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Discussions

Modelling hazards impacting the flow regime in the Hranice Karst due to the proposed Skalička Dam

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Abstract. This study examines hydrogeological risks associated with the construction of the proposed Skalička Dam in the vicinity of the Hranice Karst. Prompted by the catastrophic floods in 1997, the design of the dam aims to mitigate floods along the Bečva River downstream of the reservoir. However, concerns have been raised regarding the potential disturbance of the natural groundwater regime in the Hranice Karst and the source of mineral waters for the Teplice spa. This is particularly due to the dam's location in an area with limestone outcrops potentially susceptible to surface water infiltration. Previous studies have also highlighted the strong correlation between the water level in the Bečva River and the water level in karst formations such as the Hranice Abyss, Zbrašov Aragonite Caves, and other caves in the locality. To address these concerns, a nonlinear reservoir-pipe groundwater flow model was employed to simulate the behaviour of the Hranice Karst aquifer, and specifically the effects of the dam reservoir's impoundment. The study concluded that the lateral variant of the dam would have a practically negligible impact on the karst water system, with the rise in water level being only a few centimetres. The through-flow variant was found to have a more significant potential impact on water levels and the outflow of mineral water in the spa, with a piezometric rise of about 1 m and an increase in the karst water discharge to the Bečva River of more than 50 %. Based on these results, recommendations for further investigations concerning the design of the dam and its eventual construction were formulated to reduce geological uncertainties and minimise the potential impact of the hydraulic scheme on the hydrogeology of the karstic system.

1 Introduction

The Skalička detention dam is planned as a part of a flood protection system being constructed on the Bečva River as a response to the catastrophic floods that affected the region in 1997 and 2010. The location of the dam is planned in the Hranice Karst region, which contains numerous valuable natural monuments, such as the Zbrašov Aragonite Caves, the Hranice Abyss (Vysoká et al., 2019) and the Teplice spa, which exploits the mineral waters that rise from the deep karstic formations in the area. Potential environmental and geological ~~risks~~ associated with the construction and operation of the Skalička Dam have been described by Geršl and Konečný (2018). They point out the possible unfavourable impact of the dam on the natural groundwater regime in the Hranice Karst and the potential for the degradation of the abundant sources of mineral water used by the Teplice spa. Aside from the pumping wells that supply the Teplice spa, mineral water containing high concentrations

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of dissolved carbon dioxide rises into the Bečva River, the Zbrasov Aragonite Caves and the Hranice Abyss. Gaseous carbon dioxide may also be found at observation wells and "breathing spots" (Faimon et al., 2020) occurring in the area. However, the infiltration zone of the karstic system is still unclear; some authors (Vysoká et al., 2019; Bruthans et al., 2021) point out the significant role which may be played by surface water in the Bečva River, whose water stages probably govern water pressure in the karst formations. The older estimates of total spring discharge ranged from 12 to 17 l/s (Bruthans et al., 2021), while new research using hydrometric measurements combined with a conductivity assessment shows an amount of about 100 l/s (Il Faut, 2022). This supports the hypothesis that the Bečva River is an abundant water source for the Hranice Karst at a location lying a few kilometres upstream from the Teplice spa. At this point, limestone outcrops rise to the level of the local terrain and interfere with the Bečva River channel (Vysoká et al., 2019; Bruthans et al., 2021; Il Faut, 2022).

The dam is planned to be located about 5 km upstream from the Teplice spa in the vicinity of the aforementioned limestone outcrops, which also occur within the dam reservoir. Therefore, the question arises as to whether the construction of such a dam would have an impact on the karstic waters in the area and thus significantly affect hydrogeological conditions. One of the issues related to the construction of the new dam and the impounding of the reservoir is also its potential impact on mineral waters supplying the Teplice spa.

Building dams in karst areas is always a technical challenge. It involves a number of risks connected to unintended water losses and dam stability issues (Milanovic, 2005, 2018). Based on experience with dam construction and operation in karstic regions, Milanovic (2018) recommends that the karst in the vicinity and wider region of the proposed dam be carefully explored and understood. The groundwater regime in karstified rocks can be extremely complex and often is not readily predictable (Yevjevich, 1976), rendering it a far from friendly environment for constructing dams and reservoirs (Milanovic, 2021). The author emphasises that the amount of certainty or uncertainty in the crucial parameters (geological structure, groundwater regime, intensity and depth of karstification) should be recognised.

One of the first dams successfully constructed on limestone bedrock was El Kansera, where grouting was used to seal the bedrock (Caille, 1955). In case of the Genissait Dam, the grouting was reduced to a minimum, as the karstic channels were filled naturally with impervious clays (Delattre, 1955). Cutoffs have been also used to seal porous carbonate rocks in the subbase of dams in karst (Breznik, 1985). At the El Cajón dam in Honduras, a massive quantity of grout was applied in order to connect moderately karstified limestone with upstream impervious vulcanite (Flores et al., 1985). Large dams on karst have also been built in Turkey, such as the Keban Dam, where massive grouting, backfilling and cut-offs were performed in order to reduce water loss from the reservoir to an acceptable level (Gilmore, Tilford and Akarun, 1991). If the foundation of the dam is soluble, detailed monitoring with additional grouting must be adopted (Guzina et al., 1991). ~~Also,~~ a warning system should be implemented (Heitfeld and Krapp, 1991). The issue of locating dams in karst areas and the use of water resources in karst is addressed by numerous authors, who regularly share their knowledge at thematic workshops and seminars (Stevanovic, 2015; Milanovic and Stevanovic, 2018).

Due to the significantly varying geological conditions at different locations, the dam-related problems mentioned above are complex and site specific, which makes each dam a unique case requiring specific solutions (Talebbeydokhti et al., 2006).

Many authors from different parts of the world have addressed the problems of dams in karst in case studies, e.g. de Waele (2008), Mozafari and Raeisi (2015), and Mozafari et al. (2021), and others. Mohammadi et al. (2007) proposed a methodology which should be applied before the construction of a dam and which should include three steps: (a) recognition of geological and hydrogeological settings, (b) delineation of the system related to the future reservoir and its function, and (c) assessment of the leakage potentials. Following the application of this methodology, the most probable leakage zone(s) and path(s) at the dam site should be highlighted.

To assess groundwater regime behaviour and predict its changes due to artificial modifications (such as the construction of dams, groundwater withdrawal, etc.) modelling techniques have been used (Bear and Verruijt, 1992; Červeňanská et al., 2016). Modelling the groundwater regime in karst is a complex engineering problem (Mikszewski and Kresic, 2015). Malenica et al. (2018) presented a novel numerical model for groundwater flow in karst aquifers. They used a discrete-continuum (hybrid) approach in which a three-dimensional matrix flow is coupled with a one-dimensional conduit flow. They also conducted laboratory testing on the model. This model is applicable to well explored karstic systems. Chang et al. (2015) applied a nonlinear reservoir-pipe model to simulate a karst spring near Guilin city, China, with satisfactory results, especially with respect to the discharge peaks and recession curves of the spring under storm conditions. Jeannin et al. (2021) compared 13 models using a single data set. Neural networks, reservoir models, and semi- and fully distributed models were directly compared within their study, which drew the conclusion that most models fit the field data reasonably well, though they poorly predicted low water flow rates. Petrović and Marinović (2023) used stochastic modelling for the characterization of the Mokra Karst aquifer. They also used time series analysis.

Even though numerous attempts have been made to predict the impact of anthropogenic changes to karst groundwater, there is a lack of experience with groundwater flow modelling in poorly explored deep karstic formations. The current study aims to fill this gap by demonstrating a numerical model based on conduit flow in underground channels of unknown shape, dimensions and hydraulic characteristics (e.g. roughness). The unknown characteristics of the network of "pipes" interconnecting reservoirs in the studied locality (the Hranice Abyss - the deepest continental abyss in the world, as well as the Zbrašov Aragonite Caves and the Kuče Caves) are calibrated using ~~the~~ data from hydrological observations. In the text, the locality of interest is delineated at first, then the methods used are explained, and finally the results of the numerical analysis are presented and discussed. In this way, this study improves the existing body of knowledge about the Hranice Karst and the mechanics of groundwater flow in deep karstic formations.

2 Description of the locality

2.1 Overview

The locality of interest is located on the border of the Olomouc and Zlín regions in the Czech Republic and belongs to the administrative district of the Hranice Regional Municipality. The area of the proposed dam and reservoir is located to the north-east of the village of Skalička (Fig. 1).

Figure 1: Locality of interest (base map from CUZK)

2.2 Geological and hydrogeological conditions

According to the regional geological classification, the area of interest is located at the junction of the Bohemian Massif and the Western Carpathians. The basic geological structure consists of Paleozoic sediments of the Sudeten Formation, on which Miocene sediments, layers of Silesian tectonic units and finally Quaternary cover are deposited (Geršl and Konečný, 2018; Il Faut, 2022). In the Palaeozoic bedrock, the most prominent types of Devonian limestone are those that rise to the surface in the western part of the area between the Teplice spa and the railway cut to the east from the village of Černotín. Their very easternmost outcrop is found in the locality of Kamenec in the area of the proposed reservoir (Fig. 2). At some places, the outcrops are tectonically broken and scarred. The depressions of the post-Paleozoic relief are filled with ~~the~~ clays, claystones, sands, sandstones, gravels and siltstones that fill the Teplice Depression. Their thickness increases towards the east. These younger Tertiary sediments are also affected by dislocations from the Carpathian orogeny. From the east, the shallow shear folds of the sub-Silesian formations, mainly composed of pelitic sediments of Cretaceous and Palaeogene age, are pushed over them.

The hypogenic Hranice Karst in the area of Devonian limestone is a distinctive geological feature that has a significant influence on the implementation of the dam and its technical arrangement. These rocks are about 350 to 380 million years old and are overlain by flysch, chalk and Palaeogene sediments. The extent of the Hranice Karst and the spatial distribution of its

Devonian limestones has not been exactly specified. The demarcation of the boundaries of the karst is based on the observed limestone outcrops and the results of historical drilling. The total thickness of the limestones forming the Hranice Karst has not yet been determined because their bedrock has not been reached by the drilling works; however, it is assumed to be in the order of thousands of metres thick (Geršl and Konečný, 2018). The main karst phenomena of the Hranice Karst are the Hranice Abyss (HA), the Zbrašov Aragonite Caves (ZAC) and the Kuče Caves (KC). Until now, over 31 local caves and other karst phenomena, such as sinkholes and "breathing spots", have been registered (Faimon et al., 2020). Furthermore, the Hranice Karst is manifested by the following features:

- Kamenec - the easternmost outcrop situated in the area to be covered by the proposed reservoir. It is a separate outcrop which rises to the surface to a limited extent and steeply descends.
- Outcrops at the Bečva River bend close to the village of Černotín - the limestone outcrops reach the surface, and are also found below the Bečva river bed.
- Limestone layers in the quarry close to the village of Ústí on the left bank about 3 km downstream of the reservoir.
- Černotín quarry - extensive limestone mining.
- The Teplice spa - mineral water used for therapeutic purposes is taken from deep wells drilled into the aforementioned Devonian structures.

The area of the Hranice Karst and the location of the proposed Skalička Dam are shown in Fig. 2.

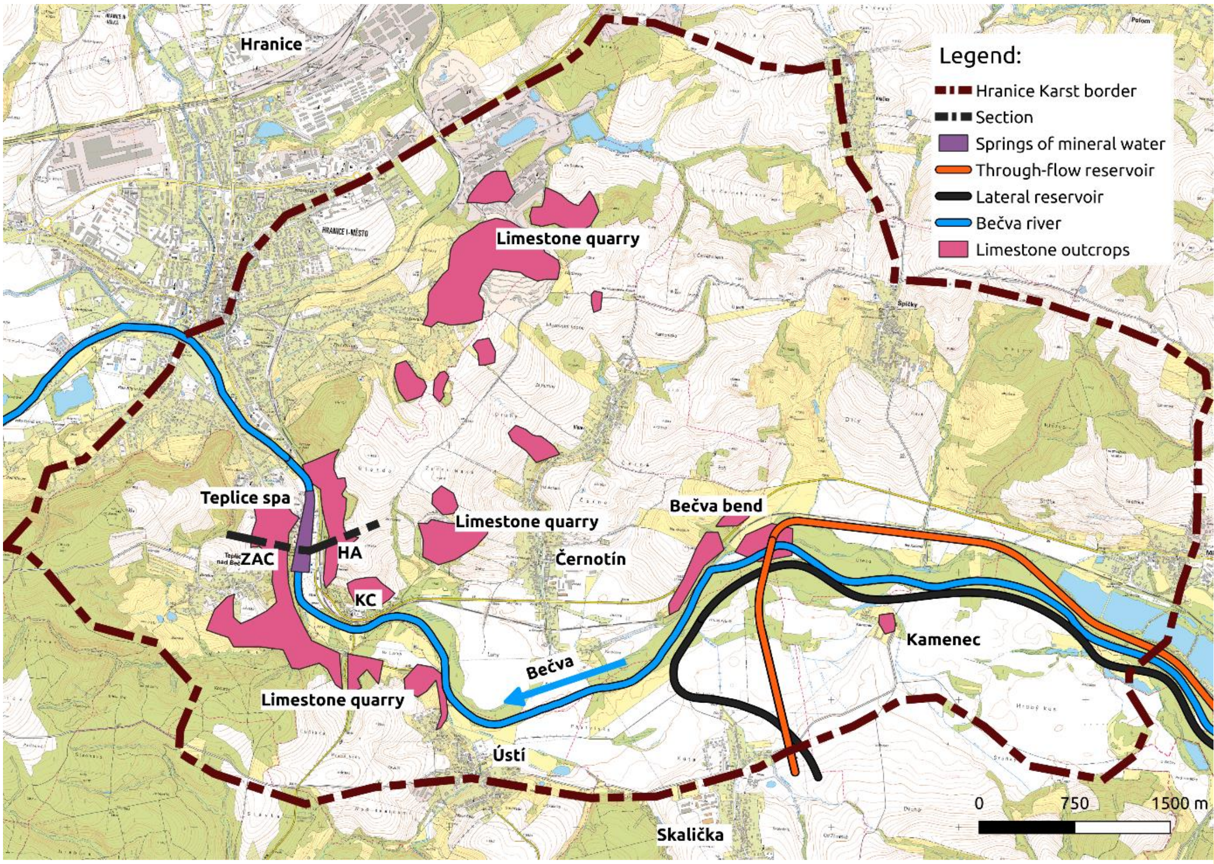

Figure 2: The Hranice Karst with the locations of the two variants (through-flow, lateral) of the dam (base map from CUZK)

The Devonian limestones are tectonically divided into several "blocks". The main fault lines proceed in an east - west direction and are followed by springs of carbonated mineral waters rising at the Teplice spa, and into the Bečva River and the Hranice Abyss (Fig. 2). According to Geršl and Konečný (2018), the Devonian limestone outcrops eastwards of the Teplice spa probably form the main infiltration zone of the springs of mineral water. The outcrop in the Bečva River bend east of the village of Černotín has been identified as the place with the best conditions for surface waters to sink ~~to the karst formations~~. It is supposed that a certain amount of the surface water from the Bečva River sinks along the faults and then flows further on to a significant depth (estimated about 1 km), where ~~at deep tectonics in the crust~~ becomes saturated with juvenile carbon dioxide (Sracek et al., 2019). After mineralisation, the water proceeds upward and emerges into the Bečva River, the pumping wells at the Teplice spa, and the Hranice Abyss.

The easternmost limestone outcrop, located in the Kamenec locality, is also characterised by local high permeability, although a direct connection to the lower karst system has not been confirmed. Even if no interconnection between the shallow groundwater and deeper karst waters was observed during the recent survey (Il Faut, 2022) in the Kamenec area, there is still a certain degree of concern among hydrogeologists about the possibility of mutual interference in the case of dam impoundment. The main doubts are related namely to the permanent water storage in the reservoir, which might cause unfavourable changes to the groundwater regime in the karst.

The observations of water stages in these surface and subsurface water bodies and in the system of observation wells have provided valuable time series used for the calibration and verification of the hydraulic model (see ~~Chapter~~ 3).

2.3 Karst landforms

For the assessment of the groundwater regime in the karst system (Fig. 3), observations of water levels in both surface and underground landforms were carried out. For the hydrological modelling and water balance calculations, basic dimensions of the significant local landforms such as the Hranice Abyss, Zbrašov Aragonite Caves and caves at Kuče were determined, namely the area of the water surface. The observations indicated that the water level in the mentioned landforms changes according to the water stages in the Bečva River with a certain time lag due to the filling/emptying of the water storage in water bodies. The surface areas (Tab. 1) were calculated using geodetic measurements performed during the no-flood period, i.e. for a steady state corresponding approximately to the mean annual discharge in the Bečva River.

Table 1: Overview of water surface areas

Storage	Area [m^2]	Note
Hranice Abyss (HA)	783	Including auxiliary system of caves
Zbrašov Aragonite Caves (ZAC)	66	All lakes in the system
Kuče Caves (KC)	220	All lakes in the system

The Hranice Abyss (Fig. 3), which is located on the right bank of the Bečva River, is the deepest abyss and the deepest lake in the Czech Republic, with a validated total depth of 473.5 m (Vysoká et al. 2019). The HA was formed by a hydrothermal hypogenic "bottom - up" karstification process. The abyss is filled with water mineralized by CO_2 (carbon dioxide) with a concentration of about 2.5 g/l (acid) at ~~a~~ temperature between 22 and 24°C. The theoretical base of the Devonian limestone probably also indicates the total depth of the Hranice Abyss, even though the total thickness of the limestones has never been verified in the Hranice Karst.

The HA consists of an open abyss and caves called the Rotunda (Fig. 3). The lake in the abyss has an area of approximately 511 m^2, while the area of the Rotunda is 272 m^2.

The Zbrašov Aragonite Caves are located at the massif on the left bank of the Bečva River at the Teplice spa. With a length of 1435 m they are the largest cave system in the Hranice Karst. They were formed by hydrothermal karst processes and include a system of passages and domes, including 6 lakes, which also contain warm acid water. Similarly as in the HA, the water in the ZAC is mineralised by carbon dioxide with a concentration of about 2.5 g/l.

The caves at Kuče are a system of smaller domes and passages with a total length of 130 m. The caves have been gradually discovered since 1950, when an exploratory adit was first excavated in the Kuče quarry by the Czech Geological Survey, and they still have not been completely explored. There are several small karst lakes with a total area of about 220 m^2.

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An important piece of information which came from the geological survey (Il Faut, 2022) is that mineral water rises into the lakes of the Zbrašov Aragonite Caves and the Hranice Abyss, and emerges into the Teplice spa and the Bečva River at the spa, while the water in the Kuče Caves, the observation wells close to Černotín and the limestone quarry (Fig. 2) has no mineralisation.

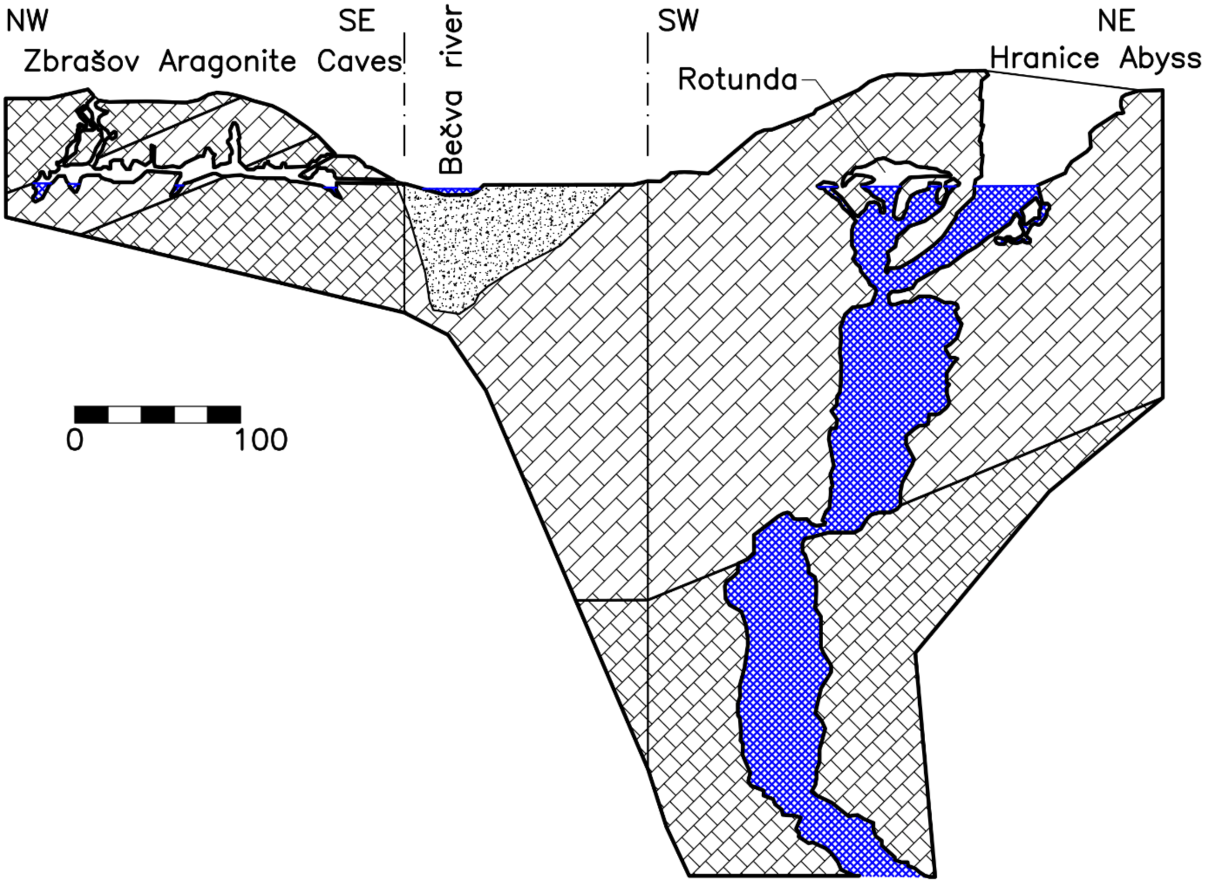

Figure 3: **Hranice Abyss and Zbrašov Aragonite Caves, location of cross section in Fig. 2**

2.4 Description of the dam concept

The idea of placing a dam on the Bečva River is quite old. The proposed location of the dam has changed several times due to the results of new surveys ~~related to the karst~~. In the latest version, it is planned that the dam will be built near the village of Skalička. The reservoir will be multi-purpose: the primary function of the scheme will be flood protection, but some water storage in the reservoir is assumed as well. Two basic concepts of the reservoir and dam layout have been studied (Fig. 2):

- First, a lateral reservoir situated on the left bank of the Bečva River. The main possible connection to the waters of the Hranice Karst is via the limestone outcrop in Kamenec.
- Second, a through-flow reservoir situated in the floodplain on both banks of the Bečva River. The main connection to the waters of the Hranice Karst are via both the Kamenec outcrops and the Bečva River bend.

In case of the lateral reservoir, the lowest bottom of the reservoir would be at a level of 251 m above sea level (a. s. l.), and the storage water level at H_z = 259.0 m a.s.l. As regards the through-flow reservoir, the reservoir bottom would be at 253 m a.s.l. and the storage water level at H_z = 261.0 m a.s.l.

The design of the cross section of the dam is mainly determined by the specific circumstances of the site and the project. There is a shortage of sealing soils in the reservoir area and its vicinity, so sealing is preliminarily expected to be provided by an asphaltic concrete membrane (Fig. 4).

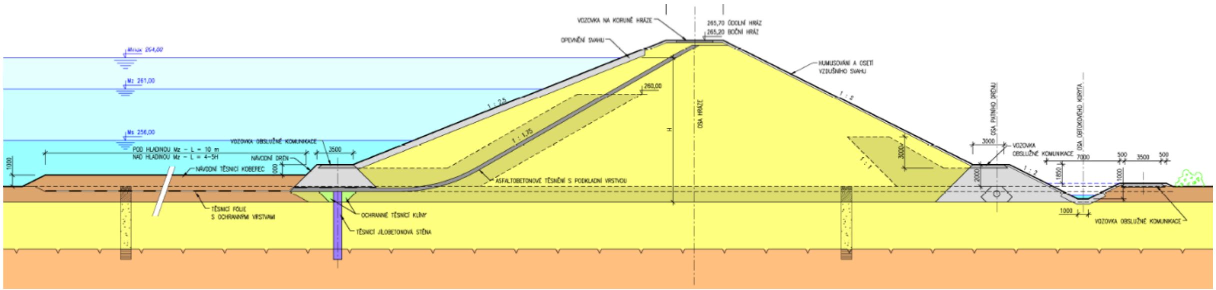

Figure 4: Cross section of the planned Skalička Dam

The design concept for the reservoir has been optimised for the attenuation of extreme floods exceeding the return period N = 500 years to the level of a harmless flood in the Bečva River, which can hold Q = 660 m^3/s (20-years flood). The aim of the study is to evaluate the impact of the reservoir's operation on the water regime in the Hranice karst when the permanent effect of the reservoir can be expected. For this reason, a flow of 25 m^3/s was chosen as the medium flow, along with a 20-year flood with a peak discharge of Q = 660 m^3/s.

3 Methods

3.1 Rationale

In principle, three approaches can be applied when modelling the water regime in a karst system (Kuniansky, 2016). These are dual-continuum porous-equivalent models (two linked sponges), hybrid models (a sponge with pipes), and pipe network models. Due to the deep formation of the Hranice Karst being only poorly explored, and the fact that there is practically no information about rock porosity, the modelling approach using a pipe network that connects the caves, domes and lakes via a system of channels was applied in this study.

The idea was to replace the channels in the karst with a system of pipes and reservoirs. The pipes represent a system of karst channels with "unknown" configurations, dimensions and hydraulic characteristics, while the reservoirs represent karst landforms with a known free surface area (HA, ZAC, KC). A confined (pressure) flow regime was expected in the channels in the deep karst formations.

Preliminary calculations have shown that due to temperature differences, the density of water in the Bečva and in the boreholes of the Teplice spa may differ by up to about 0.08%, and the effect of mineralisation on the water density is about 0.05%. Therefore, a constant water density of ρ = 1000 kg/m^3 was assumed during the modelling.

With water flow rates ranging from tens to single hundreds of l/s, a turbulent flow regime with a Reynolds criterion exceeding Re > 5000 can be expected in most karst channels. The flow will then proceed in a quadratic resistance region.

3.2 Topology of the Hranice Karst model

The network of karst channels was replaced by a system of interconnected pressure "pipes" and open "reservoirs". The system was developed based on the layout shown in Fig. 5; a schematic network diagram with the proposed interconnections of karst landforms is in Fig. 6. Expected water inlets to the system were localised at the limestone outcrops at the Kamenec locality and the Bečva River bend (sections A and B). The principle branch connects the main inflows with the outflow to the Bečva River at the Teplice spa (sections C, D, E, F). Sections connecting the Hranice Abyss (section H) and caves at Kuče (section G) are connected to the main branch. The most remote landform, the Zbrašov Aragonite Caves, is connected to the main branch close to the Bečva River (sections I and J). Each branch is represented by a pair of nodes, which are numbered in the direction of water flow along the main branch and then along the secondary branches.

During rainfall periods, the caves and abyss are supplied (next to the Bečva River) by surface runoff and subsurface sources. Node 11 represents water inflow coming from Malenik Hill. The runoff and surface inflow are also directed to nodes 8 (KC), 9 (HA) and 10 (ZAC). Their discharge was modelled using simple rainfall-runoff relations and was calibrated using the measurements taken in caves HA, KC and ZAC.

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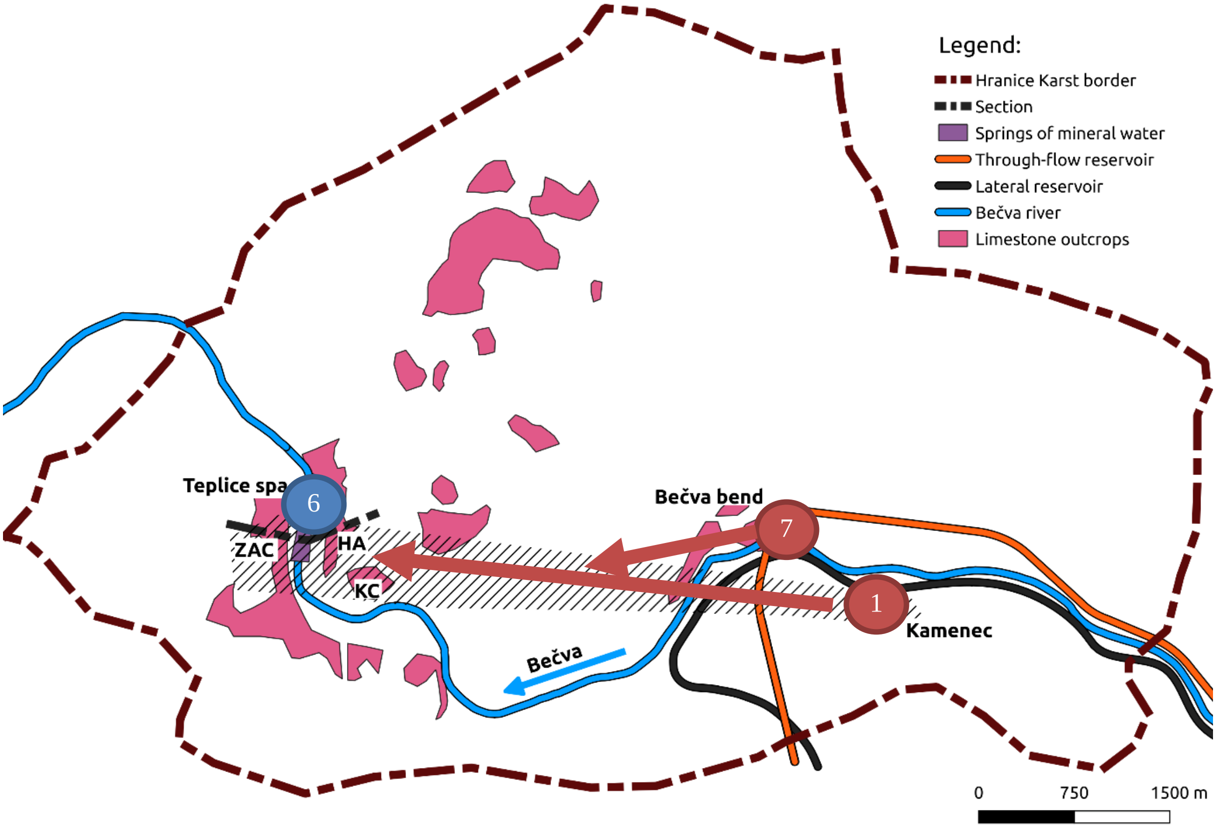

Figure 5: Layout with hypothetical connections between karst phenomena (Kamenec, Bečva bend, KC, HA, ZAC and the Teplice spa)

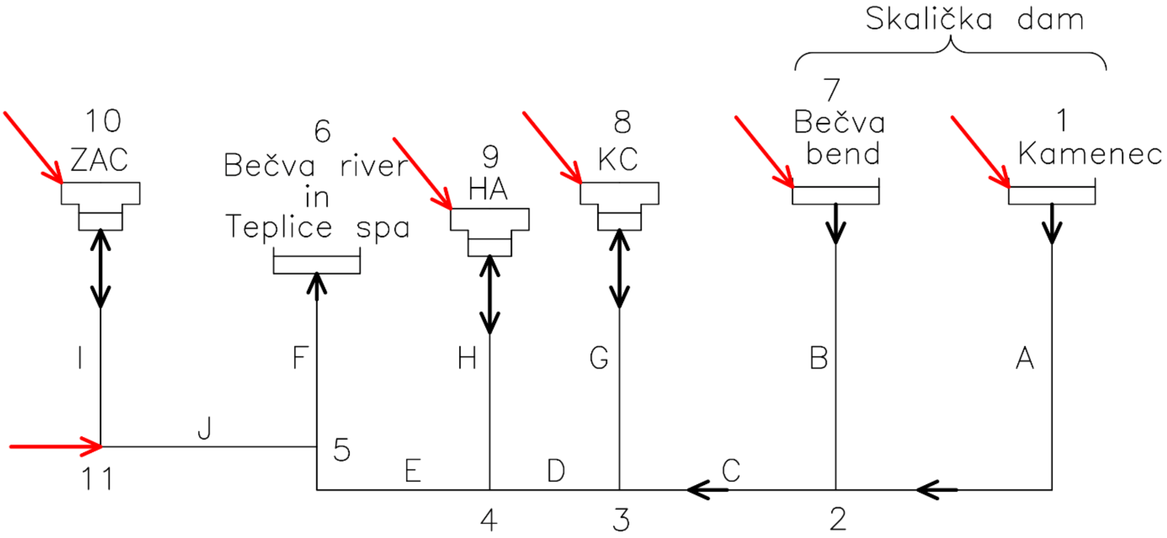

Figure 6: Diagram of the conceptual model: red arrows represent water inflows to the karst aquifer; black arrows represent flow directions in karst conduits

3.3 Mathematical model

The topological diagram in Fig. 6 is the basis for the hydraulic conceptual model of water flow in the network of karst channels and subsurface systems. While the "reservoirs" are relatively well described, the deeper karst system is practically unrecognisable, as it probably reaches a depth of up to 1000 m below ground level, or even more (Klanica et al., 2020). Therefore, its hydraulic function and characteristics are derived via backward analysis using the monitoring data.

The hydraulic state variables describing the problem are:

- piezometric (hydraulic) head *h*, representing the approximate energy level at relatively low flow velocities in karst channels,
- water flow *Q* through the "pipe" system.

The relation between hydraulic head loss Δh_i and the discharge Q_i along section *i* comes from the Darcy-Weisbach equation (Streeter and Wylie, 1979; Munson et al., 1994):

$$\Delta h_i = \frac{1}{2g}\left[\alpha_{i1}\frac{1}{S_{i1}^2} - \alpha \quad \frac{1}{S^2} - \sum \xi_{ik}\frac{1}{S_{ik}^2} - \sum \lambda_{ij}\frac{L_{ij}}{D_{ij}}\frac{1}{S_{ij}^2}\right] \cdot Q_i \cdot |Q_i| \,, \tag{1}$$

where Δh_i is the head loss along section *i* (between two adjacent nodes) of the "pipe network", *g* is the acceleration due to gravity, α_i is the kinetic energy coefficient, ξ_{ik} is the coefficient of the *k*-th form (local) loss along section *i*, λ_{ij} is the friction loss coefficient related to the *j*-th sub-length L_{ij} of the conduit, D_{ij} is the corresponding diameter of the *j*-th conduit fragment, and S_{ij} is the corresponding local cross-sectional area of the conduit fragment. Subscripts "1" and "*n*" refer to the first and last node in the system.

All loss characteristics in the brackets in Eq. (1) are unknown, therefore the coefficient κ_i aggregating all losses was introduced:

$$\kappa_i = \frac{1}{2g}\left[\alpha_{i1}\frac{1}{S_{i1}^2} - \alpha \quad \frac{1}{S^2} - \sum \xi_{ik}\frac{1}{S_{ik}^2} - \sum \lambda_{ij}\frac{L_{ij}}{D_{ij}}\frac{1}{S_{ij}^2}\right] . \tag{2}$$

κ_i expresses the aggregated flow resistance factor along section *i* and is a function of the length of the conduit, its tortuosity and roughness, and the size and shape of the flow cross-section.

When introducing Eq. (2) into Eq. (1), one obtains:

$$\Delta h_i = \kappa_i . Q_i |Q_i| , \tag{3}$$

Eq. (3) is the principal governing equation used in the numerical modelling of the flow regime in the system of conduits. The coefficients κ_i related to individual sections of the conduit were subject to calibration of the model.

Due to the relatively small velocity head (in the order of single decimetres), hydraulic loss Δh_i can be considered as both pressure and energy head loss. Therefore, the piezometric head measured in boreholes and other features such as caves and abysses may be considered as energy head expressed in metres above sea level (m a. s. l).

Free surface changes in the studied karst water bodies (HA, ZAC, KC) were determined from the relation:

$$A \cdot \frac{dh}{dt} = \sum_{l=1}^{m} Q_l , \tag{4}$$

where A is the area of the water surface, Q_l is the inflow to (outflow from) the lake, m is the number of inflows/outflows (via karst conduit, surface runoff, etc.) and h is the water level (piezometric head).

The Dirichlet boundary condition (BC) at the boundary nodes of the flow domain holds:

$$h(f, t) = h_f(t) \qquad (5)$$

where h_f is the known time course of the piezometric (energy) head in the f-th boundary node of the domain (the Bečva River, Skalička Dam reservoir). It was derived from the known time course of the level in the Bečva River in nodes 6 and 7, and in the Kamenec outcrop in the Skalička Reservoir according to the corresponding water level in the reservoir.

The Neumann boundary prescribes the outflow discharge in node 6 taken from the hydrometric measurements (Il Faut, 2022):

$$Q(6, t) = Q_6(h(t)) \qquad (6)$$

The initial condition is represented by the known piezometric head at the beginning of the unsteady solution at time $t = 0$ for individual scenarios (see chapter 3.4). The values were taken from the steady-state solution for the selected period before the flood's arrival or before the eventual filling of the Skalička Reservoir:

$$h(i,t=0) = h_i \qquad (7)$$

The numerical solution of Eq. (4) was performed using the finite difference scheme:

$$\Delta h = \frac{\Delta t}{A} \sum_{j=1}^{m} Q_j \ . \qquad (8)$$

The procedure was set up in an MS EXCEL spreadsheet. The built-in iterative procedure for finding the resistance coefficients in Eq. (3) was used to calibrate the steady state model for the no-flood period. A trial-and-error approximation procedure was used to calibrate the model for selected flood scenarios. During the simulations of each variant, the solution of Eq. (8) was performed with the time step Δt = 1 hour.

3.4 Scenarios and numerical analysis

The aim of the analysis was to evaluate the effect of the impounding of the two aforementioned variants of the Skalička Dam reservoir on the regime of karstic waters, namely on the mineral water springs in the Teplice spa. The water levels and discharges in the individual karst phenomena were analysed by comparing the present state represented by reference variants to selected scenarios of reservoir operation. The study consists of the following scenarios (see also Fig. 7):

I. Model calibration

Model calibration was carried out in order to derive resistance coefficients characterising hydraulic losses along the individual sections of the conduits (Fig. 6). The calibration procedure consisted in the approximation of measured piezometric levels by the calculated values. The calibration was carried out in two steps.

A. Long-term monitoring of the observation wells in the Bečva River and in the HA, ZAC and KC indicated no water level changes during long dry spells. Therefore, during these periods, no water flow is expected in conduits G, H, I and J. The calibration of the main conduit consisting of sections A, B, C, D, E and F between nodes 1 and 6 was carried out under the assumption of steady state flow during relatively small discharges in the Bečva River and a discharge of 115 l/s in the principal conduit. The calibration was based on the monitoring of steady water stages at all monitoring points in the locality, i.e. the observation wells and the HA, ZAC and KC.

B. To calibrate remaining sections G, H, I and J connecting the "main conduit" with the lakes in the HA, ZAC and KC, the results of the previous calibration step (steady state for dry spells) were used. The hydraulic characteristics of the sections were derived from the changes in water levels in the HA, ZAC and KC during flood events in the Bečva River using Eq. (4) and (8).

II. Reference variants

These variants represent the present state of the groundwater regime in the karst and can be used to assess the potential impact of the Skalička Reservoir:

A. Steady state scenario representing a discharge of Q = 25 m^3/s corresponding to the average discharge in the Bečva River.

B. Unsteady regime with a 20-year flood in the Bečva River. This scenario corresponds to a "harmless" level of discharge in the Bečva. After this discharge is exceeded, the filling of the Skalička Reservoir is expected.

III. Lateral multipurpose reservoir

The main concern relates to routine reservoir operation corresponding to the maintenance of permanent storage capacity at an elevation of 259 m a.s.l. The selected two scenarios for the operation of the reservoir were as follows:

A. Reservoir water level is 259 m a.s.l., discharge $Q = 25$ m^3/s in the Bečva River.

B. Reservoir water level is 259 m a.s.l., 20-year flood $Q_{20} = 660$ m^3/s in the Bečva.

IV. Through-flow multipurpose reservoir

The operational regime is the same as in scenario III. Permanent storage capacity is maintained at an elevation of 261 m a.s.l. Two scenarios were dealt with:

A. Reservoir water level is 261 m a.s.l., discharge $Q = 25$ m^3/s in the Bečva.

B. Reservoir water level is 261 m a.s.l., 20-year flood $Q_{20} = 660$ m^3/s in the Bečva.

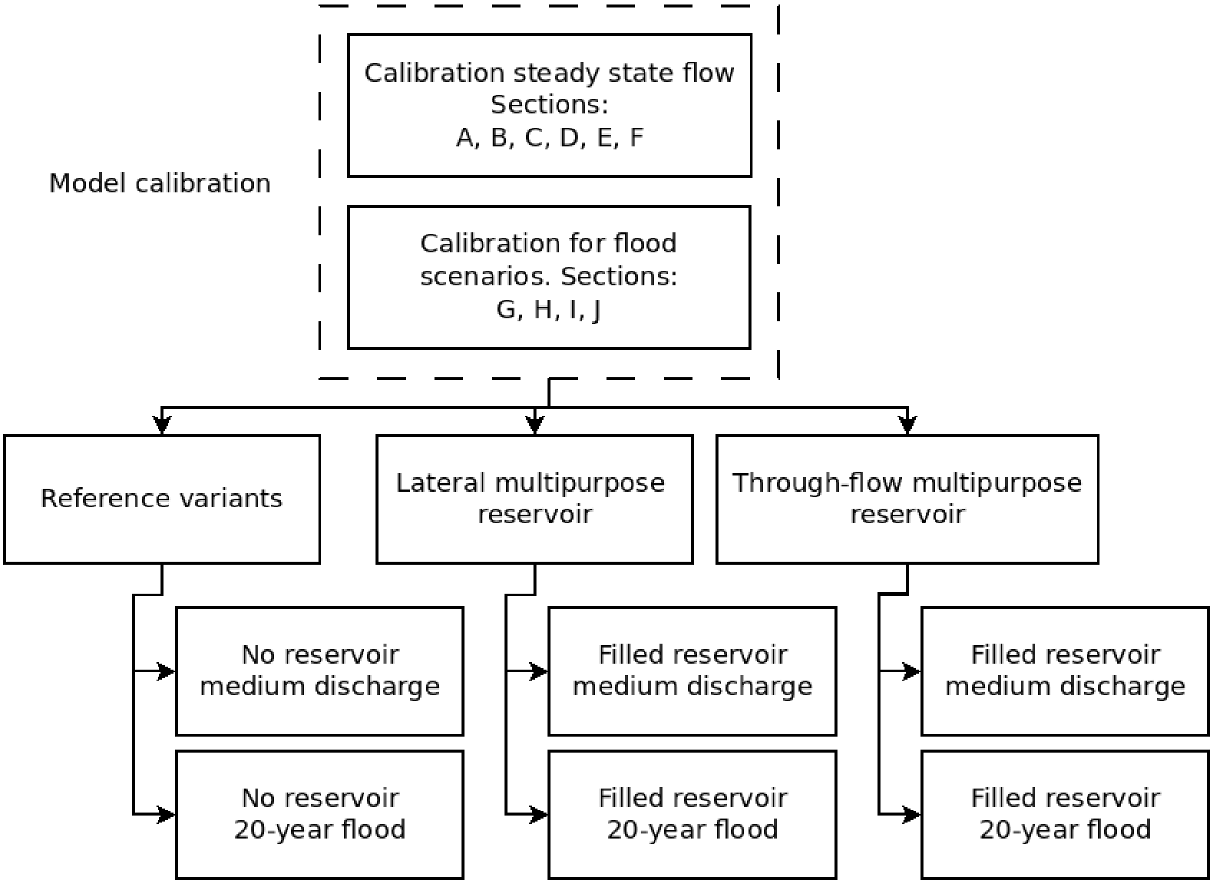

Figure 7: Calculation flowchart

4 Results and discussion

4.1 Calibration and verification

During the calibration, the resistance coefficients κ corresponding to all sections of the topological scheme (Fig. 6) were derived.

First, the calibration of the proposed model was performed for the "steady state" (scenario I.A.) during the dry season when the water levels in the Hranice Abyss and the Kuče Caves remain constant with zero inflow/outflow and only the principal karst channel consisting of branches A, B, C, D, E and F is functional. Here, based on the field tests made by (Il Faut, 2022), the flow through branch A was estimated at 20 l/s.

Secondly, the coefficients for side branches G, H, I and J supplying water to the storage areas of the HA, ZAC and KC were derived. At the same time, the amount of external water flowing during and after some rainfall episodes into the HA, ZAC and KC was verified. For the calibration, the observed unsteady rise and drawdown of water levels in the Bečva River were used as a boundary condition in Eq. (5). These resulted in changes in the water level in the reservoirs of the HA, ZAC and KC, which were also subject to monitoring.

The verification of the calibrated hydraulic model was performed using two other flood scenarios in the Bečva River. The results of the calibration and verification of the unsteady model are shown in Figs. 8, 9 and 10. The resulting calibrated values of coefficient κ_i are in Tab. 2.

Table 2: The resistance coefficients for the individual parts of the network

Section	Nodes	κ [s^2/m^5]
A	1, 2	8 398
B	7, 2	163
C	2, 3	400
D	2, 4	12
E	4, 5	30
F	5, 6	2.87
G	8, 3	2 000 000
H	9, 4	200 000
I	10, 11	60 000 000
J	11, 5	24 000 000

To quantify the efficiency of the model, the Nash – Sutcliffe efficiency was calculated (Nash and Sutcliffe, 1970):

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(H_o^t - H_m^t\right)}{\sum_{t=1}^{T}\left(H_o^t - \overline{H_o}\right)}, \tag{8}$$

where NSE is the Nash – Sutcliffe efficiency coefficient, H_0^t is the observed water level, H_m^t is the modelled water level, and $\overline{H_0}$ is the mean of the observed water levels. The results are shown in Tab. 3.

Table 3: The Nash – Sutcliffe efficiency coefficients for the calibration and verification data

Period	HA	ZAC	KC	Comment
4/2005	0.992	0.976	-	Calibration
10/2020	0.935	0.990	-	Verification
2/2021	0.566	-	0.376	Verification

From Tab. 2 it can be seen that individual karst conduits have significantly different resistance characteristics expressed by coefficient κ. These differences can be attributed to the significantly and randomly different geometries of the karst channels (length, flow profile). In general, the "vertical" branch channels supplying the caves and the abyss have significantly higher resistance, probably due to the overall smaller size of their cross section.

Table 3 shows good agreement between the measured and modelled data for the HA and ZAC. For the KC, the agreement is rather worse (Fig. 10), which is mainly due to the caves being less well explored, the extent of the lakes and the lack of calibration data, as the measurements at the KC had only recently been carried out (in 2021) and the response at higher discharges was not measured for the purpose of this study due to complications with access to the caves, which are private. Therefore, despite the lower Nash-Sutcliffe coefficient at the KC, the model calibration can be considered to have been

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355 successful. Moreover, the impact of the Skalička Reservoir on the Kuče Caves is of less importance as there are no environmental conflicts and requirements related to Kuče.

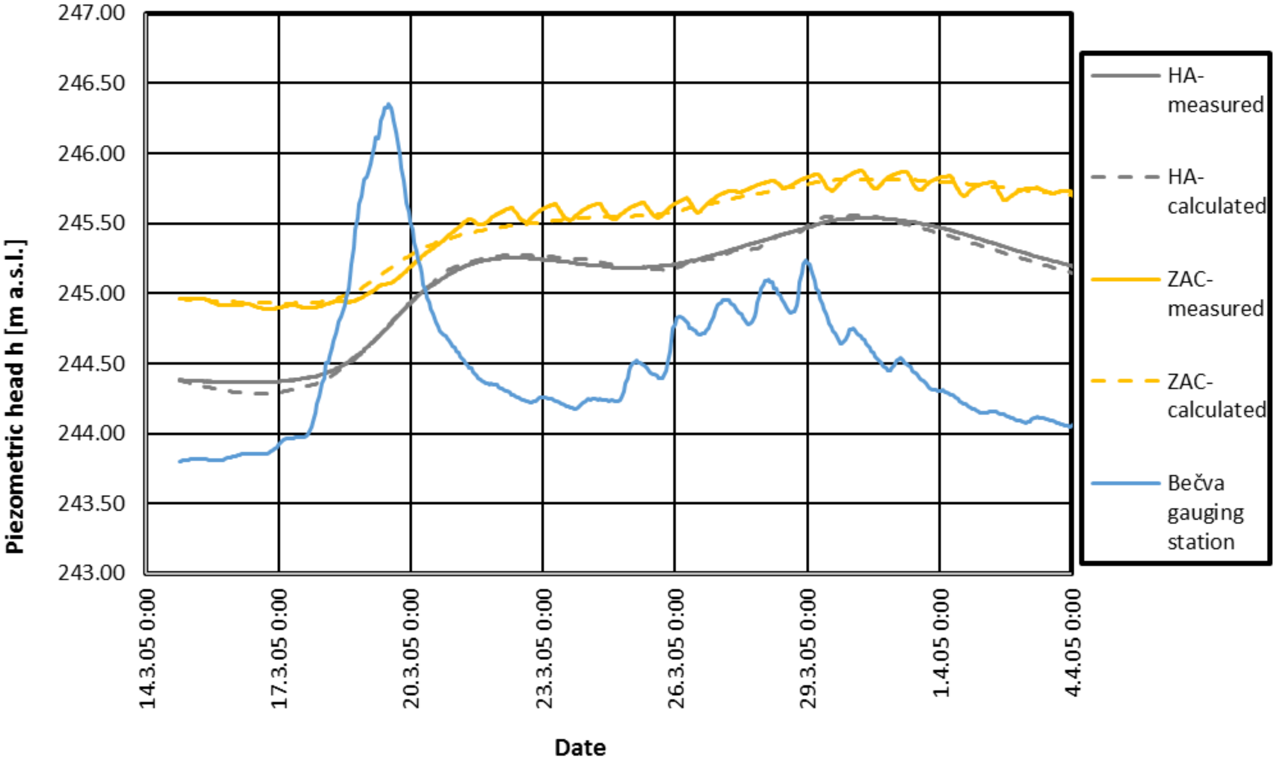
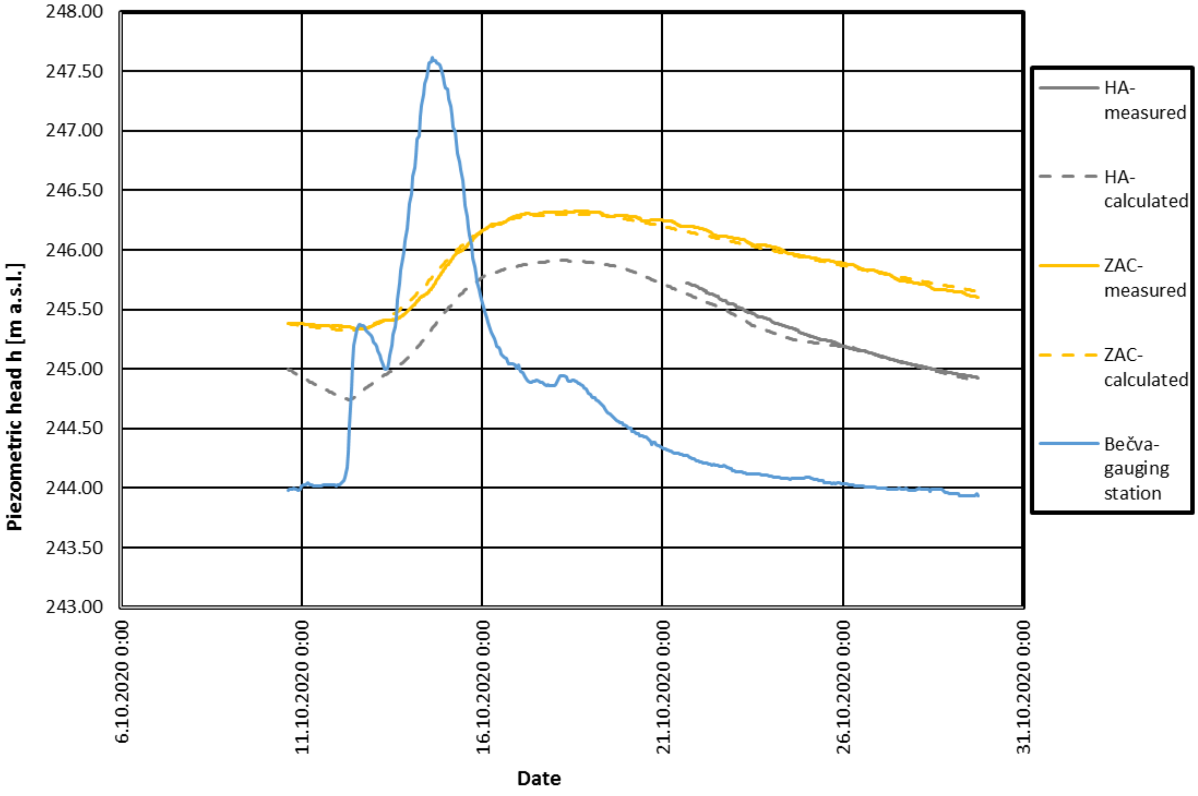


Figure 8: Calibration for March – April 2005



360 **Figure 9: Verification for October 2020**

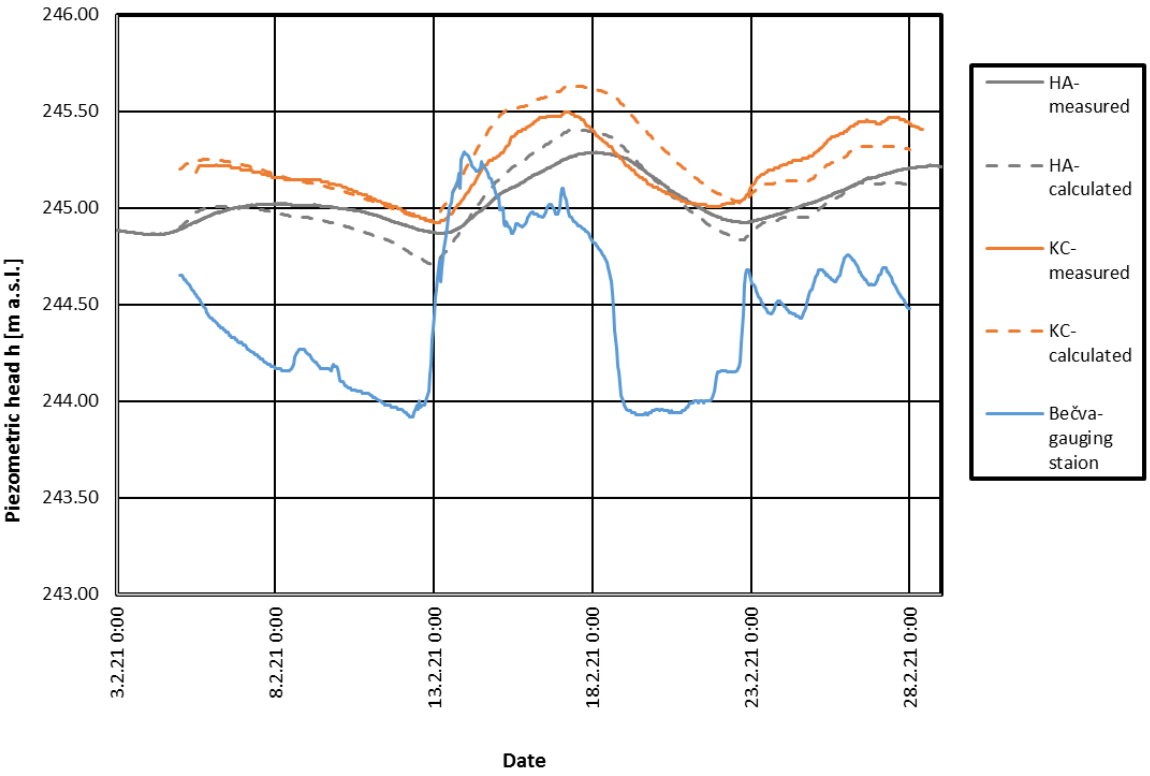


Figure 10: Verification for February 2021

4.2 Reference scenarios

For the reference scenarios the calibrated model was used.

365 Variant II.A. corresponds to an approximately average "constant" discharge of $Q = 25\ \mathrm{m^3/s}$ in the Bečva River. The boundary conditions were as follows:

The Bečva River gauging station in the spa	...	244.24 m a.s.l.
The Bečva River bend	...	251.55 m a.s.l.
Kamenec outcrop	...	253.92 m a.s.l.

370 The resulting calculated water levels in the monitored objects are:

Hranice Abyss	...	244.68 m a.s.l.
Zbrašov Aragonite Caves	...	245.24 m a.s.l.
Kuče Caves	...	244.84 m a.s.l.

The flow rate through the main conduit section F is $Q = 0.115\ \mathrm{m^3/s}$.

Scenario II.B. corresponds to a 20-year flood wave in the Bečva River unaffected by the Skalička Dam with a peak discharge of Q_{20}= 660 m^3/s. The boundary conditions for this variant are in Fig. 11. The resulting maximum water levels in individual lakes are as follows (Fig. 12):

- Hranice Abyss ... 246.59 m a.s.l.
- Zbrašov Aragonite Caves ... 246.63 m a.s.l.
- Kuče Caves ... 246.89 m a.s.l.

The flow rate through the principal conduit (emerging into the Bečva at the Teplice spa) is between Q = 0.099 m^3/s and Q = 0.107 m^3/s.

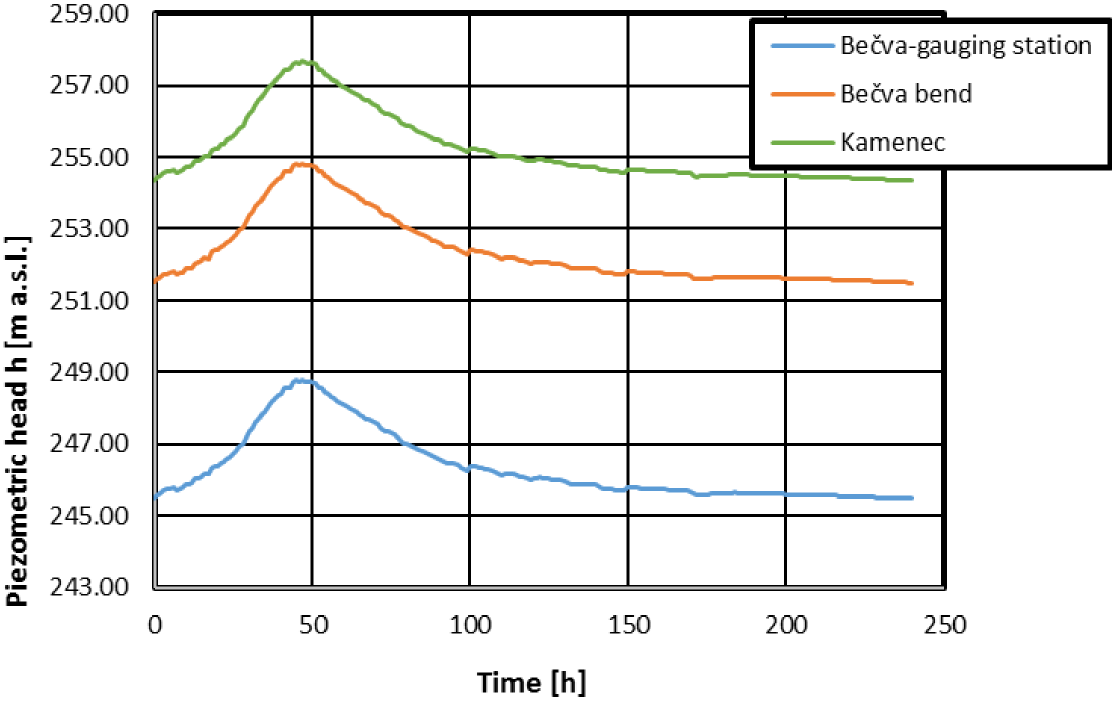


Figure 11: Boundary conditions for scenario II.B.

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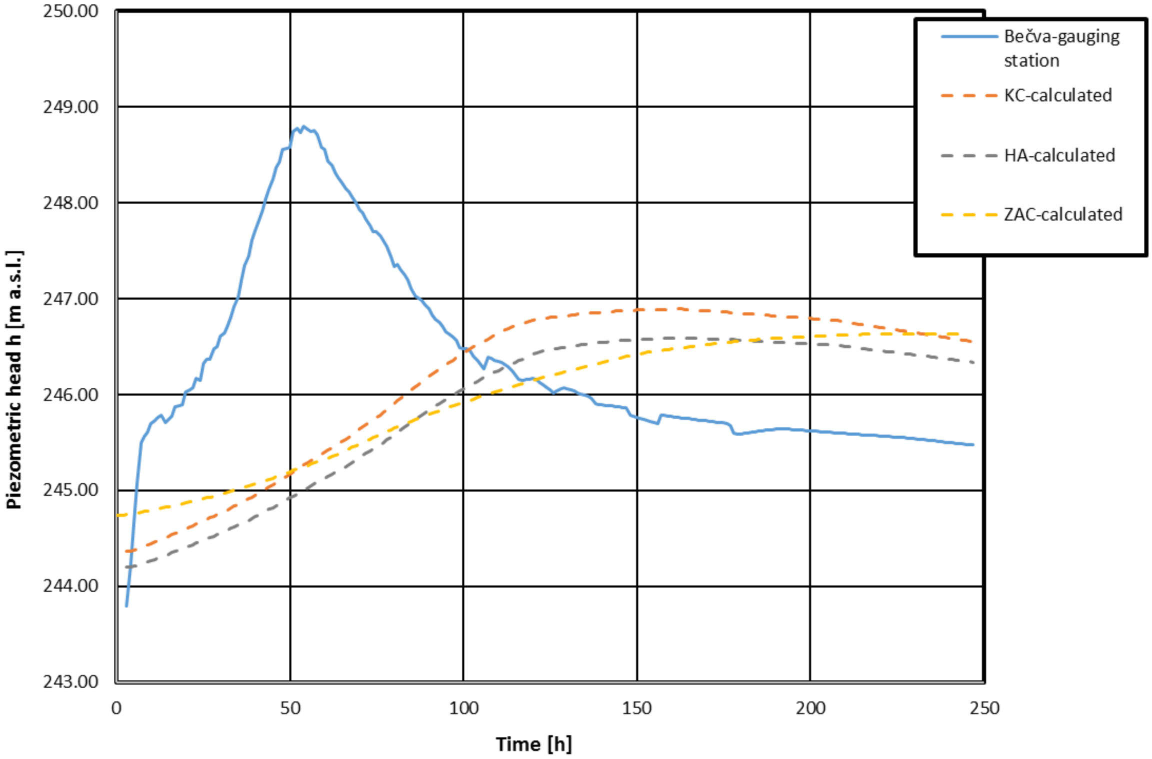

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Figure 12: Water levels in monitored objects for scenario II.B.

4.3 Reservoir operation

In case of the lateral multipurpose reservoir with the no-flood scenario (III.A.), the following boundary conditions were applied:

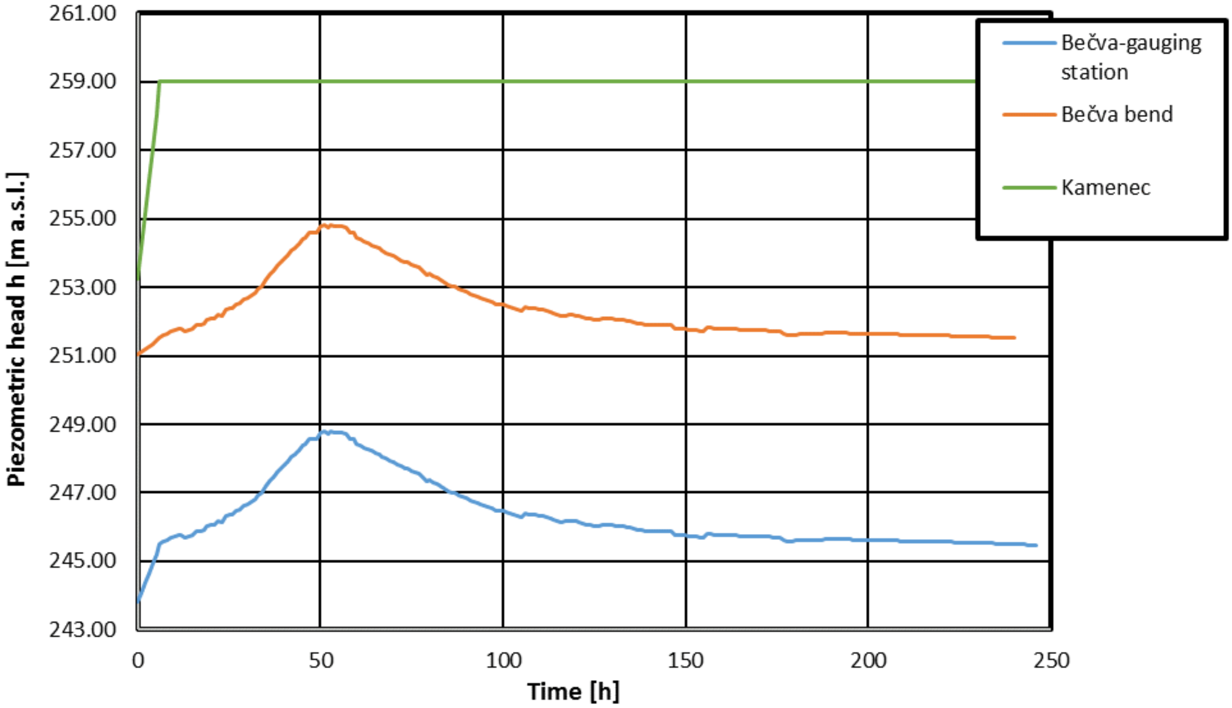
390 • The Bečva River gauging station in the spa	...	244.24 m a.s.l.
• The Bečva River bend	...	251.55 m a.s.l.
• Kamenec outcrop	...	259.00 m a.s.l.

When the results of the steady-state simulation are compared with reference scenario II.A. (Tab. 4), it can be seen that only an insignificant permanent increase in the water level in the lakes of the HA, ZAC and KC would occur. This is due to the drainage 395 effect of the Bečva, both in the spa and partly in the river bend downstream of the dam. The flow in conduit F is $Q = 0.117$ m^3/s and represents only a minor increase of 1.7 % compared to the reference variant.

400 **Table 4: Results for variant III.A.**

Locality	Maximum according to II.A. [m a.s.l.]	Maximum according to III.A. [m a.s.l.]	Difference [m]
HA	244.68	244.70	0.02
ZAC	245.24	245.24	0
KC	244.84	244.86	0.02

Scenario III.B. concerns a lateral multipurpose reservoir with a permanent reservoir water level of 259 m n. m. and a 20-year flood wave in the Bečva River passing along the dam outside the Skalička Reservoir. The boundary conditions applied to the Bečva River and the Kamenec outcrop inside the reservoir are shown in Fig. 13, and the resulting water levels in the HA, ZAC 405 and KC during the flood are shown in Fig. 14. The comparison with reference variant II.B. indicates that there is only a minor increase in the water level in the Hranice Karst and spa amounting to a mere few centimetres. Similarly as in scenario III.A., this can be attributed to the drainage effect of the Bečva, both in the spa and partly in the river bend downstream of the dam. The results can be seen in Tab. 5: the discharge in conduit F is Q = 0.100 to 0.109 m^3/s and represents an increase of about 2 % when compared to the reference variant.



410 **Figure 13: Boundary conditions for scenario III.B.**

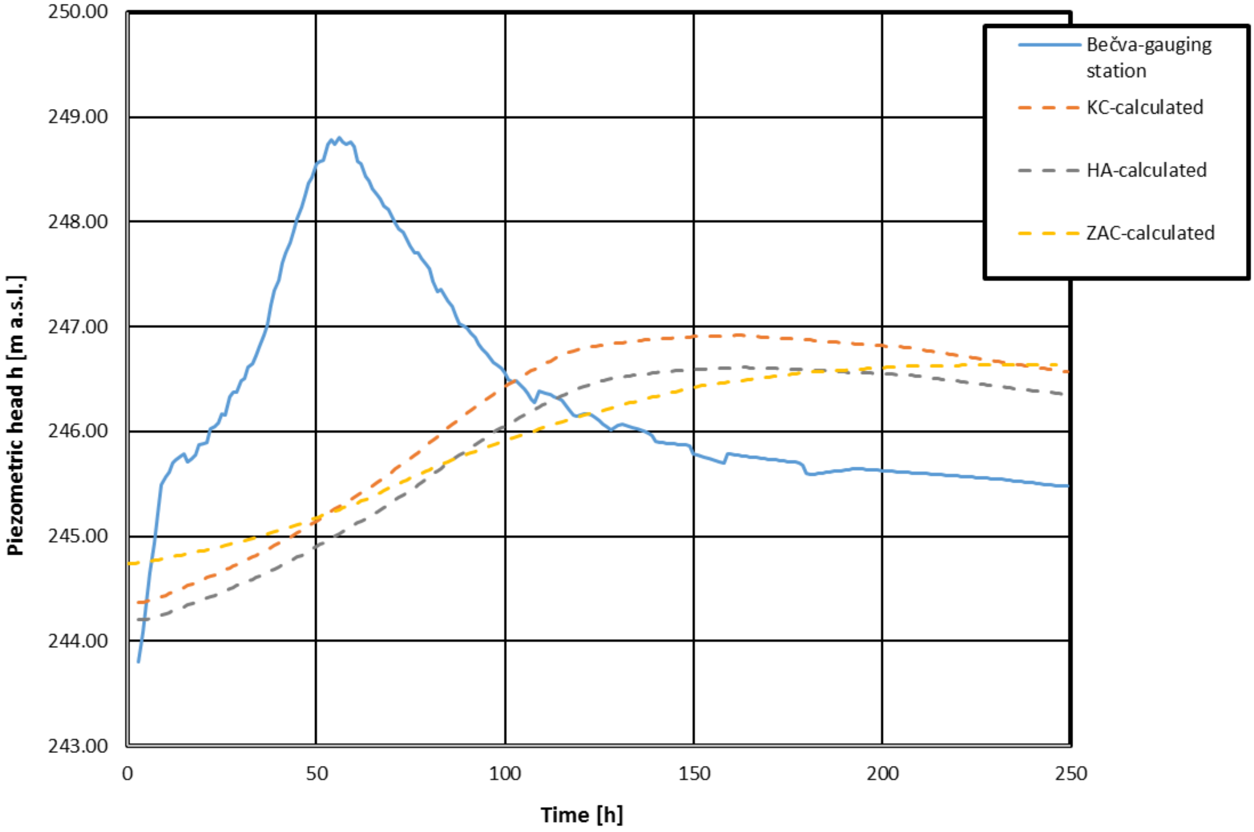


Figure 14: Results for scenario III.B.

Table 5: Results for scenario III.B.

Locality	Maximum according to II.B. [m a.s.l.]	Maximum according to III.B. [m a.s.l.]	Difference [m]
HA	246.59	246.61	0.02
ZAC	246.63	246.63	0
KC	246.89	246.92	0.03

Scenario IV.A. concerns a through-flow multipurpose reservoir with a discharge of Q = 25 m^3/s in the Bečva River passing through the reservoir. The boundary conditions are as follows:

- The Bečva River gauging station in the spa ... 244.24 m a.s.l.
- The Bečva River bend ... 261.00 m a.s.l.
- Kamenec outcrop ... 261.00 m a.s.l.

Comparison with reference variant II.A. shows a more significant increase in the water level in the HA and KC (Tab. 6), which is mainly due to the interconnection of the through-flow reservoir with the massive outcrops at the Bečva River bend at the lowest part of the reservoir supported by the effect of the Kamenec outcrops also located inside the Skalička Reservoir. Only minor changes in the water level are expected in the ZAC due to the significant drainage effect of the Bečva River at the Teplice spa, whose water level strongly correlates with the water level in the lakes of the Zbrašov Aragonite Caves. The rise in the discharge in the "outflow" conduit F is Q = 0.172 m^3/s, which represents an increase of about 50 % when compared to reference variant II.A. This increase in the outflow discharge may cause a certain degree of dilution of the mineral waters rising into the Bečva River, and also into the wells withdrawing mineral water for the spa.

Table 6: Results for variant IV.A.

Locality	Maximum according to II.A. [m a.s.l.]	Maximum according to IV.A. [m a.s.l.]	Difference [m]
HA	244.68	245.21	0.53
ZAC	245.24	245.28	0.04
KC	244.84	245.57	0.73

In scenario IV.B., when a 20-year flood wave in the Bečva passes through the reservoir, the inflow water will pass through a completely open outlet structure into the Bečva downstream of the reservoir. The boundary conditions are shown in Fig. 15. The simulation results can be seen in Fig. 16 and Tab. 7. The results show higher increase in the water levels in the observed lakes in the HA and KC in the order of decimetres (not exceeding 1 m) when compared to reference variant II.B. Similarly to the previous scenario IV.A., negligible changes in the level are expected in the ZAC due to the significant drainage effect of the Bečva River at the Teplice spa. The flow rate in conduit F is Q = 0.114 to 0.167 m^3/s, which is a rise of 15 to 56 % compared with reference variant II.B.

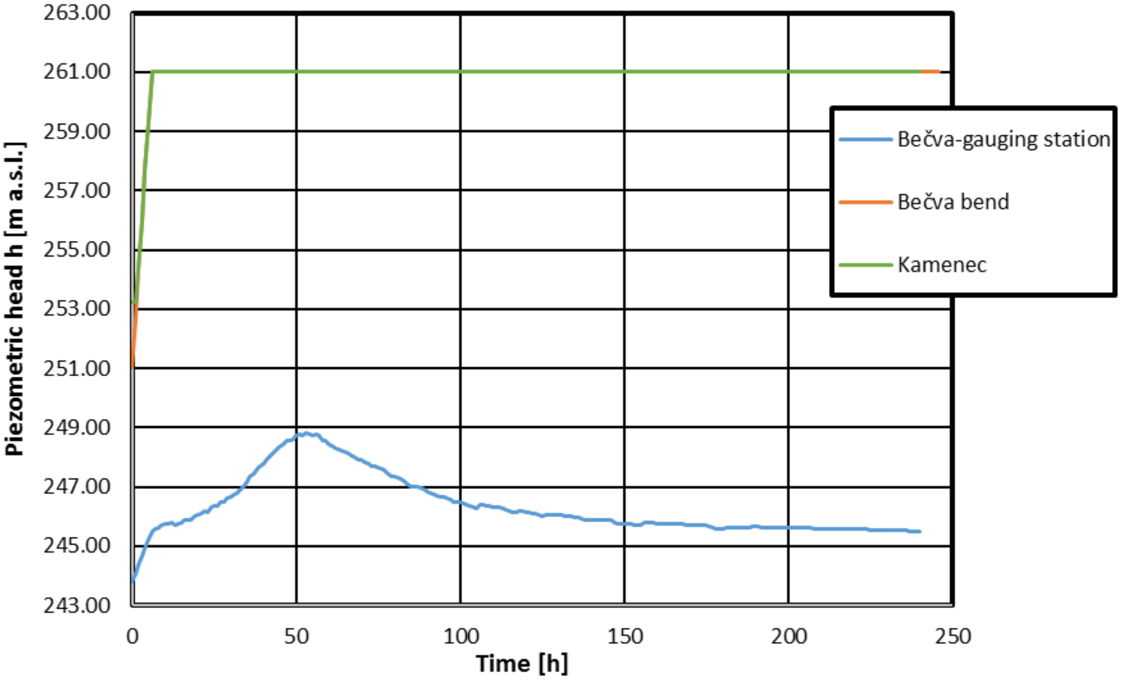


Figure 15: Boundary conditions for variant IV.B.

Table 7: Results for scenario IV.B.

Locality	Maximum according to II.B. [m a.s.l.]	Maximum according to IV.B. [m a.s.l.]	Difference [m]
HA	246.59	247.58	0.99
ZAC	246.63	246.68	0.05
KC	246.89	247.58	0.69

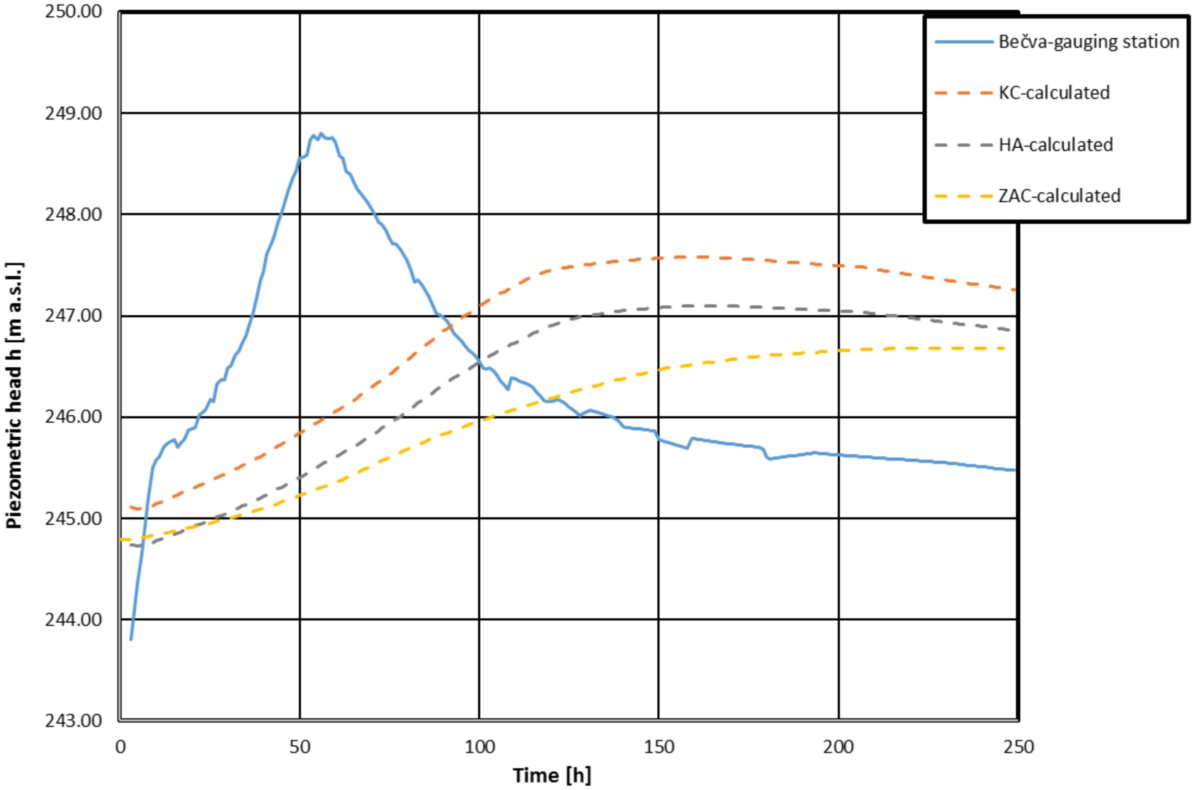


Figure 16: Results for scenario IV.B.

4.4 Conclusion

In the paper, the nonlinear reservoir-pipe model was successfully applied to simulate conditions in the Hranice Karst with the aim of assessing the impact of the proposed Skalička Dam on the groundwater regime in local karstic formations, namely in the Zbrašov Aragonite Caves and on the mineral waters at the Teplice spa. As natural extreme floods in the Bečva River temporarily influence the groundwater regime in the area, it was decided in advance that extreme flood scenarios would not be covered by the study. The main concern is that the dam would have a permanent impact on the natural conditions in the karst, so only scenarios related to standard dam operation were investigated. Two variants of the reservoir layout were considered, namely a lateral and a through-flow reservoir.

The study indicated that the through-flow scheme would result in a permanent rise in the water levels in karst landforms such as the Hranice Abyss and Kuče Caves of about 0.7 to 1 m, and the discharge of rising mineral water would increase by more than 50 %. The lateral reservoir was found to have only a minor effect, with a rise in water levels of a few centimetres. With this proposal, the outflow discharge of mineral springs would increase by only 2%, which is considered to be negligible. The results of the study provided valuable information for decision-makers and stakeholders involved in flood protection and water resource management in the Hranice Karst region. The conclusions given above resulted in the recommendation that the lateral reservoir be chosen for more detailed future investigation and studies. For more reliable model calibration, future monitoring is needed not only in the karst features (HA, ZAC, KC), but also in a set of newly installed monitoring boreholes.

5 Competing interests

The contact author has declared that none of the authors has any competing interests.

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