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

VTEI/2025/5

TOPIC

Current studies of the Department of Hydraulics, Hydrology and Hydrogeology

60 years ago in VTEI

The text for the cover is selected with regard to some of the topics of profesional articles published in the given issue of VTEI. In this case, it is the article "Protect groundwater!" by Ing. R. Hák from KVRIS Teplice, reviewed by Dr Ing. František Slepička from TGM WRI in Prague. The article was published in issue 1 of VTEI journal in 1965.

About half of the drinking water supplied by public water mains for the needs of the population, industry, and agriculture in the North Bohemian Region is drawn from groundwater sources. At the same time, 76 % of the region's inhabitants are supplied with drinking water from public water mains, while the remaining 24 % rely on public and private wells. Whereas surface waters (streams) are becoming increasingly polluted, groundwater, with the exception of the coal basin, remains clean and so far appears to be undisturbed.

Why, then, call for the protection of groundwater? Is it not unnecessary? Groundwater represents our most valuable natural treasure. In addition to tens of millions of cubic metres of water for water supply purposes, about 30 million cubic metres of groundwater are extracted annually in the course of coal mining. Thus, the aquifers are being tapped heavily. If water were not constantly replenished by rainfall and the seepage of surface waters, groundwater reserves would soon have to be exhausted. Only as much water can be permanently abstracted as is continuously renewed.

In many areas, groundwater has been declining increasingly over the past decades. Quite exceptional conditions, of course, prevail in the North Bohemian Coal Basin itself, where coal mining has led to a substantial lowering of the groundwater table.

In addition, groundwater faces the risk of being disrupted or deteriorated in quality by wastewater that is discharged directly into streams. If one adds to this the spraying agents used in agriculture, potassium lyes, wastewater from tanneries, phenols and effluents from chemical and other factories, leaks from oil, petroleum, and petroleum pipelines, all further attempts to treat this water would be in vain.

It is now clear that water pollution represents the most severe disruption of the entire biosphere of our country to date. An essential part of water management planning is also the investigation of groundwater resources and their protection. Until now, we have limited ourselves to the search for groundwater resources and their use. Today, that is by far no longer sufficient. To what extent is groundwater replenished? How fast does it flow? In which direction? Where does it come from? To which geological layers is it confined? How much can be sustainably abstracted? How suitable is it chemically and biologically? These are questions that must be investigated comprehensively. We need reliable records on groundwater.

If, in the future, we expand certain towns or villages, or plan industrial facilities, we must know the state of groundwater in advance and take it into account. Protecting groundwater means preventing its disruption, since remediation is, in many cases, impossible.

The Ministry of Agriculture, Forestry and Water Management is preparing guidelines for the protection of groundwater, which complement the existing decree of the Minister of Health on the hygienic and anti-epidemic protection of water, no. 87/53 Coll.

From the TGM WRI archives

VTEI Editorial Office

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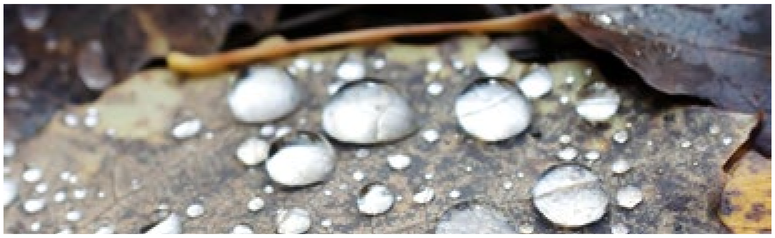
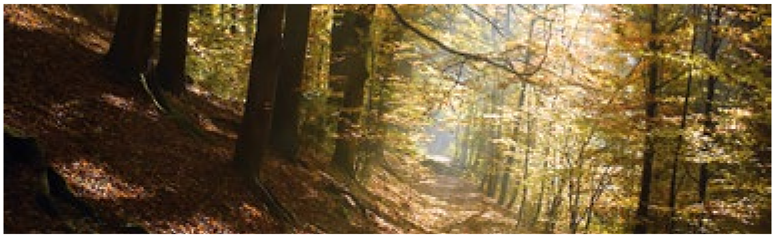
Content





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Dear Readers,

This autumn brings not only a colourful transformation of the landscape but also significant events that resonate across the water management community. Again, water management issues at this time of year receive well-deserved attention, thanks to several important meetings that underscore the significance of cross-border cooperation and interdisciplinary dialogue.

One of the most important events is undoubtedly the 2025 Magdeburg Seminar on Water Protection, focused on the management of water in the Elbe River Basin – yesterday, today, and tomorrow. Taking place in Magdeburg under the auspices of the International Commission for the Protection of the Elbe River (ICPER), the seminar provides an opportunity to review long-term efforts to improve water quality in this key European basin, while also highlighting the challenges ahead related to climate change, pollution, and growing demands on water resources.

In October, we can also look forward to the 14th Biennial Conference on Sewer Network Reconstruction and Wastewater Treatment Plants, organised by our counterparts in Slovakia. This professional forum provides an opportunity for the exchange of information and expertise among owners and operators of sewer networks and wastewater treatment plants, representatives of state and public authorities, academic and research staff, employees of design and consulting companies, and others engaged in this field.

Now a few words about the current issue of our journal, which is focused on hydraulics, hydrology, and hydrogeology. The first professional article by Anna Hrabánková and Josef V. Datel, titled "Development and current practice of groundwater balance in Czechia: from reserve classification to comprehensive assessment of natural resources" addresses the evolution of methodological approaches to groundwater balance in the Czech Republic from the 1960s to the present. In their article, the authors describe the transformation of water management balance from the original concept of a static assessment of so-called "exploitable reserves" to a comprehensive, dynamic approach based on regular comparison of actual water abstractions with natural resources over time. This approach emphasises monthly assessment intervals and the use of quantile characteristics of the base flow.

The article by Martin Vokoun, Vojtěch Moravec, and Pavel Eckhardt, titled "Dynamics of humic substances in peat habitats of Prameniště Chomutovka nature reserve" focuses on assessing the concentrations of humic substances in peatland waters of the Ore Mountains region. The aim of the research was to evaluate the impact of restoration work on the occurrence of these substances in surface and subsurface waters in areas affected by peat extraction.

In recent years, Czechia has been affected by a number of hydrological extremes of varying intensity, frequency, and spatial extent. The professional article by Veronika Táboříková and Pavel Balvín, titled "The impact of hydrological extremes on ponds and small water reservoirs" presents an assessment of ponds, pond systems, and small reservoirs in relation to the establishment and compliance with minimum residual flow, as well as the evaluation of these hydraulic structures in terms of safely conveying flood flows.

The professional article by Luděk Strouhal, Václav David, and Josef Krása, titled "Typology and effects of roads on runoff regime in protected areas" describes the principles and criteria used in designing a road network typology with regard to its influence on surface and subsurface runoff. It also presents a methodology for applying this typology in map creation, providing protected area managers with a tool to identify road sections with the greatest potential to affect hydrological regimes and serving as a basis for planning compensatory measures or restoration work in specially protected areas.

As usual, the informative section of the October issue of VTEI includes an interview, for which hydrologist Ing. Libor Elleder, Ph.D., from the CHMI, accepted the invitation. The issue is concluded by articles describing international projects launched in 2025 by the Department of Hydraulics, Hydrology, and Hydrogeology at the TGM WRI, as well as to the 21st Magdeburg Seminar on Water Protection.

On the last page, we will remember our former colleague Ing. Eduard Hanslík, CSc., who left us forever in August this year.

Thank you for your interest and support in creating a forum for professional discussion and the sharing of experiences across the entire water management sector.

VTEI Editorial Team

Development and current practice of groundwater balance in Czech Republic: from reserve classification to comprehensive assessment of natural resources

ANNA HRABÁNKOVÁ, JOSEF VOJTĚCH DATEL

Keywords: water management balance — hydrogeology — groundwater — Bohemian Cretaceous Basin — natural groundwater resources — base flow

ABSTRACT

This article presents a comprehensive overview of the evolution of methodological approaches to groundwater balance assessment in Czechoslovakia and the Czech Republic from the 1960s to the present. It outlines the transition from a static evaluation of "exploitable reserves" toward a dynamic, process-based concept, emphasizing regular comparisons between actual water abstraction and natural groundwater resources. This shift includes the adoption of monthly assessment intervals and quantile characteristics of base flow, aligning with the requirements of both national legislation (especially Act no. 254/2001 Coll., the Water Act) and European directives on water protection.

The study highlights the institutional framework and the roles of key organizations – such as the Czech Hydrometeorological Institute (CHMI), river basin management authorities, and the T. G. Masaryk Water Research Institute – in groundwater monitoring and data interpretation. A particular focus is placed on hydrogeological zoning as a key tool for spatial and balance assessments, including its historical development and relation to groundwater body delineation under the EU Water Framework Directive.

The core of the analysis is dedicated to four Upper Cretaceous hydrogeological zones (HGR 4410, 4430, 4522, and 4523) that have been consistently assessed as balance-stressed between 2007 and 2023. Long-term comparisons of base flow and abstraction data indicate a convergence trend, primarily due to declining natural recharge under changing climatic conditions. In some zones (especially HGR 4522 and 4523), excessive abstraction has contributed to negative impacts on surface water bodies, including seasonal drying, prompting regulatory responses such as reduced abstraction limits, regime-based monitoring, and mitigation measures.

The article draws on results from several ongoing research projects funded by the Technology Agency of the Czech Republic (e.g., no. SS06010268, no. SQ01010176, no. S02030027, and no. SS01010208), focusing on drought impacts, and improved delineation of hydrogeological zones, groundwater-surface water interactions, groundwater resource enhancement, and vertical stratification in groundwater flow.

The findings underscore the importance of detailed hydrogeological knowledge, continuous monitoring, periodic review of abstraction limits, and method refinement. The study concludes by stressing the need to protect infiltration areas and adopt long-term sustainable groundwater management strategies in the face of climate change and increasing anthropogenic pressures.

INTRODUCTION

This article summarises the development of groundwater balance assessment in Czechoslovakia and the Czech Republic from the 1960s to the present. It focuses on changes in approaches to evaluating the usability and balance of groundwater resources, as well as the methodological foundations and institutional frameworks that have gradually evolved in response to new knowledge, legislative changes, and the requirements of practice and European Union directives.

The text documents the beginnings of groundwater balance assessment, which were closely linked to the activities of the specialised subcommittee for groundwater within the Commission for the Classification of Deposits, where emphasis was placed on determining the so-called utilisable reserves. However, these values often did not reflect the seasonal or long-term variability of the natural regime. A significant advance came with the introduction of abstraction records in the 1970s, which enabled the compilation of regular annual balances that became part of the state water management balance.

Since the 1990s, the methodology has approached the requirement for data comparability (i.e., the comparison of actual abstractions with resources for the same period), with detailed monthly balances becoming necessary in stressed areas. The 80% quantile of base flow has become a key parameter. The text describes the current form of water management balance according to the valid Water Act and associated implementing regulations. It distinguishes between hydrological and water management balance, outlines the roles of individual institutions (CHMI, river basin authorities, and TGM WRI), and explains the principles of recording abstractions, reporting procedures, and data categorisation.

A separate section is devoted to hydrogeological zoning as a fundamental tool for spatial division of groundwater. The text traces the development of zoning from the 1950s to its most recent version in 2005 [1], which brought it into alignment with groundwater bodies defined for the purposes of river basin management plans and EU legislation. Emphasis is placed on the criteria for zoning, the link to balance units, and the connection with delineated water bodies.

Research on balance assessment methods in recent decades has highlighted the need for a specific approach to certain hydrogeological environments and structures, for which established procedures based on standard hydrological methods and base flow calculations cannot be mechanically applied. These include Quaternary deposits closely linked to surface water, karst structures, deep basin collectors, regional drainage areas, and similar features.

The practical approach to balance assessment is demonstrated using four Upper Cretaceous HGR, which are often described as balance-stressed.

DEVELOPMENT OF METHODOLOGICAL APPROACHES

History of groundwater balance assessment

The two fundamental terms used in groundwater balance assessment are hydrological balance and water management balance.

Hydrological balance evaluates changes in surface and groundwater stocks caused by temporal and spatial variability of natural factors, particularly climatic influences, and provides a basis for assessing changes in water stocks resulting from water use or other anthropogenic interventions. Thus, hydrological balance concerns the determination of natural groundwater resources within the context of the entire hydrological cycle, including spatiotemporal variability of quantitative characteristics. At present, the magnitude of natural resources is significantly influenced not only by seasonal climate variability but also by long-term trends associated with ongoing climate change. Today, the calculation of hydrological balance is inconceivable without the use of various hydrological and hydraulic mathematical models.

Water management balance is the comparison of water abstraction demands with the magnitude of natural resources at a given location and time. In this way, water management balance provides an overview of the state of water resources, degree of utilisation, and potential for future increases. Comparison of natural resources and groundwater abstractions forms the basis for assessing the balance stress of a given area. Modern water management balance assessment relies on a set of advanced statistical analyses and procedures. The results of water management balance constitute a fundamental basis for water management planning and governance.

Hydrological and water management balances together form the so-called water balance, as defined by the Water Act [2].

The following provides an overview of the gradual development of groundwater balance assessment in Czech Republic:

- In the mid-1960s, a specialised subcommittee for groundwater was established as part of the Commission for the Classification of Mineral Deposits (KKZ). The principles of this commission were largely determinative for the field of groundwater as well (*Guidelines for the Valuation of Groundwater Reserves and Principles for Submitting Reports: 1964, 1965, 1979*). Values reported as utilisable reserves represented a heterogeneous set of results. These values were generally determined with varying degrees of reliability and often represented averages over non-uniform, sometimes undefined shorter or longer periods, and therefore could not capture either the long-term variability or the seasonal changes of the natural groundwater regime.
- The early 1970s were marked by efforts to compile regular water management balances at the level of the then-existing zones. From 1979 onwards, regular annual balances became available, facilitated in large part by the introduction of abstraction records under Decree no. 63/1975 Coll.
- From 1979 onwards, groundwater balance formed part of the state water management balance, in the form of a comparison between so-called utilisable reserves and actual abstractions for a given year. The method for calculating utilisable reserves was not uniform and did not account for temporal variability of groundwater resources; as a result, the outcome did not represent the actual balance status, but rather an average over the assessed period. The ratio of reserves to abstractions was calculated, and balance status was classified as passive (< 0.9), stressed (0.9–1.1), or favourable (> 1.1).
- Since 1994, water management balance methodology has shifted towards gradual assessment of base flows, which, from a hydrogeological perspective, can generally be equated with groundwater outflow over multi-year averages, and, by extension, with natural groundwater resources, with the regimes of both quantities considered either identical or at least very similar.
- The principles of modern groundwater balance assessment in recent decades, beginning in the 1990s, aim to capture the variability of natural groundwater resources and consistently distinguish long-term values from annual ones. The fundamental purpose of this new approach is to compare comparable values for both resources and abstractions, corresponding to the same time period. It is efficient to carry out the balance assessment in two phases. If the balance status of a zone is good or satisfactory, it is sufficient to limit the assessment to a comparison of annual values. In such cases, the balance is limited to a summary of current data on the size of resources and abstractions for a specific (completed) year, together with a comparison of resources against long-term values for selected representative periods. In zones where the ratio of resource size to abstractions indicates that a stressed or even passive state may occur, a more detailed assessment is necessary. Seasonal fluctuations in both resources and abstractions can be so significant that annual values do not provide an adequate basis, and it is therefore necessary to perform the balance in a monthly step.
- From 1997 onwards, the 80% quantile of the base flow exceedance curve for 1971–1990 was introduced as the fundamental calculation value for the balance (the reference period was gradually replaced by successive 30-year periods: 1971–2000, 1981–2010, and 1991–2020). This value represents the long-term utilisable resources for water management balance.

Current water management balance of groundwater

Monitoring and assessment of the status of surface and groundwater, in accordance with Section 21 of the Water Act [2], serve to provide the basis for the exercise of public administration under said Act, for water planning (Chapter IV, Water Act), and for the provision of information to the public. It is carried out according to surface water catchments and HGRs, or groundwater bodies, and includes, among other things, maintenance of water balance (Section 21(2)(b), Water Act) and establishment, management, and updating of records pursuant to Section 21(2)(c), Water Act. The data contained in these records form part of the Public Administration Information System – VODA [3].

Water balance consists of hydrological balance and water management balance. Hydrological balance compares water gains and losses and changes in water storage within a catchment, territory, or water body over a given time interval, and it is compiled by CHMI. Water management balance compares requirements for surface water abstractions, groundwater abstractions, and wastewater discharges with the available capacity of water resources in terms of quantity, quality, and ecological status (Section 22(1), Water Act). It is compiled, within their territorial jurisdiction, by the state-owned river basin authorities pursuant to Section 54 of the Water Act [2] and further in accordance with Section 5(3) of Decree No. 431/2001 Coll. [4]. Comprehensive annual and nationwide processing of water management balance data is carried out by TGM WRI [5].

For the purposes of water management balance, CHMI has always provided source-side data of the balances by determining baseflow on the basis of information from the national monitoring network, groundwater level observations, and strength of source. This indicator of natural groundwater resources is processed annually from current data of monitoring stations. To track development of these resources over longer periods, the value of natural resources derived from long-term monitoring is used (a 30-year period, currently 1991–2020). Therefore, balance assessment includes a comparison of abstractions both with the value of actual natural resources of the previous year and with the value of long-term natural resources. The requirements of the EU Water Framework Directive have been reflected in methodological procedures used by TGM WRI in agreement with MoE (Water Protection Department). Instead of calculating baseflow, comprehensive assessment of natural groundwater resources is now anticipated, since baseflow alone may not be determinative in some environments (groundwater bodies in close hydraulic connection with surface waters, karst areas, drainage areas composed of several hydrogeological aquifers, deep basin aquifers with long residence times, etc.). In such cases, it is particularly necessary to apply modern research methods, including isotope analyses and hydraulic modelling procedures.

It is not yet possible to determine the size of natural resources for all HGRs – either they are so affected by anthropogenic activity that determination is unrealistic, or data are not available in the required structure and detail, or methodological uncertainties persist (e.g., for Quaternary regions closely linked to a watercourse). The key characteristic expressing resource capacity of a hydrogeological structure is the value of the natural resource, usually expressed in l/s and related to the area of the assessed territory (generally an HGR) and the assessment period. Natural groundwater resources are determined for each month and year, as well as the average value over a given monitoring period. Values of natural resources are established by CHMI as part of hydrological balance.

For selected HGRs, the Czech Geological Survey carried out a detailed reassessment of natural resources in the project *Rebalancing of Groundwater Reserves* [6], conducted from 2011 to 2016. Advanced numerical hydrological and hydraulic models were used for rebalancing of natural resources (rebalancing because earlier balances existed with varying quality) with input data from archival research, drilling works, hydrological and borehole logging measurements, and other direct observations, and with retrospective verification against actual data. One of the outputs is value of utilisable groundwater, based on 90% security of natural resources, considering the requirement to maintain minimum residual flows in the river network while ensuring sufficient water availability for groundwater-dependent protected ecosystems.

Groundwater abstraction records

Under Section 29 of the Water Act [2], groundwater resources are primarily reserved for the supply of drinking water to the population and for purposes for which the use of drinking water is prescribed by Act no. 258/2000 Coll. [7]. Groundwater may be used for other purposes provided that such use does not compromise the needs mentioned above.

For the purposes of the water management balance under Section 22 of the Water Act [2], groundwater users holding a permit to abstract groundwater in amounts exceeding 1,000 m^3 per calendar year or 100 m^3 per calendar month (limits effective from 2022) are required to report annually to the relevant river basin authorities the quantities of groundwater abstracted (as set out in Section 10 of the Act). The scope of these reported data and the procedure for reporting to the relevant river basin authority are defined in Sections 10 and 11 of Decree No. 431/2001 Coll. [4]. In the assessment of groundwater quantity and quality, in accordance with Decree No. 393/2010 Coll. [8], abstractions exceeding 6,000 m^3 per calendar year or 500 m^3 per calendar month are included in the balance.

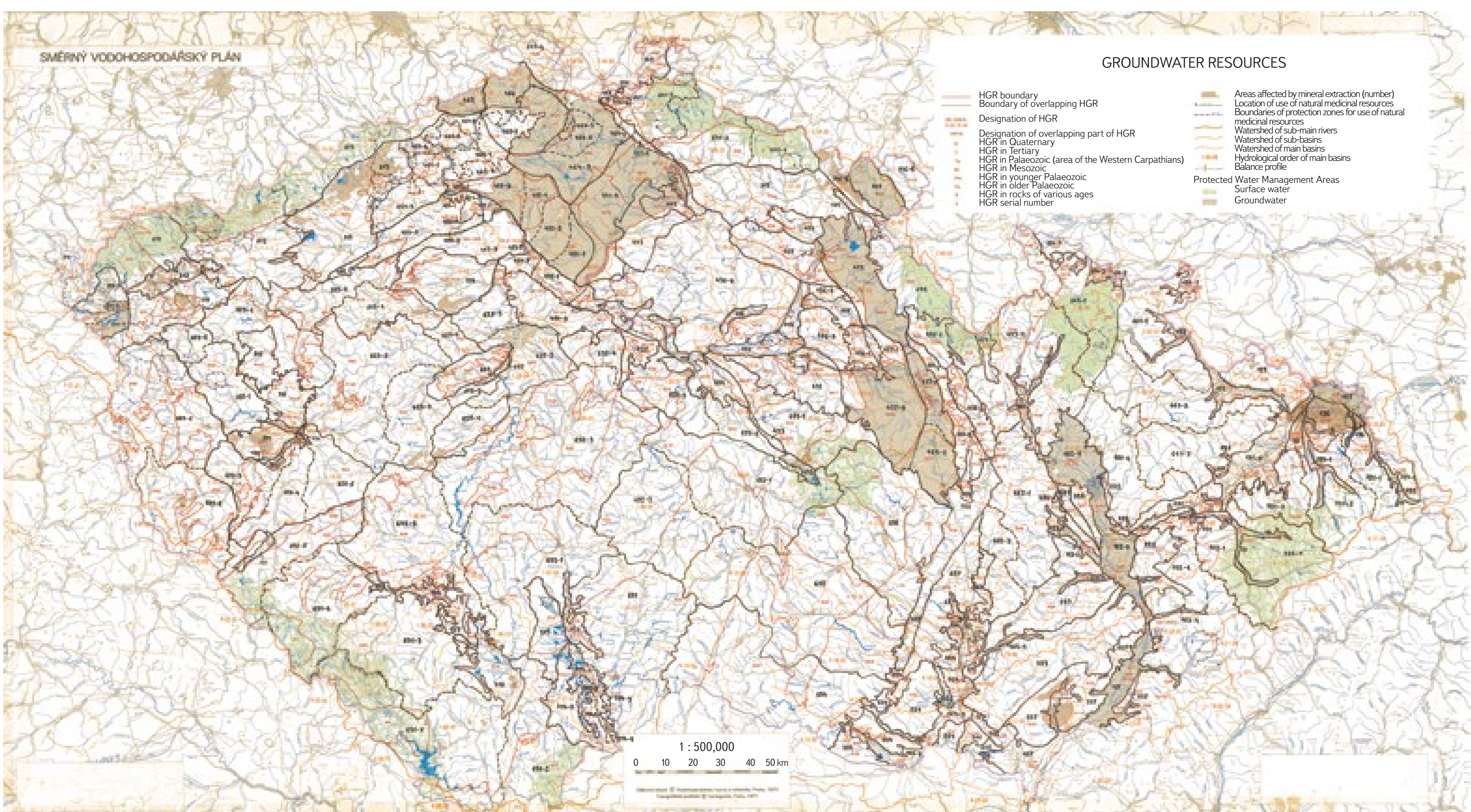

Fig. 1. Hydrogeological zones 1972 [9]

Hydrogeological zoning

The basic unit of groundwater balance is HGR. It is an area with similar hydrogeological conditions, type of aquifer, and groundwater flow, composed of one or more groundwater bodies.

Zones are delineated based on natural characteristics in the upper, main, and deep layers.

— The beginnings of groundwater zoning can be traced to the 1950s, with the first zoning approved in 1965 as part of early stages of water management planning.
— A more detailed zoning was introduced in the 1972 Master Water Management Plan (*Fig. 1*) [9].
— The revised zoning in 1986 [10] was already used as a territorial element of the national water management balance. In this revision, previously predominant geological and hydrogeological criteria were consistently complemented by a hydrological concept, so that the zones met, as far as possible, the condition of a hydrologically closed balance unit, in which all phases of groundwater flow (recharge, movement, storage, and drainage) were clearly defined. A total of 105 HGRs were delineated [10].
— The final version of hydrogeological zoning was prepared in 2005 (*Fig. 2*) [11] and remains valid to the present day. The updated zones correspond closely to the delineated groundwater bodies. Within this zoning, 152 HGRs are identified in Czech Republic: 111 in the main layer, which covers the entire country; three zones in the basal Cretaceous aquifer (in the north-western part of the Bohemian Cretaceous Basin); and 38 zones in the upper layer (Quaternary and Neogene sediments, Jizera Coniacian). Groundwater abstractions are assigned to these zones taking into account the type of hydrogeological structure (e.g., basin structures, hydrogeological massif, karst, flysch, Quaternary, Neogene). HGRs generally correspond to the delineation of groundwater bodies used for river basin management plans and are clearly assigned to individual river basins. This means that HGRs are always assessed as a whole, even if administrative boundaries would suggest they should be divided. The exceptions are HGR 6320 (Upper Vltava/Lower Vltava) and HGR 2250 (Morava/Dyje), which are divided between two sub-catchments according to the four groundwater bodies delineated within them. Two groundwater bodies fall into one sub-catchment and the other two into the second. This ensures that groundwater assessment for river basin management plans and the water management balance is always carried out for the entire sub-catchment as a whole.
— Following the new hydrogeological zoning, Decree No. 393/2010 Coll. [8] was issued by the Ministry of Agriculture (MoA), which, among other things, updates the assignment of individual HGRs to the corresponding sub-catchments. At the same time, a new decree was issued jointly by the Ministry of the Environment (MoE) and MoA, Decree No. 5/2011 Coll. [1].

Procedure for calculating water management balance

Groundwater management balance is based on a standard procedure – determining the ratio of groundwater abstractions to natural resources in a defined territory and period. The size of natural resources represents the natural dynamic component of groundwater, expressed in volumetric units over time (l/s), and is generally determined in practice by the variable magnitude of baseflow. Baseflow magnitude of is determined as part of the outputs of the hydrological balance of water quantity at CHMI, where specific values are calculated for individual HGRs based on measurements. HGR is the basic balance unit for

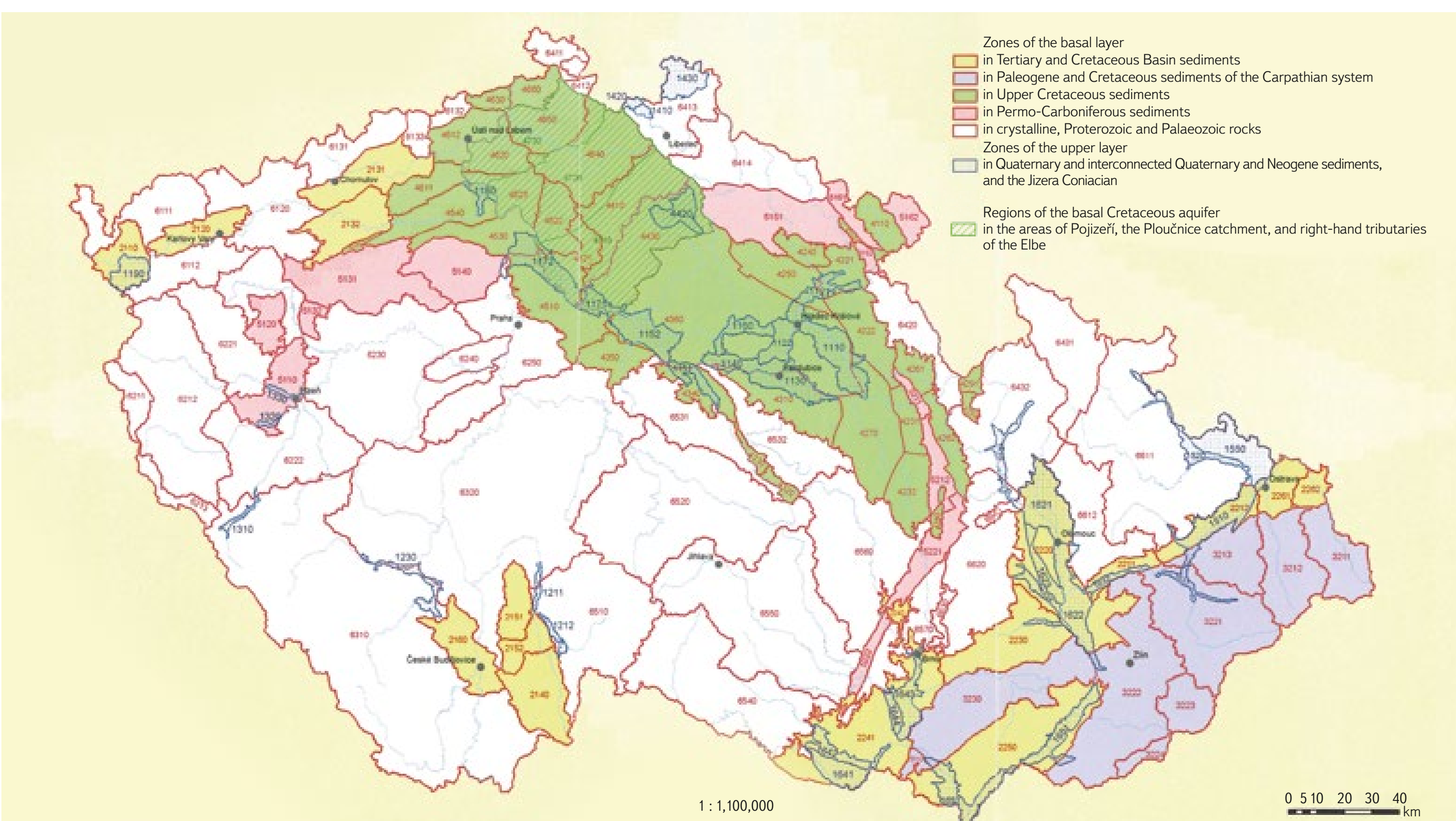

Fig. 2. Hydrogeological zones 2005 [11]

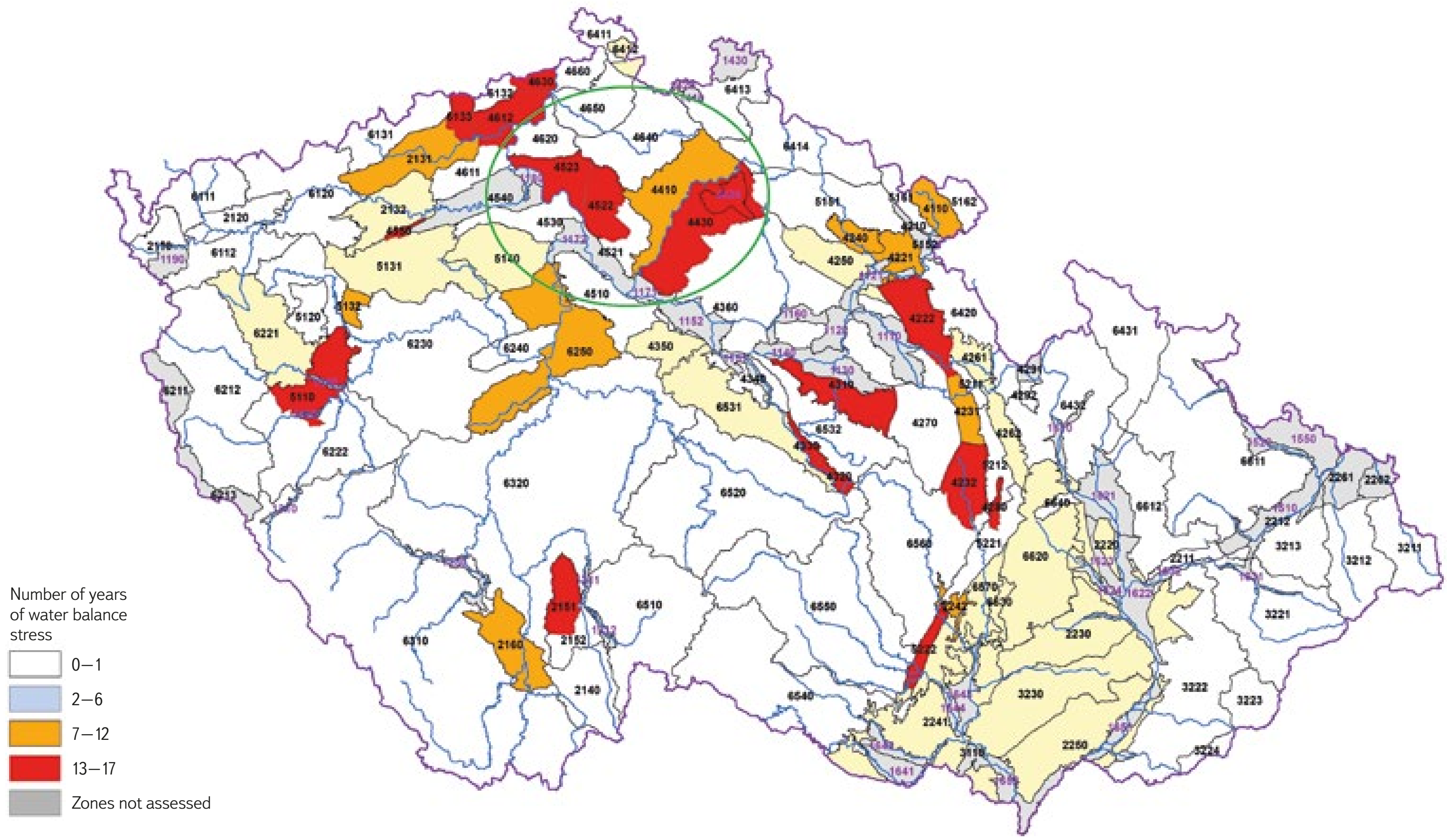

Fig. 3. Assessment of balance stress of HGR base and upper layers for 2007–2023; HGR areas discussed in the following section are shown in green

assessing groundwater quantity and includes one or several usually closed hydrogeological structures. In other cases as well (e.g., regional hydrogeological surveys from the 1960s to 1980s or the *Rebalancing of Groundwater Reserves* project), natural resource data were always collected within HGRs; therefore, more detailed data for smaller areas are generally not available.

Baseflow calculation (CHMI) is derived from total flow on a daily basis using the separation method according to Eckhardt. The recession coefficient is determined from an analysis of flow recession curves. The ratio of total to baseflow, BFImax, is calibrated to match the course of total and baseflow during the falling limbs of the hydrograph. Static groundwater reserves are determined from the Boussinesq equation, which relates storage to baseflow.

Groundwater management balance is processed annually, currently for approximately 102 HGRs (for 2023) out of a total of 152, covering just under 81 % of the area of Czech Republic (*Fig. 3*). The reason for not calculating baseflow in Quaternary sediments is the lack of input data and often the complex assessment of resources in these types of HGR, where both the influence of surface water and drainage of deeper hydrogeological structures are evident. Due to ongoing methodological uncertainties and the incomparability of the obtained values, balance assessment for these HGRs has not yet been carried out for the purposes of water management balance.

In the balance of groundwater quantity, total abstractions are compared with values of natural groundwater resources within the spatial unit (HGR, see *Fig. 3*). As a precautionary measure, TGM WRI, in agreement with the MoE (Water Protection Department) and the MoA (Water Management Department), adopted a methodological approach in which zones are assessed by the ratio of maximum monthly abstraction in a given year to minimum monthly baseflow in the same year (MAX/MIN) [12–14]. This thus identifies the potentially most unfavourable state within the assessed year. If the MAX/MIN ratio exceeds 0.5, the zones are considered balance-stressed, and further assessment in a monthly step is required, comparing monthly baseflow values with actual monthly abstractions. If balance stress is confirmed by the analysis of monthly data, a detailed hydrogeological assessment of the zone should follow, including a groundwater flow hydraulic model, to determine the actual situation, identify the problem, and explore possible remediation measures. An interesting question could be how balance stress of zones would appear if permitted abstractions were used instead of actual abstractions; however, this is beyond the scope of this article.

RESULTS: EXAMPLES OF BALANCE ASSESSMENT IN HYDROGEOLOGICAL ZONES OF THE BOHEMIAN CRETACEOUS BASIN

Fig. 3 shows the area from which four HGRs of the Bohemian Cretaceous Basin were selected as examples of the applied procedures; these HGRs are regularly reported as balance-stressed. Currently, the HGRs with regularly reported balance stress 4522, 4410, and 4430 are part of applied research funded by TA CR (projects no. SS06010268 *Understanding, Quantification, and Protection of Strategic Deep-Circulation Groundwater Resources of the Bohemian Cretaceous Basin in HGRs 4410 and 4522* and no. SQ01010176 *Impacts of Climate Change on Minimum Residual Flows in the Jizera River Network and on Groundwater Abstractions Near the River*). Due to spatial continuity, the neighbouring HGR 4523, which is also reported as stressed, was included in the assessment for the purposes of this article.

Key results are expected primarily from project no. SS06010268, which aims to improve understanding of the hydrogeological basin environment of the Upper Cretaceous sediments and, among other objectives, to determine whether the regularly observed balance stress might also be related to incorrect delineation of current zone boundaries, which may not fully characterise closed hydrogeological structures. There are already strong indications (tritium analyses, residence time calculations, tracer results using CFC/SF6, and a conceptual groundwater flow model [15, 16]) that call for a new perspective on groundwater flow directions at the interface of HGR 4522, 4410, 4521, and 4640. If these new perspectives are confirmed, the research results could also be reflected in the assessment of balance stress in these areas.

To illustrate the results achieved in water management balance assessment, four HGRs were used:

— HGR 4410 Cretaceous of the Jizera River, right-bank part
— HGR 4430 Cretaceous of the Jizera River, left-bank part
— HGR 4522 Cretaceous of the Liběchovka and Pšovka Streams
— HGR 4523 Cretaceous of the Obrtka and Úštěcký potok Streams

The selected HGRs have long been classified as balance-stressed (*Fig. 3*), noting that this assessment considers the most unfavourable condition within a given year (i.e., the ratio of maximum monthly abstraction to minimum monthly baseflow exceeds 0.5). This serves as an initial signal that, when a region is flagged as stressed, further evaluation in a monthly step is required to reveal the distribution of these indicators over the entire period. HGR 4410 has been classified as stressed regularly since 2016, HGR 4430 since 2012, and HGRs 4522 and 4523 since 2007 and 2008, respectively.

The named HGRs were therefore assessed with respect to natural groundwater resources and abstractions for the period 2007–2023. The assessment first compared maximum monthly abstraction with minimum monthly baseflow alongside long-term baseflow values (1971–2000, 1981–2010, and 1991–2020) and then compared monthly baseflow with actual monthly abstractions over 2007–2023.

HGR 4410 Cretaceous of the Jizera River, right-bank part

The area contains two separate hydrogeological Cretaceous aquifers. Basal aquifer A (which is part of two deep-layer HGRs – HGR 4710 Basal Cretaceous aquifer on the Jizera and HGR 4720 Basal Cretaceous aquifer from Hamr to the Elbe) is hosted in Cenomanian-age siltstones and sandstones, whereas aquifer C (forming the main part of HGR 4410 in the main layer) is hosted in Turonian-age sandstones and siltstones. The claystone sequence at the base of the Lower Turonian acts as a hydrogeological confining layer between the two aquifers and, by extension, between the HGRs. The main source of groundwater for water supply abstractions in HGR 4410 is the sandstones of the Jizera Formation, serving as Hydrogeological aquifer C. Part of the area is overlain by an artesian cover of Coniacian claystones [10]. Groundwater recharge occurs partly within the area of the HGR and partly via lateral inflow from adjacent HGRs, or through inflow from the Jizera River. It is clear that the largest abstractions from HGR 4410, in the Kochánky catchment, are in close hydraulic connection with the Jizera River (abstractions from the Quaternary sediments of the Jizera, which form part of HGR 4410). Abstractions in the Bělá and Strenický Stream catchments may be associated with lateral groundwater inflows from outside HGR 4410.

Fig. 4 shows that annual abstraction values remain consistently below natural resource values, or baseflow, which also holds for comparison of maximum monthly abstraction and minimum monthly baseflow. However, the MAX/MIN ratio criterion of 0.5 is regularly exceeded, and the HGR is therefore repeatedly classified as balance-stressed. Since 2014, a gradual convergence of the two values can be observed, primarily due to declining natural resources while abstraction volumes have remained constant (the MAX/MIN ratio is gradually increasing). A clear decline (about 20 %) is also evident in the consecutive 30-year averages of natural resources (1971–2000, 1981–2010, 1991–2020), undoubtedly reflecting the impacts of climate change. Comparison of baseflow and monthly abstraction values (*Fig. 5*) shows that abstractions remain consistently below baseflow in the monthly view, yet often represent more than 50 % of natural resources (baseflow); classification of the HGR as balance-stressed is therefore justified according to the applied methodology.

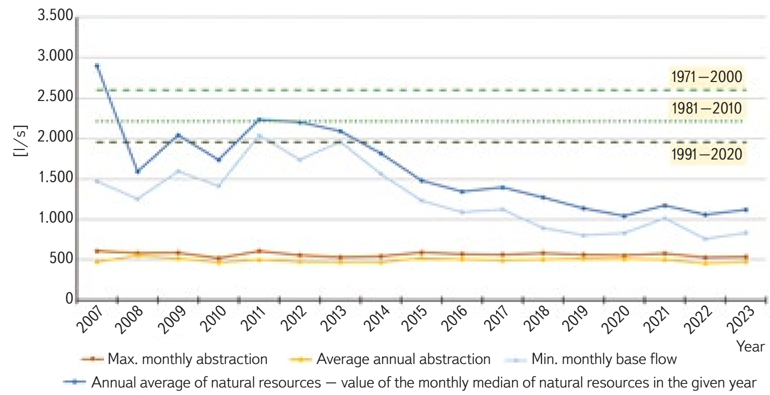

Fig. 4. Annual characteristics for basic balance assessment of HGR 4410, including long-term reference periods 1971–2000, 1981–2010, and 1991–2020

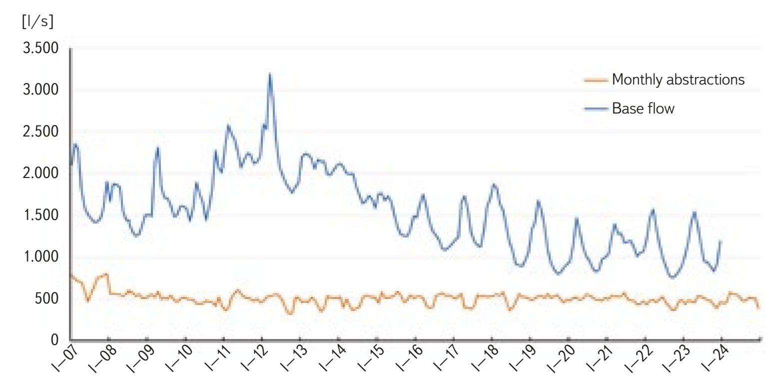

Fig. 5. Water management balance in a monthly step, 2007–2023 [17, 18]

4430 Cretaceous of the Jizera River, left-bank part

Three separate hydrogeological Cretaceous aquifers have developed in the area [10]:

— Basal aquifer A in Cenomanian psammites and aleurites (forming a separate HGR 4710 of the deep layer – Basal Cretaceous aquifer on the Jizera),
— intermediate aquifer C associated with Turonian psammites, divided by insulating layers into two main sub-aquifers, which further splits and wedges eastwards (forming the target aquifer of the 4430 main layer) and further east transitions into hydrogeologically unproductive Elbe Cretaceous with clayey development (HGR 4360),
— upper aquifer D associated with Coniacian psammites, forming a separate aquifer of the upper layer 4420, occurring over part of the 4430 aquifer area.

HGR 4430 is largely overlain by an artesian cover of Coniacian aleurites. Recharge of groundwater via direct infiltration within the area of the HGR is very limited; the majority is indirect, mediated by inflow from HGRs 4420 and 4410, or by inflow from the Jizera River, especially at abstraction points. It is indisputable that the largest abstractions from HGR 4430, in Benátky nad

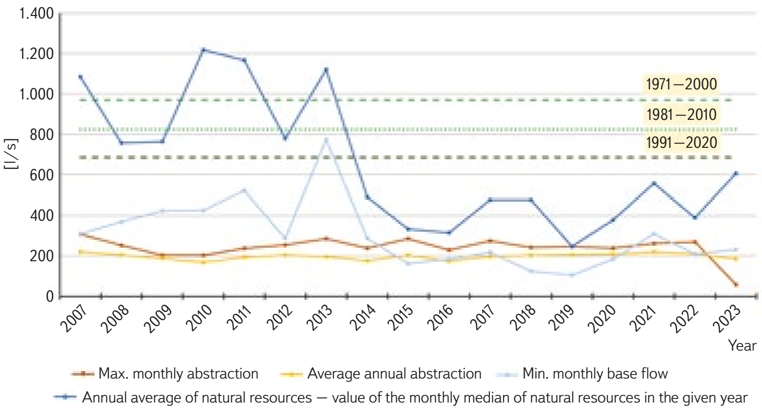

Fig. 6. Annual characteristics for basic balance assessment of HGR 4430, including long-term reference periods 1971–2000, 1981–2010, and 1991–2020

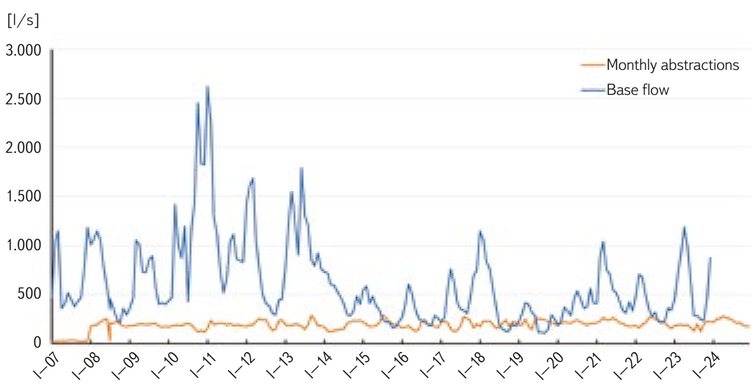

Fig. 7. Water management balance in a monthly step, 2007–2024 [17, 18]

Jizerou (from the Quaternary deposits of the Jizera), are in significant hydraulic connection with the Jizera River. Hydraulic connection with surface waters can also be expected for other, smaller abstractions across the HGR.

Fig. 6 shows that annual values of average abstractions remain consistently below the values of average natural resources, i.e., baseflow. However, the MAX/MIN criterion of 0.5 is regularly exceeded, so the HGR is consistently classified as balance-stressed. Since 2014, a pronounced convergence of the two values can also be observed, primarily due to declining natural resources while abstraction volumes remain constant (the MAX/MIN ratio gradually increases). Comparison of monthly values (*Fig. 7*) of abstractions and baseflow shows that abstractions occasionally exceed natural resource values and, especially after 2015, this long-term unsustainable situation has become the norm. The impact of the prolonged drought period 2015–2019 is also evident, as the most recent 30-year average of natural resources (1991–2020) is the lowest (up to 27 % below the 1971–2020 range), compared with the previous two periods (1971–2000, 1981–2010), clearly demonstrating the long-term effects of climate change.

4522 Cretaceous of the Liběchovka and Pšovka Streams and 4523 Cretaceous of the Obrtka and Úštěcký potok Streams

Both HGR encompass the area of right-bank tributaries of the Elbe River from Mělník to Litoměřice, where the catchments of the Pšovka, Liběchovka, Obrtka, and Úštěcký potok Streams experience significant drainage of the Cretaceous Basin sediments (key infiltration areas partly lie outside these HGR) and where very substantial water-supply abstractions take place. The area contains two main hydrogeological aquifers: basal aquifer A, associated with Cenomanian psammites and psephites (forming part of the deep-layer hydrogeological aquifer 4720 Basal aquifer from Hamr to the Elbe River), and aquifer C, associated with Turonian sediments of the Jizera Formation, which forms the HGR 4522 and 4523 discussed here. The Quaternary aquifer is hydraulically connected to aquifer C and cannot be separately delineated or assessed; it is therefore considered part of both HGR 4522 and 4523 [10]. Significant groundwater abstractions occur here from the Řepínský důl, Zahájí, Mělnická Vrutice catchments, and other sources.

It is evident from *Fig. 8* that the annual values of average abstractions in HGR 4522 are mostly higher than the values of natural resources, or baseflow. When comparing the maximum monthly abstraction with minimum monthly baseflow, this difference becomes even more pronounced and persists throughout almost the entire assessment period 2007–2023. Since 2018, the gap between natural resources and abstractions has further increased, mainly due to a slight decline in natural resources while abstraction volumes have remained relatively constant. The MAX/MIN ratio criterion of 0.5 is thus regularly exceeded (reaching values above 1), so the district is justifiably classified as balance-stressed on a regular basis. The impact of the 2015–2019 drought period is also clearly visible, resulting in the lowest 30-year average of natural resources for 1991–2020 compared with the two preceding periods (1971–2000, 1981–2010), with a reduction of up to 24 % relative to 1971–2020, undoubtedly reflecting the long-term effects of climate change. Comparison of monthly values of baseflow and abstractions (*Fig. 9*) shows that until around 2015 the situation was relatively more favourable (abstractions were mostly below baseflow values, although even then they exceeded 50 % of baseflow). From

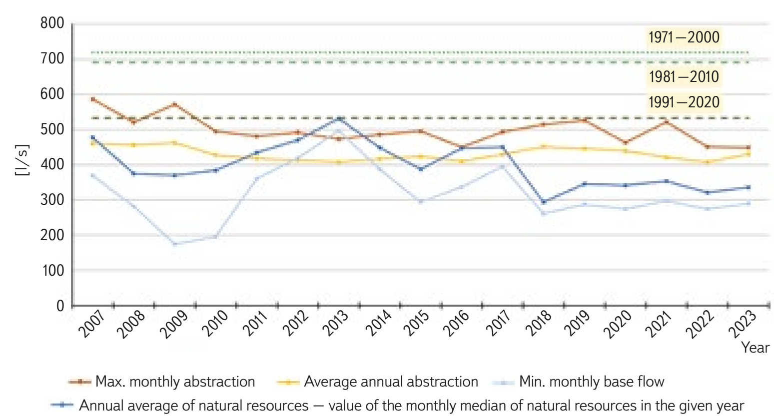

Fig. 8. Annual characteristics for basic balance assessment of HGR 4522, including long-term reference periods 1971–2000, 1981–2010, and 1991–2020

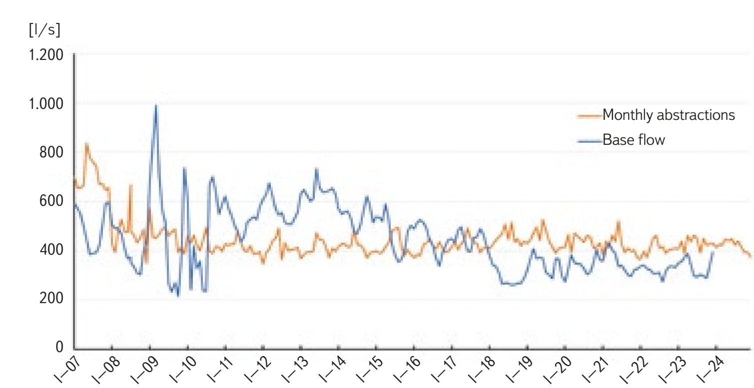

Fig. 9. Water management balance in a monthly step, 2007–2024 [17, 18]

approximately 2018 onwards, however, monthly abstractions consistently exceed baseflow values, representing a long-term unacceptable condition that should manifest in declining groundwater levels and static reserves (so called overexploitation of the hydrogeological structure).

Fig. 10 shows the state of water balance stress in HGR 4523. The situation here is a bit more favourable. Abstractions are mostly lower than the values of the annual average of natural resources, but from around 2015 the abstraction and natural resource values have approached each other significantly, mainly due to a decline in natural resources. Thanks to the current decrease in abstractions, the values have not yet exceeded natural resources. However, the MAX/MIN ratio criterion of 0.5 is regularly and consistently exceeded, and the district is therefore correctly classified as balance-stressed. A clear and very pronounced decline is also evident in successive 30-year averages of natural resources (1971–2000, 1981–2010, 1991–2020), reaching up to 37 % over the period 1971–2020, undoubtedly reflecting the impacts of climate change. Comparison of monthly baseflow and abstraction values (*Fig. 11*) indicates a more favourable situation; for most of the assessment period, monthly abstractions remain below monthly natural resource values (if the fluctuating baseflow values of 2009–2011 are disregarded, the opposite occurred only in 2018, and in recent years the situation has improved further due to a decline in recorded abstractions). The MAX/MIN ratio criterion of 0.5 is exceeded only rarely from the perspective of monthly values. From a methodological point of view, this demonstrates the great utility of assessing balance stress in a monthly step.

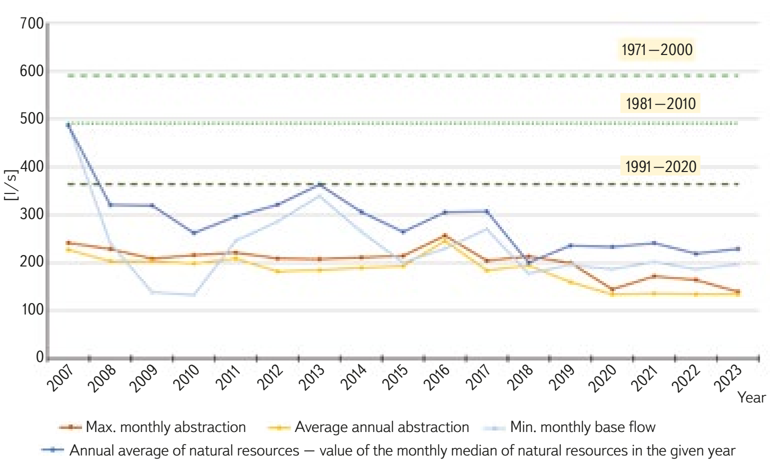

Fig. 10. Annual characteristics for basic balance assessment of HGR 4523, including long--term characteristic periods 1971–2000, 1981–2010, and 1991–2020

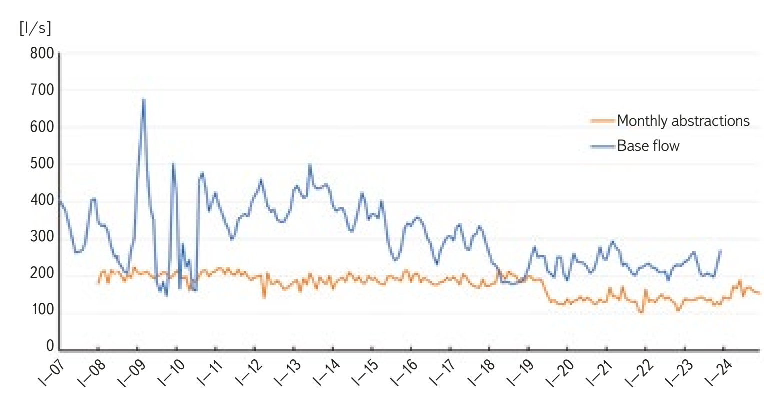

Fig. 11. Processing of water management balance in a monthly step – period 2007–2024 [17, 18]

DISCUSSION OF RESULTS

Hydrogeological zone 4410

Total abstractions from HGR 4410 have not caused regional declines in groundwater levels or reductions in static reserves. Its classification as a balance-stressed HGR (*Fig. 3*) is, however, justified by frequent exceedances of MAX/MIN criterion (*Fig. 4*), including after balance analysis in a monthly step (*Fig. 5*). Balance stress may occur locally, particularly in areas with large abstractions. It should also be noted that the difference between natural resources and abstractions is gradually decreasing, both on an annual and a monthly basis (see also progressively declining 30-year averages of natural resources), which, in connection with the impacts of climate change, raises some concern about a further increase in balance stress in the future. However, where certain abstractions from the Bělá and Strenický Streams are largely fed by groundwater originating from more distant recharge areas with longer residence times [16], the impacts of climate change on these abstractions can be expected to be considerably smaller.

From the perspective of protecting the groundwater resources of HGR 4410, we recommend that any future large abstractions be approved only after careful consideration of the available groundwater resources and their origin. Climate change will undoubtedly limit shallow-circulation resources. However, deeper groundwater flow with longer residence times (particularly from the west to northwest from HGR 4640), which is considerably more resilient to the impacts of climate change, offers significant potential for utilisation of these less vulnerable groundwater resources, whose quantification is also being addressed by the currently ongoing TA CR project no. SS06010268 [15]. In protecting the recharge of this deeper groundwater flow, the protection of infiltration areas is essential, particularly those at higher altitudes and with higher precipitation totals. Given the presence of the Jizera River and some other watercourses, there is also a certain potential in this HGR to increase groundwater resources through the application of managed aquifer recharge methods [19].

Hydrogeological zone 4430

Total abstractions from HGR 4430 have not yet caused regional declines in groundwater levels or reductions in static reserves; however, its classification among balance-stressed HGRs (*Fig. 3*) is fully justified due to frequent exceedances of the MAX/MIN criterion (*Fig.* 6), even after balance analysis in a monthly step (*Fig. 7*). Especially since 2014, abstraction values and natural resources have become very close, primarily as a result of declining natural resources due to climate change. Even after balance analysis in a monthly step (*Fig. 7*), it is evident that the two curves are close to each other, and there are even months in which total abstractions exceed baseflow values (the MAX/MIN ratio thus exceeds 1). It is also important to note the sharply declining 30-year averages of natural resources (by 27 % over the period 1971–2020), which – considering the impacts of climate change – raises further concerns for the future. These could result in either managed or unmanaged reductions in abstractions, or in abstractions being carried out at the expense of surface flows (the Jizera River and its tributaries).

From the perspective of protecting groundwater resources in HGR 4430, it should be noted that further available resources are relatively limited. In the future, any additional large abstractions should be permitted only after careful consideration of the local situation and balance stress. Relatively higher yields may be provided by sources relying on induced inflows from nearby surface streams (the Jizera River and its tributaries); however, during prolonged droughts, this could have adverse effects on streamflow characteristics and the ecological functions of these watercourses. For the protection of groundwater recharge in HGR 4430, it is essential to safeguard infiltration areas in HGR 4420 Jizera Coniacian and to consider abstraction volumes in the neighbouring HGR 4410 and 4420; a substantial increase in these abstractions would reduce the inflows from these zones into HGR 4430. It is therefore recommended, from a water balance perspective, that these three HGR be assessed together. Given the presence of the Jizera River and other watercourses, there is also some potential in this HGR to increase groundwater resources through the application of managed aquifer recharge methods [19].

Hydrogeological zones 4522 and 4523

It appears that the Cretaceous formations of the right-bank tributaries of the Elbe are an area where significant groundwater abstractions, combined with pronounced effects of climate change, result in actual water balance stress or a serious threat thereof. Observed phenomena include losses of water from surface streams (meaning that abstractions are effectively carried out at the expense of groundwater discharge to surface flow), and in some cases abstractions even actively induce a loss of surface water from the stream due to bank infiltration, all of which affect flow characteristics and minimum residual flows. A negative impact has been recorded on the lower course of the Pšovka (due to complex groundwater flow conditions), where part of the stream dries out during summer months over extended periods. Impacts have also been observed on some other streams (the Obrtka).

The situation has been closely monitored over the long term, and various measures have been implemented. Based on the Lower Elbe River Basin Management Plan (measures sheets), numerous studies have been carried out, and a series of joint meetings and hydrogeological surveys have taken place. From all these findings, the need for remedial and protective measures has emerged, including a reduction in groundwater abstractions (see reduction in abstractions after 2019 in *Fig. 11*). At present, the water supply operator holds a permit for groundwater abstraction from the Řepínský důl, Zahájí, and Mělnická Vrutice sites, amounting to 370 l/s, in which the maximum allowable abstraction at this site has already been significantly reduced. Within the Mělnická Vrutice catchment, regime monitoring is carried out with detailed evaluation. Monitoring results indicate that use of the Pšovka catchment is close to 100 % of current natural groundwater resources.

HGR 4522 is classified as highly stressed in terms of water balance, and this must be considered when permitting further groundwater abstractions within this HGR, especially in view of the anticipated deepening impacts of climate change on water conditions. For HGR 4523, the situation is only slightly more favourable. However, it shows the greatest decline in natural resources over the period 1971–2020 of all four assessed HGRs – up to 37 %. This represents the fastest reduction in available natural resources, offering a rather pessimistic outlook for future water balance stress.

If research within TA CR project no. SS06010268 demonstrates that part of the groundwater resources originates from outside HGR 4522 [15, 16], this could reduce water balance stress in HGR 4522. Simultaneously, the conceptual model indicates the existence of separate groundwater flow in deeper Turonian sub-aquifers, which was identified as part of the *Rebalancing Groundwater Resources* project. In the future, it would therefore be logical to process water balance at the level of these sub-aquifers, as there appears to be a significant difference in balance stress among them. However, a legitimate question remains as to whether there will be sufficient relevant data to carry out such a detailed sub-aquifer balance.

From the perspective of protecting groundwater resources in HGR 4522 and 4523, it should be noted that additional available resources are fairly limited. In the future, further large abstractions should not be permitted, or only allowed after careful consideration of the situation, the state of local water balance stress, and verification of the age and origin of the water inflow. Climate change will undoubtedly limit shallow-circulation resources. Deeper groundwater flow with a longer residence time, which is significantly more resilient to the impacts of climate change, does, however, provide certain opportunities for the utilisation of these less vulnerable groundwater resources [15, 16]. In protecting the formation of groundwater in this deeper flow, it is crucial to safeguard the recharge areas (both the areas of the two HGRs of interest and of HGR 4640 with higher elevations and greater precipitation totals). Theoretically, there is also some potential in both HGRs to increase groundwater resources through the application of managed aquifer recharge methods [19]; however, these considerations are constrained by the limited availability of surface water sources and lower precipitation totals. In practice, the only significant water source for infiltration is the Elbe River, so the southern parts of both HGRs could be considered for discussions on this topic, which would, however, need to include considerations of water quality of the Elbe.

CONCLUSION

This text focuses on the long-term evaluation of water management balance in selected HGRs of the Czech Cretaceous Basin for the period 2007–2023, specifically HGR 4410 (Cretaceous of the Jizera River, right-bank part), HGR 4430 (Cretaceous of the Jizera River, left-bank part), HGR 4522 (Cretaceous of the Liběchovka and Pšovka Streams), and HGR 4523 (Cretaceous of the Obrtka and Úštěcký potok Streams). The aim of the article was to illustrate the methodology and to identify the degree of stress in these zones based on the comparison of monthly groundwater abstractions with the minimum monthly values of the baseflow, also in relation to long-term hydrological characteristics (periods 1971–2000, 1981–2010, 1991–2020).

The mentioned HGR are, in most cases, evaluated as stressed over the long term, indicating the need for more careful management of abstractions and protection of water resources. Particular attention is given to HGR 4522 and 4523, where excessive abstractions (occasionally even exceeding natural resource values) cause drying of surface watercourses during drought. These impacts have led to a revision of abstraction limits, implementation of routine monitoring, and adoption of remedial measures based on the results of environmental impact assessments (EIA).

The article is set within the context of ongoing applied research (TA CR projects no. SS02030027, SS06010268, SQ01010176, SS01010208), which aim to refine knowledge of the hydrogeological environment, including redefinition of the boundaries of individual HGR, detailed clarification of the interaction between surface and groundwater, and identification of drought impacts on groundwater resources. Existing indications (e.g., results of tritium and other tracer analyses, residence-time calculations, and conceptual groundwater flow models) suggest that the boundaries of HGR 4410 and 4522 may be incorrectly delineated with respect to actual hydrogeological watersheds [15, 16], which could affect both the interpretation of balance results and planning of groundwater resource management. If partial sub-aquifers with distinct groundwater flow characteristics are identified within the previously assumed single hydrogeological aquifers, it is also a legitimate question whether separate groundwater balances should be carried out for each sub-aquifer. A combined balance encompassing several environments with mutually disconnected groundwater can distort the actual balance status. However, the actual implementation of separate balances for individual sub-aquifers depends on the availability of sufficient relevant input data. A balance analysis in a more detailed monthly step also proves to be very useful, as it provides a more precise view than the general annual analysis. If balance stress is confirmed at the monthly scale, a detailed hydrogeological assessment of the aquifer should follow from a professional perspective, including a hydraulic model of groundwater flow, in order to determine the actual situation, identify the problem, and explore possible remedies.

Overall, the text emphasises the need for a thorough understanding of the hydrogeological environment (optimally based on mathematical modelling of groundwater flow), the requirement for continuous monitoring, assessment, and potential revision of the overarching conditions for groundwater abstraction, with a focus on sustainable management and the long-term protection of water resources, as the negative impacts of climate change (reduced infiltration, declining water levels, and diminishing natural groundwater resources) are expected to become increasingly pronounced. Protecting groundwater quantity primarily means ensuring adequate protection of infiltration areas (which must first be reliably identified) and adopting a careful approach to managing groundwater abstractions, with a preference for abstractions intended for drinking-water supply (Section 29 of the Water Act [2]). The conclusions of the article provide important guidance for groundwater management, setting of abstraction permits, and overall strategic governance of water resources under conditions of climate change and increasing pressures on their use [20, 21].

To conclude, it is worth noting that the lower cost of groundwater (compared with surface water) also has a negative impact on management of groundwater resources. The price of surface water in Czech Republic is significantly higher than that of groundwater, which often leads to preferential – and in many places excessive and sometimes inappropriate – use of groundwater instead of surface water (for example, for purposes other than public water supply). Adjusting the price of groundwater abstraction could serve as a significant economic instrument for the protection of available groundwater resources. Revenue generated from higher abstraction fees, if reinvested into further exploratory and monitoring activities focused on capture and infiltration areas, would greatly contribute to improving knowledge of the hydrogeological environment and the long-term sustainable use and necessary protection of groundwater throughout Czech Republic.

Acknowledgements

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References

[1] *Vyhláška č. 5/2011 Sb., o vymezení hydrogeologických rajonů a útvarů podzemních vod, způsobu hodnocení stavu podzemních vod a náležitostech programů zjišťování a hodnocení stavu podzemních vod.*

[2] *Zákon č. 254/2001 Sb., o vodách a o změně některých zákonů (vodní zákon).*

[3] *Informační systém veřejné správy – VODA (ISVS VODA)*. Prague: MoA. Available at: https://voda.gov.cz/

[4] *Vyhláška č. 431/2001 Sb., o obsahu vodní bilance, způsobu jejího sestavení a o údajích pro vodní bilanci.*

[5] HRABÁNKOVÁ, A., DATEL, J. V. Bilancování podzemních vod v ČR na příkladech několika svrchnokřídových rajonů. In: *9. ročník odborné konference Podzemní vody ve vodárenské praxi. Studio AXIS a FINGEO, Rychnov nad Kněžnou, 24.–25. 4. 2024.* Available at: http://www.podzemni-vody.cz

[6] MIXA, P., KADLECOVÁ, R. et al. *Rebilance zásob podzemní vody*. Prague: Czech Geological Survey, 2016. Available at: https://cgs.gov.cz/projekty/668000-rebilance

[7] *Zákon č. 258/2000 Sb., o ochraně veřejného zdraví a o změně některých souvisejících zákonů.*

[8] *Vyhláška č. 393/2010 Sb., o oblastech povodí.*

[9] VRV. *Státní vodohospodářský plán 1972*. Praha: Vodohospodářský rozvoj a výstavba, a. s., 1973.

[10] OLMER, M., KESSL, J. et al. *Hydrogeologické rajony*. Prague: Státní zemědělské nakladatelství, 1990. ISBN 80-209-0114-0.

[11] OLMER, M., HERRMANN, Z., KADLECOVÁ, R., PRCHALOVÁ, H. et al. *Hydrogeologická rajonizace České republiky*. Prague: Czech Geological Survey, 2006. Sborník geologických věd, 23. ISBN 80-7075-660-8

[12] BEČVÁŘ, V. et al. *Státní vodohospodářská bilance a metody jejího zpracování. Metodika úkolu na rok 2001.* Prague: TGM WRI, MoE, 2001.

[13] DLABAL, J. et al. *Bilance, kontrola a hodnocení v oblasti ochrany množství a jakosti vod. Metodika úkolu na rok 2008*. Prague: TGM WRI, MoE, August 2008.

[14] VYSKOČ, P., PRCHALOVÁ, H., FILIPPI, R., PICEK, J., DLABAL, J. *Výpočet vodohospodářské bilance*. Prague: TGM WRI, MoE, April 2018.

[15] BRUTHANS, J., DATEL, J. V., SLAVÍK, M., HRABÁNKOVÁ, A., MAREŠ, J., PRINZ, J. *Poznání, kvantifikace a ochrana strategických zdrojů podzemní vody české křídové pánve hlubokého oběhu v hydrogeologických rajonech 4410 a 4522. Odborná zpráva k průběžné zprávě za rok 2024*. Prague: TGM WRI, Faculty of Science, Charles University, 2025. Available at: https://heis.vuv.cz/data/webmap/datovesady/projekty/strategickezdroje/

[16] MAREŠ, J., SLAVÍK, M., DATEL, J. V. Problematika starých podzemních vod v hydrogeologických rajonech 4410 Jizerská křída pravobřežní a 4522 Křída Liběchovky a Pšovky. *Vodohospodářské technicko-ekonomické informace*. 2024, 66(5), pp. 22–31. ISSN 0322-8916. Available at: https://www.vtei.cz/2024/10/problematika-starych-podzemnich-vod-v-hydrogeologickych-rajonech-4410-jizerska-krida-pravobrezni-a-4522-krida-libechovky-a-psovky-2/

[17] VÚV TGM. *Hydroekologický informační servis*. Prague: TGM WRI. Available at: https://heis.vuv.cz/

[18] ČHMÚ. *Český hydrometeorologický ústav*. Prague. Available at: https://www.chmi.cz/

[19] DATEL, J. V. et al. *Řízená dotace podzemních vod jako nástroj k omezení dopadů sucha v ČR. Projekt SS01010208. Závěrečná zpráva*. Prague: TGM WRI, 2023. Available at: https://www.vuv.cz/rizena-dotace-podzemnich-vod-jako-nastroj-k-omezeni-dopadu-sucha-v-cr/o-projektu-36/

[20] POLEDNÍČEK, P., RACÍKOVÁ, J., KALČÍK, M. *Vodohospodářská bilance dílčího povodí Ohře, dolního Labe a ostatních přítoků Labe. Hodnocení kalendářního roku 2022*. Chomutov: Ohře Basin Administration, September 2023.

[21] SKALICKÁ, I., ŠRAUT, B., VACULÍKOVÁ, Š. *Vodohospodářská bilance za rok 2022. Zpráva o hodnocení množství a jakosti podzemních vod v územní působnosti Povodí Labe, státní podnik*. Hradec Králové: Elbe Basin Administration, September 2023.

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Dynamics of humic substances in peat habitats of Prameniště Chomutovka nature reserve

MARTIN VOKOUN, VOJTĚCH MORAVEC, PAVEL ECKHARDT

Keywords: peat bog — hydrology — monitoring — revitalization — humic substances — hydrochemistry

ABSTRACT

This article focuses on evaluating the concentrations of humic substances (HS) in peatland waters in the Ore Mountains region, specifically in the area near the village of Hora Svatého Šebestiána in the Prameniště Chomutovky nature reserve. The aim was to assess the impact of restoration measures on the occurrence of HS in surface and subsurface waters in a post-peat-extraction environment. Monitoring was carried out from 2022 to 2024 on two experimental sites – one restored (site A) and one predominantly non-restored (site B) – and involved extensive monthly sampling, installation of flow weirs, shallow observation wells, and meteorological stations.

The results show that restoration affects the dynamics of HS occurrence. In surface and groundwater from the restored site, higher minimum HS concentrations and greater annual variability were observed, whereas the non-restored site showed lower minimum but higher maximum concentrations under dry hydrological conditions – when surface runoff and the associated transport of substances are minimal. The ratio of humic to fulvic acids (HA/FA), important in terms of water treatment and chemical behaviour, was less favourable in the restored site, indicating a higher proportion of poorly degradable fulvic acids.

During significant rainfall-runoff events, HS concentrations decreased, but the overall volume of mobilized organic matter increased. The study also demonstrated a notable self-purifying effect of the recipient stream, which reduced occasional higher HS concentrations from restored sites, and a positive effect of the retention reservoir on water chemistry, with reduced peak HS concentrations and an increased HA/FA ratio at the outflow.

The findings provide valuable insights for planning water management measures in peatland areas and help to clarify the dynamics of organic substances within peat bogs and their drainage systems. The results may contribute to improving the quality of water sources when planning restoration efforts in peatlands affected by peat extraction.

INTRODUCTION

The hydrological significance of mountain peatlands has long been debated, particularly regarding their contribution to the hydrological regime. This includes their role in retaining water during periods of high precipitation, supporting base flow in streams during dry periods, and influencing water chemistry through peatland restoration. Restoration typically involves blocking drainage channels, which were originally created to drain the peatland for peat extraction. Expert opinions on the influence of peatlands on the hydrological regime of catchments are contradictory; for example, study [1] highlights the benefits of peatlands and their restoration in stabilising the hydrological regime in the Šumava region. In contrast, study [2] finds no significant contribution of peatlands to water retention or the maintenance of water supplies during dry periods in the same region. To monitor these hydrological and, in particular, hydrochemical processes, and to clarify some disputed hypotheses, a comprehensive monitoring programme was initiated in the Ore Mountains peatlands near the village of Hora Svatého Šebestiána. The monitoring covers both quantitative and qualitative aspects of hydrology. This paper focuses on the results describing the content of humic substances (HS) in surface and subsurface waters in both restored and non-restored parts of the peatland.

Description of the Study Area

The study area comprises two experimental sites, A and B (*Fig. 1*), located in the central part of the Ore Mountains, southwest of the village of Hora Svatého Šebestiána, at an altitude of 850–895 m a.s.l. Both sites are peatlands with a history of completed peat extraction, which left drainage channels that artificially lowered the groundwater level. These channels are currently being gradually restored through the construction of weirs, aimed at returning the hydrological regime to a state closer to natural conditions. Site A covers approximately 0.4 km^2 and is characterised mainly by sparse dwarf pine and spruce stands in the peripheral areas, which transition into grassland. Site B occupies roughly 1 km^2 and exhibits a more diverse structure, spanning two hydrological catchments: the Chomutovka River to the north and the Prunéřovský Stream to the south. At the edge of site B lies Novoveský Pond, with an area of 3.86 ha, which historically served as a water reservoir for the Chomutovka River. At present, the area is a valuable habitat providing refuge for protected animal species. A particular feature of the site is the Chomutovka diversion channel, which supplements the natural flow of the Chomutovka River with water from the Černá River catchment. The diversion passes through both study sites and alters the natural runoff patterns, although its current function is limited due to its reconnection to the Černá River.

The geological substrate consists of rocks of the Ore Mountains crystalline complex, specifically paragneisses, orthogneisses, and amphibolites, with occurrences of skarns. Overlying these are Quaternary sediments, predominantly clayey and peat-rich. From a hydrogeological perspective, the area is a fractured-rock aquifer with very low permeability peat layers, which act as a natural barrier.

From a pedological perspective, the area is predominantly covered by modal podzols, with gley soils and histosols occurring in permanently waterlogged locations. According to Quitt, the climate falls within the mountainous CH6 region, characterised by a long, wet winter and a short, cool summer.

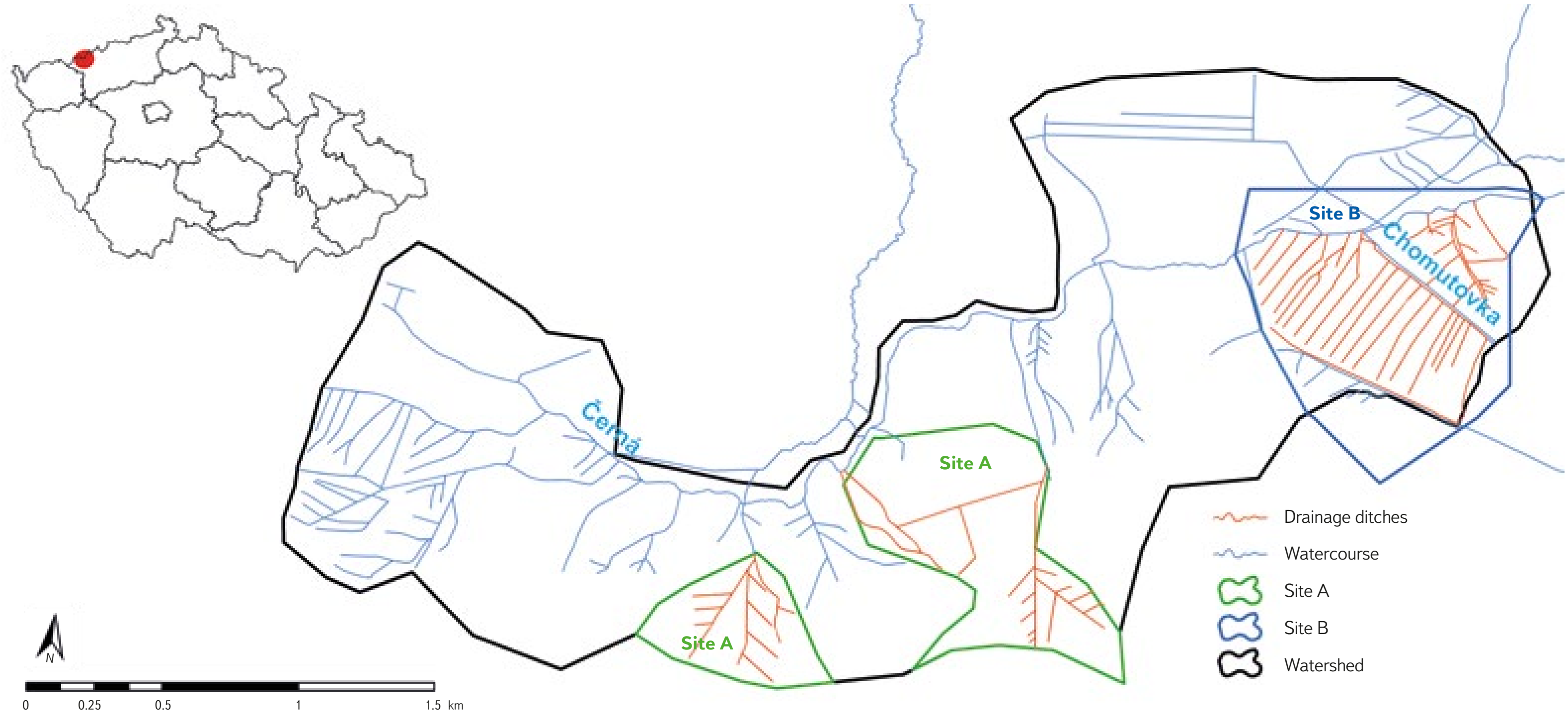

Fig. 1. Schematic diagram of monitoring sites A and B (site A on the left corresponds to the watershed for profile V1-CH1, see *Fig. 2*); in many cases, the Chomutovka watershed does not respect the slope conditions of the catchment area due to drainage channels, therefore, the watershed is based to a certain extent on field surveys and subsequent expert estimates

The site is located within the Ore Mountains protected area of natural water accumulation (CHOPAV) and lies close to the protection zones of groundwater sources supplying the village of Hora Svatého Šebestiána. Historically, the area has been affected by mining activities, particularly remnants of ore extraction from the 14th–17th centuries. These features may locally influence the hydrological regime.

Humic substances in peatlands

HS, particularly humic and fulvic acids, are the main components of dissolved organic matter (DOM), which is released in significant amounts from peatlands into surface and groundwater. These substances have a complex macromolecular structure rich in aromatic and functional oxygen groups [3], giving them a high affinity for forming complexes with metals (e.g., Fe, Al, Cu) and the ability to influence the transport of toxic substances in the environment. From the perspective of drinking water treatment, HS pose a significant problem: during chlorination, they can react with disinfectants (particularly chlorine compounds) to form disinfection by-products, many of which (e.g., trihalomethanes) are carcinogenic [4, 5]. In addition, they increase the need for coagulants and adsorbents during water treatment [6], reduce filtration efficiency, and can negatively affect the taste and smell of water [7]. In areas with peatlands, particularly during periods of high flow, the concentration of dissolved organic carbon (DOC) in raw water sources fluctuates, complicating the technological stability of treatment plants and increasing operational costs [8].

In the Ore Mountains, the occurrence and behaviour of HS in peatlands have been investigated in several significant studies, with attention given both to natural factors (hydrological regime, botanical composition) and to the influence of anthropogenic acidification and land-use changes. Pokorný et al. analysed the long-term development of peatlands using palaeoecological methods, including the impact of climatic extremes on the accumulation and transformation of organic matter [9]. Charamba et al. mapped the chemical composition of water in peatlands across central Europe, including sites in the Ore Mountains, and demonstrated that the local raised bogs have a high proportion of aromatic DOM fractions with low biodegradability [10]. Studies from the Boží Dar and Cínovec peatlands further show that following drought episodes and subsequent rewetting, there is a pronounced pulsed release of DOC into receiving waters, confirming the sensitivity of these systems to climatic extremes [11]. Some studies have also demonstrated a relationship between fulvic acid concentration and increased iron mobility, which has a direct impact on eutrophication and the water chemistry of adjacent streams [12]. These findings are crucial not only for the ecological protection of peatland ecosystems but also for the optimisation of water management measures in catchments with a significant proportion of wetland areas.

METHODOLOGY

Monitoring

Monitoring of the peatlands in sites A and B was designed as a comprehensive system to observe hydrological and climatic conditions in an environment altered by historical peat extraction. The overall aim of the monitoring is to evaluate the effectiveness of restoration measures, which involve the construction of weirs to retain water and raise groundwater levels, and to assess their impact on changes in the chemistry of surface and groundwater, with a focus on the occurrence of organic substances. Restoration in the form of blocking drainage channels has already been completed across almost the entire area of site A. In contrast, site B remains largely in a pre-restoration state, and manual sampling is focused in these areas. As part of the monitoring, wells, flow weirs, meteorological stations, and automatic samplers were installed at both sites, allowing observation of the status and chemistry of surface and groundwater, precipitation, temperature, air humidity, and snow water equivalent. For the evaluation of HS occurrence, the part of the monitoring network focused on water chemistry was used. The other measurement points served, among other purposes, to monitor background processes associated with the dynamics of organic substances in surface and groundwater.

For the comprehensive monitoring of site A (*Fig. 2*), the existing well network of series P, PA, and PV was used, in which groundwater level, temperature, and conductivity are measured manually twice a year. In addition, wells of series D1 to D5 were installed, equipped with pressure sensors for continuous measurement of groundwater level and temperature. Selected wells, such as D2 and D5, were installed as paired wells – one penetrating only the upper peat layer (acrotelm), while the other reached the lower peat layer (catotelm). Wells D1 and D3 also serve for monthly water sampling for laboratory chemical analyses.

Site A contains four flow weirs: V1-CH5, located at the eastern edge with a triangular profile (so-called Thomson weir); V2, in the west, equipped with a circular weir and built directly into the dam structure; V3, situated in the southeastern part, which drains water from the forested area; and V1-CH1, located approximately 400 m west of profile V2, which serves exclusively as a reference point for manual surface water sampling without continuous measurement. All weirs are equipped with sensors for measuring water level, temperature, conductivity, and pH, and weirs V3 and V1-CH5 are used for surface water sampling.

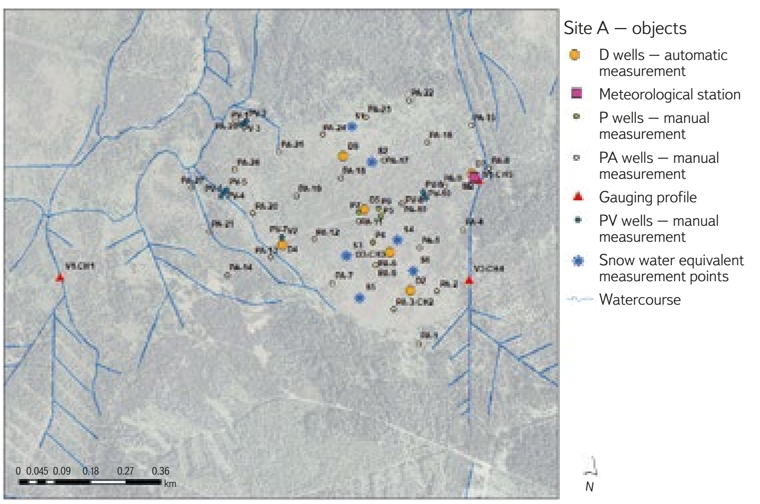

Fig. 2. Monitoring facilities in site A

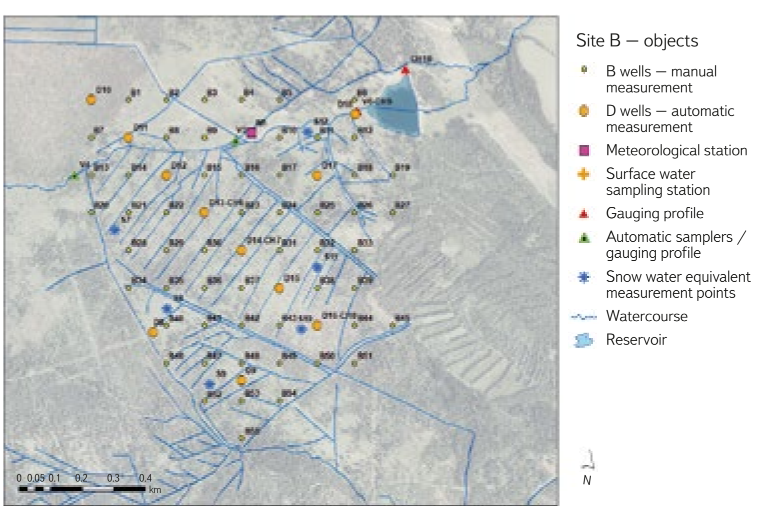

Fig. 3. Monitoring facilities in site B

Hydrological monitoring in site B (*Fig. 3*) was considerably expanded. Fifty-five shallow wells of series B, with a maximum depth of 3 m, were installed in a regular grid covering both restored and non-restored parts of the peatland. In addition, wells of series D8 to D18 were installed, with D11, D14, and D16 also set up as paired wells to compare water levels between the acrotelm and catotelm. Wells D8, D14, and D16 are also used for water sampling and chemical analysis. This observation network provides detailed information on the hydrological conditions across the peatland.

Surface waters in site B are monitored through several flow weirs. Weir V4, in the western part, is equipped with a rectangular notch and it monitors inflow from the area below Jelení hora. V5 is located on the Chomutovka diversion channel and is fitted with an ultrasonic sensor. Weir V6, situated on the Chomutovka River, is located at the last weir before the inflow into Novoveský Pond and is used for sampling. For sampling the Chomutovka River below the pond, profile CH10 is used downstream of the safety weir, where manual hydrometric measurements are conducted.

Meteorological stations are installed at both sites. In site A, a basic station records air temperature, humidity, and precipitation. In site B, a comprehensive climatological station additionally measures wind speed and direction, solar radiation, soil heat flux, and soil moisture. For year-round precipitation measurements, a heated rain gauge was installed in the village of Hora Svatého Šebestiána, which also serves to trigger automatic samplers during rainfall events.

Groundwater

Groundwater samples are collected monthly from selected wells of series D. These include wells D1-CH2 and D3-CH3 in site A, and wells D8-CH6, D14-CH7, and D16-CH8 in site B. Sampling was always scheduled at the end of each month, taking care to ensure stable and consistent meteorological and hydrological conditions. This means that no significant hydrometeorological extremes occurred during or immediately before sampling that could have temporarily affected groundwater quality. Samples are transported to the VZlab laboratory, where the following parameters are determined:

Chemical oxygen demand (COD-Mn), $N–NO_3^-$, $N–NO_2^-$, $N–NH_4^+$, total nitrogen (N_t), SO_4^{2-}, total phosphorus (P_t), Fe, Al (dissolved and particulate), DOC, A_{254}, $(A_{254}/DOC)*100$, total hardness (TH), HS, humic acids, and fulvic acids.

Surface water

Surface water samples are collected monthly together with groundwater sampling. The same rule applies: sampling is always conducted at the end of the month under as stable hydrometeorological conditions as possible. Sampling is carried out at weirs V1-CH5 (restored catchment), V3-CH4, and V7-CH1 (forest non-restored catchment) in site A, and in site B at weir V6-CH9 (*Fig. 4*) and at sampling site CH10 downstream of the safety flow weir of Novoveský Pond (non-restored catchment, *Fig. 6*). The current flow in the watercourse is recorded during sampling. Sampling sites V7-CH1 and CH10 do not have continuous water level measurements, therefore flows at the time of sampling are measured and calculated on site. At profile V7-CH1, a flow weir was installed for this purpose. At profile CH10, hydrometric measurements are conducted during sampling. Samples are then transported to the VZlab laboratory, where the following parameters are determined: COD-Mn, $N–NO_3^-$, $N–NO_2^-$, $N–NH_4^+$, N_t, SO_4^{2-}, P_t, Fe, Al (dissolved and particulate), DOC, A_{254}, $(A_{254}/DOC)*100$, TH, HS, humic acids, and fulvic acids.

The number of samples collected depends on hydrological conditions. During dry periods or generally in the summer months, groundwater levels may fall below the depth of the wells, and watercourses may dry out, making

Fig. 4. Measurement of chemical parameters of surface water at profile V6-CH9

sampling impossible. For each groundwater and surface water sample, supplementary measurements of conductivity and water pH are performed using an Aquatroll 500 multiparameter probe.

Samples are also collected using ISCO 6712 automatic samplers at profiles V4 and V5 (*Fig. 10*), designed to capture the chemical response of the watercourse to rainfall events. The parameters determined are the same as for manual sampling. Sampling is synchronous: when a hydrological event is anticipated, the sampler at V5 is activated via SMS. The V5 sampler is locally linked to the sampler at V4, which is outside stable GSM coverage, so V4 is triggered at the same time. A total of 24 samples are collected at two-hour intervals, of which 10 are selected for analysis, ideally covering the watercourse's response to precipitation. The reach between the two samplers is approximately 600 m long, receiving water from a single already restored area in site B, and the aim is to capture any chemical changes along this section.

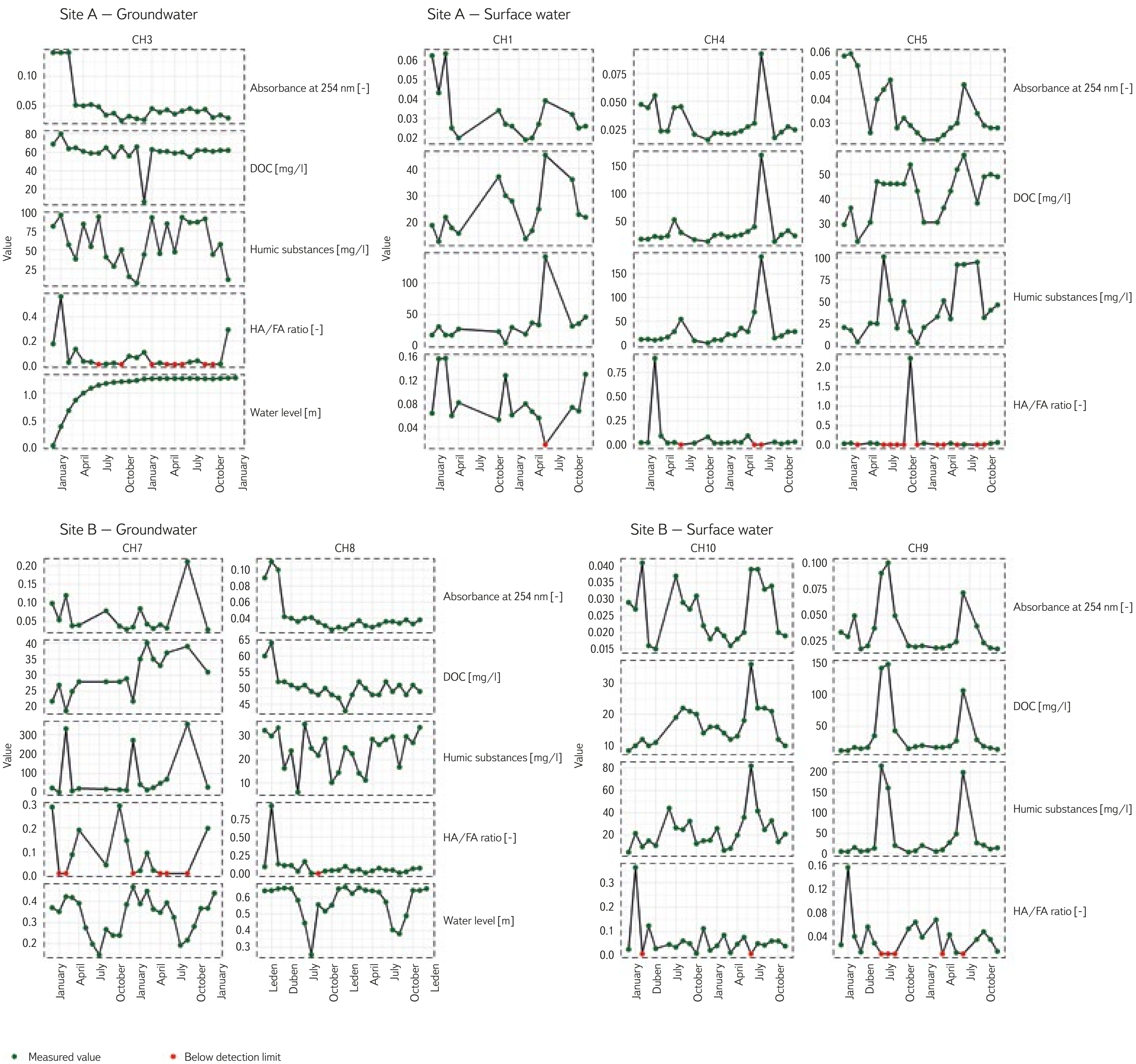

Fig. 5. Results of chemical analyses of selected parameters

Fig. 6. Sampling and measurement of chemical parameters of surface waters at profile V7-CH1

RESULTS

The following results are based on two years of monthly sampling. Of all the chemical parameters observed, this article focuses on HS and related indicators of the presence of organic matter in water (the ratio of humic to fulvic acids – HA/FA, dissolved organic carbon – DOC, and absorbance at 254 nm – A_{254}). *Fig. 5* shows the results for groundwater and surface water sampling sites CH1–CH10. Sites (wells) CH2 and CH6 were excluded from the evaluation because of the very low number of samples obtained, due to the absence of water in the wells. The results show seasonality in the HS content of surface waters, with concentrations increasing during summer low-flow conditions. In contrast, groundwater does not exhibit such pronounced fluctuations and no clear seasonality is apparent. Only well CH7 recorded three higher values, but these were measured at very low groundwater levels, which may have resulted in the sampling of sediment from the well bottom. In general, groundwater shows higher HS concentrations throughout the year, except in summer months, when surface water displays elevated concentrations not only of organic substances but, according to the analyses, also of metals (Fe, Al) and total nitrogen [13]. Other indicators linked to the presence of organic matter in water (DOC and A_{254}) exhibit similar patterns. Comparing concentration dynamics in surface water from restored (CH5) and non-restored sites (CH9 and CH10), profile CH5 shows higher minimum HS concentrations and overall greater variability during the year, while summer maxima are lower. By contrast, profile CH9 maintains consistently lower winter minima, but in summer reaches up to twice the HS concentrations. This results in fairly balanced average values over the entire monitoring period (*Tab. 1*): CH5 – 41.5 mg/l, CH9 – 40.7 mg/l. However, discharge during sampling has a significant influence on the total export of organic matter. The highest discharges usually occur in winter during snowmelt. While concentrations at profile CH9 during this period remain below 25 mg/l, those at CH5 are up to twice as high. Conversely, higher concentrations at CH9 are recorded under very low discharges of around 1 l/s or less. This results in a greater overall export of organic substances from the restored site. However, in comparison with the non-restored site, the higher concentrations in the restored site are reached even at higher discharges and during wetter periods, when the load of HS in the stream is quickly diluted by additional inflows with lower HS content. According to analyses carried out as part of a concurrently prepared bachelor thesis [14], concentrations of HS decreased by more than 80% along an approximately 5 km section of the Chomutovka Stream. To reduce the influence of occasionally occurring extreme values, *Tab.* 2 presents the median concentrations for each site: CH5 – 32 mg/l and CH9 – 15 mg/l.

For groundwater, higher HS concentrations are recorded for most of the year at well CH3 in the restored site. The overall average is highest at CH7, but this is due to the three previously mentioned outlying values. However, considering the median concentrations, well CH7 has similar HS levels to CH8, which is located in a drained but relatively intact part of the peatland and exhibits the lowest HS concentrations. The highest median concentration is observed at well CH3 in the restored site.

Water quality is affected not only by HS concentrations but also by the ratio of humic to fulvic acids (HA/FA). A higher proportion of fulvic acids negatively impacts drinking water treatment because they are more soluble and more difficult to remove. The HA/FA values are close to zero and only occasionally exceed 1. No seasonality is apparent, and each series contains one or two outliers that are unrelated to water level or season. Therefore, conclusions are based on the median values shown in *Tab.* 2. The lowest HA/FA ratio, and thus the highest proportion of more persistent fulvic acids, occurs in the restored part of site A, specifically at sampling sites CH5 and CH3. By contrast, the highest values were recorded at the profile draining the forested area (CH1), at well CH8 in the non-restored site, and at profile CH10 at the reservoir outflow.

Tab. 1. Average values of the monitored chemical parameters; the worst results in terms of water quality are highlighted in bold

Parameter	CH1	CH3	CH4	CH5	CH7	CH8	CH9	CH10
Absorbance at 254 nm [-]	0.03	0.05	0.03	0.04	**0.06**	0.04	0.03	0.03
DOC [mg/l]	24.33	**59.96**	32.33	41.9	29.88	50.46	36	16.34
Humic substances [mg/l]	34.35	59.36	29.68	41.49	**83.01**	23.8	40.7	23.59
HA/FA ratio [mg/l]	0.08	0.07	0.08	0.13	0.09	0.1	**0.04**	0.06

Tab. 2. Median values of the monitored chemical parameters; the worst results in terms of water quality are highlighted in bold

Parameter	CH1	CH3	CH4	CH5	CH7	CH8	CH9	CH10
Absorbance at 254 nm [-]	0.03	**0.04**	0.02	0.03	**0.04**	**0.04**	0.02	0.02
DOC [mg/l]	22	**61.5**	24	46	28.5	50	18	15
Humic substances [mg/l]	29.7	**55.6**	18.6	32	28.5	25.8	15	20.8
HA/FA ratio [mg/l]	0.07	0.02	0.03	**0.01**	0.03	0.06	0.03	0.05

During the monitoring period, a significant rainfall-runoff event was recorded using automatic samplers from 13 to 15 September 2024. The samplers were synchronously activated before the onset of the runoff response and collected samples at 2-hour intervals over a period of 40 hours. To capture both the rising and falling stages of the water level, 10 samples were selected for analysis at 4-hour intervals. The results shown in *Figs. 7* and *8* indicate a similar pattern of change in HS and DOC concentrations. At the start of the event, concentrations are high, and as discharge increases, they decrease during the first 12 hours to values that remain relatively stable thereafter, even though discharge continues to rise significantly. This pattern is consistent for both sampling profiles, even though channels from the restored part of site B discharge into the stream between them. HS concentrations also decrease by almost half between the sampling sites. The HA/FA ratio between the samplers increases, particularly during the peak of the event. No increase in HS concentrations caused by inflow from the restored site was observed between profiles V4 and V5. When HS concentrations are converted to the total exported mass, the results are given in *Tab. 3*. At the start of the event, under the lowest discharge and highest concentration, HS export was 258.3 mg/s. By contrast, immediately before the peak, HS concentrations are still decreasing, and export reaches 12,650.1 mg/s. At the peak, it declines to 7,628 mg/s. HS concentrations then gradually increase; however, the decreasing discharge causes a slow decline in exported HS mass. Over the 40-hour monitoring period, approximately 771 kg of HS were exported through the profile. This topic is also addressed in the bachelor's thesis [15].

Tab. 3. Calculated amount of exported HS during the significant rainfall-runoff event from 13–15 September 2024 at profile V5

Time	Flow rate [l/s]	HL [mg/l]	Exported HL [mg/s]	Exported HL [kg/4h]
13.09.2024 15:00	2.8	92.6	258.3	3.7
13.09.2024 19:00	9.7	60.6	585.4	8.4
13.09.2024 23:00	123.9	43.3	5,364.3	77.2
14.09.2024 3:00	300.5	42.1	12,650.5	182.2
14.09.2024 7:00	312.6	24.4	7,628.0	109.8
14.09.2024 11:00	268.7	32.5	8,732.5	125.7
14.09.2024 15:00	188.8	33.1	6,248.1	90.0
14.09.2024 19:00	130.6	43.9	5,733.0	82.6
14.09.2024 23:00	92.2	37.8	3,483.5	50.2
15.09.2024 3:00	67.2	42.8	2,875.4	41.4

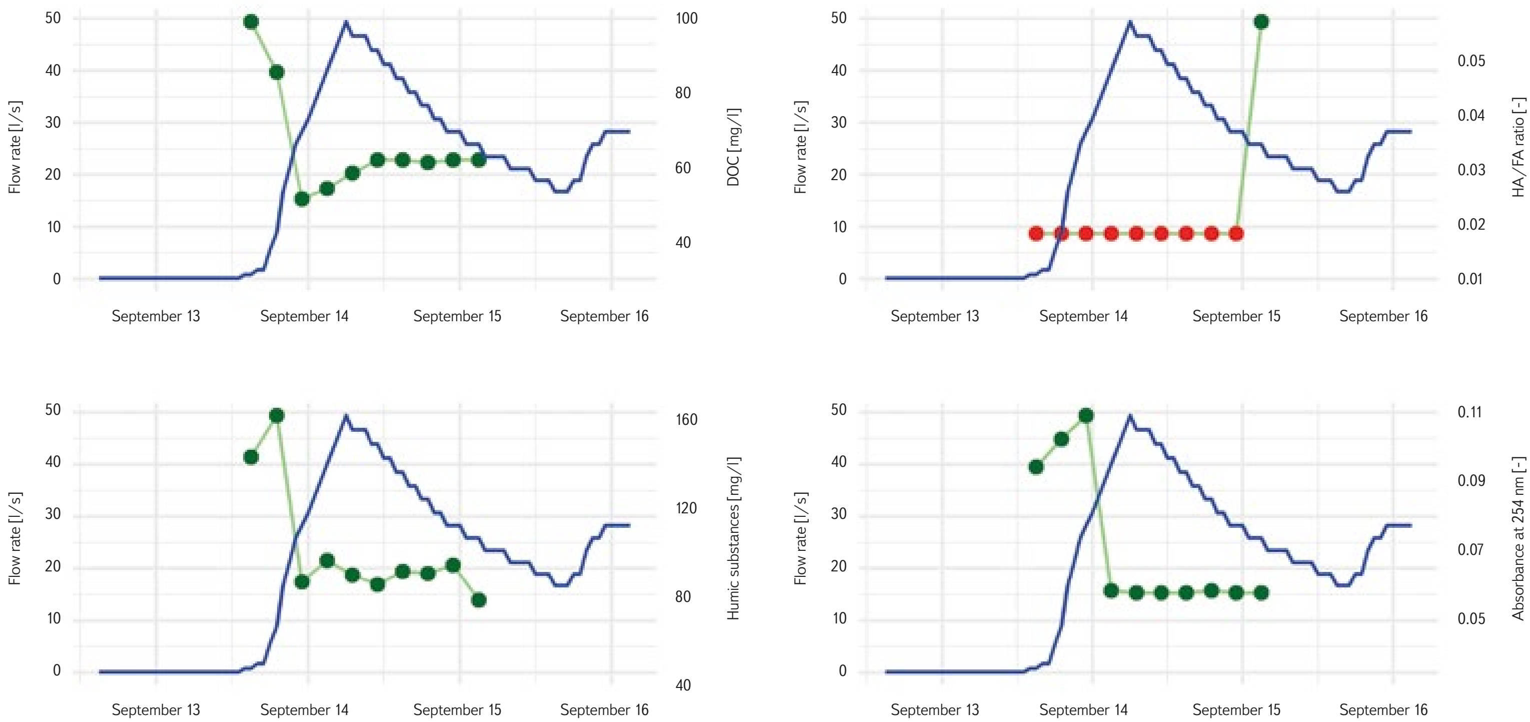

Fig. 7. Results of automatic sampling during the significant rainfall-runoff event from 13–15 September 2024 at profile V4

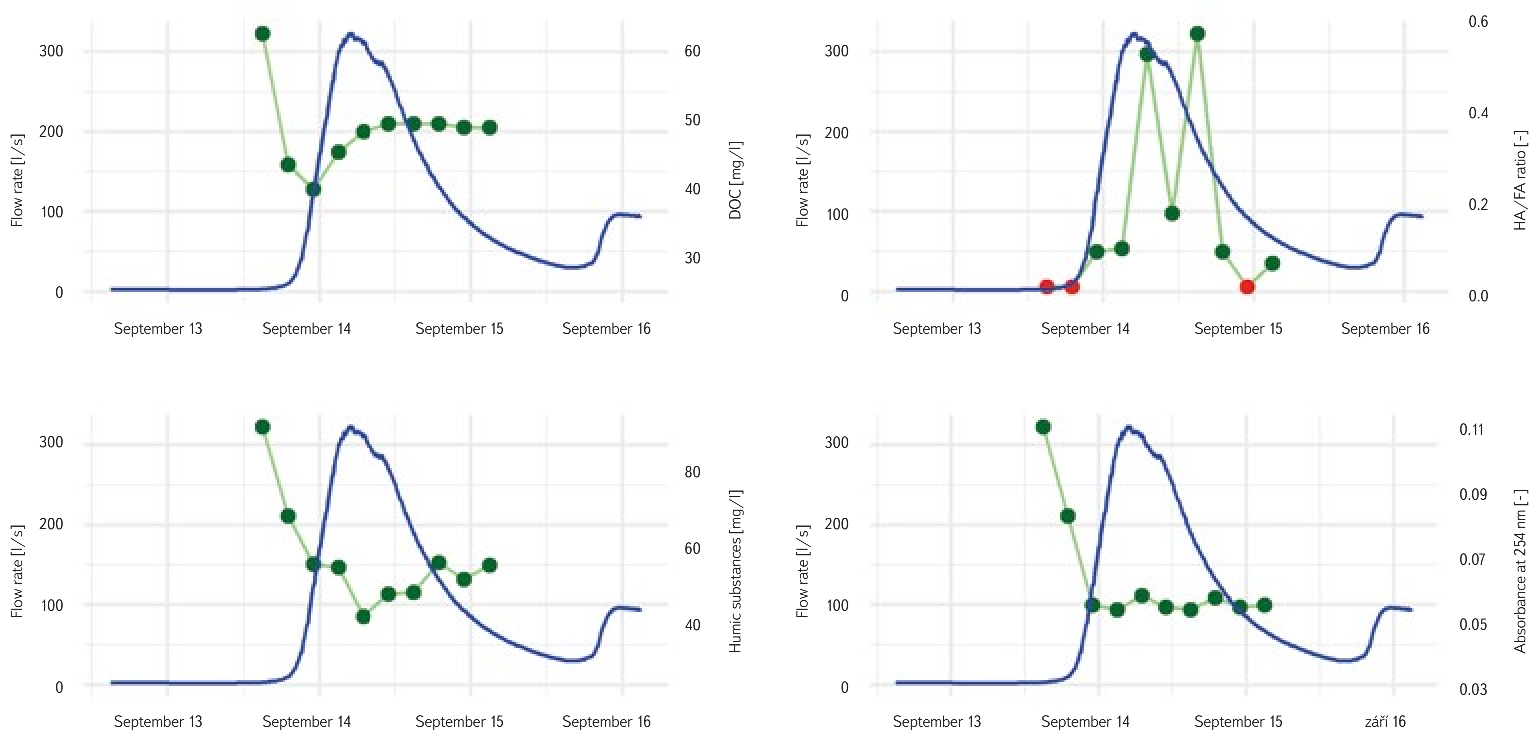

Fig. 8. Results of automatic sampling during the significant rainfall-runoff event from 13–15 September 2025 at profile V5

Given the increase in discharge between the two profiles, it can be assumed that the stream also receives a substantial contribution from the non-restored site. In this case, a precise delineation of the catchment and source areas for each sampler profile would be beneficial. However, this is essentially impossible because the stream itself is an artificially constructed channel crossing natural watercourses and is connected to a network of drainage channels, which overflow into other drainage paths during higher flows.

Effect of the reservoir on stream water chemistry

The positive effect of Novoveský Pond on stream water chemistry is already evident from the results shown in *Tab. 1*, *Tab. 2*, and *Fig. 5*. *Fig. 9* illustrates the percentage change in concentrations of all monitored substances between profile CH9 above the reservoir and profile CH10 below it. Decreases were observed for DOC, aluminium, absorbance, chemical oxygen demand determined by permanganate (COD_{mn}), conductivity, total phosphorus, total nitrogen, and sulphates. An increase in pH and the ratio of humic to fulvic acids (HA/FA), reflecting a higher proportion of humic acids, can also be considered beneficial. Acid neutralising capacity ($ANC_{4.5}$) was also increased, most likely as a result of the higher pH.

A slight increase in undesirable parameters was observed for dissolved iron concentrations. Although DOC values are low, the higher pH creates more favourable conditions for the release of metals into the water column. The increase in pH is also associated with higher bicarbonate concentrations. Values of the indicator (A_{254}/DOC) * 100 are elevated, reflecting both the higher proportion of humic acids and the decomposition of organic matter accumulated on the reservoir bottom.

Probable mechanisms contributing positively to HS content and the HA/FA ratio include exposure to sunlight, which induces photodegradation and reduces the molecular weight of humic acids. Microbial activity and the presence of iron and aluminium also play a role, facilitating complexation and the coagulation of HS into sediments [16, 17]. The transformative effect of the reservoir is also significant, as it dilutes higher concentrations entering from the inflow to lower levels. Consequently, in the stream below the reservoir, minimum concentrations of chemical parameters are higher compared with the inflow, while maximum values, typical of the water entering the reservoir, are substantially reduced.

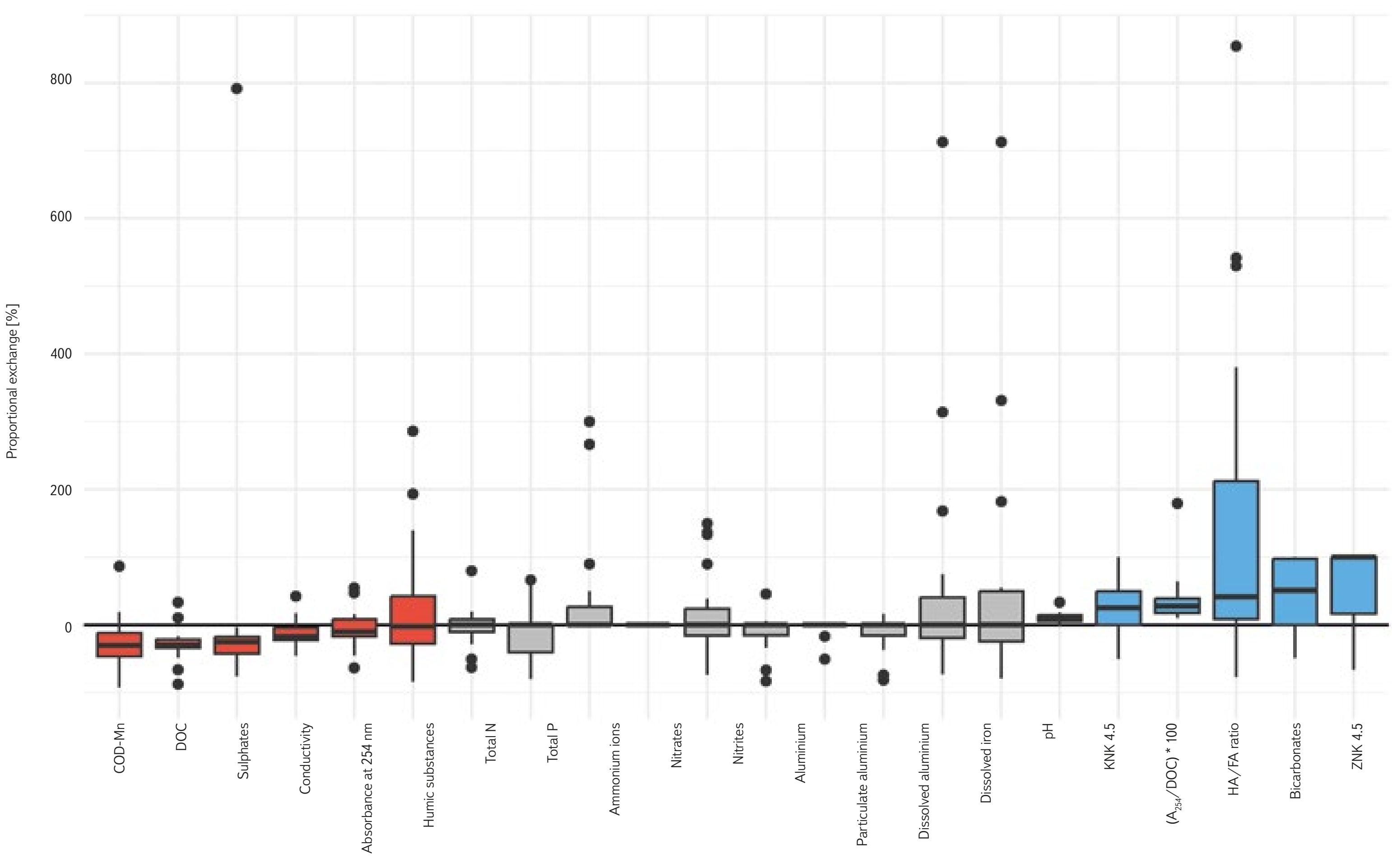

Fig. 9. Box plots of percentage change in substance concentrations between profiles CH9 upstream of the reservoir and CH10 downstream of the reservoir; the main part is the "box" between the first and third quartiles, inside which is a line indicating the median; the box has "whiskers" that show the range of data outside the quartiles (typically up to 1.5 times the interquartile range); outliers are shown as separate points outside the whiskers

Fig. 10. Water channel with an automatic sampler at profile V5

DISCUSSION

The effect of peatland restoration on HS content in groundwater and surface water cannot be generalised, as each hydrological system within a peatland may respond differently. For example, study [18] reports a long-term increase in organic matter concentrations in water. In contrast, other studies document a sudden increase in concentrations immediately following restoration, followed by a decline, although values remain higher than the original levels [19, 20]. Some studies, on the other hand, report no changes in organic matter concentrations [21, 22]. There are even studies documenting a decrease in organic matter concentrations following the damming of drainage channels and an increase in groundwater level [23–25]. For example, study [23] attributes the decline in HS concentration to the elevated groundwater level, which dilutes concentrations throughout the peatland. However, higher degrees of wetness are generally cited as a reason for increased export of organic matter.

Study [26] in the Kamenička and Fláje catchments also examined the relationship between organic matter content, precipitation, and discharge, reporting the highest export of substances 1–2 days after rainfall. In our study area, where we focused primarily on the peak flow period, concentrations of the monitored substances increased immediately at the onset of the rising water level or were followed directly by a decrease due to dilution by rainwater. However, as shown by calculations of total exported mass, a much larger quantity of organic matter is transported during periods of lower concentration combined with higher discharge than during low discharge and high concentrations. The study also describes a positive effect of the reservoir on organic matter concentrations. However, this is probably primarily due to the temporal transformation of higher concentrations at the inflow, as observed for Novoveský Pond. For example, the study reports the largest measured differences during periods of minimal discharge, when the total mass balance of substances is negligible. In contrast, during higher flows, concentrations at the reservoir outflow may exceed those at the inflow. Finally, the study confirms findings related to self-purification processes in the stream, which we also observed in the Chomutovka River.

The above results highlight the importance of site-specific research, which provides a comprehensive insight into hydrological processes and the effectiveness of remedial measures implemented locally. They also indicate that the hydrochemical behaviour of these human-impacted wetland catchments is highly variable, whether due to the age and nature of the restorations themselves or the morphology of the catchment. Consequently, findings from such sites are valuable, but their transferability is limited. Data from this monitoring will therefore be further applied in locally focused projects, such as the *RUR: Region to University, University to Region* CZ.10.02.01/00/22_002/0000210 project, which addresses conditions in the Ústí nad Labem Region.

CONCLUSION

Hydrological monitoring of peatland habitats, ongoing since December 2022 in the Prameniště Chomutovky nature reserve, focuses on hydrological and hydrochemical processes in restored and non-restored sites affected by peat extraction. The project is conducted under a public procurement for the Ústí nad Labem Region and provides results with significance extending beyond the Chomutovka catchment, as it represents a source area with higher demands on water quality for drinking water supply. The aim is to maintain long-term monitoring at the site, focused on evaluating the impacts of restoration on both quantitative and qualitative hydrology. This article presents only a portion of the monitoring results, specifically those related to the assessment of HS in surface and groundwater. The overall monitoring will continue at least until the end of 2025, providing an opportunity to present broader conclusions.

Monitoring of HS concentrations in the peatlands of the study area near Hora Svatého Šebestiána shows higher concentrations in the restored site, where drainage channels were dammed and the groundwater level increased. While concentrations in wells fluctuate within a similar range throughout the year, even during summer declines in groundwater level, surface waters exhibit a marked increase in concentrations at low flow rates. However, due to the low flow, the amount of exported organic matter at that time is small. This amount increases during runoff events in response to significant rainfall, even though HS concentrations decrease under these conditions. Based on observations from streams draining the peatlands, it can be concluded that even occasional elevated concentrations of HS from restored or non-restored sites do not have a significant impact on water quality in the Chomutovka Stream itself. Self-purification and dilution processes cause a rapid decrease in HS and DOC concentrations, as shown by results from automatic samplers installed 500 m apart, and also along approximately 5 km of the Chomutovka Stream, where HS concentrations decrease by more than 80 %.

As an appropriate measure to improve water quality and prevent short-term occurrences of elevated concentrations of substances that degrade water quality, the installation of a reservoir at the outflow from the peatland area appears beneficial. Within the monitoring, water chemistry was observed at profile CH9 at the reservoir inflow and at profile CH10 at the reservoir outflow. For HS, a temporal transformation of concentrations was observed, with a marked reduction in maximum values and a corresponding increase in minimum values, as accumulated HS are gradually released from the reservoir. This process is expected, but it is also accompanied by an increase in the HA/FA ratio at the outflow, indicating that more undesirable fulvic acids undergo decomposition or sedimentation within the reservoir. Additionally, pH and the $ANC_{4.5}$ and $BNC_{4.5}$ parameters increase, contributing to improved biological stability.

Acknowledgements

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References

[1] BUFKOVÁ, I., STIBAL, F., MIKULÁŠKOVÁ, E. Restoration of Drained Mires in the Šumava National Park, Czech Republic. In: EISELTOVÁ, M. (ed.). *Restoration of Lakes, Streams, Floodplains, and Bogs in Europe: Principles and Case Studies*. Dordrecht: Springer, 2010, pp. 331–354. ISBN 978-90-481-9264-4.

[2] VLČEK, L. et al. Retenční potenciál a hydrologická bilance horského vrchoviště: případová studie Rokytecké slatě, povodí horní Otavy. JZ. Česko. *Geografie*. 2012, 117(4), pp. 395–414. Available at: https://geografie.cz/media/pdf/geo_2012117040395.pdf

[3] KALBITZ, K., SOLINGER, S., PARK, J.-H., MICHALZIK, B., MATZNER, E. Controls on the Dynamics of Dissolved Organic Matter in Soils: A Review. *Soil Science*. 2000, 165(4), pp. 277–304. Available at: https://doi.org/10.1097/00010694-200004000-00001

[4] RECKHOW, D. A., SINGER, P. C., MALCOLM, R. L. Chlorination of Humic Materials: Byproduct Formation and Chemical Interpretations. *Environmental Science & Technology*. 1990, 24(11), pp. 1 655–1 664. Available at: https://doi.org/10.1021/es00081a005

[5] IMAI, A., FUKUSHIMA, T., MATSUSHIGE, K., KIM, Y. H., CHOI, K. Characterization of Dissolved Organic Matter in Effluents from Wastewater Treatment Plants. *Water Research*. 2002, 36(4), pp. 859–870. Available at: https://doi.org/10.1016/S0043-1354(01)00283-4

[6] EDZWALD, J. K. Coagulation in Drinking Water Treatment: Particles, Organics and Coagulants. *Water Science and Technology*. 1993, 27(11), pp. 21–35. Available at: https://doi.org/10.2166/wst.1993.0261

[7] VOLK, C., BELL, K., IBRAHIM, E., VERGES, D., AMY, G., LECHEVALLIER, M. Impact of Enhanced and Optimized Coagulation on Removal of Organic Matter and its Biodegradable Fraction in Drinking Water. *Water Research*. 2000, 34(12), pp. 3 247–3 257. Available at: https://doi.org/10.1016/S0043-1354(00)00033-6

[8] MATILAINEN, A., GJESSING, E. T., LAHTINEN, T., HED, L., BHATNAGAR, A., SILLANPÄÄ, M. An Overview of the Methods Used in the Characterization of Natural Organic Matter (NOM) in Relation to Drinking Water Treatment. *Chemosphere*. 2011, 83(11), pp. 1 431–1 442. Available at: https://doi.org/10.1016/j.chemosphere.2011.01.018

[9] JANKOVSKÁ, V., POKORNÝ, P. Reevaluation of the Palaeoenvironmental Record of the Former Komořanské Jezero Lake: Late-Glacial and Holocene Palaeolimnology and Vegetation Development in North-Western Bohemia, Czech Republic. *Preslia*. 2013, 85(3), pp. 265–287.

[10] CHARAMBA, L. V. C. et al. Tracing Sources of Dissolved Organic Matter along the Terrestrial-Aquatic Continuum in the Ore Mountains (Germany). *Science of the Total Environment*. 2024, 943, 173807. Available at: https://doi.org/10.1016/j.scitotenv.2024.173807

[11] MATOUŠKOVÁ, M. et al. Response of Dissolved Organic Carbon in Streams Draining Peatbogs to Extreme Rainfall-Runoff Events: A Case Study from Šumava (Bohemian Forest) National Park, Czech Republic. *Environmental Earth Sciences*. 2024, 83, 491. Available at: https://doi.org/10.1007/s12665-024-11804-x

[12] KOPÁČEK, J., KLEMENTOVÁ, Š., NORTON, S. A. Photochemical Production of Ionic and Particulate Aluminum and Iron in Lakes. *Environmental Science & Technology*. 2005, 39(10), pp. 3 656–3 662. Available at: https://doi.org/10.1021/es048101a

[13] VOKOUN, M., MORAVEC, V., ECKHARDT, P., PRINZ, J. *Monitoring rašelinných biotopů 2022–2025 – Závěrečná zpráva*. Prague: TGM WRI, 2025.

[14] GRZNÁR, D. *Vliv revitalizace rašelinišť u Hory Svatého Šebestiána na organické látky v Chomutovce. Bakalářská práce*. Ústí nad Labem: J. E. Purkyně University, Faculty of Environmental Sciences, 2024.

[15] BARTŮŇKOVÁ, L. *Hydrologický režim rašeliniště při vybraných srážkoodtokových událostech. Bakalářská práce*. Prague: Czech University of Life Sciences Prague, Faculty of Environmental Sciences, 2025.

[16] MORAN, M. A., ZEPP, R. G. Role of Photoreactions in Formation of Biologically Labile Compounds from Dissolved Organic Matter. *Limnology and Oceanography*. 1997, 42(6), pp. 1 307–1 316. Available at: https://doi.org/10.4319/lo.1997.42.6.1307

[17] HELMS, J. R., MAO, J., SCHMIDT-ROHR, K., ABDULLA, H., MOPPER, K. Photochemical Flocculation of Terrestrial Dissolved Organic Matter and Iron. *Geochimica et Cosmochimica Acta*. 2013, 121, pp. 398–413. Available at: https://doi.org/10.1016/j.gca.2013.07.025

[18] STRACK, M. et al. Changes in Dissolved Organic Carbon Quality in Soils and Discharge 10Years after Peatland Restoration. *Journal of Hydrology*. 2015, 527, pp. 345–354. Available at: https://doi.org/10.1016/j.jhydrol.2015.04.061

[19] KOSKINEN, M. et al. Restoration of Nutrient-Rich Forestry-Drained Peatlands Poses a Risk for High Exports of Dissolved Organic Carbon, Nitrogen, and Phosphorus. *Science of the Total Environment*. 2017, 586, pp. 858–869. Available at: https://doi.org/10.1016/j.scitotenv.2017.02.065

[20] BERNARD-JANNIN, L. et al. Hydrological Control of Dissolved Organic Carbon Dynamics in a Rehabilitated *Sphagnum*-Dominated Peatland: A Water-Table Based Modelling Approach. *Hydrology and Earth System Sciences*. 2018, 22(9), pp. 4 907–4 920. ISSN 1607-7938. Available at: https://doi.org/10.5194/hess-22-4907-2018

[21] PEACOCK, M. et al. Peatland Ditch Blocking Has no Effect on Dissolved Organic Matter (DOM) Quality. *Hydrological Processes*. 2018, 32(26), pp. 3 891–3 906. Available at: https://doi.org/10.1002/hyp.13297

[22] STRACK, M. et al. Changes in Dissolved Organic Carbon Quality in Soils and Discharge 10Years after Peatland Restoration. *Journal of Hydrology*. 2015, 527, pp. 345–354. Available at: https://doi.org/10.1016/j.jhydrol.2015.04.061

[23] GATIS, N. et al. Peatland Restoration Increases Water Storage and Attenuates Downstream Stormflow but Does Not Guarantee an Immediate Reversal of Long-Term Ecohydrological Degradation. *Scientific Reports*. 2023, 13, 15865. Available at: https://doi.org/10.1038/s41598-023-40285-4

[24] ARMSTRONG, A. et al. The Impact of Peatland Drain-Blocking on Dissolved Organic Carbon Loss and Discolouration of Water; Results from a National Survey. *Journal of Hydrology*. 2010, 381(1–2), pp. 112–120. Available at: https://doi.org/10.1016/j.jhydrol.2009.11.031

[25] HÖLL, B. S. et al. Characteristics of Dissolved Organic Matter Following 20Years of Peatland Restoration. *Science of the Total Environment*. 2009, 408(1), pp. 78–83. Available at: https://doi.org/10.1016/j.scitotenv.2009.08.046

[26] JURÁSEK, A. et al. *Výzkum možnosti minimalizace obsahů organických škodlivin ve zdrojích pitných vod v Krušných horách*. Fláje: Povodí Ohře, státní podnik, 2013. Available at: https://www.poh.cz/c-100018967-vyzkum-moznosti-minimalizace-obsahu-organickych-skodlivin-vezdrojich-pitnych-vod-v-krusnych-horach/d-1320

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The impact of hydrological extremes on ponds and small water reservoirs

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Keywords: pond — small reservoir — drought — minimum residual flow — flood — flood safety

ABSTRACT

This paper presents the methodological approach and key results of the research project *Design of ponds and small reservoirs in terms of the possibility to comply with MPF and flood safety* (TA CR, no. SS03010230). The project focused on the assessment of ponds, pond systems and small reservoirs in relation to two hydrological extremes – draught and floods. During periods of drought, the issue of maintaining the minimum residual flow is addressed. The article describes the method of determining and maintaining the minimum residual flow at these hydraulic structures. Furthermore, the article deals with the assessment of the security of these structures in terms of the safe discharge of flood flows in accordance with ČSN 75 2935 – Assessment of the safety of hydraulic structures during floods.

INTRODUCTION

In recent decades, Czech Republic (Czechia) has been affected by flood events of varying frequency and spatial extent. Simultaneously, the country has experienced periods of prolonged drought, which have required significant restrictions from the perspective of water management and agricultural production. Considering the recorded and projected climate developments [1], the occurrence of hydrological extremes in the form of droughts and floods can be expected to continue in Czechia in the future.

Czechia is home to approximately 25,000 ponds and small reservoirs. In connection with the occurrence of hydrological extremes, questions have arisen regarding how existing ponds and small reservoirs can withstand exposure to these two extremes while continuing to fulfil their primary purpose. According to ČSN 75 2405, a pond is defined as "an artificially drainable reservoir with a natural bottom, primarily used for fish farming" [2]. A small reservoir is defined according to ČSN 75 2410 as "a reservoir with a volume up to the normal water level of less than 2 million m^3 and a water depth of less than 9 m" [3]. The purpose of such a reservoir may be, for example, storage, flood protection, fish farming, recreational, landscape, economic, water treatment, or remediation. Although these hydraulic structures (HS) represent a potential tool for water accumulation in the fight against drought, they are limited by their intended purpose and impose specific requirements on the hydrological regime. For example, a small reservoir used for fish farming may find it difficult during droughts to ensure supplementary releases for minimum residual flow (MRF). From the perspective of flood protection, the issue concerns securing these existing HS against the effects of floods with regard to the protection of the surrounding land, property, and human lives downstream. They should be equipped with a sufficiently sized safety spillway; however, this is not always the case. At present, existing ponds and small reservoirs exhibit certain deficiencies that prevent them from effectively meeting the required demands. The aim of the research project, involving co-investigators from the T. G. Masaryk Water Research Institute (TGM WRI) and VODNÍ DÍLA – TBD, a. s. (VD – TBD), was to evaluate their current problems and assess the possibilities regarding compliance with MRF and flood safety.

METHODOLOGY

Input data

The first step in the study was the selection of pilot sites, primarily in the South Bohemian Region. In selecting a representative set of 50 pilot ponds and small reservoirs, consideration was given not only to issues of MRF and flood safety but also to maintaining their diversity. Pilot sites were chosen with a range of retained volumes, inundation areas, catchment sizes, design of outlet structures, and design of safety spillways. The locations of the pilot sites are shown in *Fig. 1*. The project was based on available documentation of the HS, including operational rules and accessible hydrological data.

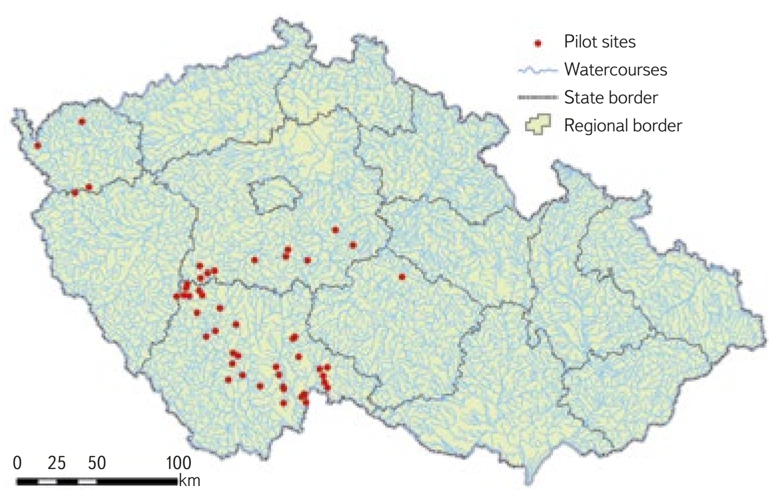

Fig. 1. Map of pilot locations

Minimum residual flow (MRF)

MRF is defined in Section 36 of Act No. 254/2001 Coll., on Waters and on Amendments to Certain Laws (the Water Act), as "the flow of surface waters that still allows general use of surface waters and ecological functions of the watercourse, taking into account the possibilities for recreational navigation" [4]. According to this section, water authorities are obliged to specify the MRF in the water use permit. In doing so, they must consider "the conditions of the watercourse, the possibilities for recreational navigation, the nature of water use, and measures to achieve the objectives of water protection adopted in the river basin plan" [4]. The method and criteria for determining MRF are to be based on government regulations.

The legislative procedure to approve the government regulation has been ongoing since the amendment of the Water Act in 2010 and has not yet been completed. Currently, the valid *Methodological Guideline of the Water Protection Department of the Ministry of the Environment for determining MRF values in watercourses* from 1998 (hereinafter referred to as the Methodical Guideline) [5], along with other related legal regulations, is available. There were several reasons for the Ministry of the Environment of the Czech Republic (MoE CR) to revise the methodological approach regarding MRF [6]. Firstly, it can be noted that the so-called Bílek Table, according to which indicative MRF values are calculated under the Methodological Guideline, was originally intended for the dilution of wastewater below wastewater treatment plants. Furthermore, based on EU Document no. 31: *Environmental Flows*, it was decided to reconsider the existing approach and bring it more in line with current standards, such as taking into account the needs of aquatic ecosystems and dividing the MRF into at least two values during the year.

Following the amendment of the Water Act in 2010, TGM WRI was tasked with reassessing the approach to determining MRF according to the Methodological Guideline and implementing additional requirements into the newly proposed approach. This proposed approach became the basis for the draft *Government Regulation of the Czech Republic on the Method and Criteria for Determining MRF* (hereinafter referred to as the Draft Regulation). The approach considers regional hydrogeological characteristics, the seasonal division of MRF values throughout the year, and the inclusion of multiple hydrological parameters in the MRF calculation. At the same time, emphasis was placed on considering the needs of the biological components of the aquatic environment.

According to the proposed approach, MRF for reservoirs and reservoir systems is determined in the same way as for watercourses. In doing so, consideration is given to the reservoir operation and current hydrological conditions in the watercourse. However, if the water management design of these HS complies with the requirements of ČSN 75 2405 – Water Management Design of Reservoirs, and if this is necessary for their intended purpose, the MRF is determined differently. The proposed approach to determining MRF in watercourses divides Czechia into four regional areas. This regionalisation takes into account the key processes involved in the formation of total catchment runoff, with particular regard to hydrological and hydrogeological conditions. It also considers the boundaries of fourth-order catchments (according to Strahler). Each area is assigned a specific compensation coefficient. The compensation coefficient for a given reservoir is determined on the basis of its classification within the appropriate area according to its hydrological catchment order number. Due to the introduction of seasonal differentiation of MRF during the year, the MRF value is determined for two periods – the main season (May to January) and the spring season (February to April).

For the main season, the MRF is determined according to the equation

$$MRF = (1 - Q_{355d} \cdot Q_a^{-1}) \cdot Q_{330d} \cdot K$$

and for the spring season, the MRF is determined according to the equation

$$MRF = Q_{330d}$$

where:

MRF is minimum residual flow ($m^3 \cdot s^{-1}$)
Q_{355d} discharge achieved or exceeded on average 355 days per year ($m^3 \cdot s^{-1}$)
Q_a long-term mean annual discharge ($m^3 \cdot s^{-1}$)
Q_{330d} discharge achieved or exceeded on average 330 days per year ($m^3 \cdot s^{-1}$)
K compensation coefficient for the given area, the value of which was derived with regard to the requirement to keep the MRF as close as possible to 25 % of Q_a (area 1: K = 1.2; area 2: K = 1.1; area 3: K = 1.05; area 4: K = 1.07).

In the proposed approach to determining MRF for reservoirs and reservoir systems, operational conditions and current hydrological conditions are also considered. During reservoir filling and operation, the prescribed MRF should be maintained at the reservoir outflow. If the inflow into the reservoir decreases below the prescribed MRF value, the reservoir outflow should equal the inflow, as shown in the following equations:

$$Q_{inflow} \geq MRF_{prescribed}\,;\, Q_{outflow} = MRF_{prescribed}$$

$$Q_{inflow} < MRF_{prescribed}\,;\, Q_{outflow} = Q_{inflow}$$

where:

$Q_{outflow}$ is outflow from the reservoir ($m^3 \cdot s^{-1}$)
Q_{inflow} inflow into the reservoir ($m^3 \cdot s^{-1}$)
$MRF_{prescribed}$ prescribed minimum residual flow according to the equations above ($m^3 \cdot s^{-1}$)

The research project *Design of Ponds and Small Reservoirs in Terms of the Possibility to Comply with MRF and Flood Safety* (TA CR, no. SS03010230) builds on previous activities of TGM WRI related to the proposed approach to determining MRF. The project adopted and applied this proposed approach. It focused on the method of determining the MRF value (according to both the proposed approach and the Methodological Guideline) and on the possibilities of maintaining MRF in reservoirs. Consideration was given to the HS water balance and to the real and technically feasible options of the outlet structure. During the legislative process, the question arose whether, in determining MRF for small reservoirs and ponds, reservoir losses (e.g. through evaporation or seepage) should be taken into account by reducing the MRF value accordingly. The research project addressed this issue.

Flood safety

In Czechia, the assessment of flood safety for HS is conducted according to ČSN 75 2935 – Assessment of the Flood Safety of Hydraulic Structures. The Czech technical standard (ČSN) is not generally binding in itself (according to Act no. 22/1997 Coll.). Standards become mandatory when they are referenced in legal regulations. An example is the reference to ČSN 75 2935 in Section 61 of the Water Act. The application of this standard results in the *Flood Safety Assessment of the Hydraulic Structures*. The assessment is prepared for all types of dam construction (local material, concrete, brick, and combined) and applies to all HS categories in accordance with Decree no. 471/2001 Coll., on Technical Safety Supervision of Hydraulic Structures. This issue was addressed in the project by the co-investigator VD – TBD. As part of the flood safety assessment, the project's task was to prepare assessments for the individual pilot sites and, based on the experience gained, to develop guidelines for applying ČSN 75 2935 to a characteristic type of historical HS (ponds) falling within categories III and IV under the technical safety supervision framework.

The main principles for preparing a flood safety assessment according to ČSN 75 2935 are as follows [7, 8]:

- The flood safety level is determined, graded according to the importance of the hydraulic structure (HS) in terms of potential damage in the event of its failure. It is expressed by hydrological data, circumstances affecting the HS's safety during a flood, and assumptions and conditions for passing floodwaters through the HS.
- The required safety level for operated HS is determined based on the performed categorization, considering potential loss of human life and the extent of damage in the event of HS failure. For the design of a new HS that has not yet been categorized, classification is carried out according to the relevant valid methodological guideline for preparing assessments to assign HS to a category under technical safety supervision (see Methodological Guideline No. 1/2010 on Technical Safety Supervision of Hydraulic Structures).
- Hydrological data refers to the design flood wave (DFW), which consists of one or more flood waves with an exceedance probability corresponding to the required safety level.
- The maximum water level (MWL) is determined based on the specific conditions of the HS, i.e., the circumstances affecting flood safety and probable causes of failure.
- The design maximum water level (DMWL) is determined according to the assumptions and conditions for conveying the DFW through the HS.
- The result of the assessment is the relationship between MWL and DMWL (i.e., DMWL ≤ MWL is acceptable) and recommended corrective or emergency measures.
- The assessment evaluates the safety and stability of the dam, individual functional structures, and foundation under the extreme load caused by the passage of the DFW. Therefore, knowledge of the HS technical condition is necessary and must be taken into account when determining the assumptions and conditions for conveying floodwaters.

The Flood Safety Assessment has the following standardized structure and chapter designations:

- A. Introduction
- B. Purpose and description of the hydraulic structure
- C. Basic data and background
- C.1. Required safety level of the hydraulic structure during a flood
- C.2. Hydrological data
- C.3. Technical parameters and documentation
- C.4. Circumstances affecting hydraulic structure safety during a flood
- C.5. Hydraulic calculations
- D. Determination of maximum water level
- E. Determination of design maximum water level in the reservoir
- F. Final evaluation
- G. Corrective and emergency measures
- H. References
- I. List of appendices

RESULTS AND DISCUSSION

Minimum residual flow (MRF)

Comparison of MRF values determined according to the Methodological Guideline and the Draft Regulation (*Tab. 1*) shows that applying the approach in the Draft Regulation does not cause significant changes in MRF values. Specifically, for 22 pilot sites, the difference in MRF between the current Methodological Guideline and the Draft Regulation was up to 5 %; for 9 sites, up to 10 %; for 7 sites, up to 15 %; and for 4 sites, the difference exceeded 20 %. For 7 pilot sites, the values were similar. It is worth noting that, in some cases, the MRF value specified in the water use permit differs from the calculated guideline values according to the Methodological Guideline. This discrepancy is either due to an older water use permit or was determined differently for a specific reason. Comparison of MRF values for selected sites, considering their classification into regions, is shown in detail in *Fig. 2*. The pilot sites, divided into regions based on the regionalization in the Draft Regulation, fall into Area 3 and Area 4. The data analysis also showed that, for the pilot sites, the Q_{355_d} flow was not undershot, with one exception (*Fig. 3*). The Draft Regulation sets Q_{355_d} as the minimum allowable MRF value, because this flow represents the threshold of hydrological drought.

Tab. 1. Comparison of the method of determining the minimum residual flow (MRF) according to the draft Regulation of the Government of the Czech Republic on the method and criteria for determining the MRF in the 2019 version (MRF NV) and according to the Methodical Instruction of the Department of Water Protection of the Ministry of the Environment to Determine the Values of MRF in Watercourses from 1998 (MRF MP 1998) shown as their percentage difference

Comparison	**Relative value difference**					
	0 %	5 %	10 %	15 %	20 %	30 %
MZP NV > MZP MP 1998	7	10	2	2	-	1
MZP NV < MZP MP 1998	7	12	7	5	-	3
Total	7	22	9	7	-	4

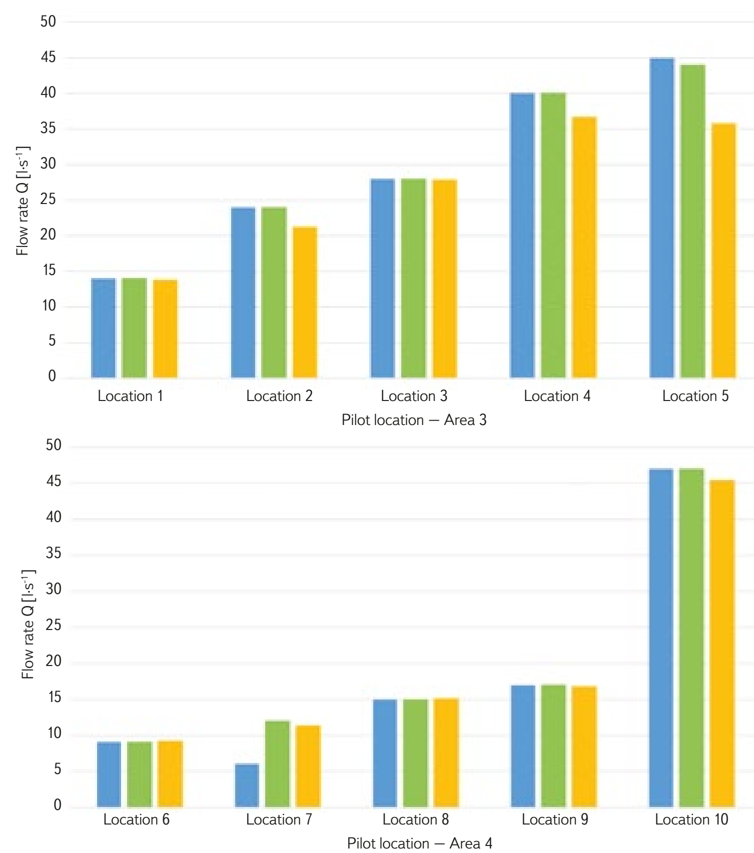

Fig. 2. Comparison of the MRF according to the draft Regulation of the Government in the 2019 version (yellow column), the MRF according to the Methodical instruction from 1998 (green column), and the MRF determined in the water management permit (blue column) for selected locations in Area 3 and Area 4

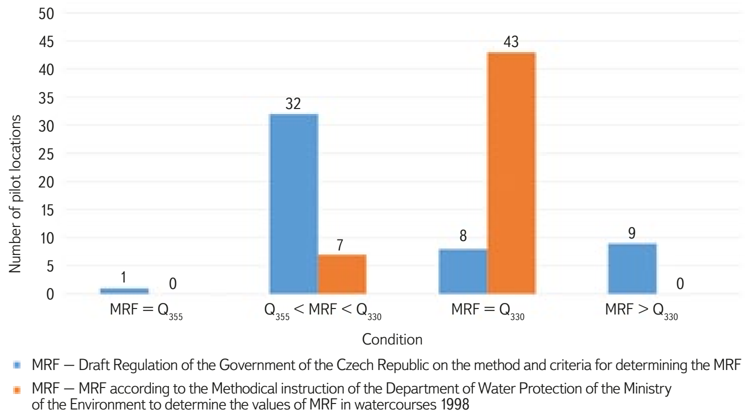

Fig. 3. Comparison of the method of determining the MRF according to the draft Regulation of the Government in the 2019 version and according to the Methodical instruction from 1998 with the *M*-day flows Q_{355} and Q_{330}

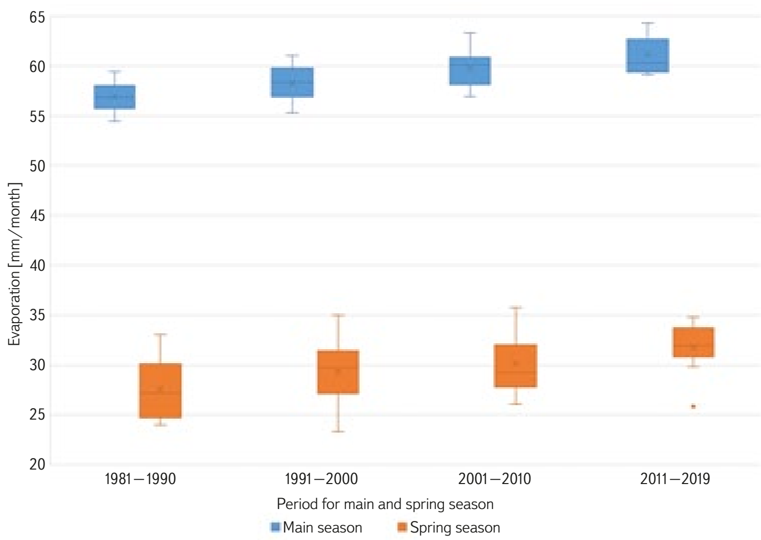

Fig. 4. Example of average decadal evaporation for the main season and for the secondary spring season for one pilot site

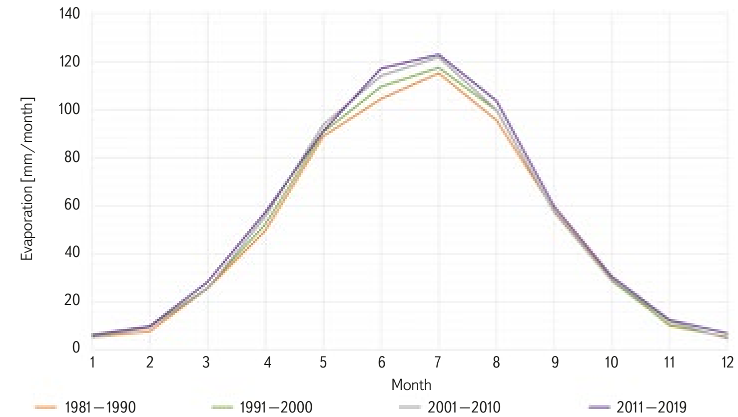

Fig. 5. Example of average decadal monthly evaporation for one pilot site

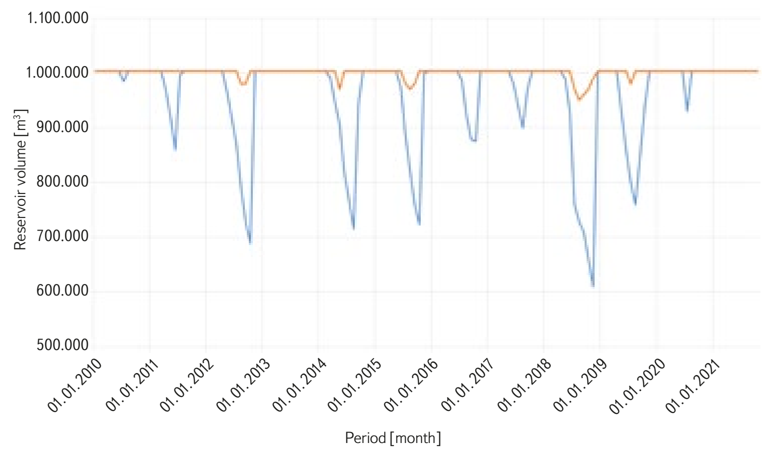

Fig. 6. Illustration of the volume the reservoir outflow MRF is met (blue curve) and when the reservoir outflow MRF is not met (orange curve) for the specified period 2010 to 2021

The project also focused on assessing the relevance of reducing the prescribed MRF by losses due to evaporation and seepage into the subsoil. Seepage into the subsoil is related to hydrogeological conditions at the HS location. The evaluation of evaporation losses, presented in *Figs. 4* and *5*, shows an increasing trend over successive decades. However, reducing the MRF by evaporation losses is not acceptable for small reservoirs and ponds, as it would lead to a reduction of the MRF itself.

The research project examined the feasibility of maintaining MRF in reservoirs, taking into account the hydrological balance of the HS and the actual and technically feasible capabilities of the outlet structure. A simplified hydrological balance of the reservoir, simulated using the MAVONA application [9], is shown in *Fig. 6* and indicates that strict adherence to the MRF at the reservoir outlet significantly affects the required reservoir volume. Uncompromising compliance with MRF throughout the year is not always realistic, especially if inflow to the reservoir drops below the prescribed MRF. In such cases, it would be necessary to supplement the outflow from the stored reservoir volume, which may compromise some of the HS functions. On the other hand, maintaining the MRF is essential to prevent negative impacts on the hydrological regime of the watercourse downstream of the reservoir caused by reduced inflow. For these reasons, operational conditions and current hydrological conditions are considered in the method for determining MRF, as described earlier in the methodology. The technical design of the outlet structures may represent a limiting factor in releasing the required MRF, since these outlets are technically adapted to the reservoir's functions. For more flexible regulation of outflow according to current hydrological conditions, it would be necessary to modify the technical design of the outlet structures and establish an appropriate inspection frequency. Typical outlet facilities used in ponds and small reservoirs include a Monk drainage system, sluice gate, slide gate, flap gate, and others. However, none of these allow flexible manipulation of outflow in accordance with changing hydrological conditions. To ensure effective compliance with MRF, it is essential to define requirements that are meaningful, technically feasible, and practical, given the large number of ponds and small reservoirs in Czechia.

Current hydrological data for the present reference period should be a key basis for determining MRF, as they reflect the current climatic conditions. With the development of climatic conditions, hydrological characteristics in the catchment and at the HS also change. The project addressed the question of whether including the preceding decade in the reference period would affect the MRF value. During the previous decade, both floods and droughts occurred in Czechia. The project concluded that values of *M*-day discharges, as well as the MRF, may decrease. There is a possibility that changing the reference period for hydrological data will alter the MRF requirements for HS.

Flood safety

The assessed pilot sites are represented according to their category under the technical safety supervision system, with 34 sites falling into Category III and 16 sites into Category IV* (IV* denotes significant HS of Category IV). The required safety level, expressed as the return period of the theoretical DFW, is 1,000 years for the 34 Category III sites, 200 years for 13 of the IV* sites, and 100 years for 3 of the IV* sites.

Based on knowledge and experience gained during the project and from previous practice in preparing safety assessments, a draft methodology for the ČSN 75 2935 application was proposed. The draft methodology serves both as a guide for preparing an assessment under ČSN 75 2935 for historic HS, with the aim of simplifying and streamlining the work, and as a source of suggestions for updating the standards ČSN 75 2935 – Assessment of Flood Safety of Hydraulic Structures and ČSN 75 0255 – Calculation of Wave Effects on Structures at Reservoirs and Impoundments. The formulated principles for preparing the assessment, presented in the form of a draft methodology, are available in the final project report [7]. An example of selected recommendations is provided below [7]:

- As part of the project, a consolidated list of circumstances affecting the flood safety of HS was prepared for the group of historic structures, to simplify and clarify the assessment process. This list is divided into three groups according to the anticipated impact on different parts of the assessment. The aim of this questionnaire-based approach is to minimize the subjective component in the evaluation process and to guide the assessor. This part of the assessment should be carried out by an experienced water management specialist, preferably a technical safety supervision expert.
- For HS classified in Categories I to III, wind data are required according to ČSN 75 2935. For historic Category III HS, it is recommended not to request wind data from the CHMI, but instead to use the wind speeds specified in ČSN 75 0255 – Calculation of Wave Effects on Structures at Reservoirs and Impoundments.
- MWL is determined for a specific type and structural design of HS as the highest reservoir level at which the current risk of failure or structural damage begins.
- Initial MWL may be decreased or increased by partial height values corresponding to the factors considered.
- DMWL during a flood is determined by solving the flood wave transformation problem considering the retention effect of the reservoir. The procedure follows the provisions of the standard.
- Water release through the bottom outlet is generally not considered due to its low capacity and the risk of blockage. Possible impacts on the capacity of functional structures from floating debris or sediment should be taken into account. In cases of uncertainty, the most unfavourable scenario is considered.
- If the required safety level of the HS during a flood, expressed as the exceedance probability of the DFW peak flow, is not specified in the categorization protocol, the procedure follows Table 1 of the standard. Table 1 of the standard provides the exceedance probability of the DFW peak flow as $p=1/N$, where N is the return period.
- The DFW is considered as a theoretical N-year flood wave.
- For the purposes of the assessment, it is advisable to verify the inundated area at normal water level using map data and to calculate the reservoir characteristics above the assumed DMWL.
- Parameters critical for the preparation of the assessment must be verified.
- From the analysis presented in the report, it is evident that for historic HS, precise calculation of the wave run-up is impractical, as it is almost always subsequently subject to substantial reduction.
- Two main proposals have emerged regarding the update of existing standards. Given the extremely low probability of the concurrence of the DFW peak and the duration of extreme wind with a return period of 25 to 100 years (e.g., for a 100-year flood, tens of millions of years; for a 1,000-year flood, hundreds of millions of years), it seems justified to open a professional discussion on the current procedure for calculating the MWL according to ČSN 75 2935. Furthermore, a revision of ČSN 75 0255 is recommended for consideration. The wave run-up calculation under this standard is very unclear and complicated. Users require significant time to navigate the calculation procedure, which often leads to mistakes, errors, or misinterpretation. In both cases, it is advisable to examine how this issue is approached internationally and within European legislation [7].

The overall assessment of the results corresponds to long-term expert estimates and observed statistics, which indicate that nearly half of historical HS do not safely pass the DFW [7]. From the representative sample, 60 % (i.e., 30 pilot sites) met the flood safety requirement. An example of the transformation of the DFW through a HS is shown in *Fig. 7*.

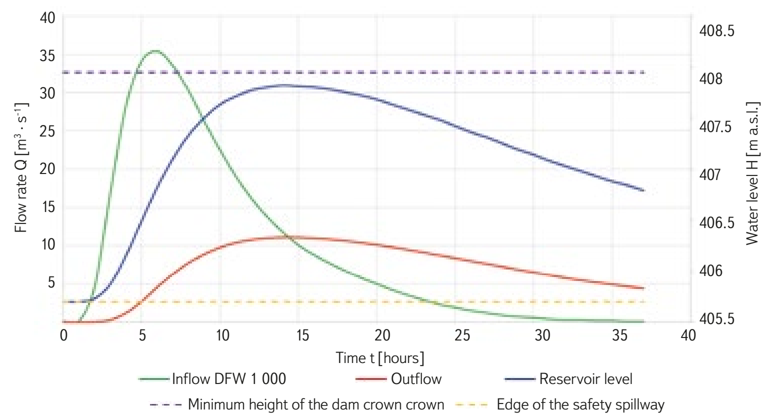

Fig. 7. Transformation of the flood wawe KPV 1 000 in the reservoir

CONCLUSION

Small reservoirs and ponds, regardless of their age, must be able to withstand hydrological extremes – droughts and floods – while fulfilling their intended function. It is essential to establish clear rules and criteria to ensure that the overall effect of the HS is not counterproductive. During periods of drought, the issue of maintaining MRF must be addressed. It is recommended that operational and current hydrological conditions be taken into account when determining MRF for small reservoirs and ponds. This means that during both filling and operation, outflow from the reservoir should be at least the prescribed MRF, and if inflow to the reservoir falls below this value, the outflow should be at least equal to inflow. Reducing MRF to account for losses through evaporation or seepage into the subsoil is irrelevant. In the context of floods, preparing a safety assessment of the HS verifies whether additional measures are necessary to ensure its safety. As part of the project, a methodology was developed to serve as a guide for preparing this assessment, including suggestions for revising procedures. The project outputs are available on the research project's website at the following link: https://heis.vuv.cz/data/webmap/datovesady/projekty/MvnMzpPovodne/

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References

[1] Český hydrometeorologický ústav et al. *Aktualizace Komplexní studie dopadů, zranitelnosti a zdrojů rizik souvisejících se změnou klimatu v ČR z roku 2015.* June 2019 [on-line]. Available at: https://mzp.gov.cz/system/files/2025-03/OAZK_Komplexni_studie_dopady_klima-aktualizace_20190716.pdf [accessed 2025-06-30].

[2] *ČSN 75 2405 – Vodohospodářská řešení vodních nádrží, 04/2017*. Classification number 75 2405.

[3] *ČSN 75 2410 – Malé vodní nádrže, 04/2011*. Classification number 75 2410.

[4] Zákon č. 254/2001 Sb., o vodách a o změně některých zákonů (vodní zákon). In: *Sbírka zákonů České republiky*. 2001.

[5] Metodický pokyn č. 9 odboru ochrany vod Ministerstva životního prostředí ke stanovení hodnot minimálních zůstatkových průtoků ve vodních tocích (1998). *Věstník Ministerstva životního prostředí*. 1998, 5, pp. 1–3. ISSN 0862-9013.

[6] BALVÍN, P. *Metodika stanovení hodnot minimálních zůstatkových průtoků v podmínkách České republiky. Disertační práce*. Prague: Czech University of Life Sciences, Faculty of Environmental Sciences. Department of Water Management and Environmental Modelling, 2022.

[7] TÁBOŘÍKOVÁ, V., SMRŽ, P., ŠVARC, O., BALVÍN, P., SKLENÁŘ, P., KRIJT, B. et. al. *Souhrnná výzkumná zpráva k projektu Řešení rybníků a malých vodních nádrží z hlediska možnosti dodržování minimálních zůstatkových průtoků a bezpečnosti při povodních*. Prague, 2023.

[8] *ČSN 75 2935 – Posuzování bezpečnosti vodních děl při povodních, 01/2014*. Classification number 75 2935.

[9] BERAN, A., KOŽÍN, R., Georgievová, I. *Aplikace MAVONA*. 2022. Available at: https://mvn.vuv.cz/

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Typology and effects of roads on runoff regime in protected areas

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Keywords: road network typology — hydrological regime — GIS runoff analyses — Krkonoše National Park — field mapping

ABSTRACT

The article presents the results of the project *Analysis of Changes in the Water Regime of Land and Watercourses in the Krkonoše National Park Caused by the Network of Roads* (TA CR, no. TITSMZP945), implemented as a public procurement commissioned by the Ministry of the Environment of the Czech Republic within the BETA2 applied research programme. The main output of the project is a two-level typology of the road network in terms of its impact on surface and subsurface runoff. This typology was applied to the territory of Krkonoše National Park (KRNAP) in the Czech Republic and presented in the form of cartographic atlases. The article describes the principles and criteria of the proposed typology and the methodology of its application in map production, which at the basic level combines spatial analyses of road network datasets, digital terrain models and the hydrographic network, and at the detailed level incorporates the results of extensive field surveys. The original analytical procedures include, among other things, the detection of directional and elevation breaks in road segments and the delineation of micro-catchments for individual sections. The resulting maps provide KRNAP Administration and other managers of protected areas with a tool for identifying road segments with the highest potential impact on the hydrological regime and serve as a basis for planning compensatory measures or restoration interventions.

INTRODUCTION

The water regime of mountain and submontane areas is naturally shaped by the influence of topography, soil, and vegetation characteristics as well as atmospheric precipitation. However, the construction of linear infrastructure disrupts natural hydrological processes, particularly in areas with a higher concentration of drainage and paved features. Forest and field roads, which often follow contour lines and fall lines, contribute to changes in water retention and accumulation, as well as to the formation of preferential pathways that alter the direction of surface runoff and its concentration in the landscape. According to studies carried out under various geomorphological and climatic conditions, the infiltration capacity of a catchment may decrease, even though the overall area of roads usually does not represent a significant proportion of the territory [1–3].

The density of roads [4–6], their spatial distribution, and their drainage have a considerable influence on peak runoff values. Some studies show that road networks primarily affect the direction and concentration of runoff, while their impact on the volume of direct runoff is only limited [7]. The reason is that roads have a distinctly linear character, and therefore their area is negligible in relation to the total area in question. For example, in the Deschutes River catchment in Washington State (USA), an increase in peak discharge values of up to approximately 12 % was observed [8]. Both studies also examined the influence of deforestation on the runoff regime and, although the authors do not acknowledge it, the results may be distorted by the fact that several types of changes occurred simultaneously in the studied areas (road construction, deforestation). The issue of accelerated runoff regime is particularly relevant in protected areas, where emphasis is placed on maintaining the natural water cycle and minimising anthropogenic disturbance.

The project *Analysis of Changes in the Water Regime of Land and Watercourses in the Krkonoše National Park Caused by the Network of Roads* (no. TITSMZP945) was carried out from 2021 to 2024 as a public procurement of the Ministry of the Environment (MoE), administered by the Technology Agency of the Czech Republic (TA CR) within the BETA2 applied research programme. The procurement specifically covered a defined set of outputs with practical applications for the management of the protected area, including: (1) typology of the road network according to its influence on hydrological processes; (2) map of the road network in Krkonoše National Park (KRNAP) with differentiation according to the developed typology; (3) Methodology for the Design of new roads and modifications of existing ones with regard to minimizing surface runoff; and (4) database of structures for water conveyance. At the time of publication of this article, the results of the project were already finalised in terms of content; however, the formal closure of the project had not yet taken place. For this reason, and due to the nature of the project as a public procurement, the outputs could not be made publicly available at the time of the article's release. Their publication is planned by the end of 2025.

Due to the structure of the public procurement and the required schedule, there was no scope within the project for conducting hydrological measurements in the field. The approach was therefore based on a synthesis of available expert knowledge, analysis of spatial data, and categorisation of roads according to their morphology, drainage type, interaction with the watercourse network, and position relative to the landscape. Based on the literature review, key types of interactions between the road network and runoff processes were identified, and the design of the road classification framework was developed at two levels: the basic level relied solely on data analysis, while the detailed typology refined the basic level using insights from field mapping, but not from measurements of the actual hydrological interaction between the road and its surroundings. These methodological limitations and the chosen framework are further elaborated in the following sections.

THEORETICAL PRINCIPLES AND FOUNDATIONS

The natural hydrological regime of mountain areas arises from the interaction of topography, soil properties, vegetation cover, and atmospheric inputs. In its natural state, precipitation water partly infiltrates into the soil and flows subsurface, while the remainder runs off on the surface, especially during high-intensity rainfall and saturated soil profile. This system, however, can be significantly disrupted by linear structures, among which roads play a particularly prominent role. Roads affect both surface and subsurface runoff, with the consequences of these impacts varying according to the road's position in the landscape, its morphology, surface modifications, and drainage measures.

Intervention in the natural terrain morphology disrupts the continuity of surface water flow. Roads often follow the fall line of a slope or are situated in slope depressions, thereby creating preferential runoff pathways. Water running off from the surrounding terrain accumulates on the surface of the compacted or paved road and is conveyed along the road alignment, or alternatively in ditches or wheel ruts. Such concentrated runoff is then directed either into the nearest watercourse or towards the slope edge, where it may trigger erosion processes and destabilise the soil profile. This phenomenon is often referred to as "the function of a road as a surface water collector." In other situations, however, roads may act as distributors – that is, water from the road or ditch is dispersed into the surrounding environment, for example by seeping into the slope or through transverse drainage features. At points where ditches, culverts, or erosion gullies connect directly to the hydrographic network, roads function as inflow points that link surface runoff directly to recipients, thereby significantly accelerating the catchment response.

Roads also significantly disrupt subsurface water flow. Due to their construction and use, the subgrade beneath higher-category roads is often heavily compacted, which reduces the soil infiltration capacity and redirects water into the surface system. In addition, natural conductive horizons are interrupted, which would normally allow lateral (slope) water flow in shallow soil layers.

Particularly problematic are situations where a road is cut into a slope and runs across it, almost or entirely along the contour lines. In such cases, the slope toe or the side of the road cut disrupts the natural shallow drainage layers through which subsurface flow occurs. Water then emerges at the surface from the disturbed slope, resulting in the conversion of subsurface runoff into surface runoff. The outcome is not only the loss of the slope's infiltration function but also an increased risk of erosion and accelerated drainage. This mechanism may lead to the formation of secondary spring outflows or even to the development of small watercourses along road embankments, although under natural conditions no surface runoff would occur at all. In some cases, these effects combine – for example, when water accumulates upslope of a road due to a barrier, increasing profile saturation and subsequently emerging at the surface as a secondary spring outflow, thereby increasing the amount of surface runoff.

The mechanisms described are supported by numerous studies demonstrating changes in the hydrological regime caused by linear structures, a brief selection of which is presented in the introduction to this article. On the basis of these hydrological concepts, a classification framework was designed that takes into account the mode of interaction between roads and both surface and subsurface runoff. This framework serves as the foundation for the road network typology, which is described in detail in the following sections.

ROAD NETWORK TYPOLOGY

The road network typology was defined in terms of its potential impact on the hydrological regime, considering both surface and subsurface runoff. It was designed and tested on the road network in the mountainous environment of KRNAP but formulated in a general way so that it could be applied more or less anywhere in the Czech Republic, primarily in protected areas. The typology was developed based on a combination of digital spatial analyses, field observations, and the hydrological principles described in the previous section.

The types of roads evaluated included all roads with the potential to influence the direction and volume of precipitation runoff: public roads as defined by the Road Act, including the network of local and purpose-built roads; roads of categories 1L–4L according to ČSN 73 6108 – Forest Road Network [9]; as well as significant hiking trails and other unregistered but mapped paved roads leading to buildings or intersecting water conveyance structures.

The proposed typology is applied not to roads as continuous entities, but to their homogeneous sections, for example those with a single type of construction or pavement, or with specific slope characteristics. The primary basis for classification is the road's function in terms of its ability to interrupt shallow subsurface and surface runoff, followed by its accumulative or conveyance function, that is, its capacity to retain runoff or, conversely, to discharge it rapidly into the hydrographic network. Point features for conveying surface water, such as small bridges and culverts, are included in the typology only to a limited extent due to their low level of mapping and documentation. The detailed procedure for dividing the road network into homogeneous sections is presented later in this text, in the Road Network Map section.

Factors for typology classification

The ability of a road section to influence runoff conditions depends on a range of factors, which carry different weights in various combinations.

The proposed classification uses the following main factors:

A. Affected component of runoff,

B. Potential runoff volume (catchment area),

C. Potential to influence runoff velocity.

The first factor enters the classification directly as a categorical variable with two classes. To represent potential runoff volume, a universal runoff characteristic in the form of catchment area was chosen, in an effort to avoid the considerable uncertainties associated with methods for quantifying runoff from mountain and forested areas in unmonitored catchments. The final main factor, the potential to influence runoff velocity, in practice depends on a range of detailed characteristics; for the proposed classification, the following were selected:

- presence of longitudinal drainage features,
- design of road drainage and the occurrence and technical design of cross drains,
- construction of the road embankment with regard to permeability,
- construction (pavement) of the road surface with regard to permeability,
- orientation of the road relative to the slope,
- arrangement of the road's cross-section relative to the landscape,
- longitudinal and transverse slope,
- tructures on the road and their water conveyance methods,
- alignment or crossing with a watercourse.

Typology levels

The road typology was designed in a structured form with two levels of detail: basic and detailed. The basic level allows for the classification of road network sections solely based on analyses of commonly available data, while the detailed level provides further refinement of the basic typology through field surveys and sophisticated data analyses. This two-tiered structure is necessary given the extent of the road network in the study area, which, under normal time and personnel constraints, does not permit complete physical mapping.

Basic typology level

This level of road network classification was designed for application solely on the basis of easily accessible data within a GIS environment. It was tested at the spatial scale of the entire KRNAP, with a view to its potential use in any other area within Czechia. The main data source is the topological network of linear road objects as recorded in the ZABAGED database (version 2021). For testing the typology, a specialized road network dataset maintained by the KRNAP GIS department was used. To determine the average slope characteristics of road sections, the DMR4G elevation model was applied, and for identifying extremes (peaks and local minima) in longitudinal profiles, the DMR5G model was used.

In the first phase of the study, general criteria were formulated for classifying road sections into classes of the basic typology level, separately for surface runoff (SR) and subsurface runoff (SSR). These are summarised in *Tab. 1*.

Tab. 1. Classes of the basic level of road typology and general combination of key characteristics for classification of individual segments

Class	Potential impact on runoff component	Characteristics influencing SR	Characteristics influencing SSR or conveyance of SSR to SR
A	Very high	Paved roads, steep longitudinal slope	Significant contributing area, strongly sloping terrain, large deviation from fall line (i.e., close to contour-aligned layout)
B	High	Paved roads, gentle longitudinal slope	Significant contributing area, section on slope (strongly sloping terrain), in contact with local minimum, moderate deviation from fall line
C	Medium	Unpaved surface, steep longitudinal slope	Significant contributing area, section with higher longitudinal slope
D	Low	Unpaved surface with gentle longitudinal slope, paved roads with very gentle longitudinal slope	Significant contributing area, other criteria without risk
E	Minimal	Unpaved surface, approximately contour-aligned layout	No contributing area, other criteria not relevant

In the first proposal of the basic typology level, the existence of longitudinal drainage features and the terrain configuration (the position of the road relative to the surrounding landscape) were also considered as key characteristics. Although these characteristics cannot be derived from commonly available data, within the framework of the project, procedures for analysing detailed DTMs obtained using airborne LiDAR techniques were tested, which have become increasingly accessible in recent years. For the analysis of pilot sites selected within the project, a DTM from 2012 with a 1 m resolution, provided by KRNAP, and a DTM with a 50 cm resolution acquired using UAVs were available. In both cases, the products were derived from laser scanning. Approximately 20 cross-sections were analysed at two sites; an example from the site below Špindlerovka, including the locations of the analysed profiles, is shown in *Fig. 1*.

Analyses of the obtained cross-sections proved to be conditionally useful for obtaining information on the terrain configuration of a road section, or on longitudinal drainage structures. *Fig. 2* shows arguably the clearest of the analysed cross-sections at the pilot site below Rennerovky. On the 1 m resolution digital model, road ditches are mostly indistinguishable, whereas at higher resolution they are generally identifiable. However, it is often difficult to identify them amidst the noise caused by remnants of elevation data processing. The terrain configuration of the road was generally satisfactorily visible even on the less detailed 1 m model, whereas the standard 2 m DMR5G model published by the Czech Office for Surveying, Mapping and Cadastre (ČÚZK) was insufficient for this purpose.

In general, a significant problem was encountered with georeferencing aerial data in forested areas and with filtering the captured point clouds. The analysis was further complicated by the positional accuracy of the road network lines, which was already insufficient for this purpose, even in the case of the corrected map dataset from KRNAP, which generally exhibited higher accuracy than the ZABAGED positional data. Automating the process of generating cross-sections and identifying longitudinal drainage features from detailed DTMs proved to be unrealistic, and manual analyses were inefficient compared with a simple field survey. For these reasons, the characteristics of terrain configuration and

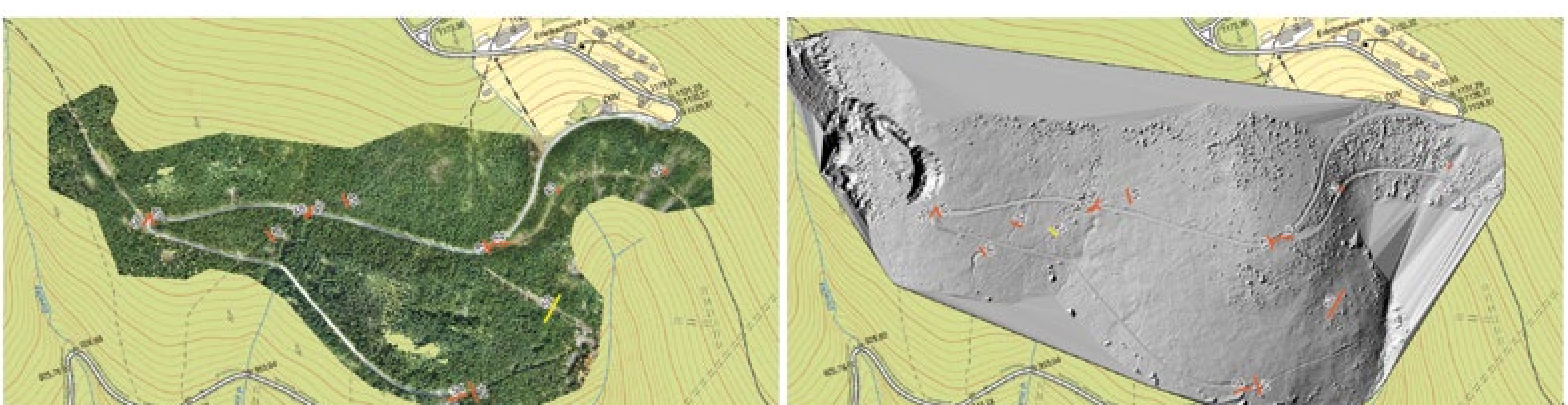

Fig. 1. Orthophoto (left) and detailed DTM (right) derived from UAV data; cross-sections in red are used for testing the identification of roadside drainage features

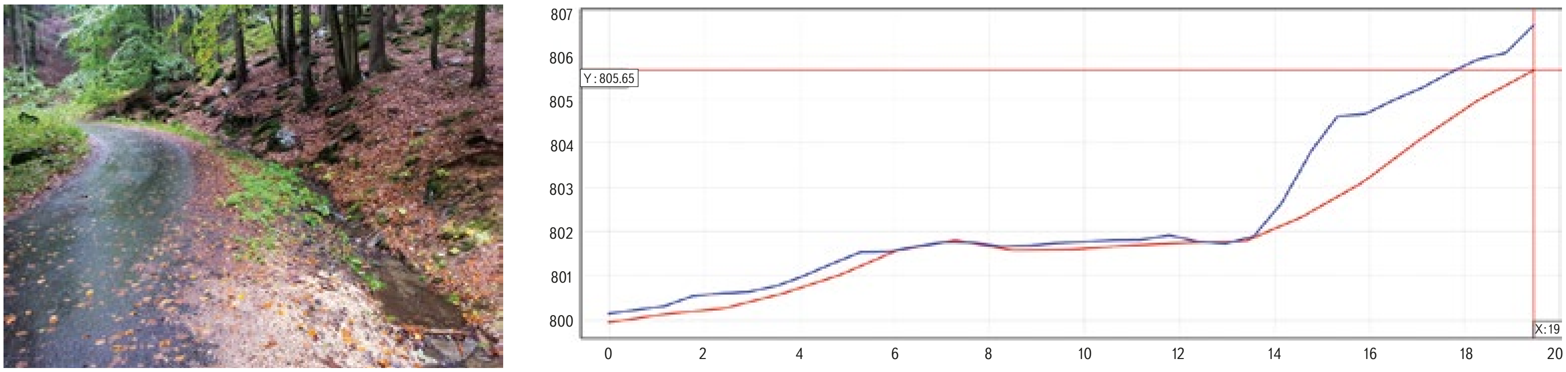

Fig. 2a, b. Cross-section of a road (right) derived from DTMs based on LiDAR scanning with 1 m resolution (red, KRNAP Administration) and 50 cm resolution (blue, CTU) for testing the identification of road terrain alignment and roadside drainage features; photograph of the actual condition from a field survey (left)

the presence of longitudinal drainage features were not used for the basic typology level of the road network and were instead assigned to the detailed level.

The following six characteristics were used for the final classification of road sections according to the basic typology level:
Z – Paved/unpaved road (1/0),
M – Connection to a local minimum or crossing with a watercourse YES/NO (1/0),
S – Average longitudinal slope of the section (%),
D – Deviation of the road from the fall line (0°–90°),
T – Transverse slope of the terrain around the section (%),
W – Contributing sub-catchment area (ha).

For the application of the basic typology level in the creation of the KRNAP Road Network Map, the classification key from *Tab. 2* was used. The threshold values of the criteria and their combinations for classifying road sections were based on a frequency analysis of the occurrence of individual parameter values across KRNAP and may therefore be influenced by the specific characteristics of this area. When applying the typology in other regions, it is advisable to carry out a similar frequency analysis and, if necessary, adjust the threshold values for class boundaries. However, any modification of the combinations of criteria used should be based on a significant objective reason, such as the absence of certain data (for example, information on road surface characteristics may be unavailable). The basic typology level of the road network is designed as an explicit combination of the potential to influence both components of direct runoff, for instance B/C. By incorporating factors identified through detailed field surveys, it can be extended to the detailed level. The application of the typology and the presentation of results are addressed in the Road Network Map section.

Tab. 2. Combinations and values of characteristics for classifying road segments according to the basic level of typology

Potential to influence surface runoff		Potential to influence subsurface runoff or conveyance to surface runoff
A	Z = 1; S ≥ 10 %	D > 70°; T > 20 %; W > 0,5 ha
B	Z = 1; 4 % ≤ S < 10 %	M = 1; 50° < D ≤ 70°; T > 20 %; W > 0,5 ha
C	Z = 0; S ≥ 10 %	Not A+B; S > 10 %; W > 0,5 ha
D	Z = 1; S < 4 % OR Z = 0; 4 % ≤ S < 10 %	Not A+B+C; W > 0,5 ha
E	Z = 0; S < 4 %	W ≤ 0,5 ha

Detailed typology level

Building on the basic typology level of the road network, which reflects the potential to influence runoff characteristics in the affected area, the detailed level provides a more in-depth analysis of the impact on runoff conditions in individual cases. It supplements the basic typology level with road network characteristics that, given the current state of available data, can only be determined through field surveys.

For the detailed survey in KRNAP, five pilot sites were designated. The survey was conducted from July to November 2022 and was slightly supplemented in 2023. Data were collected using the open mobile application QField based on QGIS technology, which allows simultaneous data collection by multiple personnel and subsequent synchronization. After two initial adjustments, the data model for collection was finalised as three separate point layers according to *Tab. 3*, with photographic annotations. The categories of individual characteristics are not provided here; following the formal completion of the above-mentioned project (no. TITSMZP945), they will be accessible in full in the results report V1 – Road Network Typology.

Tab. 3. Point data layers for field data collection and recorded characteristics

Designation	Layer name	Recorded characteristics
A	Water conveyance structures	Structure type, Inlet shape, Outlet shape, Dimensions, Material, Photo
B	Characteristic points	Road class, Slope, Terrain configuration, Longitudinal drainage, Cross drainage, Surface, Photo, Damage
C	Specific points	Point type, Forest road accessory, Inflow obstruction, Photo

During the development of the basic typology level, or its application to the map, road network sections and nodal points were defined. For the purposes of applying the detailed typology, this division is supplemented by significant specific points of type C (*Tab. 3*) identified during the field survey (e.g., the end of a longitudinal drainage feature, a change in surface type, etc.). The detailed characteristics recorded at the corresponding type B points are then assigned to the resulting road sections. From the recorded characteristics, four were selected and adopted as the criteria for the detailed typology level according to *Tab. 4*.

Tab 4. Criteria of the detailed level of road typology

Criterion	Category
Cross drainage	With cross drainage, without cross drainage
Longitudinal drainage	Without longitudinal drainage, with unpaved longitudinal drainage, with paved longitudinal drainage
Terrain configuration	On surface, in excavation, on embankment, combined on embankment/excavation
Road surface	Unpaved surface, permeable wearing course, discontinuous paving, continuous paving with impermeable wearing course

It is evident that the individual criteria are interrelated to varying degrees, and therefore the final assessment of their impact on surface or subsurface runoff must necessarily be based on all criteria simultaneously, which requires a certain level of expertise in runoff processes and hydrology in general. The effects on individual runoff components, as well as guidance for evaluating roads according to these criteria, are provided in the forthcoming project results prepared for publication: V1 – Road Network Typology and V3 – *Methodology for Recommendations on the Construction of New and Modification of Existing Roads with Regard to Minimising Surface Runoff* (hereinafter referred to as the Methodology). These criteria were applied and graphically represented in result V2 – KRNAP Road Network Map, the derivation of which is described in the following section of this text.

ROAD NETWORK MAP

As the second required output of the project mentioned in the introduction, the KRNAP Road Network Map (hereinafter referred to as the Map) was created, applying the road network typology to assess its influence on the hydrological regime of the area. It was published in the form of three cartographic atlases. The first covers the entire KRNAP area, applying the basic typology level of the road network, while the remaining two expand the basic level with detailed typology criteria for the five pilot sites, allowing a more detailed assessment of the potential to influence subsurface and surface runoff. The Map is intended primarily as one of the key resources for selecting locations suitable for implementing restoration measures and actions to reduce the negative impacts of the road network on the runoff regime within the National Park. In addition, together with the Map's accompanying documentation and Methodology, it is intended to serve future authors of similar studies in other Czech protected areas as a methodological guide and example for applying the Road Network Typology and assessing road network hydrological impacts. A brief description of the Map creation methodology follows; the full version will be provided in the accompanying documentation, which is scheduled for publication soon together with the Map.

Input data

The primary basis for creating the Map was the linear layer of the road network provided by KRNAP, which was preferred over ZABAGED data due to its higher positional accuracy and more extensive attribute set. Since not all protected areas in Czechia, where the developed methodology was intended to be applied, have access to a similarly detailed dataset, the map creation was also successfully tested on the positional layers from ZABAGED, specifically by combining the following layers:

- Roads, motorways,
- Unregistered roads,
- Streets,
- Paths.

The last-mentioned category, *Paths*, should ideally be distinguished in the final linear layer according to available detailed attributes. Since 2024, the original classification of *Paths* as *paved/unpaved* has been replaced by a new division into *Maintained/unmaintained paths*. Within the project, the nature and impacts of this change could not be analysed or assessed in detail. The above-mentioned linear layers should ideally be supplemented with data on the classification of the forest road network, which should be available from its administrator.

Digital terrain models DMR4G and DMR5G, as well as the *Watercourse* layer from the ZABAGED positional data, were also used in creating the map. For the application of the detailed typology level, the point layers of characteristic and specific points from the field survey described in the previous section were employed.

Methodology for creating the map at the basic typology level

Before assigning characteristic values for classifying roads according to the proposed typology, it was first necessary to divide the linear road elements into segments that were homogeneous in terms of alignment and elevation, road surface, and approximate length. This segmentation was carried out in several steps, which are briefly summarised here; the full procedure is provided in the accompanying Map documentation.

The first essential step was to correct the topology of the lines so that they were broken at the road network nodes. Overlaps and incomplete lines are undesirable. Pseudo nodes – i.e., the junction of two linear elements – are allowed only at locations where an attribute key to the classification of the segment according to the typology changes (in this case only a change in road surface). In the base layer provided by KRNAP, these rules were broken in several hundred instances and had to be semi-automatically removed. When using ZABAGED positional data, the topology of the resulting network must be cleaned according to these rules after merging the specified linear layers.

Division at locations of alignment breaks

Sharp changes in alignment and curves are frequent locations for changes in several road characteristics – longitudinal slope, configuration relative to the terrain, the presence of longitudinal drainage features, and others. Since standard GIS tools are unable to identify these points on linear features, custom analytical scripts were developed in the R project environment for this purpose. In the first step, sharp alignment breaks were identified where adjacent vertices formed an angle of less than 100°; in *Fig. 3*, such a break is marked with a red triangle. In the second step, sharp curves – represented in the linear data by a series of very short segments – were identified. For this purpose, each line was approximated using points at a constant spacing of 15 m, and an empirical threshold of 120° was applied to adjacent points; in *Fig. 3*, the sharp curves are indicated by circles, with colours reflecting their significance. For the final division of the lines, points that were too close to each other or located near road network nodes were filtered out, as these could otherwise have caused undesirable fragmentation of the road network.

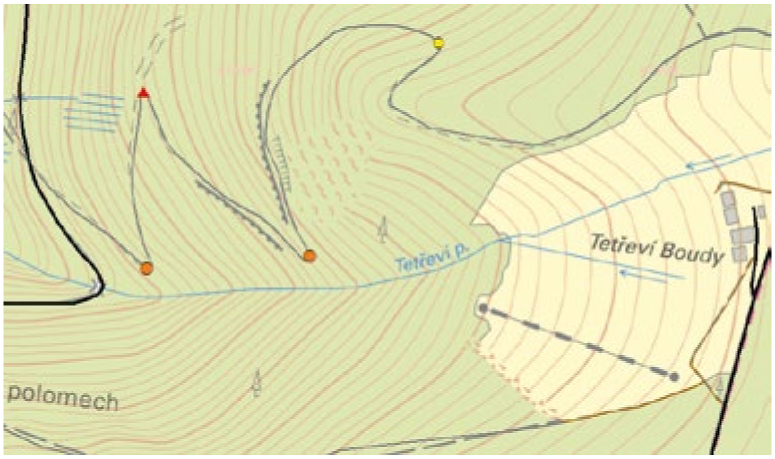

Fig. 3. Sharp break point (red triangle) and three prominent curves (orange and yellow circles) as split points of the access road to Tetřeví boudy

Crossing watercourses

It is advisable to split road lines at the point where they cross a watercourse, as such locations often (though not always) involve a change in elevation. The connection of a segment to a watercourse, or to a local elevation minimum, is also one of the characteristics used for the classification of segments according to the proposed typology. However, junction nodes of the road network (intersections) are often located close to crossings, and in such places it is undesirable to split segments, as this would lead to excessive fragmentation. In the wider area of KRNAP, more than 2,700 intersections with surface sections of watercourses were identified but, after filtering out unsuitable points, fewer than half of them were used.

Identification of elevation extremes

To ensure correct calculation of slope parameters, it is necessary to divide road lines at local elevation extremes. Since standard GIS tools do not allow for the identification of these locations, custom analytical procedures were again developed and tested in the R project environment.

For the identification of optimal tool settings, points were generated along each road segment in four spacing variants (2, 5, 10, and 20 m) and assigned elevation values from DMR5G. At each point, its elevation was assessed in the context of the two neighbouring points, and local maxima and minima were indicated according to the required elevation difference threshold (five variants ranging from 10 to 150 cm). The extremes were then classified into six levels of significance based on their height or depth, as well as their width and continuity of slope (presence of inflection) in the evaluated surroundings.

To verify potential errors in the alignment of roads, the same analysis was repeated for parallel lines on both sides of the roads at offsets of 5 and 10 m. Automatically generated longitudinal profile graphs were systematically subjected to visual inspection in groups, one of which is shown in *Fig. 4*. This approach confirmed sufficient accuracy of the alignment of road lines compared with their parallel offsets. An offset of 10 m and an elevation threshold of 70 cm proved optimal for constructing longitudinal profiles. Finally, points located close to road network nodes were removed, and the occurrence of nearby opposite extremes was corrected.

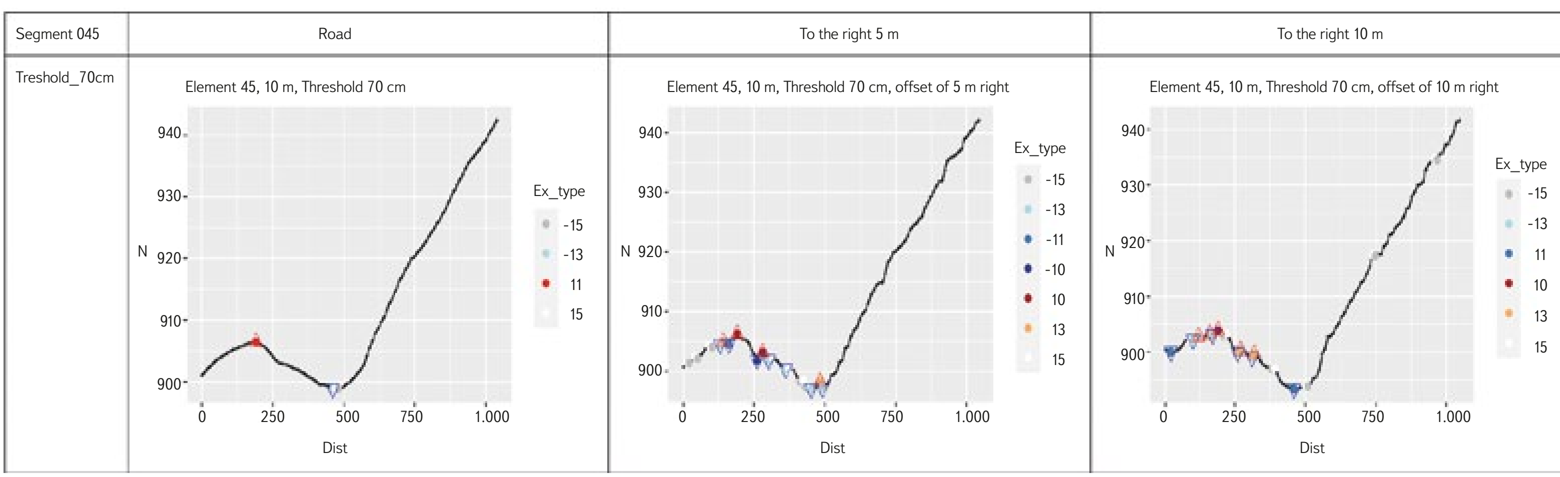

Fig. 4. Example of longitudinal profiles of the road section axis (left) and two equidistant lines at an offset of 5 and 10 m (centre and right), along with identified local elevation extremes. The profiles were derived from points with 10 m spacing, with a vertical threshold of 70 cm used to indicate significant extremes

Segmenting by length and determining segment characteristics

After accounting for directional changes, watercourse crossings, and elevation extremes, the resulting road segments were divided into 200 m lengths. This completed the homogenization of road network segments, after which the segment characteristics were calculated for the application of the typology. The average slope of each segment was derived from DMR5G along the road lines. From a smoothed DMR4G raster, a slope raster was generated, and within a 20 m buffer zone around the segment axes, the average slopes of the surrounding terrain were evaluated. A more detailed DMR5G is not suitable for this purpose, as it also captures the elevation characteristics of the road itself, such as cuttings or roadside ditches. For the same reason, DMR4G was also used to derive the contributing areas (micro-catchments) of road segments. A simplifying assumption of complete interruption of runoff by the road was adopted, since the actual capacity of a road to retain runoff cannot be determined without a detailed field survey. To derive the contributing areas, a complex procedure was developed, which involved removing the road axes and surface watercourses from the DMR and expanding the raster representation of the roads. A detailed description of this procedure is beyond the scope of this article.

Application of the basic typology level and map production

Using database processing tools, values of characteristics determining the significance of each road segment for influencing surface and subsurface runoff were assigned to vector road segments according to the developed Road Network Typology. After classifying each segment into combined categories (SR and SSR), the final Map for the entire KRNAP area was produced. Given the extent and level of detail of the information displayed, the Map was organised as an atlas of map sheets at a scale of 1 : 25,000. The potential influence on SR is indicated by variable line thickness, while the potential influence on SSR is shown using a simple accompanying label. An example map sheet is shown in *Fig. 5*.

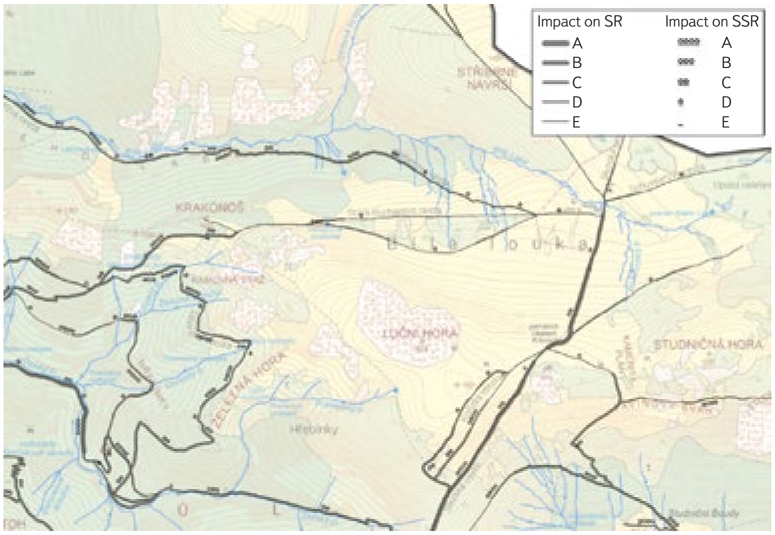

Fig. 5. Excerpt of the Road Network Map with the applied basic level of typology showing the potential impact on runoff components

Methodology for producing the detailed typology level map

The detailed typology level map of the road network expands the basic level map by incorporating insights from field surveys, specifically the characteristics listed in *Tab. 4*. These and other road characteristics were collected and compiled into three point layers, including photographic annotations, which can be appropriately displayed using standard GIS tools, although displaying multiple photographic attachments per point in ArcGIS Desktop posed a considerable challenge. The collected points naturally did not match in density the derived segmentation of the road network created during the production of the basic level map. Similarly, the points were generally not located directly on the line of the road segment, either due to inaccurate GPS positioning in forested mountain areas, errors in point placement, or even the absence of the road line in the map base. Therefore, a series of preparatory steps had to be undertaken before applying the detailed typology.

Harmonization and completion of survey data

The quality and completeness of the attributes in the field survey points is crucial for successful application of the detailed typology to road segments. Due to differences in mapping strategies among individual field workers, for the "cross drainage" characteristic, just over 1,000 of nearly 2,600 points contained either no information or only the category "other". Missing characteristics had to be completed using the collected photo documentation or, where appropriate, validated against neighbouring points. In addition to filling in missing attributes, the consistency of characteristics assigned by individual field workers was spot-checked and corrected to remove subjective bias, for example in the case of the road's configuration relative to the surrounding landscape.

Assignment of points to road segments

The positions of points collected during the field survey using GPS were subsequently corrected and linked to the corresponding road segments. GPS positional deviations of the points relative to the road centreline in the map dataset ranged from a few metres up to several tens of metres. Although in many cases there was evidence of errors in the map base, in order to maintain consistency with the original data provided by the KRNAP Administration, the road lines were not corrected; instead, the recorded points were automatically moved to the nearest position on these lines. Following testing of various values, a distance of 20 m was chosen as the maximum threshold for moving a point. Points beyond this threshold had to be assigned manually or completely excluded to avoid, for example, assigning a point that characterises a road not recorded in the map base. A thorough visual inspection and correction of incorrectly assigned points was necessary, particularly in the areas of junctions.

Additional segmentation and transfer of characteristics

Some road network characteristics included in the detailed typology can change abruptly, such as surface type or longitudinal drainage, and it is necessary to split the assessed road segment at these points of change. A subset of specific points from the field survey was used for this segmentation. The recorded vertical alignment break was checked with respect to the proximity of a network node or a local extreme identified from the DTM. Changes in surface type or longitudinal drainage were verified using the photo documentation and surrounding characteristic points. In total, around 130 road segments underwent additional segmentation.

Based on spatial coincidence, the road segments were then to be assigned attributes from the layer of characteristic points. Prior to this, however, it was necessary to check segments with multiple characteristic points assigned. The number itself is not fundamentally an issue if the points contain identical characteristics. Thanks to its easy identification in the field, the cleanest attribute was the type of surface. On the other hand, the most problematic characteristic was terrain configuration (over 100 ambiguous assignments), since these changes in the field are always rather gradual and no specific-point category had been established for them. After checking the consistency of these data using photo documentation, the road network was finally additionally split approximately halfway between two points with differing characteristics. Subsequently, road segments were assigned the attributes from the characteristic points.

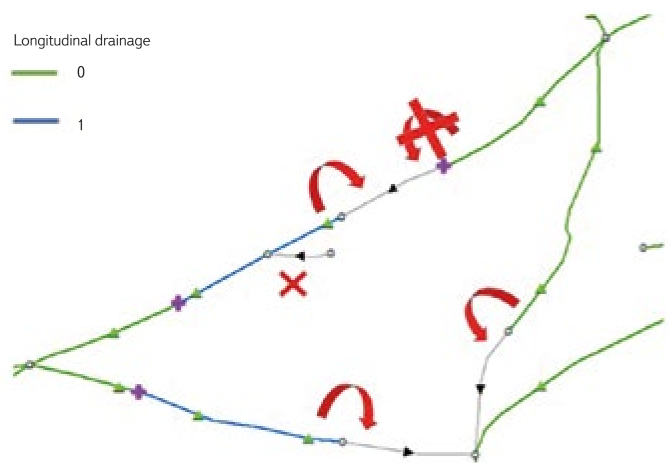

Fig. 6. Diagram of transferring the roadside drainage attribute to adjacent segments, taking into account specific points (purple crosses) marking changes in the roadside drainage system; green triangles indicate characteristic points

The final step involved addressing segments without a corresponding characteristic point. Their number depends on the density of points collected during the field survey. A typical example of the situation after projecting points onto road segments is shown in *Fig. 6*. For empty segments, attributes from neighbouring segments were transferred iteratively (forward/backward), provided that no specific point indicated a change in the given attribute between them.

Application of the detailed typology level and map creation

The map with the detailed typology level similarly builds on the basic-level map and complements it with an appropriate representation of the detailed typology criteria. The detailed map was designed as a set of two cartographic atlases: one for the subsurface component of runoff and the other for the surface component. The graphic design consists of a clear combination of line thickness (representing the potential influence on the runoff component from the basic typology level), a colour code expressing terrain configuration as a key factor affecting the hydrological regime, and accompanying symbols to depict the remaining characteristics of the detailed typology. The result is shown in *Fig. 7*.

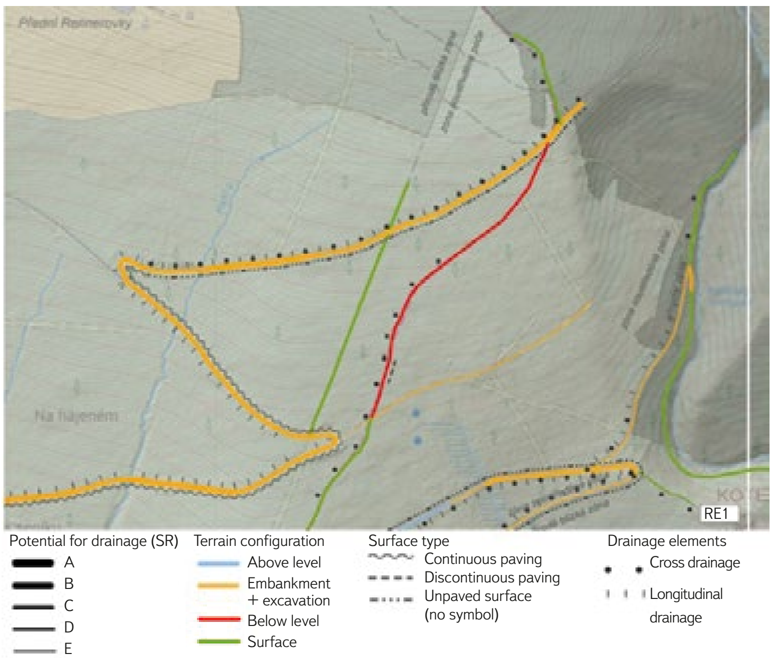

Fig. 7. Example of applying detailed typology to the road network in the Rennerovky pilot area

CONCLUSION

Linear elements in the landscape, and particularly the road network, have a significant potential to influence water runoff from an area. Under specific conditions, this influence can be positive; however, it generally tends to accelerate water runoff, which is usually considered undesirable. The project, the selected results of which are presented in this text, aimed primarily to provide the data and tools needed to identify problematic sections of the road network and to minimise their undesirable effects, which lead to accelerated water runoff from areas under special nature protection. The presented typology and methodology for its application to map outputs will assist in identifying such problematic locations, at two possible levels of detail – the basic level, relying solely on available map data, and the detailed level, utilising results of field surveys focused on a set of clearly defined road characteristics. The derived maps can serve as a basis for selecting and prioritising road sections in protected areas that are suitable for the implementation of mitigation measures, or even for the complete removal and restoration of a road. The principles of such measures are addressed in another output of the aforementioned project – the *Methodology for Recommendations on the Construction of New and Modification of Existing Roads with Regard to Minimising Surface Runoff* – which is scheduled for publication by the end of 2025. Together, these outputs provide managers of natural areas – whether under strict or general protection – with tools to better reconcile human interests in accessing the landscape with the protection of its natural runoff processes.

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References

[1] SOULIS, K. X., DERCAS, N., PAPADAKI, C. H. Effects of Forest Roads on the Hydrological Response. *Hydrological Processes*. 2015, 29(7), pp. 1 772–1 782. Available at: https://doi.org/10.1002/hyp.10301

[2] ZIEGLER, A. D., GIAMBELLUCA, T. W. Importance of Rural Roads as Source Areas for Runoff. *Journal of Hydrology*. 1997, 196, pp. 204–229. Available at: https://doi.org/10.1016/S0022-1694(96)03288-X

[3] TAKKEN, I., CROKE, J., LANE, P. A Methodology to Assess the Delivery of Road Runoff in Forestry Environment. *Hydrological Processes*. 2008, 22(2), pp. 254–264. Available at: https://doi.org/10.1002/hyp.6581

[4] CARLSTON, C. W. Drainage Density and Streamflow. *U.S. Geological Survey*. 1963.

[5] OGDEN, F. L. et al. Relative Importance of Impervious Area, Drainage Density, Width Function, and Subsurface Storm Drainage on Flood Runoff from an Urbanized Catchment. *Water Resources Research*. 2011, 47(12). Available at: https://doi.org/10.1029/2011WR010550

[6] PALLARD, B., CASTELLARIN, A., MONTANARI, A. A Look at the Links between Drainage Density and Flood Statistics. *Hydrology and Earth System Sciences*. 2009, 13(7), pp. 1 019–1 029. Available at: https://doi.org/10.5194/hess-13-1019-2009

[7] HARR, R. D., HARPER, W. C., KRYGIER, J. T., HSIEH, F. S. Changes in Storm Hydrographs after Road Building and Clear-Cutting in the Oregon Coast Range. *Water Resources Research*. 1975, 11(3), pp. 436–444. Available at: https://doi.org/ 10.1029/WR011i003p00436

[8] LA MARCHE, J. L., LETTENMAIER, D. P. Effects of Forest Roads on Flood Flows in the Deschutes River, Washington. *Earth Surface Processes and Landforms*. 2001, 26(2), pp. 115–134. Available at: https://doi.org/10.1002/1096-9837(200102)26:2<115::AID-ESP166>3.0.CO;2-O

[9] *ČSN 73 6108. Lesní cestní síť*. Prague: Úřad pro technickou normalizaci, metrologii a státní zkušebnictví, 2018. (Classification number: 736108)

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Interview with Ing. Libor Elleder, Ph.D., hydrologist from the Czech Hydrometeorological Institute, Prague

Have you ever wondered what a hydrologist might discuss at a table with historians, archivists, and chroniclers? Can historical data help us gain a better understanding of today's flood risk assessment? And might deeper knowledge of past floods prepare us for future ones linked to climate change? We put these questions to Ing. Libor Elleder, Ph.D., in the October hydrology issue of *VTEI*.

Dr Elleder, in your view, what is the significance of historical sources such as chronicles, old maps, and municipal records for hydrology today?

To put it simply, all these historical sources significantly expand our knowledge of extreme events such as floods, droughts, heavy rainfall, but also harsh winters, tornadoes, or crop failures, reaching far back into the past, beyond the reach of any instrumental records based on measurements of temperature, precipitation, or water levels. It is not just about the intensity or magnitude of floods, but also their typical seasonality, which can change gradually over time due to climatic conditions. These are just a few examples. Should we simply give up on such information? That might be the defence of historical sources. But why are such sources not generally accepted in hydrology? An impartial judge might raise that question. Were the prosecution to speak, we would probably hear about the vagueness, inaccuracy, unreliability, and "gaps" in historical sources. The devil's advocate would add that chroniclers often embellished their accounts, lacked impartiality, flood markers were moved, watercourses altered, natural conditions changed, and everything is simply different now, so such sources are useless. A member of the jury might also add that they had never even heard of anything like historical sources and that it is better to stick to "traditional" methods. The usefulness of these sources therefore needs to be carefully explained and patiently defended. It seems, however, that it is not only chronicles that are at risk of being forgotten, but also the records and documents created and preserved by generations of water management professionals fifty or a hundred years ago. The political upheavals of the twentieth century, combined with generational forgetfulness, have also deprived us of many more recent, equally irreplaceable sources.

Zlata Šámalová from the Elbe Basin State Administration recently recalled how, decades ago, water management archives were being destroyed, piled onto a large heap. At the last moment, however, it was possible to rescue some bridge projects, river engineering plans, and riverside maps, preserving them for the future. From the archives of the Sewerage Commission, most of the glass negatives documenting water management structures from the early twentieth century were reportedly sent to glassworks for melting. Even so, many were saved, including an entire truckload of these glass negatives. After all, water management and hydrology archives and documents form part of historical hydrology. It has been more than half a century, but it is important to mention.

Do you ever encounter doubts about the reliability of such sources?

In the nearly forty years I have worked in hydrology, I have met many colleagues who were somewhat sceptical about combining hydrology with history or other humanities disciplines; however, the reverse is also true. Others were enthusiastic.

It depends on one's character, personal experience, and upbringing. My parents had a humanities education: my mother studied at the Faculty of Arts and worked at the Technical Museum in Prague, while my father was a lawyer whose favourite hobby was history. So our home library was full of books on history and art, and, alongside politics, these were frequent topics of discussion. When I visited my mother at the Technical Museum, I felt very comfortable, or even great, among the old machines, drawings, and maps. One more explanatory note: my strong appreciation for visual art. Old maps, manuscripts, and books are stunningly beautiful, there is no question about that. What I want to emphasise is that historical sources never repelled me; quite the opposite.

The question, however, is how all these sources can actually be used, say, in hydrology. My grandfather came from the ancient Ille milling family in South Bohemia. At his family mill in Kostelní Radouň, there were two beautifully marked flood gauges from the flash floods of 1934 and 1949. I assumed that, just as there were floodmarks at our family mill, similar floodmarks could be found at other mills. Later, I realised that this was not quite the case. In theory, such data harbour vast informational potential. For me, they were a powerful initial source of inspiration.

The database of Czech watermills compiled by Rudolf Šimek now contains 11,904 mills. That is a substantial number, and if flood records had survived, they would be an invaluable resource – especially for smaller catchments, where no systematic records exist. Each mill would have had a flood gauge and some form of water-level measurement. It is almost certain that, at one time, most mills had at least some flood marks. However, a field survey in 2007 revealed that in most cases these marks were in a very poor state, even at sites where they had still been visible around 1930. The authors of longitudinal profiles at the Hydrological Institute recorded a number of such water levels in the Vltava, Sázava, Jizera, and Berounka rivers between 1920 and 1950. One can see that, on the Vltava before the cascade dams were built, profiles with one or more flood marks existed at almost every, or at least every second, river kilometre.

How can chronicles and municipal records be utilised?

A similar situation applies to chronicles and municipal records. Today, there are over 6,200 municipalities in the Czech Republic, many of which disappeared after the war, so the actual number was even higher. Again, this represents an enormous amount of potential data on weather and floods. Working with them does not always lead automatically to success; however, when we were analysing the floods of Rakovnický stream, a case occurred of two alternative dates for a flood on the Rakovnický and Lišanský streams. I then found an explanation in the chronicle of the village of Hředle. In May and June 1852, the village was struck by a total of five flash floods within a period of about three weeks. Both alternatives were confirmed, and moreover we obtained information on a longer period during which flash floods affected a broader area. The use of a large number of municipal chronicles also showed that May floods in the Rakovník, Podbořany, and Beroun regions are by no means exceptional, but rather something typical. The great flood of 25 May 1872 fits into the context of this area quite well. From 1836, all market towns were required to keep chronicles, and a hundred years later, this applied to all municipalities. It seems that these records of floods, droughts, and storms in local chronicles have largely been left unused.

And how far into the past can one look by means of these sources?

Going further back, written sources related to the history of royal or dependent towns can be consulted, with records beginning in the fifteenth or sixteenth century. In Prague, evidence of floods starts with Kosmas's chronicle; the earliest flood mentioned here occurred in September 1118.

Our oldest riverside maps date from the reign of Maria Theresa and her sons Joseph II and Leopold II, mainly from the period 1770 to 1795. The oldest map of the Otava showing water depths in cross-sections is from 1794, while the earliest such map of the Vltava is from around 1822 to 1825. What use are these materials? They are the only records we have of natural or human-induced changes in our rivers. They provide answers to questions such as the causes behind the separation of certain river meanders or the changes in the cross-profiles of the Vltava and the Elbe.

From 10 to 12 September 2025, the third international workshop of the Flood Working Group (FWG) of PAGES (Past Global Changes) was held in Prague. The group aims to create a global database of flood event records. It was established in 2016 at the first workshop held at the University of Grenoble. Efforts to combine methods of historical hydrology with the results of paleoflood hydrology are still developing. We were pleased that this year Czechia was represented by a key speaker, Associate Professor Jan Hradecký from the University of Ostrava, an expert in river morphology and the documentation of contemporary and past landslides. Thanks to the archaeologist Jan Havrda, we were also able to show some dated fluvial layers in Prague, even from the 14th century, when the frequency of major floods was exceptionally high according to documentary sources. A great support and model in this regard are experts from the USA, the United Kingdom, Switzerland, Spain, Germany, the Netherlands, and Israel.

Can you give a specific example where historical sources have yielded something interesting, new, or exceptionally useful?

Recently, a 1714 map of the Brandýs and Nymburk manorial estates was discovered in a Viennese archive, showing the actual confluence of the Elbe and Jizera rivers up to Stará Boleslav. It includes mill race channels, vanished fishponds, and other features. In the 1844 riverside maps of the Elbe, water depths, shallows, and stones, removed from the riverbed in the nineteenth century, are recorded.

In the 1990s in our archive in Brozany, we discovered the oldest series of daily records from Magdeburg, beginning in 1727. It is possibly the longest series of daily water levels in Europe, or even in the world. For a long time, no one knew about it. Around 1880, Professor A. R. Harlacher, head of the Hydrometric Section of the Hydrographic Commission of the Kingdom of Bohemia, had it sent to him by colleagues in Magdeburg, as he was interested in the declining trends of minimum water levels in this old record. Had the package of extracts been lost, no one would have noticed or missed it. However, as we have it, it is much better. Many similar series are considered lost, at least for the time being. This example gives hope that many more may still be found in various uncatalogued collections – perhaps in places we would not expect. My colleague Jan Řičica copied the package and sent it back to German colleagues in Magdeburg, returning it after 110 years. We divided the work of transcribing the series between the Czech Hydrometeorological Institute (CHMI) and TGM WRI equally with Ladislav Kašpárek; he did not need convincing that it was a good idea. Today, colleagues from the German research institute Bundesanstalt für Gewässerkunde (BfG) have already published two studies on changes in the Magdeburg gauge profile, including a quantification of this unique flow series.

And what do these discoveries tell us about the actual development of water management?

It is not only about floods. It is quite logical, and probably even necessary, to attempt to understand the development of water management as a discipline. Only with the insights gained from the commission inspections of the Elbe from Mělník to Cuxhaven did new information clearly emerge, for example regarding the significance of "hunger stones" and the markings on them. Their importance was clear to the commissioners at the time. When studying floods and droughts, we also need to consider the historical development of settlement along the rivers. Twenty years ago, under the leadership of Rudolf Brázdil, the book *Historical and Recent Floods* was published. Since then, we have gathered a wealth of information on both floods and the development of Prague and other settlements. This allows us to answer questions such as whether floods similar to those of 1997 or 2002 occurred in the past, with far greater certainty than before. In our country, we are fortunate to have relatively long, systematically measured series of water levels and precipitation, largely thanks to the foresight and expertise of Professors A. R. Harlacher and F. J. Studnička. However, if we look at the history of floods on major rivers such as the Sázava, Ohře, Jihlava, Dyje, and even the Jizera, we see that the recorded series only begin after the era of major floods in 1784, 1845, and 1862. Without this insight, we would probably obtain a rather distorted picture of major floods in these and other catchments. And this is just one example.

Could you give a specific example of when historical records have helped to better understand or refine flood risk assessment?

Perhaps the question could be framed the other way around: when has the absence of historical data led to mistakes and worsened disasters? Such examples are often cited in lectures by key speakers, for instance Victor Baker from the University of Arizona, or arguably Spain's leading expert in paleoflood hydrology, Gerard Benito. I will give just two examples, both connected to the year 2011. Coincidentally, both involved nuclear power stations threatened by water. In March of that year, it was Japan's Fukushima Daiichi, endangered by an earthquake and the resulting tsunami. In June, the Fort Calhoun plant on the Missouri River faced serious flooding. In both cases, historical data are available; it is just not very clear why they were not properly used in the design of the structures. Although the US power station was inundated, the event passed without major consequences; however, five years later the plant was decommissioned and gradually dismantled. In Japan, the outcome was much worse, as is widely known.

How did the scientific community view the use of historical records in the past?

Professor Nobuo Shuto of Tohoku University has studied tsunamis, both through modelling and historical cases. As he recalled, a key event for him was the great tsunami of 1983. Eyewitnesses during his field research told him that, while it was terrible, it was nothing compared to the tsunami of 1896. He then began studying historical cases; however, by that time, the Fukushima Daiichi plant had already been built.

It is quite interesting that it was precisely in the 1980s that there was a general return to the use of historical data. Even then, a number of papers appeared, including the 1982 *Science* article *Palaeoflood Hydrology* by V. R. Baker. The theoretical basis for incorporating unsystematic data into statistical analyses came with formulas published in 1987 by J. R. Stedinger and T. A. Cohn, which allow datasets above a chosen threshold (including pre-instrumental data) to be combined with annual maximum series. At the same time, Vít Klemeš published several articles criticising the derivation of flood recurrence intervals from very short records. Klemeš emigrated to Canada in 1968, where he became a recognised hydrologist. I remember lectures by V. R. Baker, who particularly highlighted Klemeš and endorsed his ideas. When Ladislav Kašpárek and I were preparing for this year's lecture on 18 March, marking the release of the book *Historical Floods on the Rakovnický Stream*, he recalled that in the 1980s, these very Klemeš articles were the ones he read and knew well.

I was not present when Ladislav Kašpárek discovered, during fieldwork after the July 1981 flood, a flood mark from 1872 on the rock above Červený Stream. He recalled this repeatedly, most recently during the aforementioned lecture this year. In 1984, he published a paper explicitly addressing the influence of incorporating historical data into statistical analyses. Today, the peak values of the Litavka and Berounka rivers in 1872 are taken for granted. However, this was by no means obvious: the reconstruction of the flood on the Litavka was somewhat daring, and publishing the results was bold.

Can we find other personalities who similarly emphasized the importance of historical floods?

There is a certain parallel here with the Japanese Professor Shuto and his field survey after the 1983 tsunami, which set him on the path toward studying historical events. Since 1978, historian and archivist Jiří Kynčil had been working on excerpts concerning historical floods in the Ore Mountains and the Ohře River Basin. He carried out this work for the state enterprise Povodí Ohře. At the time, the focus was on coal mining in the region and the future protection of surface mines. It was necessary to gather as much information as possible on floods in the short Ore Mountain tributaries of the Bílina and Ohře rivers. Less well known is a shorter publication on the Jílovský Stream. As early as 1983, Jiří Kynčil noted that estimates of flood recurrence intervals for the Jílovský Stream were probably underestimated. It is interesting to read, in the reflections of a person with a humanities background, the same objections regarding the insufficiency of thirty- or fifty-year records for deriving a 100-year flow as those raised by world-leading hydrologist Vít Klemeš; the documented floods from 1897 and 1927 had not been used. Shortly afterwards, an actual extreme flood occurred on the Jílovský Stream, which Ladislav Kašpárek then analysed. This is how the two of them became connected through the Jílovský Stream. Jiří Kynčil later inspired Oldřich Kotyza, an archaeologist from Litoměřice, to explore the topic of historical floods – a subject Kotyza dedicated his entire life to, alongside climate history. Ladislav Kašpárek believed that estimates of extreme flows were crucial. In addition to his estimates for the Litavka flood of 1872, he provided estimates for the Střela, Blšanka, Berounka, Vltava, and finally the Rakovnický Stream. In doing so, he made a substantial contribution to our understanding of potential flood risk.

How do you verify and interpret historical data, which often appear not as precise figures but as descriptions or narratives?

There are several considerations. We consider contemporary accounts (primary rather than secondary sources) to be the most reliable. We also give preference to quantitative data, which usually concern historical peak water levels. Typically, these are flood marks, so-called epigraphic sources. Equally precise can be flood heights derived from chronicle entries linked to fixed reference points. The best-known example is the Gothic sculpture of "Bradáč" (Bearded Man) in Prague. We surveyed it in 2004, which resolved doubts about the circumstances of its relocation to a new position in 1848. In this way, we now have a series of quite precise peak water levels in Prague dating back to 1481.

It could also be the floor level of a church. However, there can always be obstacles and uncertainties about past changes in the position of such a site or structure. A sad example is the Church of St. Anne in Hradec Králové, which was demolished during the construction of fortifications around 1775. A building plan of the church survives, but without elevations. In the sixteenth and seventeenth centuries, flood heights on the Elbe were repeatedly referenced to the floor level of this church. This allows us to know the relative levels of these peaks quite precisely. Yet linking this series to other extreme floods such as the devastating flood of 1775 or probably the worst floods in 1804 and 1846 remains a problem. I remember being shown around Hradec Králové by the aforementioned Zlata Šámalová, who sadly pointed out the area around the roundabout, where perhaps some tiny remnants of the church still lie buried underground.

What should be done in cases where only imprecise or qualitative descriptions of floods are available?

There are many floods where the determination of peak water levels is somewhat "fuzzy" or where we only have records of significant property damage, giving us a "qualitative" description, such as damage to crops, objects being swept away, houses damaged, or bridges destroyed. A 1-to-3 point scale is used here, with an approximate relation to *N*-year return periods provided as a guide. Clearly, if people are taking refuge on rooftops, and houses and bridges are collapsing, it is not going to be a 5-year flood, or even a 20-year one. In such cases, we either settle for an estimate or rely on a better-documented situation further downstream, where quantitative data can serve as a reference. It is important to emphasise that historical hydrology is not just the collection of flood data. One must also understand the development of a given locality over time, including any changes in the floodplain and the river channel. This can sometimes be quite challenging.

A photo of Bearded man (or in Czech "Bradáč") from a 2004 survey shows that his head is, in contrast with mine, 70 cm tall

HEX Conference, Bonn 2014. Participants in front of the Main Gate of the town of Eibelstadt, with about 20 to 30 flood marks from 1550 to 2002.

Can you provide a specific example where knowledge of the development of a locality helped to correctly interpret a flood?

One of the best examples is Prague. Here, since the construction of weirs (roughly from the thirteenth and fourteenth centuries) the riverbed did not deepen, in contrast with, for instance, in Cologne, Germany. Here, the Rhine gradually deepened its channel, influenced in part by various human interventions. Evidence of this was left in the form of drawings of German towns during his voyage along the Rhine, Main, and Danube in 1636 by the Czech etcher Václav Hollar. Weirs extending across the entire river were by no means common on larger rivers in the Middle Ages and often are not today. Mills managed without them, and on the Rhine, boat mills were more typical; constructing a stone bridge across a river was generally feasible only on smaller streams in the medieval period. The Vltava in Prague, the Elbe in Dresden, and the upper Danube in Regensburg remained, for a long time (roughly until the nineteenth century) at the limits of technical possibility. On the Rhine, floating bridges were often used, for example in Mannheim. The situation in Prague is actually quite unique; riverbed changes were slowed by the system of weirs, and alterations in terrain heights were halted by the gradual paving of the city, a process that began in the thirteenth and fourteenth century. This knowledge allows us to interpret reports of major floods, such as those occurring during the construction of Charles Bridge. At that time, Prague experienced a series of floods in 1359, 1367, 1370, and 1374, for which we can estimate peak levels approximately, based on the horizontal extent reaching churches such as St. Michael, St. Giles, or St. Linhart. This is why it is important to study in detail how the Old Town of Prague was inundated in the nineteenth century, when peak water levels are already known with high precision. Such knowledge is invaluable. It allows us to better understand what two prominent chroniclers of the time of Charles IV meant in their brief descriptions of the water reaching the Old Town. Put in modern terms, they recorded that Prague experienced roughly four "50 to 100-year floods" over a fifteen-year period beginning in 1359.

How can the reliability of historical descriptions of extreme floods be verified?

When, as part of a research project on changes in floodplains in 2007, we surveyed the floodmarks along the Sázava River, we came across reports of a flood in Ledeč nad Sázavou that had reached some two to three metres above the Q_{100} level. This might be dismissed as an unreliable record. Yet similar descriptions of flood heights were found in every surrounding town, from Žďár nad Sázavou to Kácov. These data were consistent with the descriptions of the number of drowned persons in the respective municipal and parish registers – in total, 240 people drowned. The flood in question occurred on 31 July 1714. I mention this case because we attempted to reconstruct a plausible rainfall scenario that could have produced a hydrological response corresponding to at least one chronicle description. The rise and fall of the Sázava River was in detail described by the dean of the church in Německý Brod town (today Havlíčkův Brod). The required rainfall and its intensity ultimately still "fit" under the envelope curve of maximum precipitation for our country. It worked!

In what way are historical floods systematically made accessible today?

In recent years, we have been working to bring together information on selected extremes into the MEF mapping application. MEF is built on ArcGIS. Its purpose is straightforward: to present historical floods in their full spatial extent. Major regional summer floods cover hundreds of thousands of square kilometres, while great winter floods – such as those in February 1374 and 1784 – affected an extraordinary area stretching from France to Bohemia, possibly even beyond. Processing such events can be time-consuming, but the reward lies in being able to view each episode as a whole and compare it with other historical situations. The key motivation here is precisely the verification of data within the overall context. An example is the February 1374 flood; on Czech territory, we have only two mentions – from Prague and the Ohře Basin – yet these are confirmed by dozens of descriptions across Central and Western Europe. The credibility of later chronicle records, where more detailed notes survive, is reinforced by matching evidence: for instance, the travel times of flood waves in 1675, 1784, 1824 or 1890 between towns such as České Budějovice, Prague, Dresden and Magdeburg, or the mutually consistent descriptions of damage and peak water levels.

When researching historical events, do you collaborate with historians, archivists or other experts outside the natural sciences?

Over time, I found several colleagues who were either interested in the subject or at least willing to engage with it – sometimes both. Perhaps the best example was

Photograph with a floodmark on a monastery in Plasy showing that in 1872 I would have had no chance at this spot.

the archaeologist Oldřich Kotyza. When, in 1995, he published his booklet *Historic Floods on the Lower Elbe and the Vltava* on the occasion of the anniversary conference of the 1845 flood, I was thrilled. That was hydrology in practice! In 2003, we met the renowned Prague archaeologist Ladislav Hrdlička at the conference *City and Water*. He helped us a lot with understanding the development of Prague's terrain. He also introduced me to his colleague Zvonimír Dragoun, a surveyor who worked in nature conservation, heritage preservation, and archaeology. Today I can hardly imagine my work without him. In Prague, the archaeologist who now comes closest to the issues of fluvial sediments and their dating is Jan Havrda. Over the past thirty years, Prague archaeology has made great progress, particularly in interpreting changes in floodplain areas that are of such interest to us – for example, the development of Malá Strana, Kampa, and Klárov, the evidence of terrain changes around the Klementinum, or the position of the old wooden bridge that was deeply submerged during the flood of 1118.

We have received help from staff at Prague Museum and from many other museums and archives – in total, dozens of people. Our most substantial joint work, however, has been with the historian Jan Lhoták, a specialist on the history of the Šumava region and the town of Sušice. In 2013 we published together an extensive collection on the floods of the Otava River from 1432 to 1900. We had hoped that a follow-up in book form would also find support, but to our surprise there was no interest. I believe that interdisciplinary collaboration is far more natural in Western Europe, though it is gradually gaining ground here as well. If I were to name people internationally who study the history of floods, I must mention the historian Andrea Kiss, who works at the Technische Universität (TU) Wien alongside the hydrologist Professor Günter Blöschl. Within the community of scholars dedicated to historical floods in Europe, one finds archaeologists, historians, geographers, and geologists. This diversity is also evident at meetings and conferences, where the "balance of forces" is strikingly varied.

How can knowledge of past extreme events help in preparing for future floods in the context of climate change?

Yes, it may seem illogical. Everything changes, so why look back to the past? Yet the climate has always changed to some degree. We can see this in floods in our region as well: during the colder periods of the seventeenth and eighteenth centuries, large winter floods were more common, but from the second half of the nineteenth century, summer floods prevail. In 2019, together with Professor Rüdiger Glaser from University of Freiburg, I stood in Riederalp above the Aletsch Glacier, where he pointed out the "1850 moraine". Since 1850 the glacier has been retreating, and the place where we stood just six years ago is now at risk of landslides. Climate change and global warming may have consequences that are difficult to foresee today. But not everything changes. The laws of physics will remain in force, and the morphology of the landscape, the floodplains and river channels, as well as the river network, are unlikely to undergo fundamental changes – at least not on the time scale we are concerned with now.

Even if the atmosphere were to undergo very substantial changes, it is certain that knowledge of past extreme events will remain useful. The already mentioned classic figure of historical flood research, Victor Baker, summed it up in a single sentence: "What has happened once can happen again, because it is real." Indeed, floods that have actually occurred have one undeniable advantage over those merely modelled – they cannot be dismissed. However astonishing their parameters may sometimes appear, they must be accepted as fact.

It is possible that future events may occur in somewhat different ways – for example, with greater frequency. It is evident that in the past five centuries there have been several periods when floods were both more frequent and more intense. These often coincided with times when the troposphere had been subjected to a powerful impulse, such as after the major volcanic eruptions in Iceland and Japan in 1783. In the period that followed, Europe experienced severe winters, devastating floods, and other anomalies.

It is difficult to prove a direct influence of climate change, or global warming, on recent floods. The outcome of our efforts in this regard was the project led by Professor G. Blöschl, which evaluated long historical series of flood peaks, from 1500 to the present. Our joint paper was published in *Nature*. The period 1993–2016 was assessed as the second most intense in terms of flooding in Europe since 1500. Is this evidence of the impacts of climate change? For some, yes; for others, not yet.

Throughout your scientific career, you've worked with many experts, including our recently deceased colleague Ladislav Kašpárek, a hydrologist at TGM WRI. Could you describe your collaboration with him and share a fond memory, please?

I had probably known Ladislav Kašpárek since around 1985 or 1986, during the fifth year at CTU – so roughly forty years. He taught an optional course in Hydrological Modelling as an external lecturer. It lasted just one semester. For my diploma thesis, I was assigned the task of carrying out automatic optimization of the hydrological Tank Model using the Rosenbrock method. The thesis supervisor was Miroslav Kemel, and Ladislav Kašpárek served as consultant. My task was not only to calibrate the model based on a historical event on the Otava River, but also to describe the very clever Rosenbrock optimization method. Yet even this method, capable of efficiently searching in a multidimensional parameter space for the optimum of an objective function, often fell into the trap of local optima. It was a good lesson in the importance of staying "down to earth" and applying logic and common sense alongside the powerful mathematical apparatus. I believe Ladislav Kašpárek was a real support in this regard.

A photograph of Ladislav Kašpárek acting as a scale figure, holding a rod above the 1616 mark.

After I returned from military service in September 1987, Ladislav Kašpárek changed jobs and moved to TGM WRI. His position as head of the Department of Regime Data Processing was taken over by Oldřich Novický. Yet traces of Ladislav Kašpárek's work were everywhere – for example, in his initiative to establish and organize the hydrology photo archive together with the meticulous technician Eva Bařinová. The photographs of hydrological structures were arranged by type, and the flood photographs chronologically. Ladislav Kašpárek more than anyone else realized how essential such an archive would be. The same applied to many other seemingly simple things. My cooperation with him continued even after he left the Prague branch of CHMI, whether it concerned artificially generated time series, methodologies for calculating water balance, or flood wave analyses. When my interests turned toward historical hydrology, I found in him clear support and understanding.

How did Ladislav Kašpárek support you in your work on historical hydrology?

Later, when I began my dissertation, he offered to collaborate on the evaluation of the 2002 flood, specifically in searching for historical parallels to that event. This form of cooperation continued further, also leading to co-authorship of IF articles. I prepared historical materials for various studies, including work on the Rakovnický Stream. Very often, I simply asked him whether this or that was a good idea. To conclude, I would like to share a memory that contains neither a humorous punchline nor a hidden deeper meaning. It is, however, a memory that I enjoy recalling in my mind. It relates to the catastrophic period of drought. Hydrological drought began to manifest as early as 2014 and continued until spring 2020. Every cloud has a silver lining: we had long awaited the opportunity to observe the hunger stone in Děčín rise as much as possible above the water. The best chance to record all thirty markers of minimum water levels on its surface came in August 2015. After phone calls and some theoretical preparation, Ladislav Kašpárek organised the expedition. We travelled in an off-road vehicle driven by Jan Kašpárek, his son. Naturally, the surveyor Zvonimír Dragoun, an indispensable collaborator, accompanied us. Excavating and cleaning the stone is a task for four people, taking roughly half a day. Despite the contribution of the Vltava cascade, the water level had dropped very low, so all the markers were clearly visible. That day – I believe it was 14 August 2015 – the afternoon temperatures in Děčín reached around 38 °C, yet Ladislav handled the spade with great skill. By around three o'clock, however, we had all had enough. The stone was fully excavated and clean. At the side, where the famous inscription reads "Wenn du mich siehst, dann weine" (*"If you see me, weep," editorial note*), something else appeared beneath the water – perhaps a five-pointed star. Was there a marker somewhere beneath it as well? We could not go any deeper, unless the outflow from the Střekov weir was temporarily reduced. Calmly, Ladislav said, "Well, let's build a little dam then." We quickly constructed a small barrier around the side of the stone. We removed the water using a plastic mineral water bottle and, I believe, even a pump originally intended for cleaning and rinsing the stone. It was a battle between seepage and the pump's capacity. Jan Kašpárek shovelled gravel and mud tirelessly until the job was done. In the process, he unearthed the lowest marker from 1934. It turned out that the measurements previously taken at the gauge and the heights of the markers matched almost exactly. The difference between the annual minimum recorded at the gauge in 1868 and the corresponding marker was zero! We used the same, slightly refined, method again when scanning the stone in 2018.

Which joint project or topic would you consider central to your collaboration?

If I were to identify the common thread of our collaboration, it would almost certainly be the flood of May 1872. Since 1981, this flood never left Ladislav Kašpárek's mind; he returned to it again and again. He initiated renewed work on the topic in 2000, which involved field surveys along the Střela and Blšanka streams. Subsequent steps focused on more detailed information about damage to water mills and ponds, as well as using Aqualog for re-simulation. The final step was the estimation of the Rakovnický Stream's flow, culminating in the book on historical floods (*Historical Floods on the Rakovnický Stream, editorial note*). After the joint lecture presenting this book on 18 March at TGM WRI, we spoke for another two hours in the office. Eventually, we went to his archive in the corridor and up to the attic. He pointed out the essential items that should be preserved. Sadly, this is now the very last memory…

Dr Elleder, we sincerely thank you for the interview and for providing the photographs.

Ing. Adam Beran, Ph.D.
Mgr. Zuzana Řehořová

Ing. Libor Elleder, Ph.D.

Ing. Libor Elleder, Ph.D., was born on 11 July 1963 in Prague. He studied at the Faculty of Civil Engineering at Czech Technical University, specialising in Hydraulic Structures and Water Management. He focused on hydrology, including his master's thesis on *Automatic Optimisation of a Hydrological Tank Model.* After completing his studies, he joined the Czech Hydrometeorological Institute. Until 1993, he worked in the Data Regime Processing Department, focusing on flood recurrence intervals calculations, generation of synthetic series, and data processing in unmonitored profiles, also serving as a programmer for a range of tasks. From 1993 to 2013, he worked as a forecaster, specialising in hydrological predictions. Since the 1990s, he has also been engaged in historical hydrology. In 2009, he defended his doctoral dissertation at Charles University on *The Use of Proxy Data in Hydrology*. Since 2013, he has worked in the Department of Applied Hydrology, focusing on research. He has co-authored and authored numerous scientific articles, contributed to several professional books, and worked on an ArcGIS-based application for flood mapping. Currently, he is a member of the Floods Working Group Pages and collaborates with the Working Group for the History of Hydrology.

Department of Hydraulics, Hydrology and Hydrogeology: international projects starting in 2025

At the T. G. Masaryk Water Research Institute (TGM WRI), two international projects were launched in 2025. These include the *SWIM* project, funded under the Horizon Europe programme, and the *FrauNyLu* project, supported by the Interreg cross-border cooperation programme. Both projects also address hydrological topics, which will be managed by the Department of Hydraulics, Hydrology and Hydrogeology.

THE *SWIM* PROJECT (HORIZON)

The *SWIM* project (*Sustainable Water and Integrated Management of Fish Migration and their Habitats in the Danube River Basin and NW Black Sea*) focuses on the restoration, protection, and improvement of habitats for migratory fish species in the Danube River Basin and the north-western Black Sea region. The project is implemented within the framework of the European Restore our Ocean and Waters Mission; it builds on long-term activities in the field of international cooperation for the protection of aquatic ecosystems. More than 20 partners from Central and Southeast Europe are involved in the project, including key scientific research institutions, river basin authorities, environmental organisations, and regional governments.

Objectives and main activities

The main objective of the *SWIM* project is to restore river network connectivity, improve habitat quality, and strengthen the protection of key migratory routes of fish populations. The project is structured into thirteen activities implemented at seven pilot sites along the upper, middle, and lower Danube, including the Danube Delta and the Black Sea coast.

The key outputs of the project include:

- identification and mapping of key habitats for fish migration,
- design and implementation of measures to restore river connectivity (e.g. lateral reconnections, fish passes),
- establishment of *ex-situ* conservation facilities for breeding selected endangered fish species (e.g. sturgeons, Black Sea salmon, gudgeon),
- creation of a network of protected areas (fish refuges) and preparation of plans for their long-term management,
- use of digital technologies for monitoring and data sharing (including the extension of the MEASURES Info system and integration with the European Digital Twin Ocean),
- involvement of local communities and support for sustainable local models (e.g. eco-tourism, environmentally friendly aquaculture).

SWIM

Sustainable Water and Integrated Management of Fish Migration and their Habitats in the Danube River Basin and NW Black Sea

The role of TGM WRI in the *SWIM* project

TGM WRI focuses primarily on providing hydrological support to the project, assessing the impacts of climate change, and designing restoration and adaptation strategies. This also includes modelling the water regime at pilot sites and evaluating the effectiveness of nature-based solutions for ensuring connectivity and improving conditions for fish migration.

The Institute is also involved in methodological harmonisation of monitoring procedures and in sharing experience among research partners from different countries. An important component is the engagement of local stakeholders, including the general public, which contributes to raising awareness of the importance of fish migration for the conservation of biodiversity and ecological stability of aquatic ecosystems.

Significance of the project for the Czech Republic and international cooperation

The *SWIM* project represents a significant advancement in the protection of migratory fish species within the Czech Republic, particularly through research on the upper Danube and its tributaries. The restoration of migratory routes and the improvement of the ecological status of river stretches contribute to the achievement of the objectives of the Water Framework Directive (2000/60/EC), the EU Biodiversity Strategy for 2030, and the new Nature Restoration Regulation.

Thanks to its transnational approach and collaboration across scientific disciplines and administrative levels, the project has the potential to become a model example for the restoration of river ecosystems throughout Europe. Through its involvement in the *SWIM* project, TGM WRI is actively contributing to shaping future approaches to the protection of freshwater biodiversity and the adaptation of water management to climate change.

The *SWIM* project represents a unique opportunity to link ecological restoration, research, innovation, and regional development. Its success will depend not only on a professional scientific approach but also on the ability to engage the wider public, relevant institutions, and communities along the watercourses. In the coming years, TGM WRI will play a key role in achieving the objectives of this ambitious international project.

THE *FRAUNYLU* PROJECT: *JOINT SOLUTIONS FOR SAFE DRINKING WATER SUPPLY IN THE CZECH–BAVARIAN BORDER REGION* (INTERREG PROGRAMME)

TGM WRI has also become involved in the new cross-border *FrauNyLu* project, which will assess the interconnection of the Nýrsko, Lučina, and Frauenau water reservoirs. The aim of the project is to develop joint measures that will enhance

the resilience and safety of drinking water supply in the Czech–Bavarian border region, particularly in view of the expected impacts of climate change.

The *FrauNyLu* project was initiated in response to a shared challenge faced by both regions: to establish long-term sustainable and efficient water resource management in an environment characterised by low rock retention capacity and limited groundwater availability. The crystalline regions of the Šumava, Český les, and Bavarian Forest are highly sensitive to droughts and precipitation fluctuations, which are becoming increasingly frequent and intense due to climate change. The project therefore aims to strengthen cooperation and create a comprehensive system for information sharing, water balance assessment, and the design of joint technical and organisational measures.

Joint approach

A completely new approach applied in the *FrauNyLu* project is cross-border assessment of the current and future state of water supply based on mutually harmonised methods and jointly shared data. Whereas similar analyses were previously carried out separately at the national level, the *FrauNyLu* project provides an integrated perspective on the entire area supplied by the key water sources – the Nýrsko, Lučina, and Frauenau reservoirs.

Based on the established database, it will be possible to determine the water resource balance, assess potential deficits, and propose specific adaptation measures. These may include technical solutions (e.g. system interconnections, resource sharing during periods of drought) as well as organisational measures (intelligent management of water abstractions, contingency scenarios, and coordination platforms).

The *FrauNyLu* project will deliver tangible benefits to both the Czech and Bavarian parts of the region, particularly in the following areas:

- increased resilience of drinking water supply during periods of drought or in the event of emergencies,
- improved planning of investments in water management infrastructure through shared analyses and models,
- utilisation of synergies in water resource management – reducing duplication and making efficient use of existing capacities,
- strengthening Czech–Bavarian cooperation at both local and institutional levels,
- enhanced safety and self-sufficiency of residents in areas with potential water scarcity.

The role of TGM WRI in the *FrauNyLu* project

TGM WRI contributes to the project primarily in a professional capacity, providing hydrological analysis and designing adaptation measures. In doing so, it draws on long-term experience in water balance modelling and the development of methodologies for assessing the impacts of climate change on the water regime.

TGM WRI contributes expertise gained from previous international projects, such as *Thaya* (Interreg), *Dyje* (Czech Science Foundation), *RAINMAN* (Interreg), and the *DALIA* project (Horizon Europe). The Institute also actively contributes to the transfer of research results into practice, both within public administration and in collaboration with water users, such as farmers and reservoir managers.

Cross-border cooperation

The aim of the *FrauNyLu* project is to demonstrate that joint management of water resources across national borders is crucial not only for ensuring an adequate supply of drinking water but also for maintaining ecological balance in the Czech–Bavarian border region. Given the similar natural conditions and shared challenges, a coordinated approach is more effective than isolated national solutions.

The use of large reservoirs as strategic multi-year water storage facilities in areas with low groundwater retention potential is crucial in the context of climate change. The project therefore represents not only a technical and institutional innovation but also a symbol of cooperation and solidarity between neighbouring countries.

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Magdeburg Seminar on Water Protection 2025: Water in the Elbe River Basin — yesterday, today, and tomorrow

On 8–9 October 2025, the 21st Magdeburg Seminar on Water Protection will take place in Magdeburg, Germany. This regular international event, held alternately in the Czech Republic and Germany, has, over more than three decades, established itself as an important professional and scientific platform for the exchange of knowledge in the field of water management and water protection in the Elbe Basin.

THEME FOR 2025

This year's seminar carries the central theme "Water management in the Elbe Basin – yesterday, today, and tomorrow," reflecting the long-term development, current challenges, and future perspectives in managing the region's water resources.

The seminar's content is structured into three main thematic areas:

- Security of water resources and ecosystem functions in the context of climate change,
- The Elbe as a waterway – opportunities and limitations,
- Strategies for water monitoring and management.

PROGRAMME AND INVOLVEMENT OF INSTITUTIONS

The seminar programme includes 27 professional lectures, a poster session, and three specialist excursions focusing on practical aspects of water protection and utilisation. T. G. Masaryk Water Research Institute (TGM WRI) is actively involved in the programme through two lectures and four poster presentations.

As with all German seminars, the main organiser of this year's event is the Helmholtz Centre for Environmental Research (UFZ). When the seminar is held in Czechia, the role of main organiser alternates between the Labe, Vltava, and Ohře River Basin Authorities.

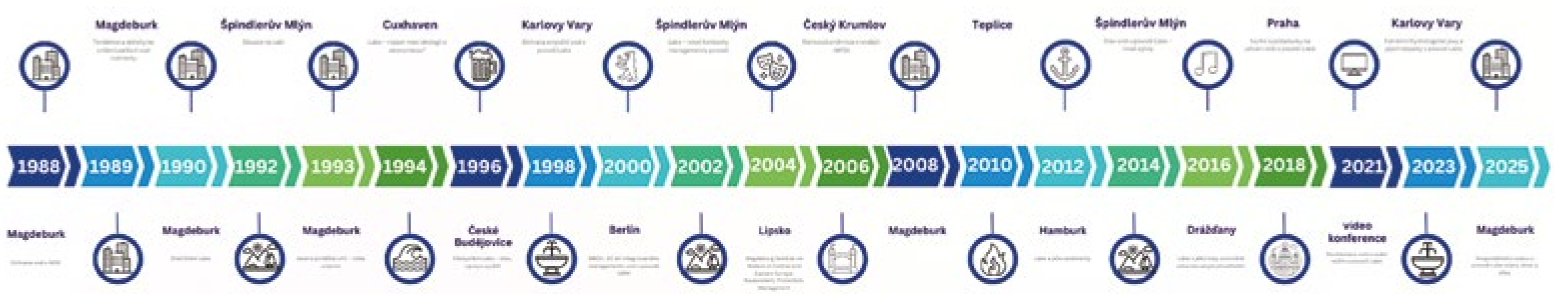
INTERNATIONAL COOPERATION AND PROFESSIONAL PROGRAMME

The seminar is prepared with the involvement of a programme committee composed of representatives from institutions in both Czechia and Germany. The International Commission for the Protection of the Elbe River (ICPER) also plays an important role, providing organisational, professional, and linguistic support for the entire event through its secretariat.

The programme offers a wide range of lectures. On the German side, notable contributions include Norbert Kamjunke (UFZ) with his presentation "Transformation of nutrients and dissolved organic matter in the river from source to sea," and Jörg Tittel from the same institution with "Elbe river modification for navigation reduces floodplain water resilience to climate change – studies on the middle Elbe near Magdeburg."

The Czech side will also be represented by a number of contributions. Notable examples include Pavel Richter (TGM WRI) with his presentation "Current state

TIMELINE OF PAST SEMINARS



of the landscape at the site of a former pond system in the Doubrava Basin and possibilities for its transformation in the context of ongoing climate change," and Karel Březina (Vltava River Basin Authority) with "Reassessment of the security of surface water supply from reservoirs under conditions of climate change."

As the seminar topics suggest, attention will also be given to the issue of Elbe navigation. Examples include Iris Brunar (BUND: Friends of the Earth Germany) with her presentation "Perspectives for a free-flowing Elbe: navigation, trends and potential," and Vojtěch Dabrowský (Ministry of Transport of the Czech Republic) with "The Elbe waterway as part of the European inland waterway network."

HISTORY AND SIGNIFICANCE OF THE SEMINAR

The first Magdeburg Seminar on Water Protection was held in 1988 in Magdeburg. Since 1992, the seminar has alternated regularly between Czechia and Germany. It was last held in Magdeburg in 2008, while the most recent seminar (2023) was organised in Karlovy Vary by the Ohře River Basin Authority in cooperation with the ICPER.

For more than thirty years, the seminar has been a key forum for experts from science, public administration, and water management practice. It provides a space for sharing up-to-date scientific knowledge, discussing strategic approaches, and strengthening cross-border cooperation within the Elbe Basin. Its importance was underlined by the words of the current ICPER President, Ing. Tomáš Fojtík:

"Water management in the Elbe Basin is a task that transcends state borders and generations. I believe that the discussions at this year's seminar will contribute to finding solutions that will ensure the sustainable use of our water resources for future generations."

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International Commission for the Protection of the Elbe River (ICPER) (Czech Republic)

Informative article that is not subject to peer review.

In memory of Ing. Eduard Hanslík, CSc.

In August 2025, Ing. Eduard Hanslík, CSc., passed away. He devoted his professional life to the T. G. Masaryk Water Research Institute, where he served for an extraordinary 59 years. He was among the pioneers of radioecology in Czechoslovakia and later in the Czech Republic, particularly in the monitoring of the occurrence and behaviour of radionuclides in the hydrosphere. From the time he joined the Institute in 1959, he contributed to key projects focused on mine and wastewater, issues related to radon, and later also the impacts of nuclear power plant operations on the aquatic environment.

His work became an integral part of research, standardisation, and practical measures in the field of water quality. The results of his research were applied not only in Czech water management but also internationally. He was the author and co-author of numerous scientific publications and monographs, contributed to the supervision of master's and doctoral theses, and was an active member of professional committees and councils. Through his expertise, perseverance, and kindness, he earned the respect and recognition of colleagues and students alike, both at the T. G. Masaryk Water Research Institute and within the wider professional community.

We remember him not only as a respected expert but also as an extraordinary person who, through his work, inspired entire generations of water management professionals. His legacy will remain closely linked with both the history and the present of our Institute. Honour to his memory.

References

REDAKCE, R. Rozhovor s radioekologem Ing. Eduardem Hanslíkem, CSc. *Vodohospodářské technicko-ekonomické informace*. 2016, 58(1), pp. 46–48. ISSN 0322-8916.

HANSLÍK, E. 60 let radiologie ve Výzkumném ústavu vodohospodářském T. G. Masaryka. *Vodohospodářské technicko-ekonomické informace*. 2018, 60(6), pp. 62–64. ISSN 0322-8916.

Colleagues from TGM WRI

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A STOP IN RÝMAŘOV: THE BYGONE TIMES OF THE JESENÍK REGION

The Indian summer is slowly drawing to a close, the birds fall silent, and dusk arrives ever earlier. So too comes to an end this small series devoted to historic waterworks in the Jeseníky Mountains, with a stop near Rýmařov. The flume in Žďárský Stream can be found on Stříbrný Stream, above its confluence with Podolský Stream. Today it remains only a fragment of a once extensive multipurpose system of flumes and reservoirs in the catchment of Podolský Stream and its tributaries. This system served for timber floating (hence the German name of one of the tributaries, Klautzenbach), for driving a sawmill (until 1885, when a steam engine was installed) and a downstream mill, and finally also for powering Girardot's turbine at Anenská Huť (smelter), which operated there from 1885 to 1955. The technical curiosities of Žďárský Stream (then known as Brandseifen) also include a forest narrow-gauge railway with a track gauge of 700 mm. Of it, only fragments have survived, mostly in the form of remnants of earthworks (embankments, cuttings, etc.), rather than any part of the track itself. The millrace itself is now 0.88 km long, with its diversion structure on Stříbrný Stream at an elevation of 691 m a.s.l. It ends in a system of reservoirs, heavily silted with sediments, and a feeder channel leading to the now-demolished aqueduct across the road at 684 m a.s.l. The difference in elevation compared to the channel of Podolský Stream at the site of the former outlet is about 11 m. From the other side, Podolský Stream supplied water to the balancing reservoirs through a tunnel about 0.8 km long, built during the First World War, which in itself is an outstanding engineering feat. Anenská Huť was once an important supplier of iron in Moravia; however, it gradually declined under the growing influence of Vítkovice ironworks. The furnace was shut down in 1881, and in 1955 the enterprise ceased to exist entirely.

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

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