Dear Xiaolang Zhang,

First of all, thank you very much for your valuable comments. In this phase, we will answer the questions you raised, referring to the parts/lines of the new supplementary material (*SM*) or the unmarked manuscript (*MS*) that has been modified based on reviewers' comments.

General comment:
Some papers dealing with the combined effects of water table topography, thermal and haline buoyancy were mentioned in the Introduction (Hoyos et al., 2012; Gupta et al., 2015; Magri et al. 2015). The only one of these was the paper by Magri et al. (2015), whose results could be compared in a meaningful way, and we did so in the Discussion. Agreeing with your suggestion, other connecting papers (e.g. Zech et al., 2016; Kaiser et al., 2013a) are discussed in the manuscript (*MS, Line: 550–562*) as well as potential areas will be presented, where considering the effect of topothermohaline convection, might be warranted in the future (*MS, Line: 636–645*).

In the Abstract, "water table topography" should be revised to "water table undulations."
We accept that 'water table undulation' is a slightly more accurate term to describe the phenomenon than 'water table topography'. However, topography-driven groundwater flow is the common expression (Mádl-Szőnyi et al., 2023), and topothermohaline convection includes this part. Thus, we would like to keep the original term, especially in the first sentence of the Abstract. In the first part of Introduction, a brief correspondence is made between water table topography and undulation (*MS, Line: 41*).

Line 35: Should "horizontal variations in the water table" be "vertical variations"?
In classical Tóthian models (Tóth 1962;1963), where the upper boundary of the model was horizontal ($h_{wt}(x)$), clearly the horizontal variation of the water table ($\partial h_{wt}(x)/\partial x$) results in groundwater flow. However, in recent numerical models (like those presented in this manuscript), where the upper flow boundary of the model geometry follows the water table, it has (a minor) vertical variation as well resulting in a slight difference between the numerical solutions. In order to cover this ambiguity, the adjective 'horizontal' was deleted (*MS, Line: 35*).

Line 38: Revise "thereof."
To clarify, a minor modification was made in the sentence: 'can be considered as its subdued replica' (*MS, Line: 39*).

Line 144: How do you account for the relationship between salinity and density?
Water density depends on the temperature (6th order polynomial), the pressure (2nd order polynomial) and the salt concentration (1st order polynomial). A linear relation between the water density and the concentration of

$$\rho_w(c) = \rho_{ref}(1 + \beta c)$$

was applied after the recommendation of Kohfahl et al. (2015), where $\beta=7.1\cdot10^{-4}$ l/g. This term was built in the whole formula of $\rho_w(T,p,c)$ which has been quantified in a new Supplementary material (*SM, Part 1*).

Line 173: How do you ensure that the model discretization (time step and spatial mesh size) meets the requirements for the Peclet number and Courant number?

For the simulations, we used COMSOL Multiphysics 5.3a, which is a finite element software package to solve coupled partial differential equation systems (Zimmerman, 2006). For discretization of time stepping in COMSOL, the Backward Differentiation Formula (BDF) was chosen, which is suggested for diffusion and convection problems due to its stability and robustness. To control BDF,

- the maximum time step was fixed at 100 yr for synthetic model calculations and 20 yr for simulating topothermohaline convection along a 2D section in the Buda Thermal Karst system having more complex geometry.
- A backward Euler scheme with an order of 1 or 2 was chosen to generate linear equation system, which was solved by a direct solver (MUMPS). If the global error (including both time stepping error and algebraic solution error) obtained from BDF exceeded a threshold (controlled by both relative and absolute tolerance), the time step was refused and
    i. the size of the time step was decreased (typical), or/and
    ii. the order of time discretization was increased

  to reduce the global error (summing up local errors) and to ensure the accuracy and the robustness of the numerical solution.
- In addition, both the non-dimensional Courant and Péclet numbers were calculated for each finite element and time step to check manually the local distribution of spatial and temporal quality of numerical solution.
- For example, the cell Péclet number, *Pe* was calculated for the mass transport (Darcy flux*cell size/molecular diffusion), which exceeded the value calculated for heat transport by orders of magnitude. In this way, *Pe* was much larger than 2 as a classical limit to characterize the accuracy of spatial discretization. However, this strict criterion is rarely used in practice, as it would require a very small element size. Instead, we applied consistent stabilization (crosswind and streamline diffusion), as a trade-off between sufficient accuracy and adequate element size (e.g. Diersch and Kolditz, 2002).
- Finally, a 1D stationary analytical model was built up to check the spatial accuracy of age transport simulation (Szijártó et al., 2025). Comparison between analytical and numerical solution of water age proved that the average and maximum relative deviations are below 10^{-3}% and 10^{-1}%, respectively, even for $Pe \gg 2$.

Line 184: The boundary condition for a constant salinity concentration seems unreasonable. While the heat source can originate from deep geologic units, where does the constant salt flux come from?

In advance, all boundary conditions are artificial and only an approximation of reality. In Hungary, it is typical that the salt concentration of water increases with depth. It is a consequence of (1) the sedimentation that took place predominantly in a marine, saline water environment and (2) the precipitation providing recharge that mainly reduces the salinity of the shallower layers. Consequently, a basement beneath the aquifer modelled has a higher salinity due to its lower permeability. It is worth noting that the model itself clearly shows that the low-permeability clayey Oligocene layer is able to retain its original salinity (HS6 in Fig. 11), despite (1) being at relatively shallow depths and (2) the presence of high-permeability aquifers below and above it. In addition, there are a number of hydrogeological situations where the aquifer is located above evaporites, halite formations (e.g. Kaiser et al, 2011; 2013b; Gupta et al. 2015; Magri et al., 2015; Zech et al., 2016), and thus salt source from a lower aquitard is almost constantly ensured. Nevertheless, the constant salt concentration prescribed along the bottom boundary was varied in a very wide range from 2 to 200 g/l, including many

hydrogeological situations. Furthermore, a new model will be presented in the Supplementary material, in which the evolution of the BTK system will be investigated using (1) different lower boundary condition for the salt concentration (*SM, Part 4*) and (2) temperature-, pressure- and concentration-dependent water viscosity. The main findings from the new simulation are presented in the Discussion section of the revised manuscript (*MS, Line: 610–624*).
Finally, we emphasize that the salinity concentration along the bottom boundary was constant during the simulations and not the salt flux.

Figure 10: The caption font is too small to read.
Thank you, the indexes are clearly readable in the original file format, but pdf generation deteriorated its quality. We will take care of it and now we attach the original figure.

Furthermore, minor stylistic and grammatical errors have been corrected in the revised manuscript, which has been uploaded at the editor's request.

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Dear Yipeng Zhang,

We thank you for your review of the manuscript and for your comments, corrections and suggested modifications. These comments have been carefully considered and are responded to below referring to the parts/lines of the new supplementary material (*SM*) or the unmarked manuscript (*MS*) that has been modified based on reviewers' comments:

Major concerns:

First, the bottom boundary condition for salt is assigned to be constant value, which means that there is unlimited salt comes from underlying aquifer/aquitard. The reason to assign a constant salt boundary condition should be explained, and the potential influences of using such boundary condition on the result should be at least mentioned.

Reviewer 1 also addressed this problem, to which we gave a similar response. In basin areas where sedimentation has taken place in a marine environment, such as the Pannonian Basin, it is a common hydrogeological situation that salinity generally increases with depth. The main reason for this is that the near-surface geological environment is in active contact with precipitation through recharge zones, while the deeper, more confined areas are much less so. Hence, the salinity of the aquitards below the basin exceeds that of the aquifers above, providing a continuous salinity supply to the basin. The phenomenon develops spontaneously in the BTK system itself, as the higher salt concentration in the low-permeability Oligocene cover persists over geological time, although it is interbedded with high-permeability aquifers from above and below. In addition, there are several hydrogeological situations where the bedrock of the basin is formed by evaporites, halite formations (e.g. Kaiser et al, 2011; 2013; Gupta et al. 2015; Magri et al., 2015; Zech et al., 2016), increasing the salinity of the basin through dissolution. Furthermore, in the synthetic parameter analysis, we varied the salt concentration of the lower boundary over a very wide range, c_b=2–200 g l^{-1}, to ensure that almost all hydrogeological situations were included.

Unfortunately, for the BTK system, there is no geological/geophysical/geochemical information available on the basement, and thus its exact salinity is not known. Therefore, a boundary condition corresponding to the initial condition (sediment deposition in a marine environment) was imposed in the model, c_b=35 g l^{-1}. However, as a consequence of the concern raised, a new simulation was also performed, in which an impermeable layer is located beneath the HS11 Lower Triassic-Paleozoic Aquitard in the BTK model, and a constant boundary condition of c_b=35 g l^{-1} is prescribed at its lower boundary, allowing only diffuse bottom salt transport. As a result, the salinity of the confined geothermal reservoir decreased, thermohaline convection intensified, and the groundwater mean age decreased. At the same time, the nature of the complex flow regime that developed in the BTK system did not change: topography-driven groundwater flow in the unconfined karst area, thermohaline convection in the confined karst, eastern reservoir with high geothermal potential, etc. The newly performed simulation and its interpretation can be found in the new Supplementary material (*SM, Part 4*) and in the revised manuscript (*MS, Line: 610–624*) attached to the manuscript.

Second, how is the application model in the BTK system verified to be representative for the pattern in the real system. Also, some discussion on the BTK system model should be added to show their implications in other regions globally.

Agreeing with the suggestion, the Discussion was substantially expanded. In the discussion part, we have already compared the numerical solution of the BTK with (1) the temperature and salinity of observed springs, (2) the temperature and salinity of geothermal projects at shallower depths, and (3) available water age data. Furthermore, we have pointed out the strong analogy between the flow-temperature-salinity regimes of the BTK and the Tiberias Basin to emphasize that the Buda Thermal Karst system is not a unique hydrogeological formation. In the revised version of the manuscript, both sections are expanded and completed to enhance the linkage of our research to other hydrogeological systems around the world. Additional salinity observations (*MS, Line: 567–575*) and temperature-elevation profiles (*MS, Line: 579–583*) are compared to our numerical results, and two other studies (Zech et al., 2016; Kaiser et al. 2013) are presented (*MS, Line: 550–562*) to illustrate the connection between processes of thermohaline convection occurring in BTK and other regions.

Specific comments:

Line 11 It is weird to use water table topography, find a better word. Please also revise them accordingly in the later part of the manuscript.

Reviewer 1 suggested the use of 'water table undulation', and a short explanation was inserted in the Introduction for clarification (*MS, Line: 41*). However, the usual scientific term to describe this phenomenon is 'topography-driven groundwater flow' (e.g. Mádl-Szőnyi et al., 2023), which has been modified to emphasize that it is not the topography of the surface but the topography of the water table that causes forced convection. In addition, in the expression of 'topothermohaline convection', the first term thus directly refers to the effect of the water table topography. For these reasons, we would like to keep the original expression 'water table topography'.

Line 13 Replace "combined" with "coupled".

Replaced, thank you for clarification (*MS, Line: 13*).

Line 37 What is Robinson and Love (2013) improved?

Robinson and Love (2013) accomplished an analytical stagnation point analysis and investigated the flow pattern asymmetry in a hierarchically nested groundwater system based on the Tóthian unit basin (Tóth 1963). We have inserted a short explanation into the manuscript (*MS, Line: 37–38*) and added the missing reference (*MS, Line: 935–936*).

Line 70 What is "increase heat transport" mean?

We have modified the expression in the revised manuscript: 'intensifies heat transport' (*MS, Line: 71*).

Line 132 Replace "balance" with "equilibrium".

Done in the revised manuscript (*MS, Line: 133*).

Line 157 & Table1 Why are the longitudinal and transverse dispersivity set to 0 m in the synthetic models, and what is the potential influence of setting dispersivity to 0 m.

In the synthetic models, we aimed to focus attention on the phenomenon of topothermohaline convection, so we compiled the simplest possible model framework, choosing to eliminate the effect of mechanical dispersion. At the same time, we have already taken into account the heterogeneity in nature in the real BTK system (α_L=100 m, α_T=10 m). In response to the question raised, we incorporated longitudinal and transverse dispersivity (α_L=100 m, α_T=10 m) into the synthetic base model (Table 2), and the model results are presented and interpreted in the Supplementary material (*SM: Part 2*) attached to the revised manuscript, and the effect of dispersion is briefly summarized in the Discussion section (*MS, Line: 625–630*).

In short, mechanical dispersion has strengthened the thermohaline dome that forms beneath the discharge zone, increasing its relative size from A_{sal}=35% to 50%. This resulted in an increase in the average salt concentration, temperature and water age of the basin, while the average Darcy flux decreased. The change is due to two factors: (1) transverse dispersivity increases the salt flux entering the bottom of the basin, and (2) longitudinal dispersivity effectively mixes the waters in the basin. By the way, the effect of mechanical dispersivity on topohaline (topography-driven forced & haline buoyancy-driven free) convection was analysed in detail by Galsa et al. (2022).

Line 164 Replace "supposed"
Replaced to 'proposed' (*MS, Line: 167*)

Line 170 The quantitative relationship between groundwater density, salinity, and temperature should be incorporated.
The quantitative relation of the water density and the molecular diffusion depending on the temperature, pressure and salt concentration is presented in the new Supplementary material (*SM: Part 1*).

Line 210 Please include references to support the selected values used in the sensitivity analysis.
Yes, references have been inserted into the modified manuscript (*MS, Line: 218–223, 262–263, 303–304, 337–338*) to support the parameter ranges selected. Note that the parameter ranges used in the sensitivity analysis are so wide that they cover almost all hydrogeological situations.

Line 391 Have the hydrogeological parameters of the fault been characterized separately? A brief discussion on the potential effect of fault in upwelling old, warm and saline groundwater in the discharge area should be added.
In this study, we have not investigated the role of the conduit/barrier faults. The faults shown in Figures 10 and 11 only separate the individual geometric units without any specific physical parameters. However, Szijártó et al. (2021) studied the role of conduit faults in the 'topothermal model' of the BTK system and found that they can influence the temperature distribution and the flow field mainly locally. If conduit faults were present in the environment of a high-temperature reservoir, they could, in theory, cause local anomalies both in temperature and salinity, but such surface manifestations do not exist. Only at the margin of the confined and unconfined karst, along the Danube River, the occurrence of springs with different temperatures, chemical composition and yields can be seen even near each other, as already mentioned in the Discussion of the manuscript. To clarify the potential role of faults, a separate paragraph has been dedicated to this point in the Discussion (*MS, Line: 586–594*).

Figures 6, 8 &12 Some words in the figures are difficult to read, possibly due to the use of the color light green. Consider adjusting the color or increasing the font size.
In Figures 4, 6, 8 and 12, light green colours have been changed to darker 'grass green'. If the manuscript is accepted, we will probably have to change some of the colour schemes as well.

Furthermore, minor stylistic and grammatical errors have been corrected in the revised manuscript, which has been uploaded at the editor's request.

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Dear Fabien Magri,

Thank you very much for your thorough review of the manuscript, your helpful comments and suggestions for further work, which have contributed to its improvement. The questions raised in your review are answered below, indicating separately where changes have been made in the unmarked version of the revised manuscript (MS) and/or in the new supplementary material (SM).

General Comment

The manuscript by Galsa et al. presents a detailed numerical investigation into the interaction of topography-driven groundwater flow and thermohaline convection. Usually this process is referred to as "mixed convection".

Yes, groundwater flow is considered a mixed convection system if it involves both forced convection (advection in physics) and free convection. However, we find it useful to distinguish between mixed convection regimes in which the flow is controlled by topography-driven forced convection and haline buoyancy (topohaline convection), or by topography and thermal buoyancy (topothermal convection), or even by all three components as topothermohaline convection. Thus, we can distinguish the driving forces in the umbrella term of 'mixed convection regime'.

Specific Comments

- **Temperature-dependent viscosity**

  Yes, the assumption of a constant dynamic viscosity of water is indeed a simplification of reality, as it was stated in the original version of the manuscript. The reason for this was to be able to investigate the dynamics of topothermohaline convection over the widest possible parameter range (water table amplitude, heat flux and salt concentration) with the available computational resources (for some models where the computation converged slowly to the quasi-stationary solution, the CPU demand of the simulation was even 2–3 weeks on an Intel Server with 2 Xeon Gold 6334 CPU @ 360 GHz using 32 threads).

  On the other hand, due to the importance of the question raised, we decided to investigate the effect of the variable viscosity on the BTK model result. In the modified model, the viscosity of the water is now dependent on temperature, pressure and salt concentration (Likhachev, 2003; Adams and Bachu, 2002; Palliser and McKibbin, 1998). We found that the dynamic viscosity of the water in the parameter range under investigation is mainly influenced by temperature. Thus, in the regions of higher temperature, the viscosity of water decreased, which intensified the thermohaline convection within the confined geothermal reservoir, contributing to a decrease in the extent of the temperature anomaly and an increase in the salt flux entering through the lower boundary. The more intense flow reduced the water age in the reservoir. As the viscosity of the colder waters near the surface increased, the outflow salt flux was reduced, and the average salt concentration of the basin increased slightly. However, these changes have not altered the conceptual bigger picture established in BTK, which is that (1) topography-driven water flow is the dominant driving force in unconfined karst, while (2) thermohaline convection is the dominant flow regime in the confined reservoir, (3) the clayey Oligocene cover is saturated with saline and aged synsedimentary waters, and (4) young, cold and fresh waters from the western side are mixed with aged, hot and saline waters from the eastern side in the confined karst. (5) The water, mixed in temperature and chemical composition, continues to reach the surface in the main discharge zone along the Danube. The results of the simulation using $\mu(T,p,c)$ are presented and interpreted in the new Supplementary material (*SM: Part 4*) attached to the manuscript, and the main conclusions are also presented in the Discussion part of the revised manuscript (*MS, Line: 610–624*).

- **Boundary Conditions in Table 2**

In the synthetic simulation series, the bottom salt concentration was fixed and varied over a very wide range (c_b=2–200 g l^{-1}) in the parameter analysis to cover as many hydrogeological situations as possible, from quasi-freshwater saturated basement to evaporites (e.g. 280–345 g l^{-1} for Zechstein salt in Zech et al. (2016), Kaiser et al. (2013)). The c_b=70 g l^{-1} chosen for the base model is an 'average' value between the two extremes, which could dominate the groundwater flow in the basin for certain model parameters (e.g. low water table amplitude and heat flux) and is negligible for others (e.g. high water table amplitude and heat flux). It is therefore a suitable transition value. Reviewer 2 recommended that the ranges used in the synthetic parameter analysis should be justified and referenced, so this has been done in the revised manuscript, together with the value of the salt concentration chosen for the bottom boundary (*MS, Line: 218–223*).
Unfortunately, in the case of the BTK real hydrogeological model, there is no hydrogeological/geophysical/geochemical evidence of the salinity of the basement, so we chose the value of c_b=35 g l^{-1} to reconcile with the initial value (sedimentation in a marine environment (Mádl-Szőnyi et al., 2019)). At the same time, we also investigated how the evolution of the system is affected by the reduction of the basement salinity through diffusion. For this purpose, we defined an impermeable layer under the BTK model (between z=5 and 6 km asl) and imposed boundary conditions at the bottom of this layer. The simulation results are published in the Supplementary material (*SM: Part 4*), and the main conclusions of the results are incorporated in the Discussion section of the manuscript (*MS, Line: 610–624*).

- **Boundary Condition Dominance in Figure 2**

Any boundary condition — whether it is a lateral boundary condition on the flow or a lower boundary condition on the salt concentration — affects the solution, i.e. the behaviour of the complex system. To address this question, we studied how the appearance and physical character of the thermohaline dome beneath the discharge zone are influenced by the no-flow vertical boundary condition. For this purpose, two unit basins were conjoined at the discharge zone, so the vertical boundary at the thermohaline dome was eliminated.
For the synthetic base model, the simulation was carried out in the doubled model domain, where the dome of saline, warm and aged water still formed in the middle part of the model, beneath the discharge zone, in which intense thermohaline convection was developed. The thermohaline dome, separated from the topography-driven flow regime on both sides by dynamic boundaries, was slightly weakened in its physical parameters (relative area, temperature, salt concentration and water age decreased by 4%, 9%, 12% and 21%, resp.), but the character of the flow was fully consistent with the flow/temperature/salinity/water age pattern developed in the unit half-basin. Thus, the behaviour of the topothermohaline system observed in the synthetic simulation series — thermohaline dome beneath the discharge zone — is clearly not a consequence of the lateral boundary condition. The results of the simulation are detailed in the Supplementary material (*SM: Part 3*).

- **Implementation of Faults in BTK Model**

In this study, we have not investigated the role of the conduit/barrier faults. The faults shown in Figures 10 and 11 only separate the individual geometric units without any specific physical parameters. However, Szijártó et al. (2021) studied the role of conduit faults in the 'topothermal model' of the BTK system and found that they can influence the temperature distribution and the flow field mainly locally. If conduit faults were present in the environment of a high-temperature reservoir, they could, in theory, cause local anomalies both in temperature and salinity, but such surface manifestations do not exist in this particular hydrogeological environment. Only at the margin of the confined and unconfined karst, along the Danube River, the occurrence of springs with different temperatures, chemical composition and yields can be seen even near each other, as already mentioned in the Discussion of the manuscript. To clarify the potential role of faults, a separate paragraph has been dedicated to this point in the extended Discussion (*MS, Line: 586–594*).

- **BTK Model – Validation Against Observed Data:**

The primary aim of our study was to visualize the phenomenon of topothermohaline convection and to quantify the dynamics of the complex hydrogeophysical system. At the same time, we intended to demonstrate the phenomenon in a real hydrogeological field where both topography-driven forced convection and free thermohaline convection can be present. Therefore, we chose the Buda Thermal Karst system. We would like to emphasize that the study is not a case study, so — in our opinion — a comprehensive comparative quantitative analysis between the numerical model and the real system would be beyond the scope of the manuscript. These case-specific synthesising studies have already been accomplished (e.g. Mádlné Szőnyi et al, 2018; Mádl-Szőnyi et al., 2019; Mádl-Szőnyi, 2019). Therefore, we deliberately focused only on the phenomena identified within the conceptual model framework.

On the other hand, this comment of the reviewer is fully understandable, so as a compromise, in addition to the previously reported data (temperature and discharge rate of springs, water age data), we have included new data (salinity of water samples from wells) (*MS, Line: 567–575*) and general observations from temperature-elevation profiles in the Discussion as a validation (*MS, Line: 579–583*). We are hopeful that this effort, complemented by comparison of the BTK system with other topothermohaline systems and other possible systems where topothermohaline convection may be important (*MS, Line: 636–645*), will meet the reviewer's expectations.

Furthermore, minor stylistic and grammatical errors have been corrected in the revised manuscript, which has been uploaded at the editor's request.

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