# Response to reviewer's comments - Reviewer 2

**The text below contains our response to the reviewer´s comments and suggestions. The text in blue is the reviewer´s comments, while the black text is devoted to our remarks, explanations, etc. Green background indicates text, which will be added to the manuscript. The numbering of lines, figures and tables refers to the original manuscript.**

**The authors thank the reviewer for the helpful recommendations and suggestions.**

1. (L285) I have some principle difficulties to understand the definitions of the scenarios.

Scenarios‘ description was upgraded. Following text will be added at the beginning of the Section 3.4:

Prior the simulations the model was calibrated using the measured water levels in the Bečva river and lakes in HA, ZAC and KC.
Presently hydrological extreme floods in the Bečva River temporarily influence the groundwater regime in the area including the karst system. However, experience shows that in few weeks the groundwater system returns back to the pre-flood conditions. Therefore, the main concern is associated with a permanent increase of the water level in planned reservoir that is represented by the levels 259 m a.s.l. in case of lateral reservoir (variant III.) and 261 m a.s.l. in case of through-flow variant (variant IV.). For each reservoir variant two scenarios were investigated, namely at the average discharge in the Bečva river counting about 25 m3/s (III.A., IV.A.) and during the flood with return period 20 years with the discharge about 660 m3/s (III.B., IV.B). For these scenarios the results were compared with corresponding reference variants (II.A., II.B.).

2. (L365) Is it correct that scenario II.A is similar to the steady state calibration? Then, what is the meaning of this scenario?

Yes, in principal they are similar. However, the discharge and water stages in the Bečva river and water stages in HA, ZAC, KC used at the calibration scenario (I.A.) correspond to measured values, in the reference variant II.A. water stages in the Bečva river correspond to 25 m3/s and water stages in HA, ZAC and JC are the result of the calculation. Variant IA. served for the calibration of hydraulic characteristics in channels A, B, C, D, E and F while the variant II.A. is a reference one for comparison with results of scenarios that include an impact of the dam. Following text will be added to the Section 4.2:

Compared to the calibration scenario I.A. the water level in the Bečva River in the reference scenario II.A. is rather higher due to higher discharge in the Bečva river. This results in higher water level in monitored lakes while the outflow discharge via the conduit F practically does not change.

3. (L390) The boundary conditions of the scenarios III.A and IV.A, which seems steady state simulations are not clear.

The boundary conditions in these variants represent steady state at no flood period. Results of these scenarios, when compared with the reference variant (II.A), enable the assessment of the impact of two spatial variants (lateral - III.A., through-flow - IV.A.), namely changes of water levels (pressures) and discharges in the karst formations such as ZAC and HA. Text will be added - see suggestion No. 5.

4. (L365) How can the relation to the discharge of 25 m^3/s be understood?

The discharge 25 m3/s approximately corresponds to the average discharge in the Bečva river.

Explanations will be added to the Section 4.2:

The scenario II.A. corresponds to no flood period with constant average discharge of Q = 25 m3/s in the Bečva River.

5. (L388-L439) What is the difference in boundary conditions between scenario III.A and III.B (and IV.A and IV.B)? How are they related to different discharges?

The difference is related to different type of the dam (lateral, through-flow). The main difference is that in case of the through-flow scheme the Bečva river bend outcrop (which is considered as main source of groundwater in the karst) is inside of the dam reservoir and changes of water level in the reservoir directly influence the pressure and discharges in the karst. In case of lateral dam only certain water communication via Kamenec outcrop is possible while the Bečva river bend is outside of the reservoir. Following text will be added to the Section 4.3:

This scenario represents steady state situation with the discharge of 25 m3/s in the Bečva River and with reservoir permanent water level (259.00 m a.s.l.) so only Kamenec infiltration zone may be affected by the reservoir.

This scenario represents steady state situation with the discharge of 25 m3/s in the Bečva River and with reservoir permanent water level (261.00 m a.s.l.) which affects both Kamenec and the Bečva river bend infiltration zones.

6. (L340) The calibrated values of the resistance coefficients are varying over several orders of magnitude. A discussion on the physical meaning and the sensitivity of the single values is missing, even if a very simple modeling approach is applied.

Following text will be added into the new Section 4.4 Discussion.

As can be seen from Tab. 3 the calibrated values of the coefficient of aggregated resistance are varying over several orders of magnitude. Eq. (2) indicates that the aggregated flow resistance factor depends on local (form) losses (i.e. changes of shape and direction of the flow), the length of canals and their tortuosity, diameters, micro and macro roughness, existence of subsurface caves, sediments, etc. Significant variability of the resistance coefficient indicates considerable changes in the shape, length and other above mentioned factors. From Eq. (2) it can be seen, that e.g. doubling the "pipe" diameter may result in increased the coefficient about 30 times, fivefold increase in "pipe" diameter (which is not uncommon in karst channels) results in the coefficient increase by more than 3 orders.

7. (L362) No data from ZAC are presented in Fig. 10 without further explanation.

There were no data available in ZAC for this period. The measurements in ZAC are complicated due to high CO2 concentrations close to the lakes inside the caves. Therefore, measuring device and dataloggers are not easily accessible and controllable, entrance is possible only with masks and with the guide as there is not public access into the caves. Following text will be added to the Section 2.5:

At the locality the monitoring of water stages and discharges in the Bečva river has been carried out since 1960 in the gauging stations in the Teplice spa and in the Bečva river bend. Occasional monitoring of water levels was carried out in lakes of HA, ZAC and KC during some months in the years 2005, 2020 and 2021. Unfortunately, the series are not complete and continuous and some data are missing in some formations due to various reasons. The measurements in the Bečva river are complete and continuous. In HA and ZAC, the measurements were quite difficult as an entrances to the caves and abyss are not public, due to the high carbon oxygen concentration the personnel must enter in the mask, at least two people are required. Therefore, it was complicated to check the measuring device and data logger and to perform remedial works in case of their outage permanently. The KC are private and the entrance could be possible only when accompanied by an owner.

The outflow discharge from the karst to the Bečva river in Teplice spa was determined using current meter, hydrometric propeller, by the acoustic Doppler current profiler and by the measurements of electric conductivity of water in the Bečva river in the spa (Il Faut 2022).

The surface areas of the lakes in the caves are specified in the Section 2.3.

Moreover, short explanation will be added to the Section 4.1

Unfortunately for available flood scenarios in the years 2005, 2020 and 2021 there were not complete data for monitored lakes in HA, ZAC and KC. Therefore, one calibration and two verification scenarios were used to determine the aggregated roughness coefficients in conduits G, H, I.

8. (L435 - L480) The results of the scenarios III and IV seems not to be correct. The simulated period is too short. The maximum level at ZAC was not reached.

The maximum in ZAC is reached shortly before the end of the simulation (see table A below). The total time of the simulation was 246 hours. The calculated maximum water levels at ZAC and corresponding times as well as the water level at the last time steps are shown in table A below. This is shown to prove that the maximum at ZAC was reached before the end of the simulation. As the decrease of water level is quite small (see Tab. A), it is not clearly visible in Figs. The longer simulations showed that the more significant (visible) decrease in ZAC occurs after 350 h. Therefore, in all figures the simulation time corresponds to 246 hours, at which in all scenarios the maximum water levels have been reached.

**Table A. The calculated water level at ZAC for selected time reached for scenario III and IV.**

| Scenario | Time and water level at ZAC | Time and water level at ZAC |
|---|---|---|
| III.B (Fig. 14) | 238 h. – 246.63 m a.s.l. | 246 h. – 246.61 m a.s.l. |
| IV.B (Fig. 16) | 238 h. – 246.68 m a.s.l. | 246 h. – 246.66 m a.s.l. |

Following text was added to the Section 4.4 Discussion:

Time dependent reference and simulation scenarios were solved with time step 1 hour, the simulation period was 246 hours. During this time maximum water level was reached at all landforms, namely HA, ZAC and KC.

9. (L410, 440) Fig. 14 seems to be identical to Fig 12. Due to the difference in time variant boundary conditions different result are expected.

There is a very small difference between results of these two scenarios (see table B below with the summary of results). Therefore, we concluded that the effect of the dam is practically negligible.

**Table B. Summary of results reached for scenarios used in Fig. 12 and Fig. 14**

| Location | Fig. 12 - maximum calculated water level | Fig. 14 - maximum calculated water level |
|---|---|---|
| HA | 246.60 | 246.61 |
| KC | 246.89 | 246.92 |
| ZAC | 246.63 | 246.63 |

10. (L438) For IV.B the inflow boundaries are constantly on a high level. Therefore, no falling water tables should in the caves. A description of the scenario results with respect to the system behavior is largely missing.

The scenario IV.B. represents the situation when the water level in the reservoir does not change in time, but there is flood situation in the Bečva river (return period 20 years). Even if the water level in the reservoir is stagnant, interconnected system is influenced by temporarily increased water levels in the Bečva river both in the ned (inflow to the system) and in the spa where water springs out of the karst.

11. (L443) Furthermore, a detailed discussion of the usability and shortcomings of the applied modeling approach could be expected in the 'conclusions'.

New section 4.4 Discussion will be added with the following text:

The model presented was used for the assessment of the effect of the permanent increase of water level in the Skalička reservoir in two variants. The model calibration was carried out using rather incomplete monitoring data namely due to complicated accessibility into HA, ZAC and KC. Moreover, for the complete model calibration monitoring during flood situation in the Bečva river is necessary. Therefore, the model calibration and verification was carried out for three periods when temporary increase in the Bečva river was identified, namely during the March/April 2005, October 2020 and February 2021.

During the model calibration and verification, fairly good agreement of measured and calculated water levels in HA and ZAC were obtained. In case of less explored KC the verification provided rather worse agreement, in KC the only one data series measured in 2021 was available.

Following text was added to the Conclusions:

Based on calibration and verification results the applicability of simplified hydraulic model is justified, especially if the knowledge about the deep karst formation is very poor. In contrary to purely regression models (Vysoká et al. 2019) the model proposed is physically based, pipe and reservoir hydraulics is incorporated into the solution.

For further refinement of the model extensive hydrogeological survey is need and more extensive long-term parallel monitoring data should be provided in all karst phenomena in the area. The model indicated that additional places of surface water inflows to the karst system exist and should be systematically measured. These are namely inflows to the caves and abyss.

12. (L195) Finally, the descriptions have several depths of detail. For instance, the technical sketch of the dam is not of importance for this manuscript.

The cross section of the dam was originally attached as relevant reservoir water levels were depicted. New sketch (newly Fig. 4) will be added showing the water levels in the reservoir, the original Fig. 4 and paragraph describing the dam body will be omitted.

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

Miroslav Spano[1], Jaromir Riha[1]

[1]Water structures institute, Faculty of Civil Engineering, Brno University of Technology, Brno, 602 00, Czech Republic

*Correspondence to*: Miroslav Spano (Miroslav.Spano@vut.cz)

**Abstract.** This study examines hydrogeological hazard associated with the construction of the proposed Skalička Dam in the vicinity of the Hranice Karst. Prompted by the catastrophic regional floods in 1997 and 2010, 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

In the Bečva river catchment (Fig. 1) in the eastern part of the Czech Republic extreme regional floods occurred in 1997 and 2010 (CHMI, 1997, 2010). The Skalička dam is planned in two variants (through-flow and lateral) as a part of a flood protection system being constructed on the Bečva River as a response to the catastrophic floods mentioned above. The more detailed description of the locality and scheme can be found in the section 2. ~~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 hazards 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 of dissolved carbon dioxide rises into the Bečva River, the Zbrašov Aragonite Caves (ZAC) and the Hranice Abyss (HA). 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).

Parise et al. (2018) generally summarize current knowledge about karst areas, including karst geology, geomorphology and speleogenesis, karst hydrogeology, karst modeling, and karst hazards and management. Numerous authors deal with the karst environment which is characterized by distinctive landforms related to dissolution and a dominant subsurface drainage which brings risks for the planning, construction and operation of engineering works (Gutierrez et al. 2014; Parise et al. 2015). Klimchouk (2007) provides an overview of the principal environments, main processes and manifestations of hypogenic speleogenesis. He states that elementary patterns typical for hypogenic caves are network mazes, spongework mazes, irregular chambers and passage clusters. Palmer (1991) presents various types of cave systems that can gradually form in the karst area under the action of water. The process of the formation and expansion of cave systems usually takes more than 10 ths. years which significantly exceeds the live cycle of dams.

The Skalička 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. 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 should 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 latter 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 Genissiat 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 at the dam site and karst formations with additional grouting of permeable zones in dam foundations must be adopted (Guzina et al., 1991). Further, 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, and many problems have been described during the construction and after the completion of such engineering works (Palma et al., 2012; Stevanovic, 2015; Milanovic and Stevanovic, 2018; Golian et al., 2021).

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 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 simulate behaviour of the Hranice Karst using numerical model based on hydraulics of conduit flow in underground channels of unknown shape, dimensions and hydraulic characteristics (e.g. roughness) coupled with reservoir model simulating filling the Hranice Abyss and caves in the area. 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 (KC)) are calibrated using data from hydrological observations. The final objective was to assess an impact of the proposed Skalička dam on the Hranice Karst and the source of mineral waters in the Teplice spa.

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).

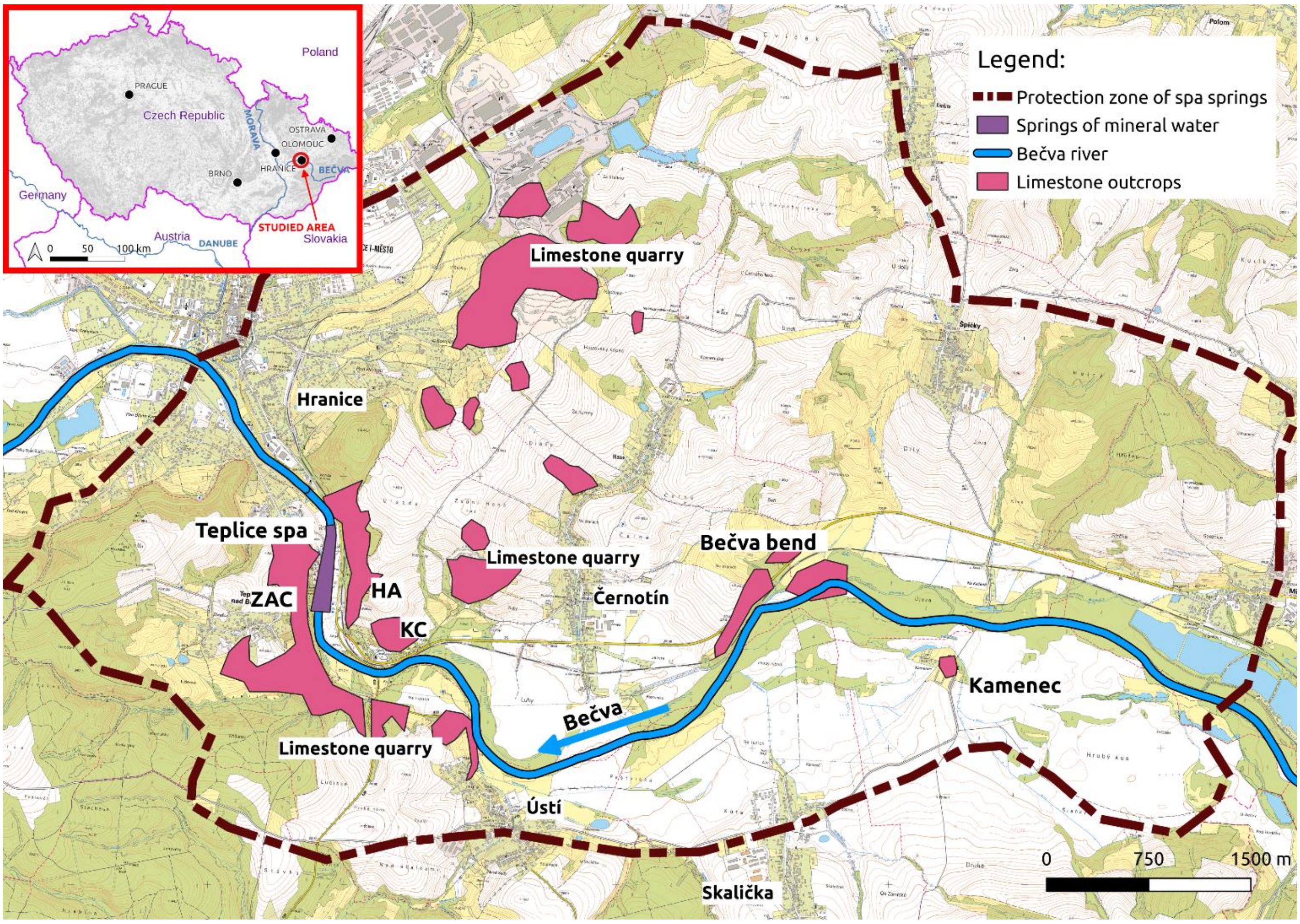


**Figure 1: Locality of interest - present state (base map from CUZK 2024)**

### 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 locality, 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). Concern exists about the seepage of the water from the reservoir to the karstic system. 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 Hranice Karst is hypogenic karst at which confined karst water flow is upward (Klimchouk, 2009). The 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.~~ For the protection of the Teplice spa and valuable mineral springs the protection zone was declared (Fig. 1) based on the observed limestone outcrops and the results of historical drilling. The total thickness of the limestone 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, the Zbrašov Aragonite Caves and the Kuče Caves. Until now, over 31 local caves and other karst phenomena, such as sinkholes and "breathing spots" (the sites on a karst landscape surface, across which air is exchanged between the external atmosphere and an underground cavities), 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 detail of the Hranice Karst and the location of the proposed Skalička Dam are shown in Fig. 2.

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 it 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.

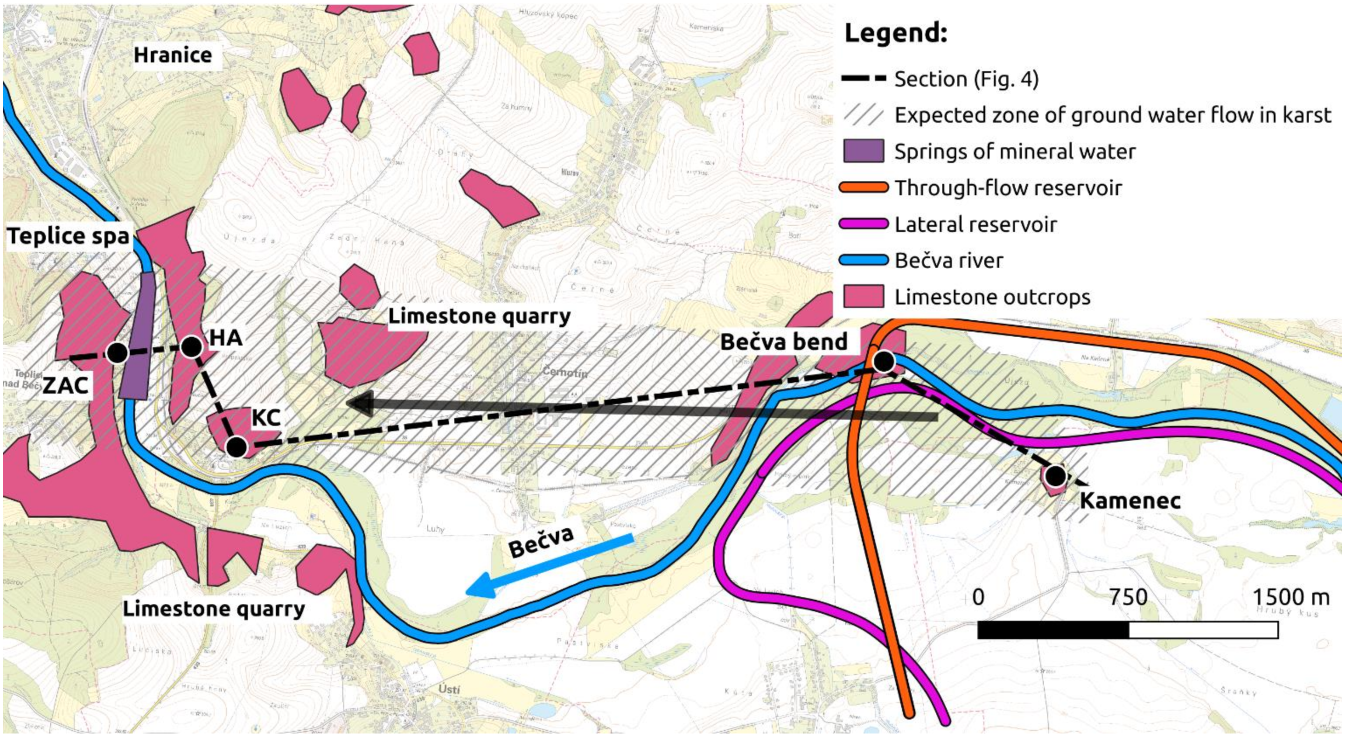


**Figure 2: The detail of the Hranice Karst with the locations of the two variants (through-flow, lateral) of the dam (CUZK, 2024)**

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 Section 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$^2$.

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.

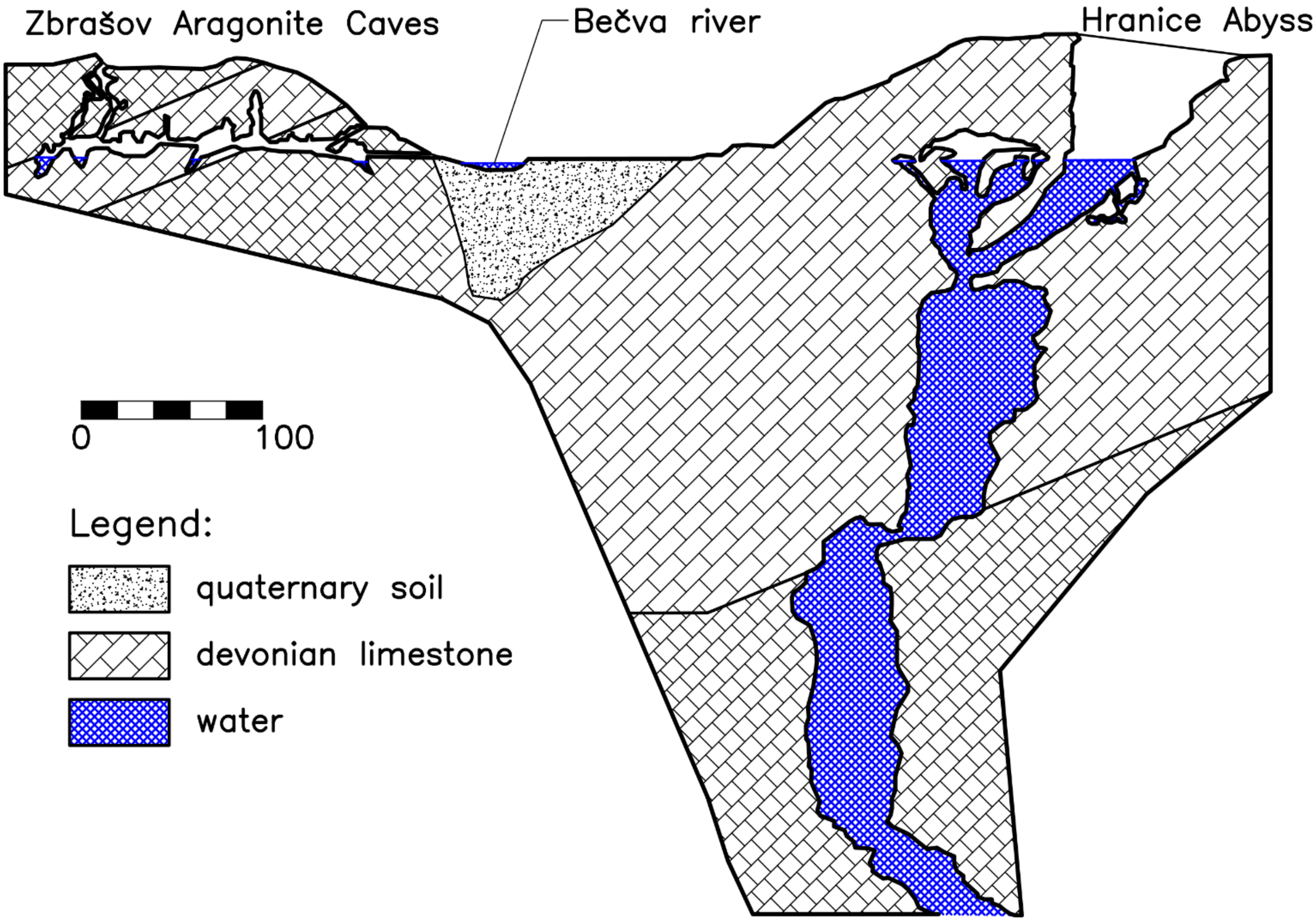


**Figure 3: The detailed interpretation of ZAC and HA in the Teplice spa, cross section from ZAC to HA in Fig. 2 (Sracek et al., 2019), vertical and horizontal scales are the same.**

### 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 water storage in the reservoir will be divided into permanent and flood control storages. 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 251.0 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 253.0 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).~~

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 $m^3/s$.

### 2.5 Available data

At the locality the monitoring of water stages and discharges in the Bečva river has been carried out since 1960 in the gauging stations in the Teplice spa and in the Bečva river bend. Occasional monitoring of water levels was carried out in lakes of HA, ZAC and KC during some months in the years 2005, 2020 and 2021. Unfortunately, the series are not complete and continuous and some data are missing in some formations due to various reasons. The measurements in the Bečva river are complete and continuous. In HA and ZAC, the measurements were quite difficult as an entrances to the caves and abyss are not public, due to the high carbon oxygen concentration the personnel must enter in the mask, at least two people are required. Therefore, it was complicated to check the measuring device and data logger and to perform remedial works in case of their outage permanently. The KC are private and the entrance could be possible only when accompanied by an owner.

The outflow discharge from the karst to the Bečva river in Teplice spa was determined using current meter, hydrometric propeller, by the acoustic Doppler current profiler and by the measurements of electric conductivity of water in the Bečva river in the spa (Il Faut 2022).

The surface areas of the lakes in the caves are specified in the Section 2.3.

## 3 Methods

### 3.1 Rationale

Various types of mathematical models can be applied for groundwater flow modelling in a karst system (Stevanovic, 2015; Hartmann et al., 2015; Kuniansky, 2016; Leins et al., 2023). ~~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 the configuration of karst channels, the modelling approach using a hypothetical 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. To describe hydraulic behaviour of the deep karst formations, aggregated flow resistance factor was introduced and calibrated for each channel of the pipe network using the monitoring data (see following sections).

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 $\rho$ = 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 of hypothetical "pipes" was developed based on the layout shown in Fig. 2 and on the schematic sketch of the functioning of the karst system (Fig. 4). The network diagram with the proposed interconnections of karst landforms is in Fig. 5. The water inlets to the system were localised at the limestone outcrops at the Kamenec (node 1) and at the Bečva River bend (node 7), the water outlet is represented by the Bečva river in the Teplice spa (node 6), where the springs of mineral water can be observed in the river.

The conduits A and B interconnect the sources of water (nodes 1 and 7) with the network of the deep karst channels (conduits C, D, E, F). The conduits connecting the Hranice Abyss (H) and caves at Kuče (G) are linked to these hypothetical deep channels. The most remote landform, the Zbrašov Aragonite Caves on the left bank of the Bečva river (node 10), is connected to the main branch adjacent to the Bečva River (conduits I and J).

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.

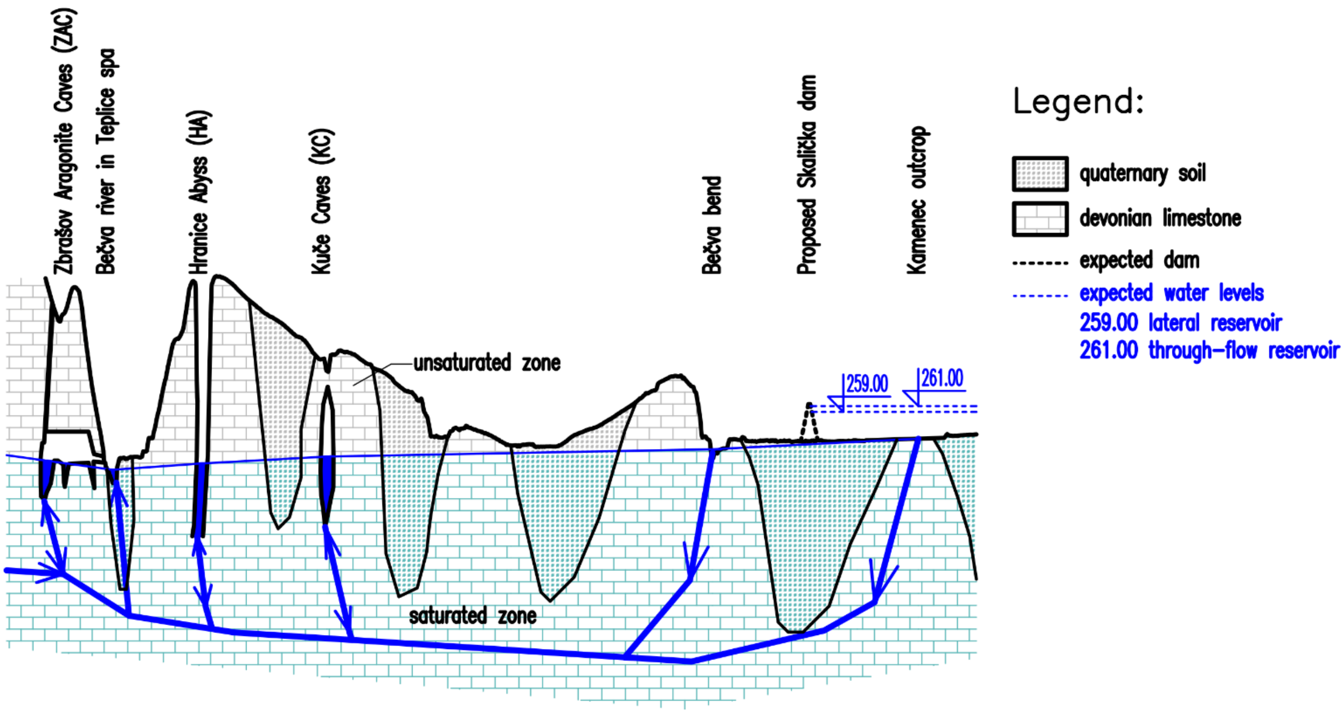


**Figure 4: The sketch with conceptual model of a karst system**

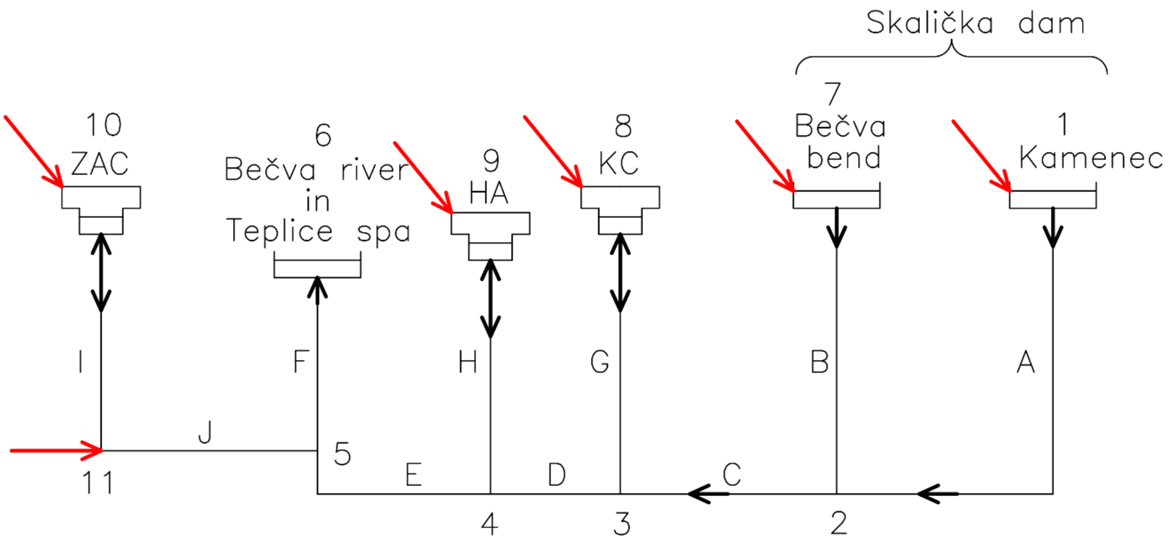


**Figure 5: Diagram of the conceptual model: red arrows represent water inflows to the karst aquifer; black arrows represent flow directions in karst conduits.**

### 3.3 Mathematical model

The topological diagram in Fig. 5 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 $\Delta h_i$ and the discharge $Q_i$ along conduit *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 $\Delta h_i$ is the head loss along conduit *i* (between two adjacent nodes) of the "pipe network", *g* is the acceleration due to gravity, $\alpha_i$ is the kinetic energy coefficient, $\xi_{ik}$ is the coefficient of the *k*-th form (local) loss along conduit *i*, $\lambda_{ij}$ 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 $\kappa_i$ aggregating all losses was introduced:

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

$\kappa_i$ expresses the aggregated flow resistance factor along conduit *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 $\kappa_i$ related to individual conduits were subject to calibration of the model.

Due to the relatively small velocity head (in the order of single decimetres), hydraulic loss $\Delta h_i$ 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:

$$h(f, t) = h_f(t) \tag{5}$$

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):

$$Q(6, t) = Q_6(h(t)) \tag{6}$$

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 Section 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:

$$h(i,t=0) = h_i \tag{7}$$

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

$$\Delta h = \frac{\Delta t}{A}\sum_{j=1}^{m} Q_j \,. \tag{8}$$

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 $\Delta t$ = 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 and water levels in the lakes in ZAC. 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. Prior the simulations the model was calibrated using the measured water levels in the Bečva river and lakes in HA, ZAC and KC. Presently hydrological extreme floods in the Bečva River temporarily influence the groundwater regime in the area including the karst system. However, experience shows that in few weeks after the flood the groundwater system returns back to the pre-flood conditions. Therefore, the main concern is associated with a permanent increase of the water level in planned reservoir that is represented by the levels 259 m a.s.l. in case of lateral reservoir (variant III.) and 261 m a.s.l. in case of through-flow variant (variant IV.). For each reservoir variant two scenarios were investigated, namely at the average discharge in the Bečva river counting about 25 $m^3/s$ (III.A., IV.A.) and during the theoretical flood with return period 20 years with the discharge about 660 $m^3/s$ (III.B., IV.B). For these scenarios the results were compared with corresponding reference variants (II.A., II.B.).

The study consists of the following scenarios (see also Fig. 6):

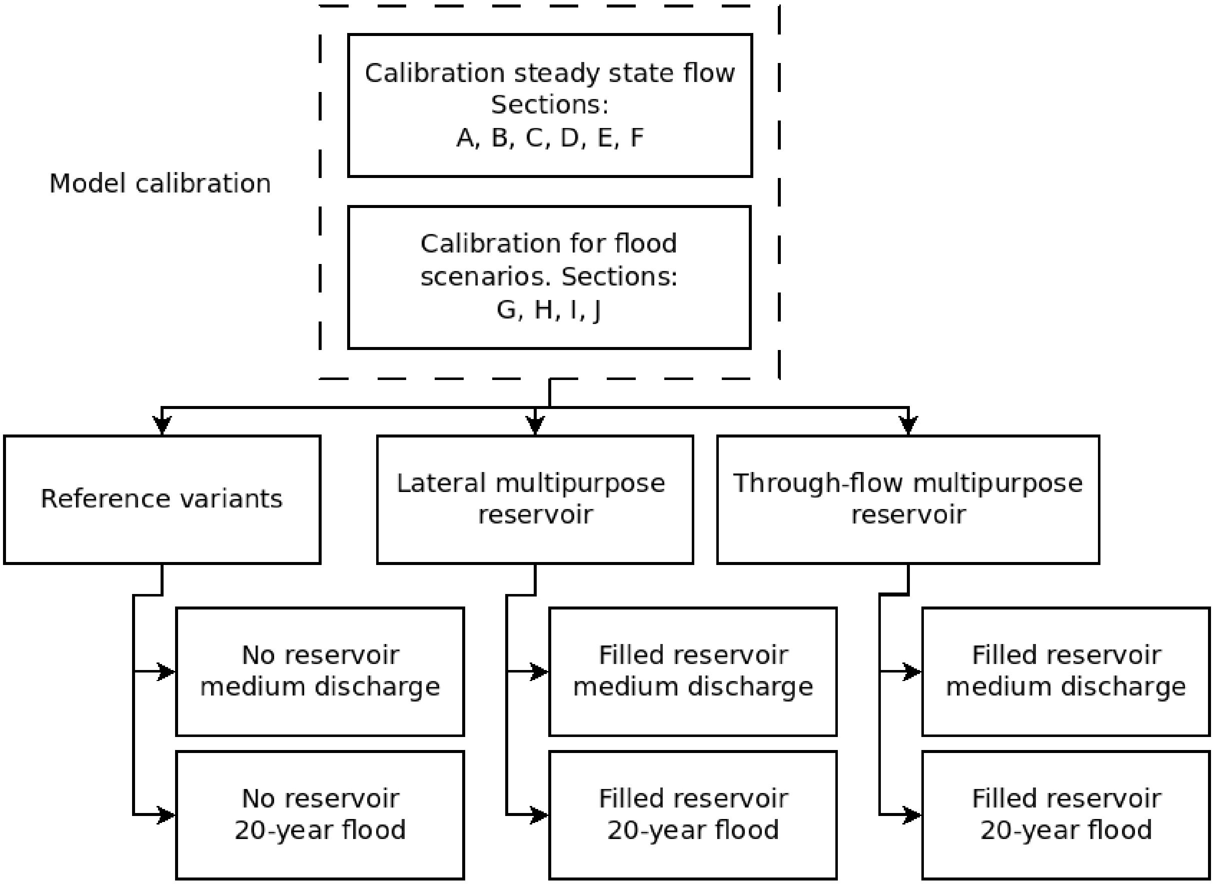


**Figure 6: Calculation flowchart**

I. Model calibration

Model calibration was carried out in order to derive resistance coefficients characterising hydraulic losses along the individual conduits (Fig. 5). 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 in the Teplice spa and in its bend and in the HA, ZAC and KC indicated steady water levels with no change over time during long dry spells. Therefore, during these periods, no water flow is expected in conduits G, H, I and J. The calibration of the conduit consisting of conduits 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 118 l/s in the conduit F at the effluent of the mineral water to the Bečva river in the spa. It was found (Il Faut 2022) that this effluent discharge practically does not change for various small water stages in the Bečva river, as the difference of water levels in the Bečva between the bend and spa does not change. At the same time no external inflows to the caves were observed during dry spells.

B. The calibration was based on the monitoring of steady water stages at all monitoring points in the locality, i.e. the Bečva river, in the HA, ZAC and KC. The steady state conditions correspond to the period.

C. To calibrate remaining conduits G, H, I and J interconnecting 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 calibrated conduits G, H, I and J 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 not affected by planned dam Skalička. These variants have been used as reference to assess the potential impact of the Skalička Reservoir:

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

B. Unsteady regime with a 20-year flood in the Bečva River with the peak discharge 660 $m^3/s$. This scenario corresponds to a "harmless" discharge in the Bečva. After this discharge is exceeded, the flood routing by the Skalička reservoir starts, which is not aim of the assessment (see explanation above).

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 two scenarios for the operation of the reservoir correspond to the reference variants (II.A., II.B.):

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 with the peak discharge $Q_{20}$ = 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 corresponding to the reference variants 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 with the peak discharge $Q_{20}$ = 660 $m^3/s$ in the Bečva.

## 4 Results and discussion

### 4.1 Calibration and verification

During the calibration, the resistance coefficients $\kappa$ corresponding to all conduits 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 in June and July 2019 when the discharge in the Bečva river was 4.5 $m^3/s$ and the water levels in the Hranice Abyss and the Kuče Caves remained constant with zero inflow/outflow and only the karst channels A, B, C, D, E, F and J were functional. Here, based on the field tests made by Il Faut (2022), the flow through the branch A was estimated at 20 l/s. Measured water stages in nodes and discharges along individual conduits according Fig. 5 at the steady state scenario of the model calibration are shown in Tab. 2.

**Table 2: Discharges along individual conduits and water stages in nodes at the steady state scenario for the model calibration**

| Conduit | Nodes | Discharge [l/s] | Node | Water stage [m a.s.l.] |
|---|---|---|---|---|
| A | 1, 2 | 20 | 1 | 253.28 |
| B | 7, 2 | 97.8 | 6 | 243.77 |
| C | 2, 3 | 117.8 | 7 | 251.48 |
| D | 2, 4 | 117.8 | 8 | 244.37 |
| E | 4, 5 | 117.8 | 9 | 244.20 |
| F | 5, 6 | 118 *) | 10 | 244.74 |
| J | 5, 11 | 0.2 | | |

*) Measured value

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 calculated using simplified rainfall-runoff model. 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. Unfortunately for available flood scenarios in the years 2005, 2020 and 2021 there were not complete data for monitored lakes in HA, ZAC and KC. Therefore, one calibration and two verification scenarios were used to determine the aggregated roughness coefficients in conduits G, H, I. 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. 7, 8 and 9. The resulting calibrated values of coefficient $\kappa_i$ are in Tab. 3.

**Table 3: The resistance coefficients for the individual parts of the network**

| Conduit | Nodes | $\kappa$ [$s^2/m^5$] |
|---|---|---|
| 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):

$$NSE = 1 - \frac{\sum_{t=1}^{T}(H_O^t - H_m^t)}{\sum_{t=1}^{T}(H_O^t - \overline{H_O})}, \quad (8)$$

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. 4.

**Table 4: 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 $\kappa$. These differences can be attributed to the significantly and randomly different geometries of the karst channels (length, flow profile). In general, the branch channels G, H, I, J supplying the caves and the abyss have significantly higher resistance, probably due to the overall smaller size of their cross section (see discussion in the Section 4.4).

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 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.

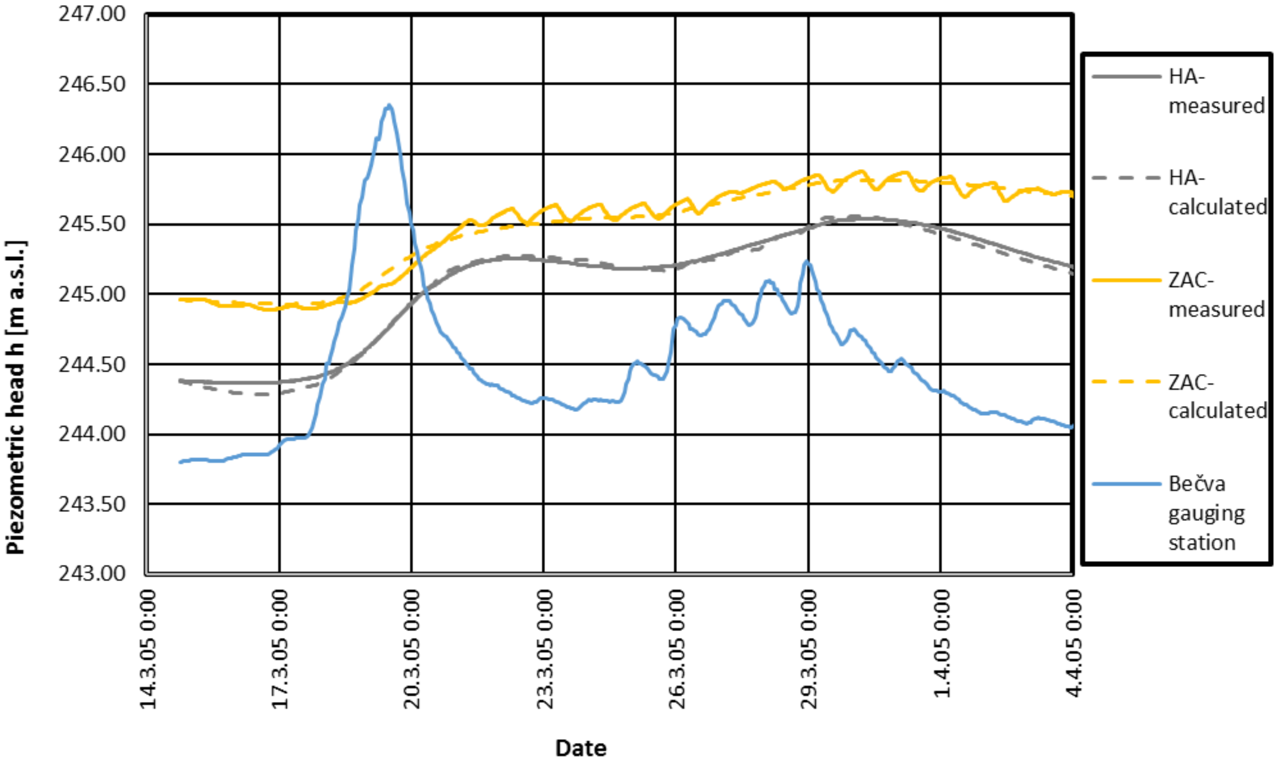


**Figure 7: Calibration for March – April 2005**

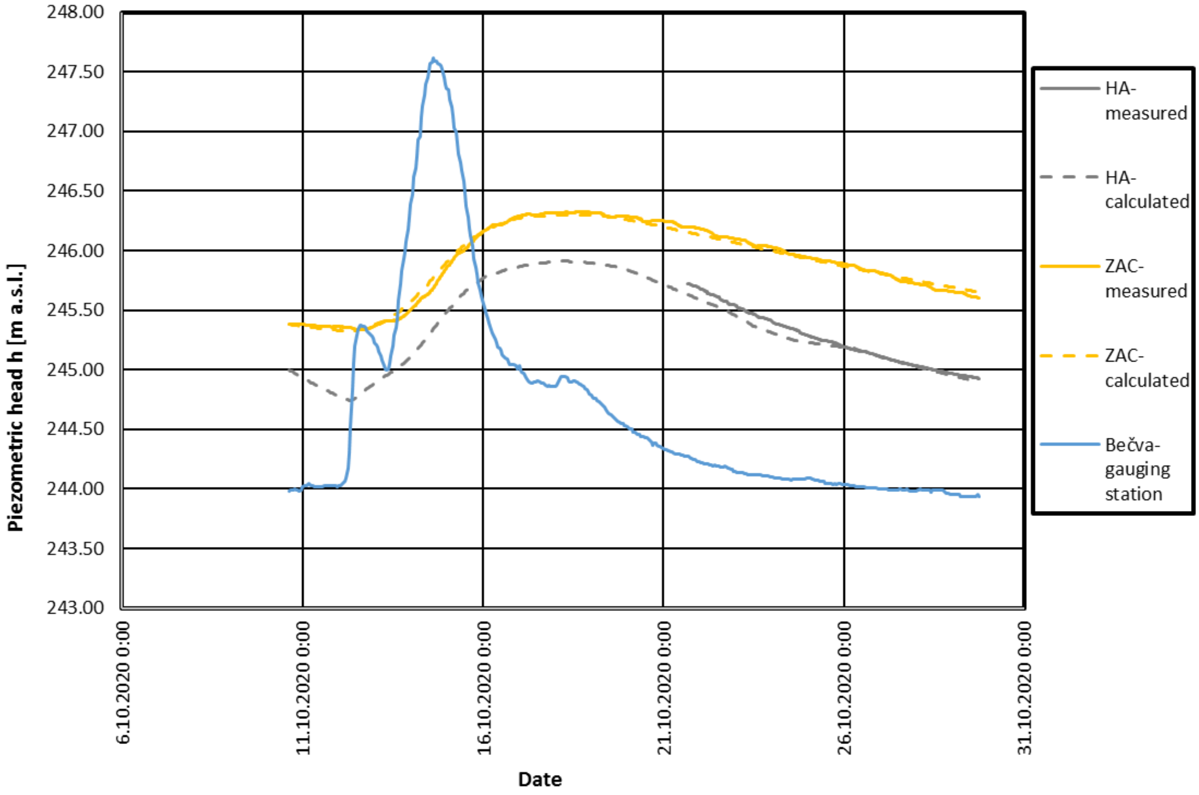


**Figure 8: Verification for October 2020**

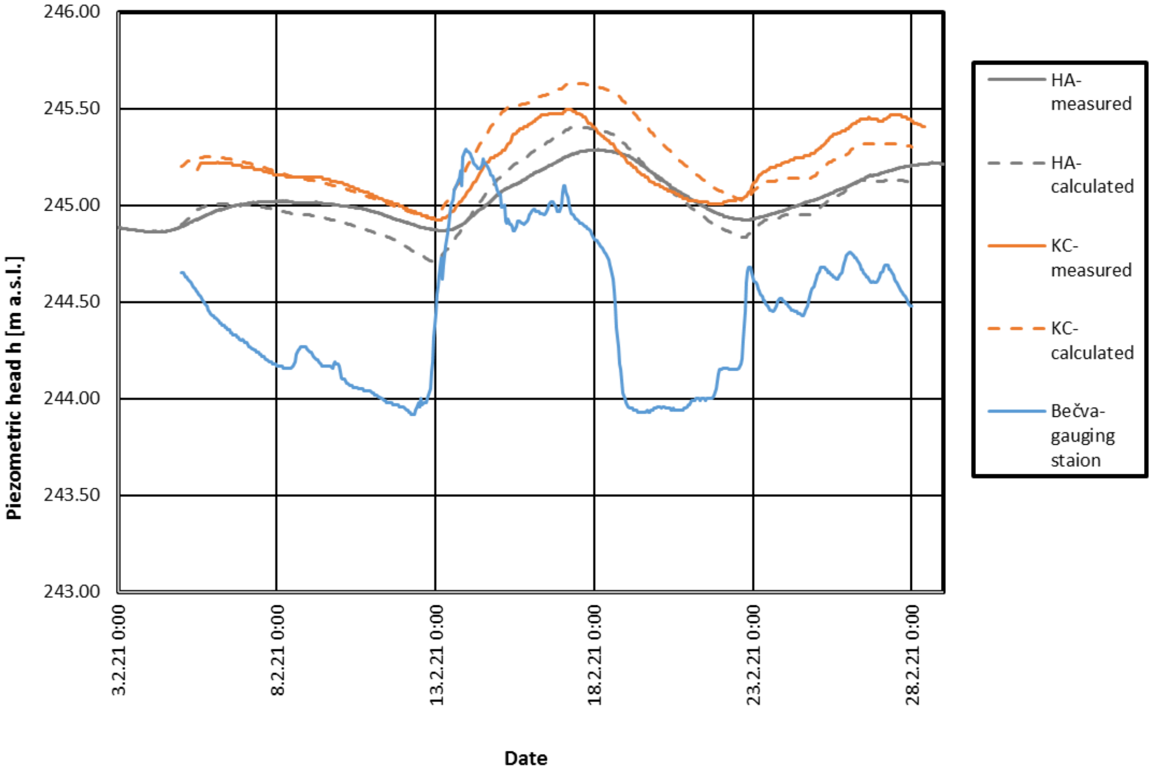


**Figure 9: Verification for February 2021**

### 4.2 Reference scenarios

For the reference scenarios the calibrated model was used.

The scenario II.A. corresponds to no flood period with constant average discharge of 25 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.

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 outlet conduit F is $Q$ = 0.118 $m^3/s$.

Compared to the calibration scenario I.A. the water level in the Bečva River in the reference scenario II.A. is rather higher due to higher discharge in the Bečva river. This results in higher water level in monitored lakes while the outflow discharge via the conduit F practically does not change.

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 $m^3/s$.

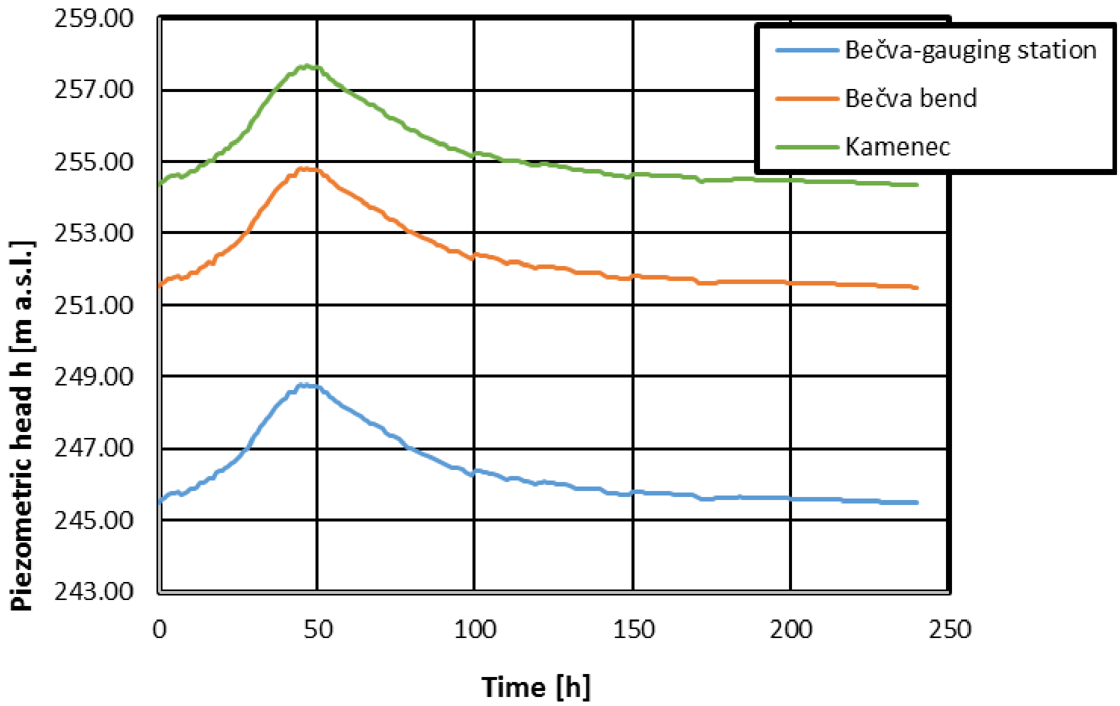


**Figure 11: Boundary conditions for scenario II.B.**

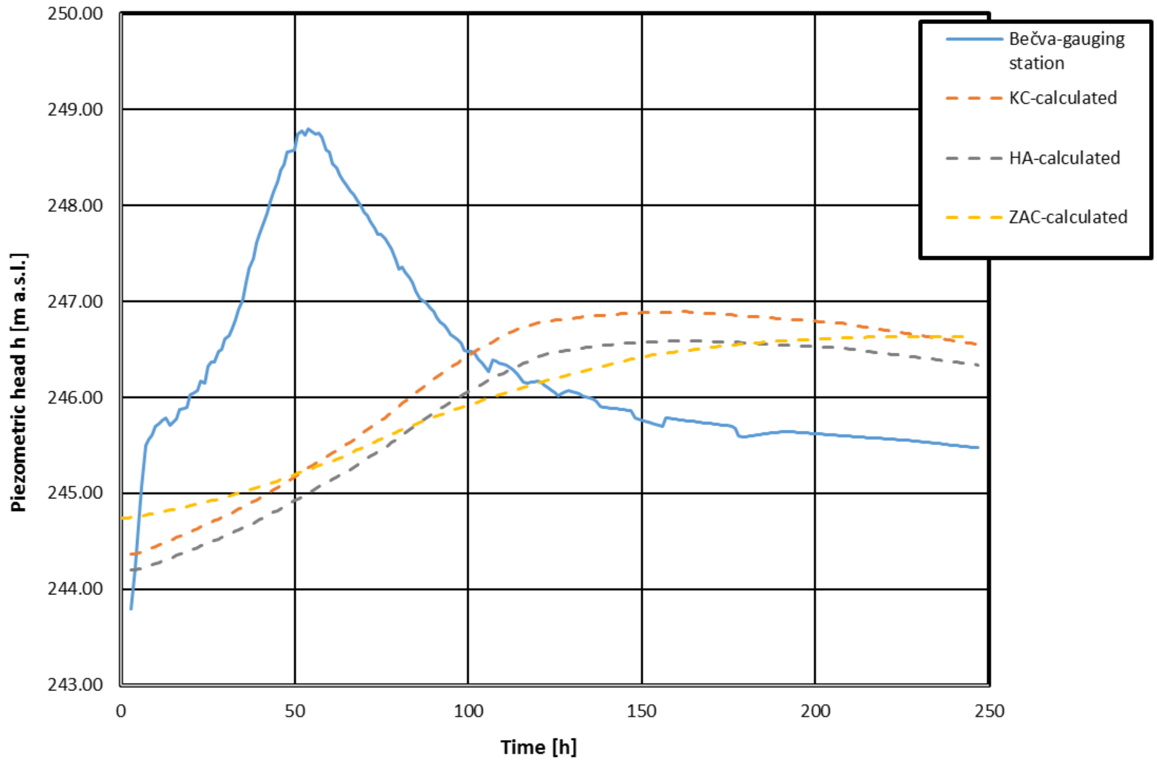


**Figure 12: Water levels in monitored objects for scenario II.B.**

### 4.3 Reservoir operation

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

- 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.

This scenario represents steady state situation with the discharge of 25 m3/s in the Bečva River and with reservoir permanent water level (259.00 m a.s.l.) so only Kamenec infiltration zone may be affected by the reservoir.

When the results of the steady-state simulation are compared with reference scenario II.A. (Tab. 5), 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 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.

**Table 5: Results for scenario 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 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. 6: 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.

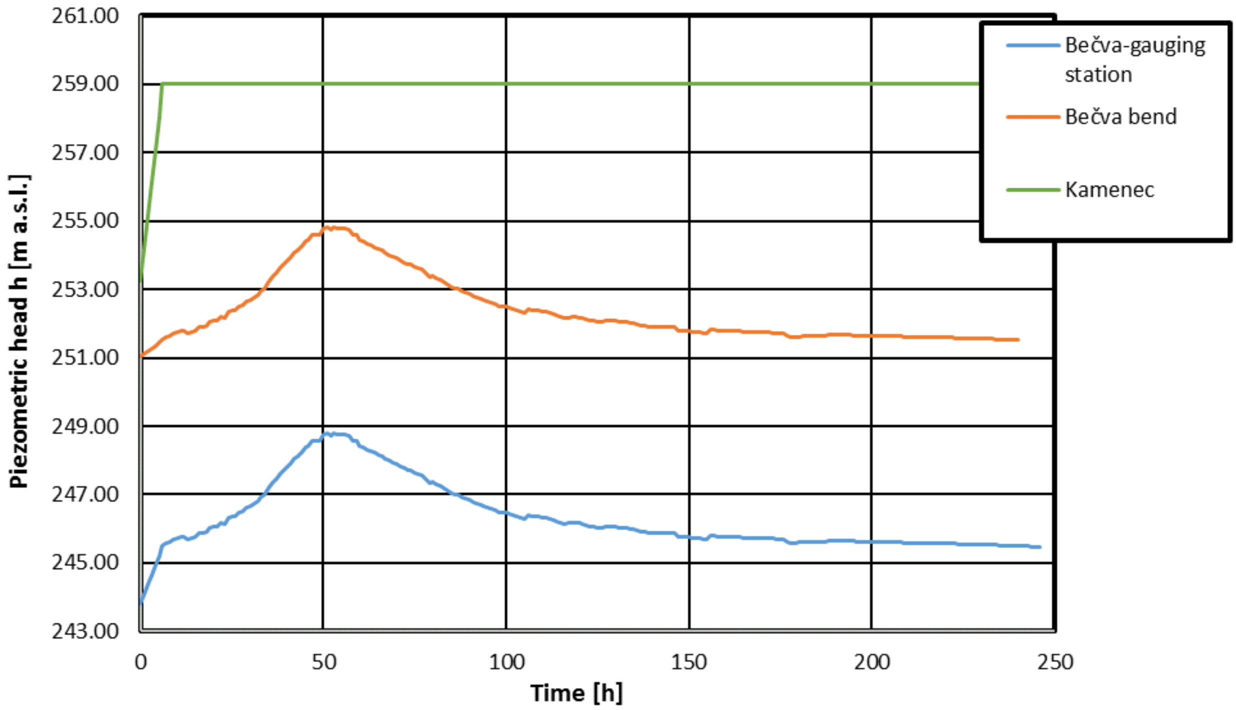


**Figure 13: Boundary conditions for scenario III.B.**

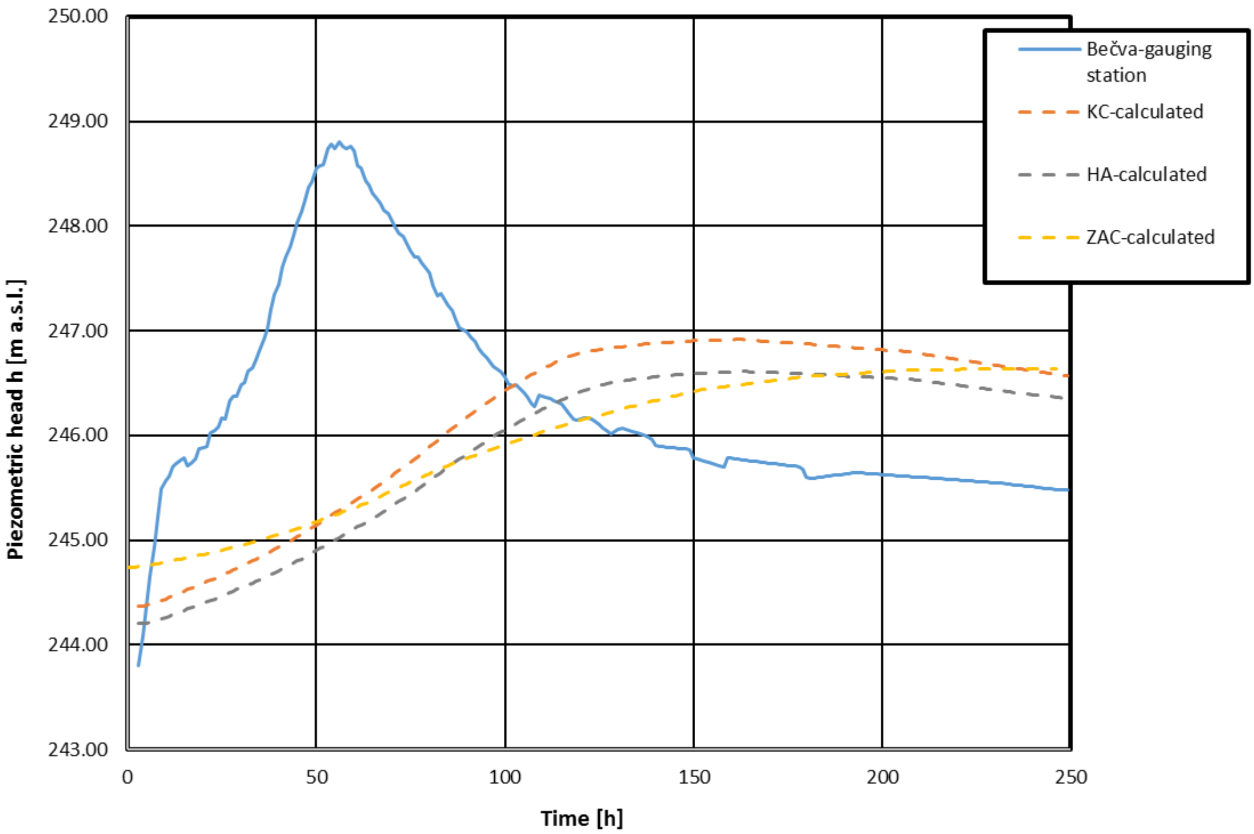


**Figure 14: Results for scenario III.B.**

**Table 6: 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.

This scenario represents steady state situation with the discharge of 25 m$^3$/s in the Bečva River and with reservoir permanent water level (261.00 m a.s.l.) which affects both Kamenec and the Bečva river bend infiltration zones.

Comparison with reference variant II.A. shows a more significant increase in the water level in the HA and KC (Tab. 7), 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 7: 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. 8. 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.

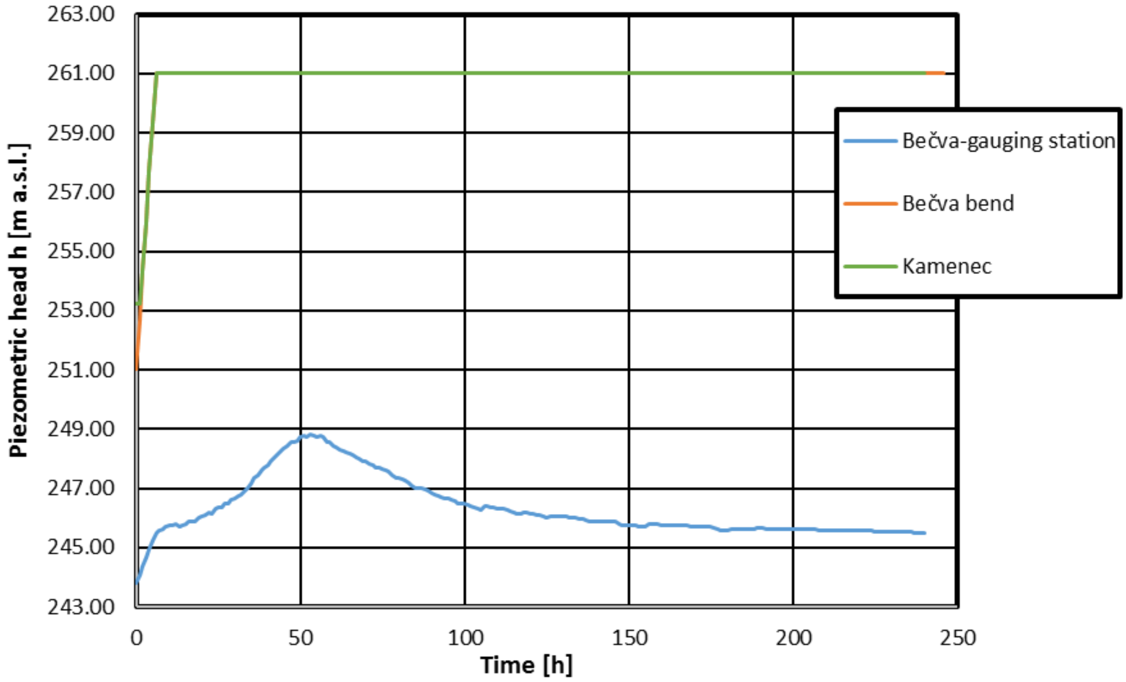


**Figure 15: Boundary conditions for variant IV.B.**

**Table 8: 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 |

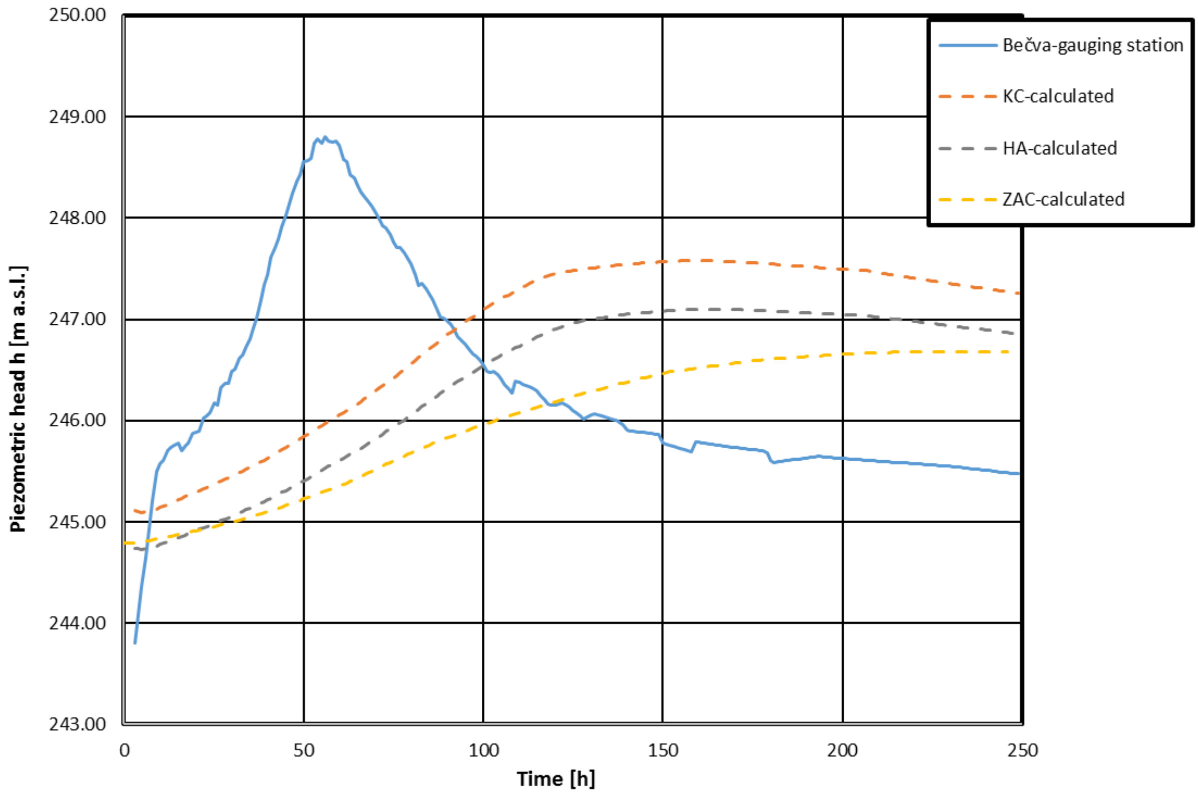


**Figure 16: Results for scenario IV.B.**

## 4.4 Discussion

The model presented was used for the assessment of the effect of the permanent increase of water level in the Skalička reservoir in two variants. The model calibration was carried out using rather incomplete monitoring data namely due to complicated accessibility into HA, ZAC and KC. Moreover, for the complete model calibration monitoring during flood situation in the Bečva river is necessary. Therefore, the model calibration and verification was carried out for three periods when temporary increase in the Bečva river was identified, namely during the March/April 2005, October 2020 and February 2021.

During the model calibration and verification, fairly good agreement of measured and calculated water levels in HA and ZAC were obtained. In case of less explored KC the verification provided rather worse agreement, in KC the only one data series measured in 2021 was available.

As can be seen from Tab. 3 the calibrated values of the coefficient of aggregated resistance are varying over several orders of magnitude. Eq. (2) indicates that the aggregated flow resistance factor depends on local (form) losses (i.e. changes of shape and direction of the flow), the length of canals and their tortuosity, diameters, micro and macro roughness, existence of subsurface caves, sediments, etc. Significant variability of the resistance coefficient indicates considerable changes in the shape, length and other above mentioned factors. From Eq. (2) it can be seen, that e.g. doubling the "pipe" diameter may result in increased the coefficient about 30 times, fivefold increase in "pipe" diameter (which is not uncommon in karst channels) results in the coefficient increase by more than 3 orders.

Time dependent reference and simulation scenarios were solved with time step 1 hour, the simulation period was 246 hours. During this time maximum water level was reached at all landforms, namely HA, ZAC and KC.

## 5. 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, the Hranice |Abyss and on the mineral waters at the Teplice spa. The main concern is that the dam with a permanent storage would have an impact on the natural conditions in the karst. Two variants of the reservoir layout were considered, namely a lateral and a through-flow reservoir.

Based on calibration and verification results the applicability of simplified hydraulic model is justified, especially if the knowledge about the deep karst formation is very poor. In contrary to purely regression models (Vysoká et al. 2019) the model proposed is physically based, pipe and reservoir hydraulics is incorporated into the solution.

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 further refinement of the model extensive hydrogeological survey is need and more extensive long-term parallel monitoring data should be provided in all karst phenomena in the area. The model indicated that additional places of surface water inflows to the karst system exist and should be systematically measured. These are namely inflows to the caves and abyss.

## 6 Competing interests

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

## 7 Acknowledgement

The paper is part of the project FAST-S-24-8513 - Analysis of the influence of input variables on the results of numerical models used in the safety assessment of water structures.

**8 References**


Bear, J. and Verruijt, A. (1992) Modeling Groundwater Flow and Pollution, D. Reidel Publishing Company, 414 p.

Breznik, M. (1985). Exploration, Design and construction of cut offs in karstic regions. In ICOLD Question No. 58, Lausanne.

Bruthans, J., Vysoká, H., and Grundloch, J. (2021). Natural yield of thermal waters in the Teplice nad Bečvou, their hydraulic connection with Bečva river and discussion of location of recharge area. – Geoscience Research Reports, 54, 1, 13–21. (in Czech)

Caille, J. (1955). Le barrage d'el Kansera u Beth sur l'oued Beth. In ICOLD Question No. 16, Paris.

Červeňanská M., Baroková D., and Šoltész A. (2016) Modeling the groundwater level changes in an area of water resources operations. Pollack Periodica, 11 (3), pp. 83 – 92. DOI: 10.1556/606.2016.11.3.8.

Chang, Y., Wu, J., and Jiang, G. (2015). Modeling the hydrological behavior of a karst spring using a nonlinear reservoir-pipe model. *Hydrogeology Journal*, *23*(5), 901.

CHMI (1997). Evaluation of the flood in July 1997. Summary report. Ministry of Environment of the Czech Republic, 173 p. https://www.chmi.cz/files/portal/docs/hydro/povodne/pov97/Povodn%C4%9B_1997_KOMPLET.pdf (last viewed in 5/2024).

CHMI (2010). Evaluation of the flood in May and June 1910. Summary report. Ministry of Environment of the Czech Republic, 172 p. https://www.chmi.cz/files/portal/docs/hydro/povodne/pov10/pdf/vuv_szpr.pdf (last viewed in 5/2024).

CUZK. (2024). State Administration of Land Surveying and Cadastre. https://www.cuzk.cz/en. (last viewed in 5/2024).

de Waele, J. (2008). Interaction between a dam site and karst springs: The case of Supramonte (Central-East Sardinia, Italy). Engineering Geology Volume 99, Issues 3–4, 23 June 2008, Pages 128-137. https://doi.org/10.1016/j.enggeo.2007.11.010

Delattre, P. (1955). Barrage de Génissiat sur le Rhone. Utilisation du remplissage naturel des vides karstiques du rocher. In ICOLD Question No. 16, Paris.

Faimon, J., Lang, M., Geršl, M., Sracek, O., and Bábek, O. (2020). The "breathing spots" in karst areas - the sites of advective exchange of gases between soils and adjacent underground cavities. Theoretical and Applied Climatology. https://doi.org/10.1007/s00704-020-03280-7.

Flores, R., Rodrigues, J. Kreuzer, H., and Schneider, T. (1985). Unusual grout curtain in karstic limestone for the El Cajón arch dam in Honduras. In ICOLD Question 58, Lausanne.

Geršl, M. and Konečný, O. (2018). Geological hazards resulting from the planned construction of a water dam "Skalička" near the Hranice Karst and the Hranice Abyss. – Geoscience Research Reports, 51, 1, 75–79. (in Czech)

Gilmore, J., Tilford, N., and Akarun, R. (1991). Keban dam in Turkey – a large dam on karst. In ICOLD Question No. 66, Vienne.

Golian, M., Teshnizi, E. S., Parise, M., Terzić, J., Milanović, S., Vakanjac, V. R., Mahdad, M., Abbasi, M., Taghikhani, H. and Saadat, H. (2021). A new analytical method for determination of discharge duration in tunnels subjected to groundwater inrush. Bulletin of Engineering Geology and the Environment (2021) 80:3293–3313. https://doi.org/10.1007/s10064-021-02140-6.

Gutierrez F., Parise M., De Waele J. & Jourde H., 2014, A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews, vol. 138, p. 61-88.

Guzina, B., Saric, M., and Petrovic, N. (1991). Seepage and dissolution at foundations of a dam during the first impounding of the reservoir. In ICOLD Question No. 66, Vienne.

Hartman, A., Goldscheider, N. Wagener, T., Lange, J. and Weiler, M. (2015). Karst water resources in a changing world: Review of hydrological modeling approaches, Rev. Geophys., 52, 218–242, doi:10.1002/2013RG000443.

Heitfeld, K. and Krapp, L. (1991). Problems associated with sulphate karst – flood control reservoir Salzderhelden/Germany. In ICOLD Question No. 66, Vienne.

Il Faut. (2022) The Dam Skalička - Hydrogeological Study. (available online http://skalicka.pmo.cz/download/vd-skalicka-hydrogeologicka-studie.zip).

Jeannin, P.-Y.; Artigue, G.; Butscher, C.; Chang, Y.; Charlier, J.-B.; Duran, L.; Gill, L.; Hartmann, A.; Johannet, A.; Jourde, H.; Kavousi, A.; Liesch, T.; Liu, Y.; Lüthi, M.; Malard, A.; Mazzilli, N.; Pardo-Igúzquiza, E.; Thiéry, D.; Reimann, T.; Schuler, P.; Wöhling, T., and Wunsch, A. (2021). Karst modelling challenge 1: Results of hydrological modelling. *Journal of Hydrology,* 600, 126508. https://doi.org/10.1016/j.jhydrol.2021.126508

Klanica, R., Kadlec, J., Tábořík, P., Mrlina, J., Valenta, J., Kováčiková, S., and Hill, G.J. (2020). Hypogenic versus epigenic origin of deep underwater caves illustrated by the Hranice Abyss (Czech Republic)—The world's deepest fresh-water cave. Journal of Geophysical Research: Earth Surface,125,e2020JF005663. https://doi.org/10.1029/2020JF005663

Klimchouk A.B. 2007. Hypogene speleogenesis. Hydrogeological and morphogenetic perspective. National Cave and Karst Research Institute, Carlsbad, Special Paper Series 1, 77 p.

Klimchouk, A. (2009). Morphogenesis of hypogenic caves. Geomorphology 106 (2009) 100–117.

Kuniansky, E. (2016). Simulating Groundwater Flow in Karst Aquifers with Distributed Parameter Models—Comparison of Porous- Equivalent Media and Hybrid Flow Approaches. Scientific Investigations Report 2016–5116. U.S. Department of the Interior and U.S. Geological Survey.

Leins, T., Liso, I. S., Parise, M. and Hartmann, A. (2023). Evaluation of the predictions skills and uncertainty of a karst model using short calibration data sets at an Apulian cave (Italy). Environmental Earth Sciences (2023) 82:351. https://doi.org/10.1007/s12665-023-10984-2.

Malenica, L., Gotovac, H., Kamber, G., Simunovic, S., Allu, S., and Divic, V. (2018) Groundwater Flow Modeling in Karst Aquifers: Coupling 3D Matrix and 1D Conduit Flow via Control Volume Isogeometric Analysis—Experimental Verification with a 3D Physical Model. *Water*, *10*, 1787. https://doi.org/10.3390/w10121787

Mikszewski, A. and Kresic, N. (2015). Mathematical Modeling of Karst Aquifers. In Karst Aquifers – Characterization and Engineering, Editor: Stevanovic, Z. Springer. ISBN 978-3-319-35422-4.

Milanović, P. (2005) Water Resources Engineering In Karst, CRC PRESS, Boca Raton London New York Washington, D.C., 2005.

Milanovic, P. (2018). Engineering karstology of dams and reservoirs. CRC Press Taylor & Francis Group. Boca Raton. ISBN: 978-1-4987-4807-0.

Milanovic, P. (2021). Dams and reservoirs in karst? Keep away or accept the challenges. Hydrogeology Journal, vol. 29, no. 1, pp. 89–100, 2021. doi:10.1007/s10040-020-02273-0.

Milanovic, S. and Stevanovic, Z. (2018). eds. Proceedings of the International Symposium KARST 2018 Expect the Unexpected, Trebinje / Bosnia and Herzegovina / 6-9 June 2018.

Mohammadi, Z., Raeisi, E., and Bakalowicz, M. (2007). Method of leakage study at the karst dam site. A case study: Khersan 3 Dam, Iran. Environ Geol 52, 1053–1065. https://doi.org/10.1007/s00254-006-0545-1

Mozafari, M. and Raeisi, E. (2015). Understanding Karst Leakage at the Kowsar Dam, Iran, by Hydrogeological Analysis. *Environmental & Engineering Geoscience* 21 (4): 325–339. doi: https://doi.org/10.2113/gseegeosci.21.4.325

Munson, B., Young, D. F., and Okiishi, T. H. (1994). Fundamentals of Fluid Mechanics. Second edition. John Wiley & Sons, Inc., New Your, 892 p.

Nash, J. E. and Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. Journal of Hydrology. 10 (3): 282–290. doi:10.1016/0022-1694(70)90255-6.

Palma, B., Ruocco, A., Lollino, P. and Parise, M. (2012). Analysis of the behaviour of a carbonate rock mass due to tunneling in a karst setting. In. ARMS7 - The 7th Asian Rock Mechanics Symposium, October 15-19, 2012.

Palmer AN. 1991. Origin and morphometry of limestone caves. Geological Society of America Bulletin, 103 (1), 1–21.

Parise, M., Closson, D., Gutiérrez, F. and Stevanovič, Z. (2015). Anticipating and managing engineering problems in the complex karst environment. Environ Earth Sci (2015) 74:7823–7835. DOI 10.1007/s12665-015-4647-5.

Parise, M., Gabrovsek, F., Kaufmann, G. and Ravbar, N. (eds) (2018). Recent advances in karst research: from theory to fieldwork and applications. Geological Society, London, Special Publications, 466, 1–24.

Petrović, B. and Marinović, V. (2023). Quantitative and Geochemical Characterization of the Mokra Karst Aquifer (SE Serbia) by Time Series Analysis and Stochastic Modelling. In: Andreo, B., Barberá, J.A., Durán-Valsero, J.J., Gil-Márquez, J.M., Mudarra, M. (eds) EuroKarst 2022, Málaga. Advances in Karst Science. Springer, Cham. https://doi.org/10.1007/978-3-031-16879-6_8

Sracek, O., Geršl, M., Faimon, J. and Bábek, O. (2019). The geochemistry and origin of fluids in the carbonate structure of the Hranice Karst with the world's deepest flooded cave of the Hranicka Abyss, Czech Republic. Applied Geochemistry, Volume 100, pp. 203-212, ISSN 0883-2927, doi: https://doi.org/10.1016/j.apgeochem.2018.11.013.

Stevanovic, Z. (Ed.) (2015). Karst Aquifers - Characterization and Engineering. Springer, 692 s.

Streeter, V. L. and Wylie, E. B. (1979). Fluid Mechanics. Second edition. Mc-Graw Hill Company, New York, 562 p.

Talebbeydokhti, N; Fattahi, MH., and Shamsai, A. (2006) Analytical and comparative study on problems and treatments world's dams. In Dams and Reservoirs, Societies and Environment in The 21st Century, Vols 1 And 2. International Symposium on Dams in the Societies of the 21st Century. Taylor & Francis Ltd11 New Fetter Lane, London, England.

Vysoká, H., Bruthans, J., Falteisek, L., Žák, K., Rukavičková, L., Holeček, J., Schweigstillová, J., and Oster, H. (2019). Hydrogeology of the deepest underwater cave in the world: Hranice Abyss, Czechia. Hydrogeology Journal, 27:2325–2345, https://doi.org/ 10.1007/s10040-019-01999-w.

Yevjevich, V. (1976). Karst hydrology and water resources. Proceedings of the Yugoslavian Symposium, Dubrovnik, June 2–7, 1975. Fort Collins, Colorado: Water Resources Publications.