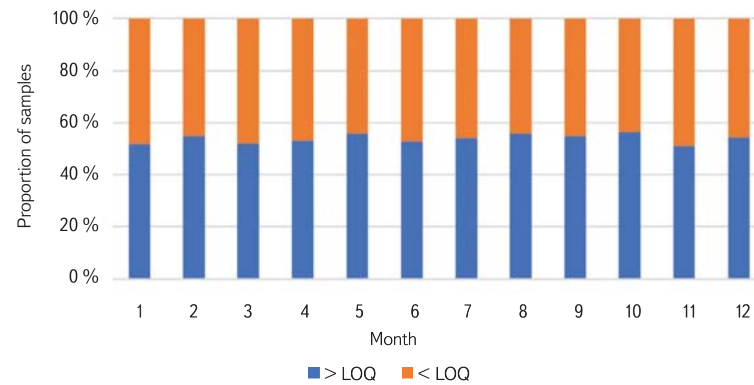

Fig. 7. Alachlor – ESA – numbers of records below and above the limit of quantification in each month

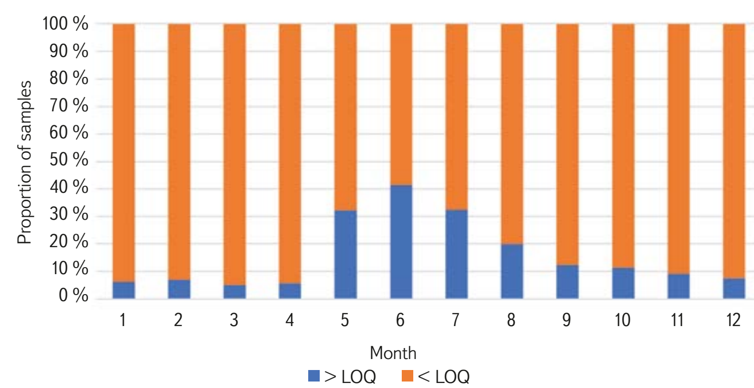

Fig. 8. Metolachlor – numbers of records below and above the limit of quantification in each month

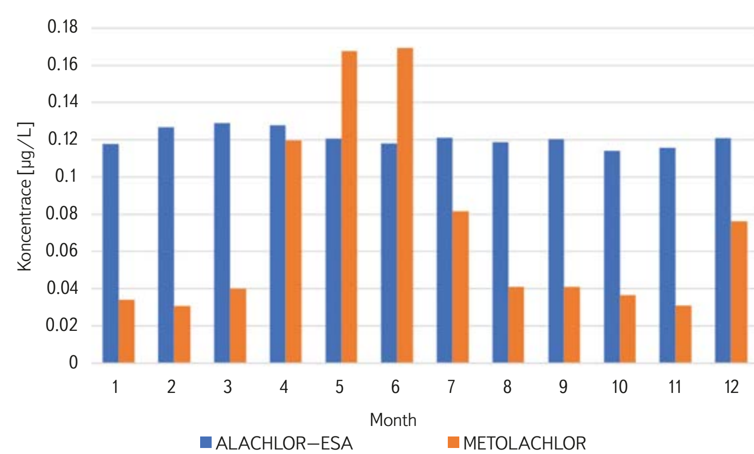

Fig. 9. Alachlor – ESA and Metolachlor – average measured concentrations in each month

C-Q relationships

Using the C–Q slope method, relationships between concentration and discharge can be divided into three basic types:

1. chemostasis, where concentration remains more or less constant regardless of discharge,
2. enrichment, where concentration increases with increasing discharge,
3. dilution, where concentration decreases with increasing discharge.

Chemostasis

Chemostatic behaviour of substances can be attributed to stable long-term stores within the catchment and the significant influence of groundwater.

Arsenic provides an example of chemostasis in the test dataset: its concentration varies little with discharge, with only a slight increase during extreme drought events, and even this increase is not particularly pronounced (*Fig. 10*).

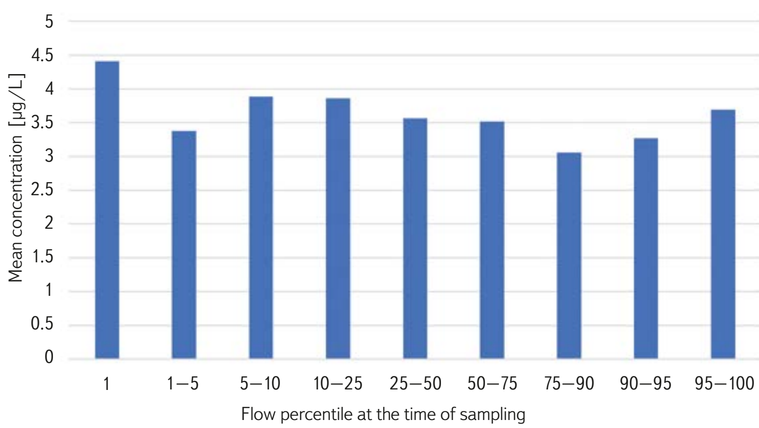

Fig. 10. Average arsenic concentrations (µg/L) by flow percentile – example of a chemostatic relationship

Enrichment

Enrichment is a relationship in which concentration increases with increasing discharge. It is typical of substances bound to sediment and those strongly influenced by surface runoff. In the test dataset, iron provides a clear example of enrichment (*Fig. 11*): concentrations remain stable at below-average and average flows, increase slightly at higher flows, and then rise severalfold under extreme flow conditions.

A similar pattern can be observed for some polycyclic aromatic hydrocarbons (PAHs) (*Fig. 12*), with concentrations remaining stable under normal conditions but in some cases increasing sharply at higher discharges.

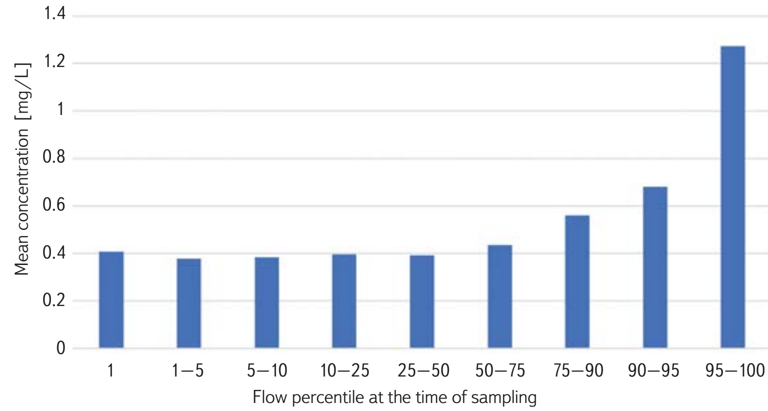

Fig. 11. Average iron concentrations (mg/L) by flow percentile – example of enrichment

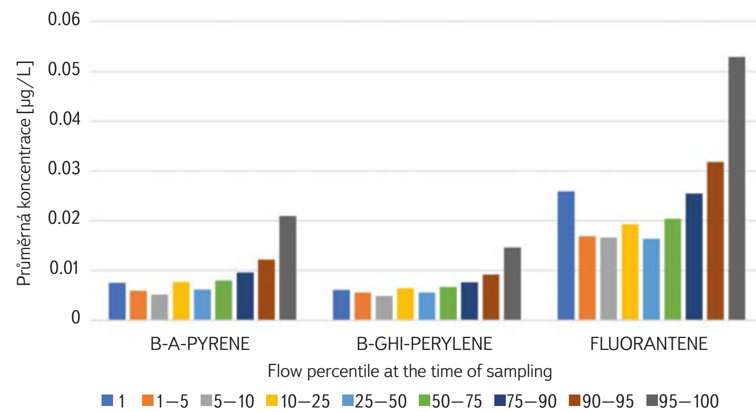

Fig. 12. Average concentrations of selected polycyclic aromatic hydrocarbons (µg/L) by flow percentile – example of enrichment

A somewhat different enrichment pattern is seen for nitrate nitrogen (*Fig. 13*): concentrations increase progressively across the flow range, while the additional increase under extreme flow conditions is only slight.

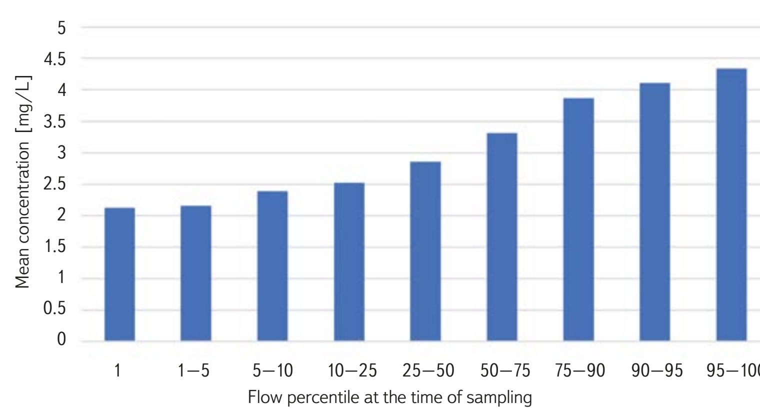

Fig. 13. Average nitrate nitrogen concentrations (mg/L) by flow percentile – example of another type of enrichment

Dilution

A relationship in which concentration decreases with increasing discharge may occur for substances entering surface waters primarily from groundwater; their decline may indicate a decreasing contribution of baseflow relative to surface runoff (e.g. calcium, *Fig. 14*). In some cases, however, dilution can also indicate pollution from point sources, which is independent of hydrological conditions.

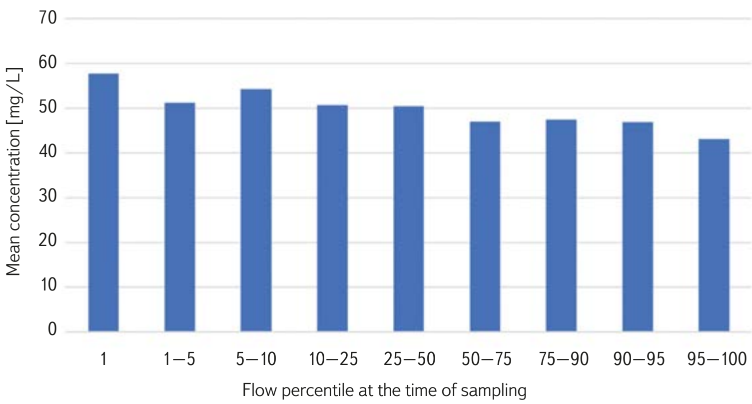

Fig. 14. Average calcium concentrations (mg/L) by flow percentile – example of dilution

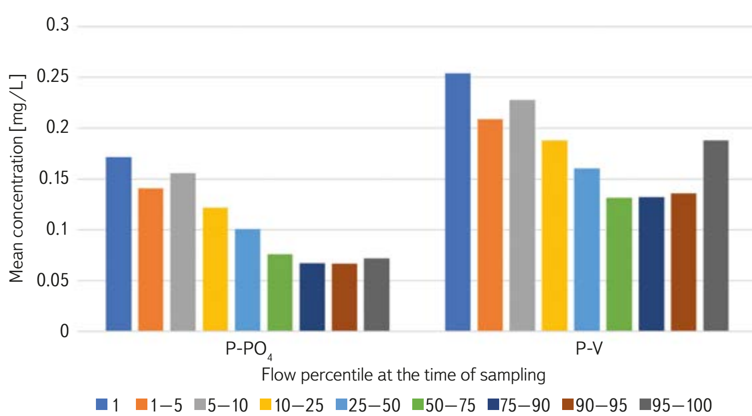

Fig. 15. Average concentrations of phosphate phosphorus (dilution) and total phosphorus (combination of dilution and enrichment) (mg/L) by flow percentile

Combination

The resulting pattern may reflect a combination of several factors, with extremes occurring at both ends of the flow range. *Fig. 15* shows a classic dilution pattern for phosphate phosphorus. Total phosphorus follows a broadly similar pattern at lower flows, but concentrations increase again at high flows.

Influence of catchment characteristics

Catchment characteristics have a major influence on the relationship between hydrology and water quality. The basic characteristics examined – catchment size and the proportions of arable and urban land – also proved important in the test dataset. The following figures illustrate these effects using nutrients as examples.

Figs. 16 and *17* compare nitrate nitrogen and total phosphorus concentrations in small (< 500 km²) and large (> 2,000 km²) catchments. At average and high flows, nutrient concentrations are almost identical in small and large catchments, whereas differences emerge at low flows, with higher concentrations particularly evident in small catchments. For total phosphorus, this pattern occurs in both large and small catchments but is considerably more pronounced in small catchments. For nitrate nitrogen, concentrations in large catchments continue to decline at low flows, whereas those in small catchments remain similar to concentrations at intermediate flows.

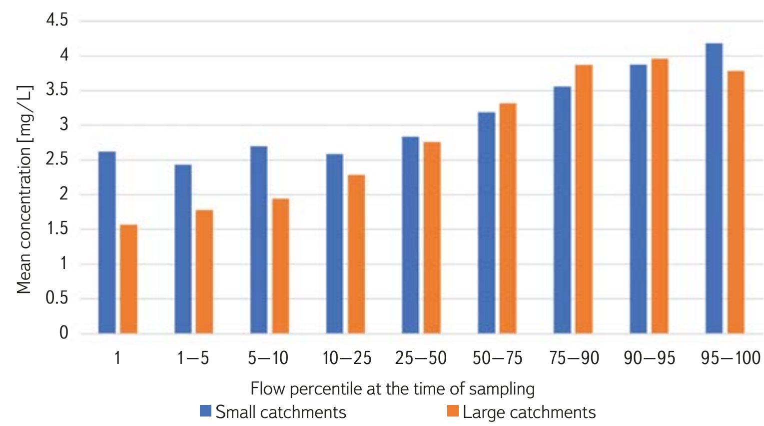

Fig. 16. Differences in the C–Q relationship for nitrate nitrogen (mg/L) by catchment size

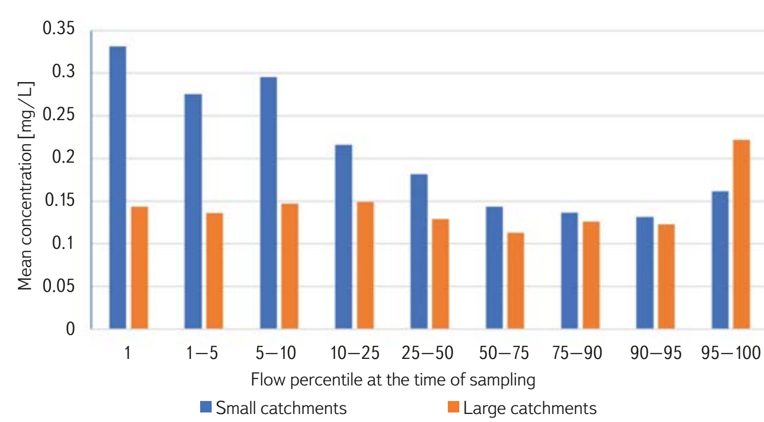

Fig. 17. Differences in the C-Q relationship for total phosphorus (mg/L) by catchment size

The differences are even more pronounced between catchments with high and low proportions of arable land (*Figs. 18* and *19*). For total phosphorus, the overall pattern is broadly similar, but concentrations are considerably higher in catchments with a high proportion of arable land. For nitrate nitrogen, however, the patterns are completely opposite. In catchments dominated by arable land, nitrate concentrations increase with increasing discharge, whereas in catchments with a low proportion of arable land they remain constant or even decrease.

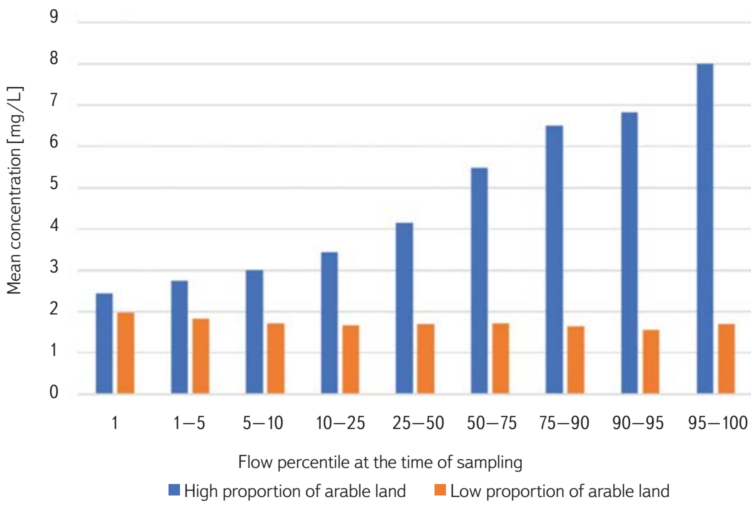

Fig. 18. Differences in the C-Q relationship for nitrate nitrogen (mg/L) by proportion of arable land in the catchment

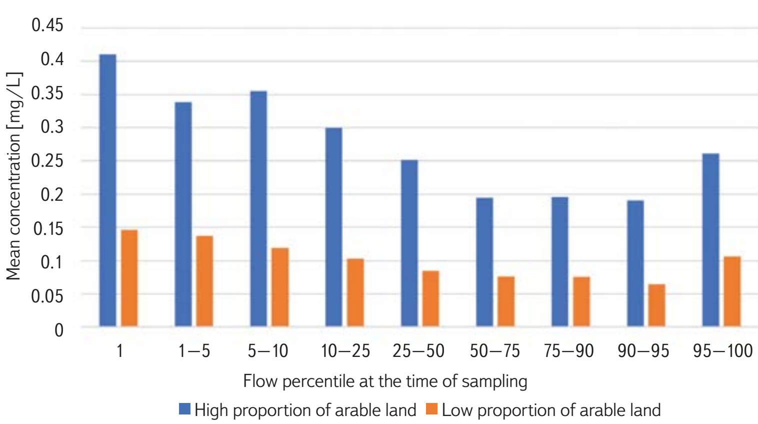

Fig. 19. Differences in the C-Q relationship for total phosphorus (mg/L) by proportion of arable land in the catchment

In the example shown, the proportion of urban land is reflected more in an overall increase in concentrations than in a change in the pattern (*Figs. 20* and *21*).

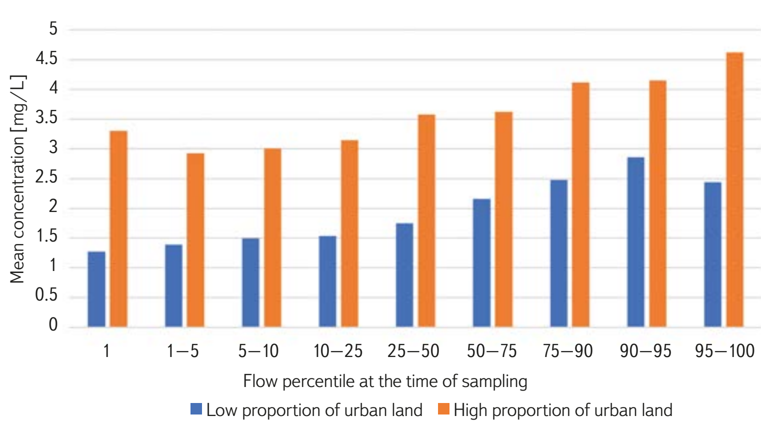

Fig. 20. Differences in the C-Q relationship for nitrate nitrogen (mg/L) by proportion of urban development in the catchment

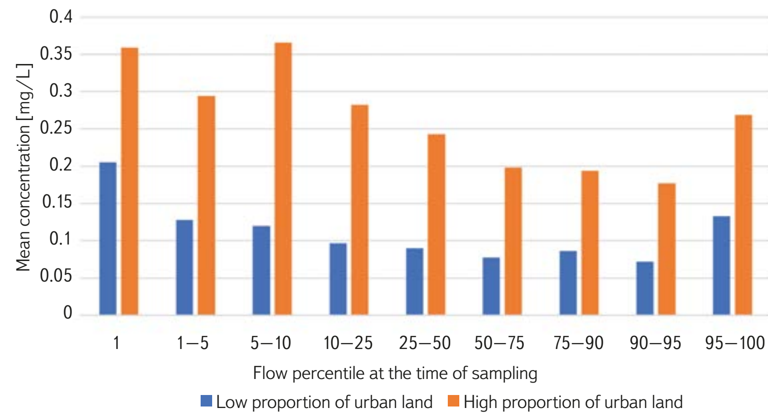

Fig. 21. Differences in the C-Q relationship for total phosphorus (mg/L) by proportion of urban development in the catchment

DISCUSSION

The simple method used here clearly demonstrates the wide range of questions that can be asked and the various aspects of the relationship between hydrological and water quality parameters that can be examined. However, detailed evaluation and the drawing of conclusions require many factors to be taken into account, which must be addressed according to the specific purpose of the analysis.

For comparative purposes, independent (non-overlapping) catchments should be selected. Analysis of catchment characteristics requires a more thorough examination of correlations among the characteristics themselves, for example between population density and agricultural activity. In this analysis, settlement area was represented only by its proportion of land use; population and the structure of wastewater treatment would be more appropriate predictors. The use of mean daily flows does not capture the dynamics of individual extreme events, such as the first flush during extreme flow events [13], or differences in the effects of drought depending on its duration.

The test data also demonstrate, among other things, the influence of arable land on nitrate concentrations. This influence is sufficiently strong to reverse the pattern of the relationship: enrichment predominates in catchments with a high proportion of arable land, whereas dilution predominates in catchments with no arable land. This pattern suggests a likely combination of sources that could be captured by more complex models, such as that described in [10], which distinguishes between enrichment, predominating in agricultural catchments in winter, and dilution, predominating in all catchment types in summer. A similar model appears likely to be applicable under conditions in the Czech Republic. The results also show that enrichment does occur at extremely high flows, but is not pronounced. Small catchments are more vulnerable to drought.

A number of authors have investigated phosphorus in the Czech environment, e.g. [13, 14]. The test data confirm that dilution is the predominant relationship for phosphorus; enrichment occurs only for total phosphorus under extreme flow conditions. Further research should examine whether enrichment at high flows occurs in all types of catchment or only in those with a higher proportion of arable land. Small catchments with dense development and intensive agriculture are the most vulnerable in terms of phosphorus, with dry periods potentially leading to severalfold increases in concentrations. A more detailed analysis would be possible with more comprehensive data on population and wastewater management.

Similar statistical methods can be applied to any parameters for which sufficient data are available. Substances other than nutrients are much less well represented in the literature. The test data clearly show a positive relationship between the concentrations of most PAHs and discharge – i.e. enrichment – which becomes more pronounced as flows become more extreme. This relationship mirrors that observed for suspended solids and, for example, iron, indicating an association with the proportion of surface runoff. Further investigation could usefully compare the influence of impervious surfaces with that of other land-cover types, such as erosion-prone arable land. As this relationship is relatively consistent, it could potentially be used to model concentrations based on correlations with discharge or suspended solids. Fieldwork could then focus on validation measurements, or the relationship could be used to improve estimates of emissions, as required for priority substances under the Water Framework Directive.

Analysis of the pesticide results yields interesting findings, although these are severely limited by data availability. Given the large number of results below the limit of quantification and the inconsistent limits used for different measurements, one option is to include these data and focus on the probability of exceeding the limit of quantification.

Overall, the influence of hydrological conditions can be so strong that it obscures long-term improvements in pollution levels. Many substances responsible for failure to achieve good status are sensitive to both extreme rainfall events and, in particular, episodes of drought.

C–Q relationship models can be used, with a certain degree of uncertainty, to compensate for limited data availability, for example to improve estimates of constituent loads.

CONCLUSION

Many statistical methods are available for working with large datasets and, with appropriately formulated questions and carefully selected data, they can yield valuable insights. Such analyses inevitably involve a degree of simplification and cannot replace detailed analysis of the catchment under study. On the other hand, statistical analyses of existing data are quick and inexpensive and can provide valuable information, for example for analysing pollution sources within a catchment, modelling responses to proposed measures, or planning monitoring campaigns to obtain as much information as possible at the lowest cost.

Despite the numerous challenges encountered, the dataset and analytical approach proved effective.

The data and methods used show that hydrological conditions have a major influence on surface water quality. Summer drought episodes significantly increase phosphorus concentrations, with a greater effect in small streams than in large rivers with extensive catchments. Slight to moderate increases in discharge are associated with higher nitrate concentrations, particularly in winter, but only in catchments with a substantial proportion of arable land; concentrations remain constant in catchments without arable land. Concentrations of PAHs increase very sharply at high to extreme flows. Pesticides warrant a separate, more detailed investigation.

The simple visualizations demonstrate clear relationships for both nutrients and other parameters. Future research should focus on additional or more precise catchment characteristics (e.g. population and connection to public sewerage systems rather than the crude proportion of built-up land) and investigate other parameters in greater detail – particularly pesticides and pharmaceuticals – where sufficient measurements are available under a range of conditions.

Acknowledgements

This article was produced as part of Technology Agency of the Czech Republic project No. SS02030040, Prediction, Assessment and Research into the Sensitivity of Selected Systems and the Effects of Drought and Climate Change in Czechia (https://www.perun-klima.cz/). We thank the River Basin Authorities and the Czech Hydrometeorological Institute for providing the data.

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The Czech version of this article was peer-reviewed, the English version was translated from the Czech original by Environmental Translation Ltd.

DOI: 10.46555/VTEI.2026.05.004

ISSN 0322-8916 (print), ISSN 1805-6555 (on-line).

Predicting effluent BOD_5 in wastewater treatment using machine learning

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Keywords: Biochemical Oxygen Demand (BOD_5) — wastewater treatment — machine learning — soft sensor — XGBoost — BOD_5 prediction — process optimization

ABSTRACT

Accurate and quick prediction of effluent Biochemical Oxygen Demand (BOD_5) is important for maintaining regulatory standards and improving the operation of wastewater treatment (WWT) plants. Traditional laboratory tests for BOD_5 take several days, causing delays in assessing water quality and adjusting plant performance. To overcome this issue, this study develops a machine learning model to estimate effluent BOD_5 using easily available plant data. A dataset from a large-scale wastewater treatment plant was used, comprising 12 variables from both influent and effluent data, such as pH, Chemical Oxygen Demand (COD), conductivity, Total Suspended Solids (TSS), BOD_5, and temperature, with effluent BOD_5 as the target variable. The data were cleaned and processed using the Interquartile Range (IQR) method to remove outliers, and new features were created to better reflect process behavior. Among several tested models, XGBoost showed the best performance, achieving an R^2 of 0.9695 and a Mean Squared Error (MSE) of 0.05, based on a time-based train/test split (80 % / 20 %). The study demonstrates that machine learning can serve as a powerful predictive tool for BOD_5 estimation, significantly reducing the five-day analytical lag of laboratory testing and supporting faster, data-driven decision-making in WWT management.

INTRODUCTION

The proper management and treatment of municipal and industrial wastewater are essential to preserve water resources and protect human and ecosystem health. Among the various parameters used to evaluate effluent quality, the Five-Day Biochemical Oxygen Demand (BOD_5) is one of the most widely adopted indicators. It reflects the amount of oxygen required by microorganisms to biologically decompose organic pollutants in water over a five-day period [1]. Because BOD_5 provides a direct measure of biodegradable organic load, it serves as a critical benchmark for assessing treatment efficiency and environmental impact. Consequently, regulatory authorities across the globe have established strict discharge limits to maintain acceptable BOD_5 levels in treated effluents [2].

Despite its importance, the conventional BOD_5 test has significant limitations. The standard method requires a five-day incubation period, delaying feedback on treatment performance and limiting the ability to make timely operational decisions [3]. Moreover, factors such as sample toxicity, nitrification effects, variability in microbial seeding, and preservation challenges can compromise measurement accuracy and reproducibility [4–7]. These drawbacks highlight the need for rapid, reliable, and continuous BOD_5 estimation methods.

Machine learning (ML) and soft-sensor modeling have emerged as effective tools for rapid BOD_5 estimation, enabling predictions from routinely measured operational parameters such as COD, pH, conductivity, temperature, and TSS [8, 9]. Unlike empirical or deterministic models [7, 8], which often fail under variable conditions due to the complex biochemical and hydrodynamic processes in full-scale wastewater treatment plants (WWTPs) [10, 11], ML approaches can capture nonlinear interactions and system dynamics, supporting proactive process control, early anomaly detection, and more sustainable plant operation.

Recent studies show that modern machine-learning methods can achieve very strong predictive performance for BOD_5 and other water-quality parameters. For example, Dantas et al. [12] demonstrated that artificial neural networks (ANN), which are computational models inspired by the way biological neurons process information, perform well when forecasting BOD_5 and COD in full-scale treatment plants. Zhang et al. [13] used a Random Forest model, an ensemble of many decision trees that collectively improve prediction accuracy, to estimate BOD_5 in river water, achieving an R^2 of approximately 0.89. Jafar et al. (2022) [14] employed deep neural networks (DNN), a more complex form of neural-network architecture capable of capturing highly non-linear relationships and reported R^2 values between 0.89 and 0.93. Other studies have shown comparable results: XGBoost (short for Extreme Gradient Boosting) models, which use gradient-boosted decision trees, have reached R^2 values around 0.92 in ecological applications [15], while RVFL (Random Vector Functional Link) networks have achieved $R^2 \approx 0.924$ in WWTP settings [16]. In contrast, simpler models often provide lower accuracy. For instance, Ali et al. [17] reported an R^2 of about 0.88 using CatBoost (Categorical Boosting), which efficiently handles categorical and numerical data with minimal preprocessing. It should be noted that linear regression models are not robust under varying wastewater treatment conditions, as they often fail to capture non-linear interactions and complex system dynamics [18].

Accurate and timely estimation of the biochemical oxygen demand (BOD_5) remains a persistent challenge in WWT, as traditional laboratory analyses require a five-day incubation period. This inherent delay limits the speed of process evaluation and prevents proactive operational control. To address this challenge, this study proposes a predictive framework leveraging the XGBoost algorithm, selected for its superior ability to handle high-dimensional data and non-linear relationships. By integrating a robust data-driven methodology with domain-informed feature engineering, the model seeks to accurately capture the complex dynamics of the treatment process under realistic operating conditions. The primary objective of this work is to provide a reliable alternative for rapidly assessing wastewater quality, thereby facilitating faster decision-making and enhancing wastewater management response. The following sections detail the methodology and model development process used to achieve these objectives.

METHODOLOGY AND MODEL DEVELOPMENT

Presentation site and data collection, area characteristics

The dataset used in this study was collected from the municipal wastewater treatment plant (WWTP) of Skikda Province, located in north-eastern Algeria (36.89°N, 7.01°E). The facility operates a medium-load activated sludge process designed to handle variable organic loads from domestic and municipal sources. The plant has a design capacity of 46,000 m^3/day and serves approximately 279,700 population equivalents.

The treatment process includes preliminary screening, grit removal, primary sedimentation, biological oxidation in aeration tanks, secondary clarification, and final disinfection (see *Fig. 2*). The system is designed for an average influent BOD_5 load of about 280 mg/L, corresponding to 14,950 kg of BOD_5 per day, 34,383 kg of COD per day, and 17,250 kg of suspended solids (TSS) per day.

Treated effluent is discharged into the Oued Safsaf River, a sensitive water body that plays an important ecological role in the region. The produced excess sludge is dewatered and reused as an agricultural fertilizer, which highlights the need for reliable effluent quality control. Incomplete organic removal increases the amount of residual biodegradable matter, raising the moisture content and hindering drying, thereby reducing the quality of the final biosolid product.

Samples used in this study (2015–2024) were digitized from the WWTP's historical archives. The dataset represents continuous monitoring of influent and effluent streams across all 12 months of each year. The monitored parameters included biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), pH, temperature, Electrical Conductivity, and dissolved oxygen (DO). All analyses were performed in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2017) [4].

Workflow and modeling strategy

This section delineates the development of a high-accuracy model for predicting effluent BOD_5 in a WWTP. The approach uses real operational dataset we applied the XGBoost algorithm to optimize performance.

Domain-informed feature engineering was applied to enhance model accuracy, and a time-based train/test split (80 % / 20 %) ensured realistic evaluation. The pipeline includes data preprocessing (handling missing values and removing outliers), feature creation, model training, and evaluation using R^2, MSE, and MAE. *Fig. 1* illustrates the complete workflow, from raw data to final prediction, highlighting a data-driven framework for effluent BOD_5 estimation.

Data collection, cleaning, and preprocessing

Data collection and initial screening

The dataset spans nine years (2015–2024) and includes 410 valid records, corresponding to an average of (3–4) measurements per month due to irregular sampling frequency. Each record contains 15 operational parameters measured at both the influent (inlet) and effluent (outlet) of the treatment process. These variables were selected based on their relevance to biological treatment performance and the availability of consistent data.

Tab. 1. Water treatment process monitoring data

Features	Unit	Inflow	Outflow
Date	dd/mm/yy	Date	Date
Potential of hydrogen (pH)	-	pH_int	pH_out
Biochemical Oxygen Demand at 5 days (BOD_5)	mg/L	BOD_5_int	BOD_5_out
Chemical Oxygen Demand (COD)	mg/L	COD_int	COD_out
Electrical Conductivity	µS/cm	Cond_int	Cond_out
Total Suspended Solids (TSS)	mg/L	TSS_int	TSS_out
Temperature (T)	°C	Temp_int	Temp_out
Dissolved Oxygen (DO)	mg/L	O_2_int	O_2_out

BOD_5_out was selected as the target variable because it is the primary measure of wastewater quality. The standard 5-day test is considered too slow for active management; however, rapid estimation is facilitated by predictive modeling compared to conventional measurement methods. This allows problems to be caught early and the plant to be run more efficiently.

Fig. 2 illustrates the temporal trends for influent and effluent BOD_5 concentrations between 2015 and 2025. While influent levels (BOD_5_int, blue) show significant volatility, peaking during 2017–2018 due to seasonal factors or hydraulic surges, the effluent levels (BOD_5_out, green) remain stable and low from 2019 onward. This stability confirms consistent treatment efficacy despite variable influent loads. Data gaps in 2016, 2018, and 2022 resulting from sensor or logging issues were managed during the preprocessing phase.

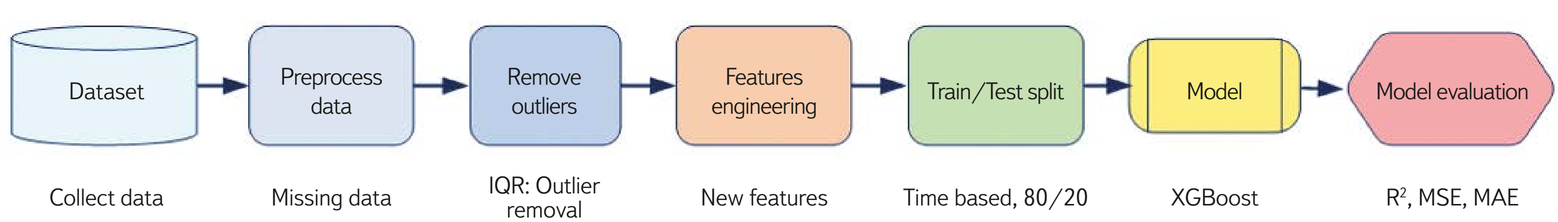

Fig. 1. Flowchart of the modeling pipeline for predicting effluent BOD_5

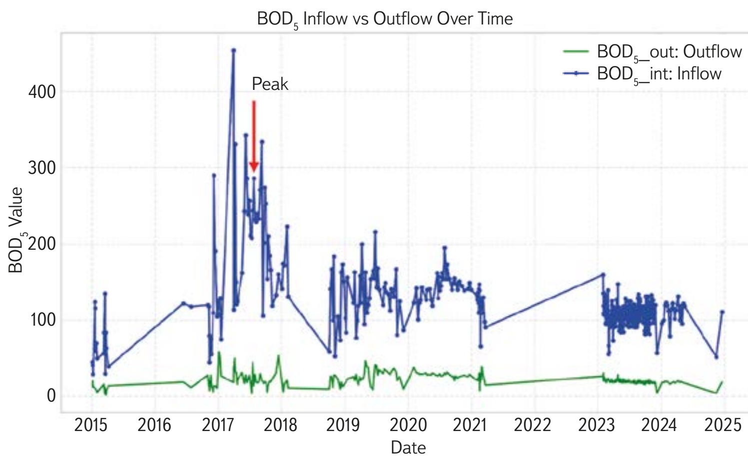

Fig. 2. Time series of BOD_5 inflow and outflow showing consistent treatment performance despite significant fluctuations

Fig. 3 illustrates the relationship between influent and effluent BOD_5 values, highlighting the overall removal performance of the treatment system across a wide range of influent loads. A dense cluster of data points, where influent BOD_5 ranges from 80 to 180 mg/L and effluent concentrations remain between 10 and 47 mg/L, indicates consistent and effective organic load reduction across operational cycles. This corresponds to an estimated removal efficiency of approximately 74–88 %, as illustrated in *Fig. 3* by the region bounded between the lines (y = 0,26x) and (y = 0,12x), which represent 74 % and 88 % removal, respectively. Notably, the majority of effluent BOD_5 values remain below the regulatory discharge limit of 35 mg/L, in accordance with the discharge limits established by Algerian environmental regulations [19]. The observed non-linear distribution reflects the inherent complexity of biological treatment processes, thereby supporting the application of advanced machine learning approaches for performance modeling. As shown in *Fig. 3*, several isolated data points deviate from the main cluster, exhibiting relatively high effluent BOD_5 concentrations despite moderate influent loads. These deviations are not random but likely correspond to transient operational disturbances, such as temperature fluctuations or hydraulic shocks (sudden increases in flow rate or organic loading), that affect microbial activity and treatment efficiency. They may also reflect measurement errors or temporary equipment malfunctions. Confirming the exact cause of these events is challenging, however, due to the absence of supplementary data such as detailed flow rates, rainfall records, ambient temperature, or on-site operational logs. Despite this limitation, the presence of such anomalies underscores the importance of rigorous data preprocessing, particularly for effluent BOD_5. It also highlights the need for adaptive modeling strategies capable of maintaining predictive accuracy under variable and non-ideal operating conditions.

The BOD_5_int and BOD_5_out histograms in *Fig. 4* show right-skewed distributions, with most values clustered around central peaks (e.g. ~200 mg/L for BOD_5_int) and a few high values extending to the right (> 400 mg/L). These extremes are not necessarily errors; they may reflect real events like industrial discharges or stormwater inflows. However, they require careful handling during preprocessing stage, since they can distort model training and affect its accuracy and credibility. A balanced approach was used: extreme values linked to actual disturbances were retained; isolated outliers were removed to ensure data quality.

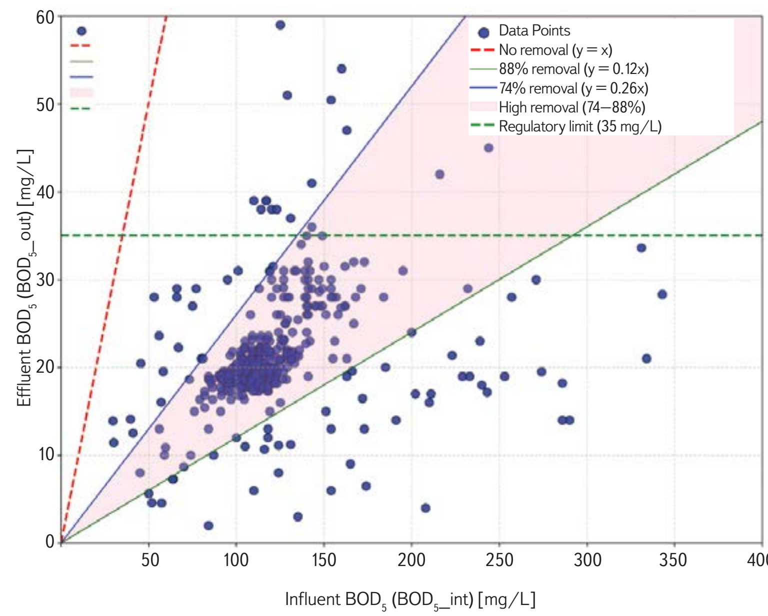

Fig. 3. Scatter plot of effluent versus influent BOD_5

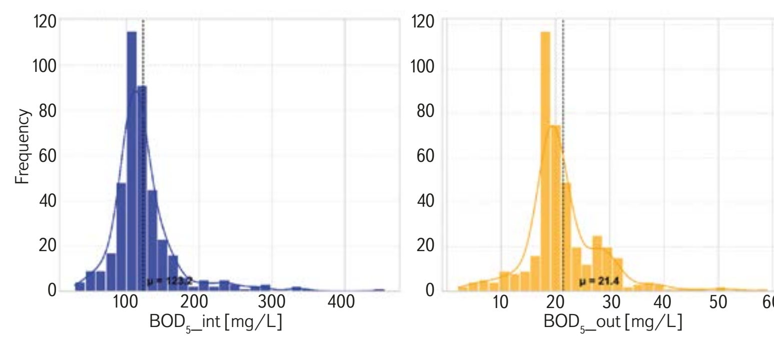

Fig. 4. Distribution of influent and effluent BOD_5 values between 2015 and 2024; there is a clustering around central values with right-skewed tails, which indicates the occurrence of rare, high-load events

Data preprocessing

Raw data exhibited missing values, inconsistencies, and outliers due to measurement and logging issues. A structured preprocessing pipeline was applied to enhance data quality, covering missing data treatment, outlier detection, and temporal alignment.

Handling missing data

The initial examination of the dataset revealed that missing values were represented by the symbol '/', particularly in the dissolved oxygen variables (O_2_int and O_2_out). More than 62 % of the observations in these columns were missing, likely due to sensor downtime, maintenance activities, or intermittent data recording issues, rendering them unsuitable for reliable modeling. Keeping such variables would introduce significant bias or require heavy imputation, potentially distorting the true process behavior. Therefore, to preserve data integrity, both variables were removed from the analysis.

After replacing all '/' entries with NaN and converting the remaining inlet (int) and outlet (out) measurements to numeric format, the other variables (pH, BOD_5, COD, TSS, temperature, and the recording date) were found to be complete with no missing values. It is evident that the number of variables has been reduced from 15 (the sampling date, 7 influent variables, and 7 effluent variables, as listed in *Tab. 1*) to 13 following the exclusion of Dissolved Oxygen (DO) from both the influent and effluent data. Moreover, no missing values were identified that required imputation. These predictors were therefore used directly in the modeling process.

It should be emphasized that dissolved oxygen (DO) is a fundamental operational parameter in activated sludge systems, as it directly governs microbial activity and nitrification efficiency [11]. Its exclusion from the present analysis was driven by substantial data loss exceeding 60 %, rather than by any diminished relevance of (DO) to the underlying treatment processes.

Outlier detection and removal

Outliers in the target variable, effluent BOD_5 (BOD_5_out), were identified using the Inter-Quartile Range (IQR) method, a robust statistical approach commonly applied in environmental data analysis [20]. The IQR is defined as:

$$IQR = Q_3 - Q_1 \quad (1)$$

where:

Q_1 and Q_3 represent the 25th and 75th percentiles, respectively.

Observations outside the following bounds were considered outliers:

$$\text{Lower Bound} = Q_1 - 1.5 \times \text{IQR} \quad (2)$$
$$\text{Upper Bound} = Q_3 + 1.5 \times \text{IQR} \quad (3)$$

For BOD_5_out, Q_1 = 18.18 mg/L and Q_3 = 28.63 mg/L, yielding an *IQR* of 10.45 mg/L. Accordingly, the lower and upper thresholds were calculated to be 2.50 mg/L and 44.30 mg/L, respectively. Applying this criterion resulted in the removal of 53 extreme observations, including unusually high values (e.g., 59 mg/L) that were likely attributable to measurement errors or occasional process disturbances. This reduced the dataset from 410 to 357 samples.

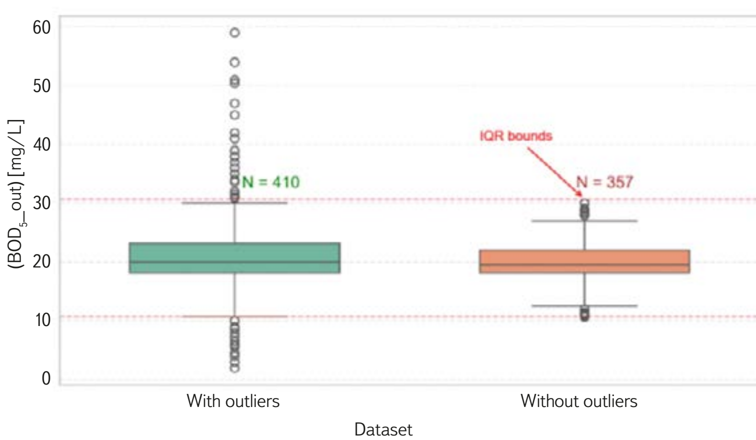

Fig. 5. Box plot comparison of BOD_5_out before and after outlier filtering

Next, rows containing missing values in either the target variable or key predictors were excluded. The final curated dataset for modeling consisted of N = 357 complete samples. As shown in *Fig. 5*, these preprocessing steps improved the symmetry and reduced the spread of the distribution, thereby strengthening the robustness and generalizability of the predictive models.

Temporal Alignment of Data

The data column was parsed into a datetime format and used to sort the dataset chronologically. This approach was adopted to ensure the preservation of temporal dependencies, thereby facilitating the validation of the model's realism.

Feature expansion and target selection for improved prediction

When developing the machine learning model, it became apparent that the initial dataset contained insufficient features to achieve high predictive accuracy. To address this limitation, we expanded the feature space through targeted engineering, carefully selecting the most relevant input and output features. This section outlines the process of generating new features and defining the target variable to improve model performance.

Selection of feature and target variable

In predictive modelling, all available system parameters may be considered as candidate inputs, but not all contribute equally to performance. Selecting and engineering informative features is therefore essential, as irrelevant variables can reduce accuracy [21]. To improve predictive capacity, the effluent outlet parameters were also integrated as inputs, a strategy shown to enhance accuracy in similar applications.

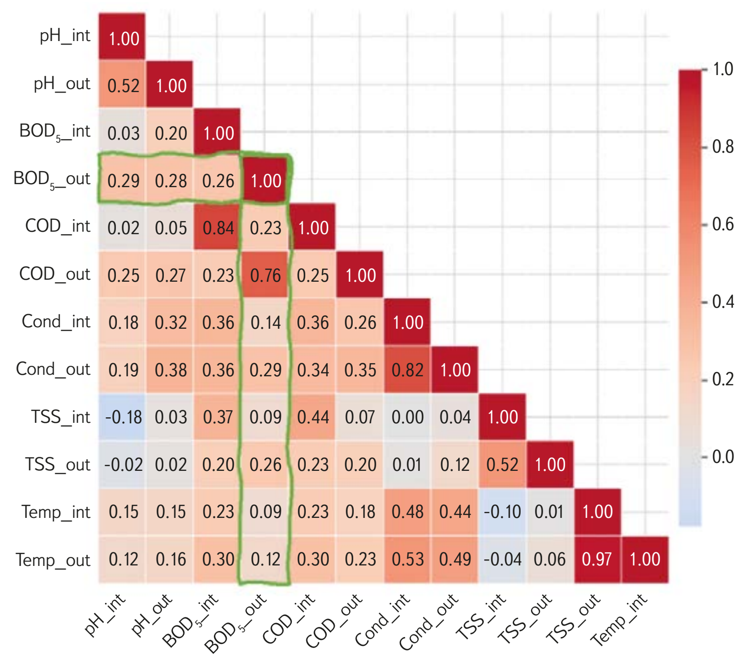

Fig. 6. Pearson correlation matrix

Fig. 6 displays the Pearson correlation matrix, showing the linear relationships among operational variables in the dataset. Strong positive correlations (red) indicate variables that increase together (e.g., COD_int and BOD_5_int), while negative correlations (blue) show opposite trends. As expected, influent BOD_5 and COD display a strong positive correlation (r = 0.84), and effluent BOD_5 and COD are also highly correlated (r = 0.76). Temperature and TSS_int show weak correlations with other variables, suggesting they have little impact on short-term BOD_5 changes. Temperature (Temp_int, Temp_out) and suspended solids (TSS_int) exhibit weak correlations with the remaining features (*Fig. 6*). However, these variables were retained to capture subtle influences on biological oxygen demand (BOD_5) and enhance model precision. This brings the total feature count to 13 variables for the final model architecture.

Feature engineering: creating new predictive input

Feature engineering transforms raw data into informative variables that enhance model interpretability, predictive performance, and generalization [20, 21]. Guided by WWT principles, domain-informed features were derived to better capture treatment dynamics. Six additional features were engineered: removal efficiencies, ratios, and rate-of-change indicators. This expanded the initial 13-variable set to a total of 18 variables, excluding the sampling date. Preliminary evaluation confirmed that these domain-specific variables improved model accuracy, particularly for process control tasks. All engineered features are summarized in *Tab. 2,* including their mathematical definitions and physical interpretations. Each feature was validated for physical plausibility and analyzed for its correlation with the target variable, BOD_5_out.

Tab. 2. Engineered features and their mathematical descriptions

Engineered Feature	Formula		Notes
COD_removal_eff	$\frac{COD\_int - COD\_out}{COD\_int}$	(4)	Efficiency of COD removal; higher values mean better pollutant reduction.
pH_change	$pH\_out - pH\_int$	(5)	Difference in pH between influent and effluent, showing neutralization effects.
COD_BOD_5_ratio_int	$\frac{COD\_int}{BOD_5\_int}$	(6)	COD/BOD5 ratio at the inlet; high values indicate low biodegradability.
COD_out_BOD_5_int_ratio	$\frac{COD\_out}{BOD_5\_int}$	(7)	The COD/BOD_5 outlet/inlet ratio indicates how treatment affects biodegradability and how much pollution remains compared to the input.
BOD_5_int_pH_int	$BOD_5\_int \times ph\_int$	(8)	Models how pH levels influence the ability of bacteria to break down organic matter (BOD5).
Cond_ratio	$\frac{Cond\_out - Cond\_int}{Cond\_int}$	(9)	The total increase or decrease in conductivity (Cond_int, Cond_out) from inlet to outlet.

Train/test split strategy

Because the dataset spans nearly a decade (2015–2024) and contains sequential time-stamped measurements, a time-based train/test split was applied to preserve temporal order and prevent data leakage. Unlike random splitting, which risks introducing temporal bias by allowing future data to influence training, this approach chronologically allocated the first 80 % of samples (286 observations, January 2015–December 2022) for training/validation and the remaining 20 % (71 observations, January 2023-May 2024) for testing, thereby simulating real-world deployment where models are trained on historical data evaluated on feature periods [22, 23].

This approach evaluates the model under realistic forecasting conditions that capture both seasonal variation and long-term operational trends. The performance metrics used in this study, including R^2 (which indicates how much of the variability in effluent BOD_5 the model can explain), MSE (which highlights the presence of large prediction errors), and MAE (which reflects the average deviation between predicted and measured values), therefore provide a meaningful picture of the model's true predictive ability. By strictly separating the test data from the training and tuning phases, the evaluation remains unbiased and representative of real-world deployment.

Selected model: XGBoost architecture and hyperparameters

XGBoost (Extreme Gradient Boosting) was selected for its high computational efficiency and superior performance in handling non-linear biological data. It is a highly optimized implementation of gradient boosting that combines decision trees in an additive manner, using gradient descent to minimize prediction error. It enhances training efficiency and model performance through:

- Second-order gradients (Hessian-based optimization), enabling faster convergence,
- Built-in L1 (Lasso) and L2 (Ridge) regularization to control complexity and reduce overfitting,
- Column and row subsampling to improve generalization.

Due to its robustness, speed, and high predictive accuracy, XGBoost has become a leading algorithm in machine learning competitions (e.g., Kaggle) and real-world applications across engineering, finance, and environmental sciences [24–25].

In this study, the XGBoost model was trained using the following hyperparameters:

- n_estimators = 200: number of boosting rounds (trees),
- learning_rate = 0.05: step size shrinkage to prevent overfitting,
- max_depth = 5: limits tree depth to balance model flexibility and interpretability,
- subsample = 0.8: uses 80 % of samples per tree to introduce randomness and improve robustness,
- colsample_bytree = 0.8: randomly selects 80 % of features at each split, enhancing diversity,
- reg_alpha = 0.1, reg_lambda = 0.1: applies mild L1 and L2 regularization to penalize large coefficients.

These parameters were selected based on prior experimentation and align with best practices for regression tasks. The model was implemented using the xgboost Python library (version 1.7.6).

Performance evaluation metrics

The predictive performance of the models was assessed using three standard regression metrics: Mean Absolute Error (MAE), Mean Squared Error (MSE), and the Coefficient of Determination (R^2). The mathematical definitions are as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |y_i - \hat{y}_i| \qquad (10)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad (11)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2} \quad (12)$$

where:

- y_i is the observed BOD^5_out value
- $\hat{y}_i$ the predicted value
- $\bar{y}_i$ the mean of the observed values
- n the number of samples in the test set

MAE measures the average magnitude of prediction errors, treating all deviations equally and providing a clear and intuitive indicator of overall accuracy. It is widely used for its interpretability, particularly in environmental and geospatial modeling. MSE, by squaring each error before averaging, assigns greater weight to large deviations, making it effective for detecting models prone to producing substantial outliers [26]. R^2 complements these metrics by indicating the proportion of variance in the target variable explained by the model, a value close to 1 reflects a strong fit, whereas lower values indicate weaker explanatory capability. All performance metrics were calculated on the held-out test set (January 2023–May 2024), ensuring an unbiased assessment of the model's generalization ability.

RESULTS AND DISCUSSION

This section presents the performance of the individual base models and the stacked ensemble in predicting effluent BOD_5 (BOD_5_out). The analysis includes quantitative results, visualizations, and contextual interpretation to highlight the model's accuracy, robustness, and practical relevance.

Model performance analysis

The predictive performance of the XGBoost model was evaluated after rigorous data cleaning and feature engineering. From the initial dataset, 357 high-quality samples remained for analysis, which were partitioned into a training set (n = 286) and a test set (n = 71).

The model was constructed using 18 features, comprising both raw sensor measurements and engineered indicators such as removal efficiencies and COD/BOD_5 ratios. Of these, 17 features served as input variables, including 11 original influent and effluent parameters and 6 engineered variables. The remaining variable (BOD_5_out) was designated as the target output. Performance metrics for the test dataset are summarized in *Tab. 3*.

The results demonstrate a high degree of predictive accuracy. An R^2 of 96.95 % suggests that the model effectively captures the non-linear dynamics of the treatment process. The low MAE (0.146) is particularly significant, as it indicates that the model's average prediction error is negligible relative to the regulatory limits of BOD_5.

Tab. 3. XGBoost performance metrics for BOD5 prediction

Metric	Value
Mean Squared Error (MSE)	0.05
Mean Absolute Error (MAE)	0.146
Coefficient of Determination (R^2)	**96.95 %**

Fig. 7 shows the close alignment between actual and predicted BOD_5 levels. The model accurately tracks both stable periods and fluctuations, maintaining high precision even during high-load events. This performance exceeds results in previous studies [13–16]. Additionally, our use of time-based validation ensures the model is reliable for real-world operations and free from data leakage.

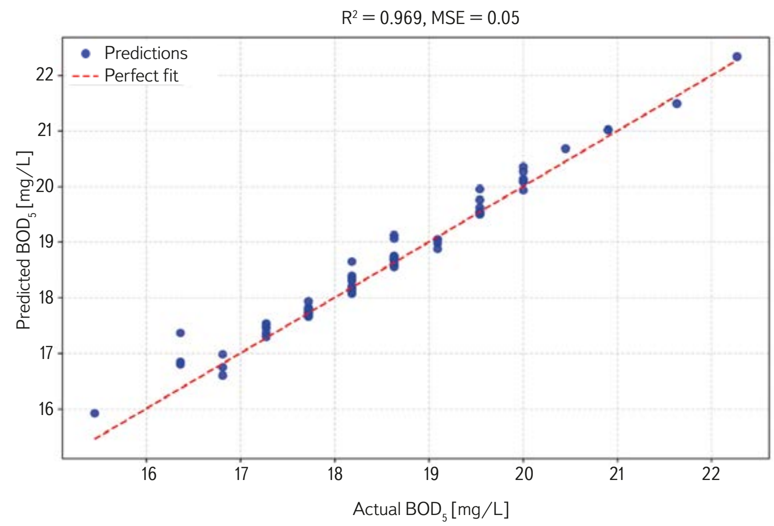

Fig. 7. Actual vs. predicted BOD_5_out values; the red dashed line represents perfect prediction (y = x)

Feature importance and process insights

The inclusion of a total of 17 features was pivotal to the model's success. Specifically, the integration of domain-informed features, such as COD_removal_eff, COD_out_BOD5_int_ratio, BOD5_int_x_pH and the net change in conductivity Cond_ratio, (equation 4, 7, 8 and 9 in *Tab. 2*), provided the model with deeper context regarding the biological health of the system. The low MSE (0.05) further confirms the model's stability, showing that it does not produce large, erratic errors (outliers).

This robustness is critical for dependable monitoring under operational conditions, as it allows plant operators to trust the predicted effluent values for proactive process adjustments.

Temporal prediction accuracy

Fig. 8 illustrates the temporal evolution of actual versus predicted BOD_5 over the test period. The model accurately tracks the dynamic behavior of the treatment process, including short-term spikes and gradual trends. Despite minor fluctuations, the model swiftly recovers and continues to provide precise tracking. Residual analysis further confirms stable performance. As shown in *Fig. 9*, residuals are randomly distributed around zero, with no visible trend or increasing variance over time. This indicates homoscedastic errors and the absence of structural bias, both of which are essential properties for reliable deployment in real-world monitoring systems.

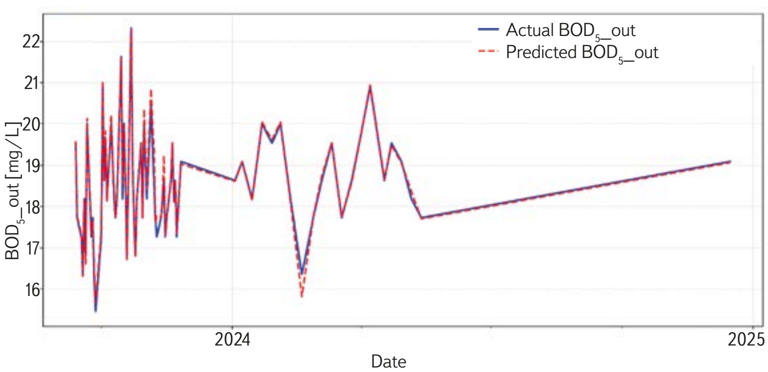

Fig. 8. Temporal comparison of actual and predicted effluent BOD_5 over the test period

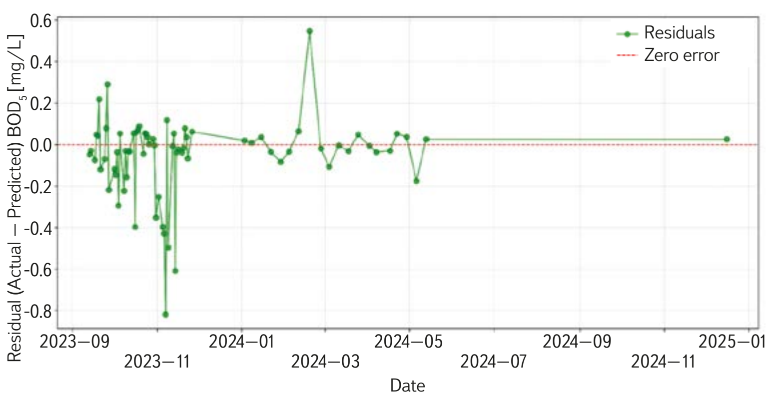

Fig. 9. Residuals over the test period; errors are centered around zero, with no systematic drift

Comparison with literature

Tab. 4 compares the performance of this study with recent works on BOD_5/COD prediction in WWTPs. Our model outperforms several existing approaches in terms of R^2. Notably, many previous studies used random train/test splits, which may lead to inflated performance estimates due to temporal leakage. In contrast, this study employs a strict chronological split (80 % / 20 %), preserving the time-series nature of the data and ensuring its generalizability under real deployment scenarios. In contrast, our model provides high accuracy while using strict validation procedures and ensuring full reproducibility.

Tab. 4. Comparative performance of BOD_5 prediction models in recent literature

Study	**Method**	**R^2 [%]**
Zhang et al. (2025) [13]	Random Forest	~89 %
Jafar et al. (2022) [14]	Deep Neural Network	89–93 %
Sethy et al. (2025) [15]	XGBoost	~93 %
Ali et al. (2025) [17]	CatBoost	~88 %
This study	XGBoost (time-split)	**96.95 %**

Generalizability and transferability considerations

Despite the strong performance achieved at the study site (R^2 = 0.9695), the model's applicability beyond this context remains constrained by its reliance on site-specific training data. Predictive performance is strongly influenced by local influent characteristics, operational conditions, and environmental factors embedded in the training dataset. Consequently, reliable performance is expected primarily for facilities with similar process configurations and operating regimes.

Factors limiting the model's transferability include variations in influent composition, hydraulic loading, and process design (e.g., aeration strategy, sludge age, and nutrient removal stages), as well as regional conditions such as climate variability and industrial discharge profiles. Applying the model to plants with substantially different characteristics without recalibration may result in reduced accuracy or increased uncertainty. Additionally, the model is primarily suitable for medium-load operations and may not be directly applicable to low-load treatment plants.

Future work should focus on multi-site validation and the integration of domain adaptation or transfer learning techniques to enhance model robustness and enable broader deployment across diverse wastewater treatment systems.

CONCLUSION

This study demonstrates that a standalone XGBoost model can achieve highly accurate prediction of effluent BOD_5 (BOD_5_out) using nearly a decade of operational data (2015–2024) from a full-scale WWTP. With an R^2 of 96.95 %, MSE of 0.05, and MAE of 0.146 mg/L on a chronologically held-out test set, the model delivers exceptional performance while avoiding the complexity of ensemble fusion strategies.

Crucially, this level of accuracy was achieved through a combination of domain-informed feature engineering, including COD removal efficiency, pH variation, and COD/BOD_5 ratios, together with rigorous time-based validation that ensures realistic evaluation under forecasting conditions.

Despite the absence of dissolved oxygen from the dataset, the model maintained strong predictive performance, indicating that routinely monitored variables such as effluent COD, conductivity, and influent pH captured sufficient information about process conditions and biological activity. Consequently, while the fundamental importance of DO in treatment kinetics remains undisputed, these findings indicate that highly correlated operational parameters can partially mitigate the absence of direct DO measurements in predictive modeling.

More importantly, the model acts as a practical sensor, providing nearly instantaneous estimates of BOD_5 from direct measurements. By replacing the 5-day laboratory delay with instant predictions, it turns BOD_5 from a static compliance value into a useful control variable. This allows:

- Early detection of process upsets: Continuous BOD_5 prediction enables early detection of abnormal biological performance caused by load variations or hydraulic disturbances, allowing timely operational interventions before effluent quality deteriorates.
- Optimization of aeration energy use: Predicted BOD_5 allows for precise aeration control, ensuring oxygen supply matches organic load. This eliminates energy waste from over-aeration while maintaining high process performance.
- Proactive adjustments to maintain regulatory compliance: Anticipatory BOD_5 forecasting enables preventive operational adjustments when predicted values approach discharge limits. This ensures consistent regulatory compliance, thereby avoiding heavy fines as well as environmental and economic damage.

In summary, this study shows that a straightforward model can still achieve excellent accuracy. With proper data handling and domain knowledge, a tuned XGBoost model can equal or surpass more complex methods while remaining faster, easier to interpret, and simpler to deploy. This makes it a strong option for scalable wastewater management applications.

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This paper has been peer-reviewed.

DOI: 10.46555/VTEI.2026.05.003

ISSN 0322-8916/


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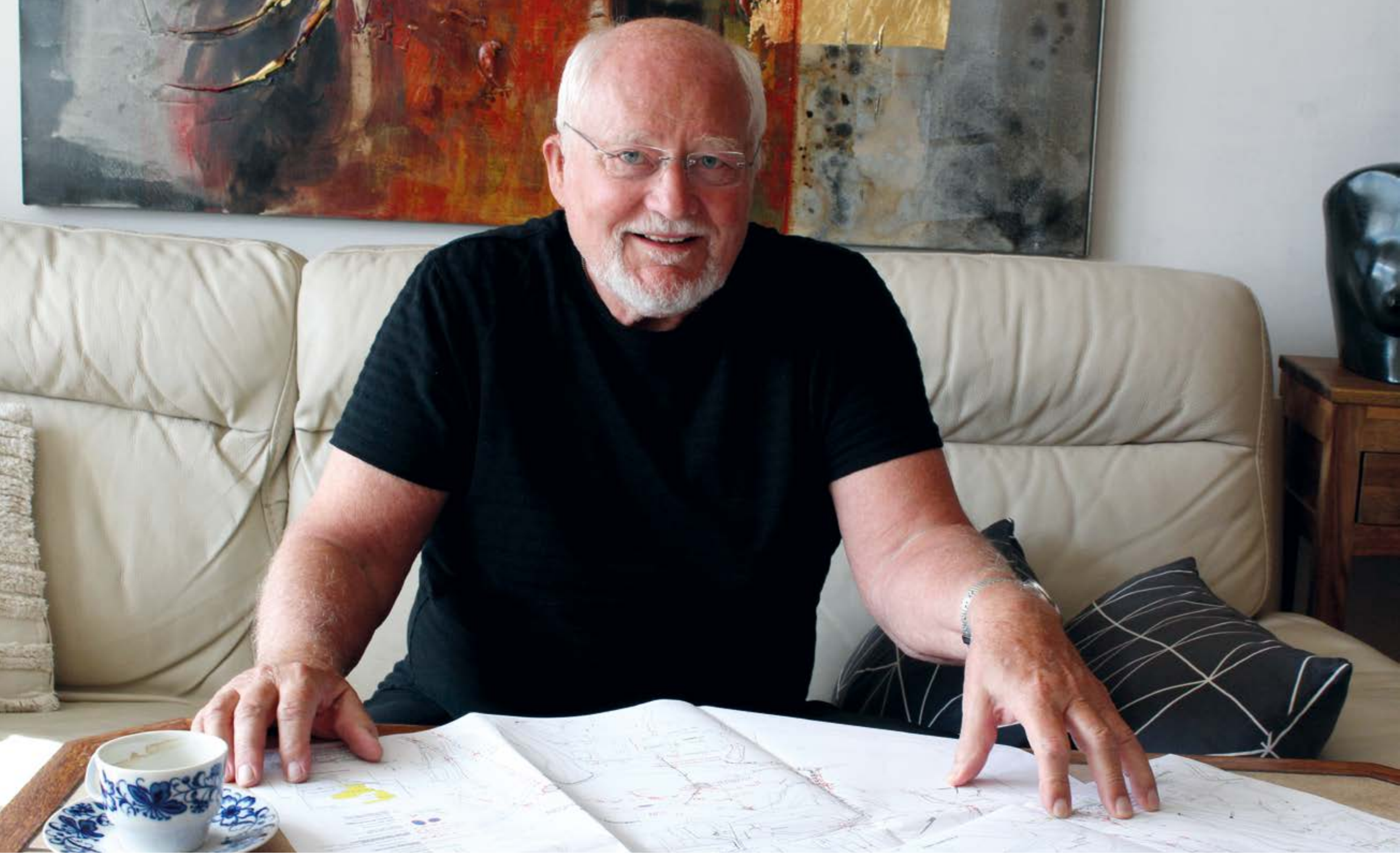

Interview with Ing. Jiří Jílek, design and hydraulic engineer

Ing. Jiří Jílek is one of the leading figures in Czech hydraulic engineering. Throughout his professional career, he has designed, delivered, and supervised the construction of numerous water management projects, including river restoration schemes and urban water features. His work includes the system of ponds in Prague's Stromovka Park, including the unique raft connection to the island, the water feature on Letná Plain, the Braník Water Biotope, the restoration of fire ponds in Lysolaje and Dolní Chabry, the restoration of the Rokytka River and the Botič, Kunratický, Motolský, and Šárecký streams, as well as the currently ongoing project to utilise mine water on Petřín Hill. In this interview, he reflects on his experience with major engineering projects, the importance of first-hand knowledge of the site, working with stone as a construction material, and why hydraulic structures should not only be functional but also sensitively integrated into their surroundings.

Mr Jílek, about eight years ago I discovered your pond on the Lysolaje stream. What brought you to this creation and to working with water?

I come from eastern Bohemia, specifically the town of Vysoké Mýto, which is home to the country's oldest water management school. It was founded in 1897, and by 1903 it already was known as the Agricultural and Grassland Management School. Even then, it enjoyed an excellent reputation among professionals, thanks to its outstanding teachers and a wonderful community. Although I was more of a technically minded, hands-on person than an excellent student, the school was fantastic and gave me the opportunity to acquire a lot of technical knowledge.

So did you already know back then that you wanted to work with water?

After graduating from secondary school, my teacher Jiří Muzikant convinced me that I should continue my studies, so I enrolled at the Faculty of Civil Engineering at the Czech Technical University, where I studied Hydraulic Engineering and Water Management. There were experts on weirs, dams, and river engineering; thanks to them, I was able to delve deeper and deeper into the field. I think it's a fascinating discipline, one that's closely connected with both everyday life and the way our civilisation functions.

I've always been a fairly creative person, and I've never liked the idea of simply hiding behind standards and prescribed procedures. Standards are, of course, important, but every site and every project is different, and that's how they should be approached.

Fig. 1. System of interconnected ponds and water features in Stromovka Park, restored following the 2002 floods. The project included not only the restoration of the ponds, but also the rehabilitation of stream channels, culverts and pools, together with the construction of new bridges and footbridges, a duck pontoon, a raft providing access to the island, a paddling area, a central fountain jet, and the renovation of the ornamental fountain

After graduating, the choice of where to work was an easy one – I joined Hydroprojekt, which was already a major engineering company at the time, with offices across the Czech Republic and Slovakia. It brought together experts from almost every discipline, including architects, mechanical engineers, and geologists. It was there that I gained a wealth of experience that would be hard to come by today.

And this was in the eighties?

That was in 1974. Even then, I was surprised that, as a young newcomer joining such a large company, there was a noticeable gap between generations. I had just graduated, while most of my colleagues were in their fifties or older. It was quite a striking age gap for the time.

At that time, I was most interested in major water engineering projects. I joined a department that worked on all kinds of water management structures, from stream restoration and river training projects to weirs, power plants, and dams.

What was the first project you worked on?

As the youngest member of the team, I was assigned almost immediately to the Josefův Důl Dam, which is now an important water-supply reservoir. At first, I did just about everything. In those days, project teams weren't nearly as large as they are today. A project of that scale was prepared by just a handful of people, of course under the guidance of experienced specialists. I wasn't just involved in the design work; I also bound reports, ran off copies on a mimeograph machine, assembled the documentation, and generally helped put everything together. It was demanding work, but for a young engineer it was an exceptional learning experience.

Every now and then I surprised people by approaching things a little differently. For example, I used to draw reinforcement layouts as mirror images, which wasn't common practice at the time. But once my colleagues saw the technical logic behind it, they accepted the idea without hesitation.

At the time, Hydroprojekt employed specialists who each focused on a particular area of work, and it was obvious that they really knew their field. I think that's extremely important. These days, it's quite common for one person to be expected to do almost everything, but they may not have enough experience in every aspect. And it's often that lack of experience that leads to solutions which are not often the best ones.

You stayed with Hydroprojekt even after 1989. How did you eventually make the move into running your own design practice?

I stayed there until 1992. People often used to say that staff were never the problem, that you could always find people. I've always seen it differently. In my view, what really matters are people who genuinely know what they're doing. Managers can be replaced, but finding people with the skills and experience to actually deliver the work is much harder.

Around that time, environmental issues were becoming a major topic, so together with a new team that I was able to put together, we started working on landfill engineering. It was a very timely field then. Entirely new lining and sealing systems were coming from Western Europe, and standards were being developed for how landfills should be designed, built, and financed. It was a completely new body of know-how.

And was that what brought you to large-scale water engineering?

Yes, because after a while I found it all a bit repetitive. You were constantly having to explain to people that building a landfill wasn't always the best solution. Many people think it's a lucrative business, but in reality it all depends on the specific circumstances.

Gradually I lost interest. What I enjoy is creativity – having each project present a different challenge. That's exactly what river restoration offers. I much prefer complex, unconventional sites where you really have to think carefully about how to work with the landscape.

Since I have always had a strong interest in structural analysis, soil mechanics, and geology, I also carried out various remediation projects various remediation projects – not just landfill remediation, but also repairing embankments, for example where water was seeping through them. In Prague, that included sites such as Černý Most, Nové Butovice, and Čimice.

From what you're saying, it sounds as though you're still very busy. How many projects are you working on at the moment?

The demand is certainly greater than I can handle in the standard of quality that is expected – I'm not getting any younger. At the moment, I'm working on about three major projects.

Fig. 2. The romantic raft providing access to the island in one of the many ponds in Stromovka Park, one of the park's main attractions, had to be subsequently reinforced to accommodate adult visitors

And sometimes you're brought in to rescue projects…

In addition to supervising construction work, I'm often asked to step in and help fix problems I see in other people's projects after the client or contractor has become frustrated with the results and turns to me. Sometimes the solution is fairly straightforward; other times it's much more complicated.

The fact is that the technical expertise in some areas of our profession is beginning to decline. There are fewer people with the depth of practical experience. The worst answer I can hear is, *"We've always done it this way."* I don't like that approach at all, because every solution should be based on the specific site, the particular structure, and the conditions on the ground. You can't apply the same solution everywhere.

When I can see that a proposed design isn't the right one, I try to get involved and help improve it as best I can. Of course, nobody has a monopoly on good ideas, but practical experience is invaluable in this field. These days there are very few people still actively working who have been involved in several major dam projects and who also have decades of experience working with construction companies, contractors, and subcontractors.

Do you have a favourite project – one that has stayed with you over the years and that you still enjoy going back to?

Not long ago, I was travelling by train, and every time it stopped I realised how many places I'd worked in over the years. There is an incredible number of projects. But if I had to choose one, it would probably be Stromovka. At the time, I didn't really believe I'd win the competition for the project. My aim was to restore the area, which had been devastated by the 2002 floods, using natural approaches. It was an ideal place to make use of simple structures with a flexible function.

The stream Malá Říčka had been completely torn apart by the flood, and I offered to put it back together. I designed a new weir and a cascading inlet from the navigation channel, and it's become a place where people enjoy spending time. It's not a conventional design – there are no rectangles, squares, or right angles. That kind of approach is much more in keeping with nature.

The expansion of water surfaces at the former Rudolf Pond created further challenges regarding the integration of valuable areas. A significant tree left standing on a small island called for an unconventional approach; to design something interesting that would allow people to reach it by more than just a footbridge. That's how I came up with the idea of a cable-guided raft. Originally, it was meant to be supported by two large puppet figures, but that idea was eventually rejected and replaced with ordinary posts. At first, I imagined it mainly as something fun for children, but then I ran into problems because attractions like that have to meet certification requirements. In the end, following an agreement with Prague City Hall, I increased the raft's buoyancy – since adults were also riding on it – and today it serves as an operational facility.

You mentioned certification requirements. You're very much old school in the best sense of the word. Has today's bureaucracy made it harder to design and build water engineering projects than it was thirty or forty years ago?

Unfortunately, yes. We seem to want to fit everything into neat little boxes, but I don't think that's the right approach. It leads to a kind of standardisation that often does more harm than good. History shows us that the great structures built by earlier civilisations weren't based on templates – they were original solutions, created by teams of true professionals. Sadly, I think we're losing some of that professionalism today. The specialisation of construction companies in particular types of structures has practically disappeared, and this is reflected in the structures themselves.

On top of that, we're constrained by standards and regulations, leaving less and less room for independent thinking. As a result, engineers can end up assembling projects from predefined components instead of developing creative solutions.

Do you think that also has something to do with the way engineers are trained today?

One of the biggest problems, in my view, is that projects often fail to take account of all the conditions that really need to be considered. Clients can't always be expected to know exactly what they should ask for. That's why designers shouldn't just respond to a brief – they should think for themselves about what's important for the site and the project, and make sure those considerations are reflected in the design.

I don't think it's acceptable to make excuses afterwards by saying something couldn't be done, or that the client did or didn't ask for it, or that nobody knew about a particular issue. That's the wrong approach. The same applies to project documentation. We often spend a great deal of time describing things in minute detail, but not always to any real benefit. A lot of the documentation has become an administrative exercise rather than something with genuine technical value.

Fig. 3. Water reservoir in the western part of Letná Park (design proposal), showing the inlet cascade beneath a wrought-iron grille, designed to induce water circulation within the lake, which is characterised by exceptionally clear water throughout the year

Fig. 4. The Braník aquatic biotope is supplied by groundwater, which is not usual. It was created in spring 2023 not only as a new landscape feature on previously open grassland, but also, together with a short educational nature trail, as part of environmental education for the people of Prague. It is now home to hundreds of edible frogs, smooth newts, grass snakes, and 27 species of aquatic and wetland plants

Fig. 5. Revitalisation of the fire pond on the Lysolaje stream and the upper section of its channel below one of Prague's most productive springs, the so-called Miraculous Spring (Zázračná studánka). The recreational biotope is now fed by this spring, making it one of the coldest water bodies in Prague

Fig. 6. Planned comprehensive revitalisation of the now-dry pond in Jezerka Park, Nusle, including the creation of a new surface water channel and the bridging of its part beneath the piazza of the adjacent Jezerka Theatre. The project will also include an underground retention tank with a flow-regulation function, enabling the park's water features to be supplied with rainwater collected from the theatre roof even during prolonged dry periods

Do you have a trusted team of people you like to work with? I remember watching one of your excavator operators place a boulder exactly where you wanted it – it was incredible to see how skilfully and efficiently he worked.

There are plenty of contractors, of course, but not all of them have teams of operators, technicians, and labourers who are truly outstanding at what they do. Fortunately, there are still people who are exceptionally creative, highly skilled, and willing to listen and learn. I enjoy working with people like that. You can talk things through with them – they immediately understand what you're trying to achieve, what you want them to do, and why. And it doesn't matter whether they're Czech, Ukrainian, or from anywhere else. On construction sites you meet people from all kinds of backgrounds. Some are even trained engineers who eventually swapped the drawing board for heavy machinery because they found it more rewarding – and they're excellent at it.

Have you ever encountered any major technical difficulties while building water engineering structures? Is it even possible to predict everything in advance?

No, it's impossible to predict everything with complete certainty. Even with a thorough geological survey, you're still working from a series of sampling points and applying that information to a much larger area. So, on rare occasions, unexpected problems can arise. The most serious difficulty I encountered was when a flood struck a project that was still under construction; there's only so much you can do to protect against something like that. Even so, a designer should anticipate the risk as far as possible and warn the contractor where the flood hazard is greatest.

In my case, it happened during the construction of a special intake structure on the Elbe at the Opatovice Power Station. The flood virtually tore apart the unfinished section of the project. But you can insure yourself against this in advance and plan for a somewhat larger reserve.

Fig. 7. Revitalisation of the lower reach of the Kunratice stream in Braník, in Za mlýnem Park, commissioned by the Prague City Hall (construction supervision) in cooperation with the Prague 4 Municipal District. This extensive restoration project also incorporates the use of decorative boulders and large woody debris

Is there a general recipe for designing a successful river restoration project? I know, for example, that you're particularly fond of using basalt for bank protection.

I think the first step is to really get to know the place you're working with. It's not enough just to know the size of the site. You need to spend time there, get a feel for it, and only then start thinking about what should be done with the stream and the surrounding landscape so that the result is functional, interesting, and fits naturally into its surroundings.

I'm not a fan of restoration projects that amount to nothing more than a few neat little meanders cut into the channel, or that produce a straight trapezoidal watercourse or a perfectly rectangular pond. Unfortunately, you still see that kind of thing, but to me it rarely looks right. The design should always respond to the character of the landscape it's being built in.

A good example is the restoration of the village pond at Točná in Prague 12, which I'm working on at the moment. I wanted it to be more than just another ordinary pond. I used basalt not only for the bank protection but also for the footpaths, created an interesting shoreline, and gave the whole site a slightly unconventional character. When about twenty of us met there – including the director of Prague Water Supply and Sewerage – I actually received a verbal compliment. *(laughs)* That really meant a lot to me, because people often take these things for granted and don't even notice them.

I know that for the Braník Water Biotope you personally selected a particular stone from the quarry because you wanted it to catch people's eye. How important is the choice of materials to you?

That one was chert instead. When rock is blasted in a quarry, the structure of the particular stone can produce remarkably interesting and distinctive shapes, and I think those should be put to good use in the right setting. That's why I often tell contractors not to let someone simply load the stones onto the truck. We first agree on exactly where to source them, so they suit the project, or, if necessary, I'll go to the quarry and choose individual stones myself. You have to think ahead about how the stones will fit together, how the exposed faces will look, and how their colours will complement the site. Of course, to some extent, that's also a matter of personal aesthetic judgement.

The aim of water engineering isn't to transform an entire landscape. Only the part directly affected by the project should be altered. There are many different types of stone you could use, but when it comes to subtle surface textures and the way the stones fit together, basalt and chert are hard to beat. Granite is perfectly serviceable, but I don't find it nearly as interesting. Its grain size and colour vary a lot, and, more importantly, it tends to split along flat planes, producing rather blocky shapes. I've never been much of a fan of square blocks of stone.

How do you see the future of water engineering? You mentioned that even when you joined Hydroprojekt there was a significant generation gap in the profession. Do you see a new generation ready to take over?

Unfortunately, history seems to be repeating itself – we're seeing the same generation gap all over again. There simply aren't enough young engineers coming through who are ready to build on what we've done. On top of that, fewer and fewer students are choosing engineering because the courses are demanding. Another problem is that, although many technical secondary schools still culminate in the *maturita* school-leaving examination, the vocational training programmes that used to give people real hands-on skills are disappearing. And for water engineering, those practical skills are essential.

What has a career in water engineering given you – and what has it taken away?

It's work that I've genuinely enjoyed, and not everyone can say that. A lot of people go to work simply because they need a job and a salary, and sooner or later that shows in the quality of what they do. Even under the communist regime, water engineers got along well with one another. Politics didn't really come into it. What mattered was that they understood their profession. You simply can't approach work with water in a superficial way.

I also don't like hearing people say, *"If you're not earning enough, just find another job."* How can anyone become truly good at what they do if they're constantly changing jobs for a higher salary? That's not how you achieve real expertise. Money isn't everything, even though, unfortunately, it's often treated as if it were.

And what has working with water taken away? Time – above all, time. I've spent my life chasing deadlines.

Let's finish with your current project – the restoration of the pond in Jezerka Park. Are you looking forward to it, or are you expecting a few challenges along the way?

I think it's going to turn out well. Looking back, most of the projects I've worked on have been well received, and I'm confident that this restoration will benefit Jezerka too.

One of the reasons I took it on was that it isn't a routine project. It's not just about designing a channel, a path, or a single engineering structure. It's about working with both surface water and groundwater, the park landscape, and the overall character of the site. When all those elements come together, you can create something that genuinely enhances the whole area.

Of course, a lot will depend on how the project is ultimately carried out. With this kind of work, I think it's essential that the engineering, the way the water is managed, and the aesthetics all come together naturally. I'm optimistic that we'll achieve that at Jezerka.

And when you're not working with water or on a construction site, how do you like to spend your time?

I've always enjoyed being active and making things with my hands. I played volleyball for many years, and these days I enjoy skiing, although I'm a bit more careful than I used to be. Ever since I was young, I've also enjoyed working with wood, blacksmithing, sculpture, and painting. I renovated and built a substantial part of my cottage myself, with my girlfriend's help. I also handle the selection of accessories the same way. Building stairs, laying floors, or installing tiling poses no problem for me.

I think all of that has helped me as an engineer. When you've worked with materials yourself and understand how things are actually built, it's much easier to judge what's practical and what is simply a nice idea on paper that's going to be difficult to build in reality.

Thank you very much for the interview. I wish you many more original challenges and successful projects.

RNDr. Tomáš Hrdinka, Ph.D.

Ing. Jiří Jílek

Ing. Jiří Jílek was born on 6 April 1950 in Vysoké Mýto. After graduating from the Secondary Technical School of Civil Engineering in Vysoké Mýto, he continued his studies at the Czech Technical University in Prague, specialising in Water Structures and Water Management. In 1974, he joined Hydroprojekt Prague, where he worked until 1992. In the same year, he established his own licensed design practice, Hydro-Natur, followed by the engineering consultancy Ekotechnik-Inženýring, Ltd. Over the course of his career, he has designed more than 300 new water management and environmental engineering projects. He has also been involved in the repair and rehabilitation of existing structures and the remediation of unsuccessful designs prepared by others, with projects implemented throughout the Czech Republic and Slovakia. In recent years, his work has focused primarily on Prague and its surrounding area. In addition to design work, he remains actively involved in project implementation, serving as a construction supervisor. His personal interests include woodworking, craftsmanship of all kinds, the arts, travel, the history of construction and engineering, and, since 2000, renovating and maintaining a country cottage. Until the age of 65, he played volleyball competitively, and he continues to enjoy skiing. He lives in the Chodov district of Prague, is widowed, and has three children.

Photo (pp. 54–59): T. Hrdinka

Fig. 8. Revitalisation of the middle reaches of the Rokytka and Svépravický streams within the floodplain of the Čihadla dry retention basin, including the creation of flow-through pools to enhance biodiversity in aquatic and wetland habitats

VTEI/2026/4

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A scientific bimonthly journal specialising in water research. It is included in the List of peer-reviewed non-impacted periodicals published in the Czech Republic. VTEI is part of Scopus and DOAJ databases.

Volume 68

Published by: Výzkumný ústav vodohospodářský T. G. Masaryka, veřejná výzkumná instituce, Podbabská 2582/30, 160 00 Praha 6

Sources of photographs for this issue:
VÚV TGM, 123RF.com, doc. RNDr. Jan Unucka, Ph.D., RNDr. Tomáš Hrdinka, Ph.D., Mgr. Zuzana Řehořová, Milan Blšťák

Graphic design, typesetting and printing:
ABALON s. r. o., www.abalon.cz

Number of copies: 400.
Since 2022, the VTEI journal has been published in English at https://www.vtei.cz/en/

The next issue will be published in October 2026. Instructions for authors are available at www.vtei.cz

ISSN 0322-8916
ISSN 1805-6555 (on-line)
MK ČR E 6365

VTEI.cz

A SPIDER'S MISTAKE

I am very fond of the landscape and nature of the Central Bohemian Uplands, especially the area around Sloup v Čechách. Even more so, I enjoy the higher-lying Lusatian Mountains Protected Landscape Area. These are places where a photographer can set out knowing that they are unlikely to encounter another person all day. The meadows are especially beautiful in the morning, when they are still wet with dew and the sun is low enough that the droplets have not yet dried. Late summer was drawing to a close, and the season of Indian summer was just beginning. Inevitably, the air was filled with drifting gossamer and spider webs covered in dew, creating a paradise for macro photography. At first glance, however, this spider's web was clearly unusual, and it was precisely its asymmetry that caught my attention. As I adjusted my camera and searched for the best angle, I found myself wondering what could possibly have thrown the little spider so off course that it produced such an odd creation. As it happened, I had spent a long night with friends, enjoying good food and drink. Perhaps the spider had heard our singing and guitars from afar and celebrated with us until dawn. So I wasn't at all surprised that things had gone just a little "off the rails". :-)

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