Journal of Hydrology: Regional Studies 56 (2024) 101961

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Quantifying the overlooked groundwater component in the water budget of a shallow soda lake in Hungary amidst climate change concerns

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ARTICLE INFO

Keywords:
Surface water–groundwater interaction
Lake level projection
Topography-driven groundwater flow systems
Visual MODFLOW
Regional climate models

ABSTRACT

Study region: Lake Velence.
Study focus: Soda lakes are extreme habitats whose special hydrochemical characteristics can partly be explained by groundwater inflow. The relationship between groundwater and Lake Velence has never been properly investigated. A significant decrease in the lake's level in recent years urged an evaluation of the components of the lake's water budget, including groundwater as well. A 3D transient numerical groundwater flow simulation, using Visual MODFLOW, was performed between 1990 and 2021 to evaluate the lake's relationship with groundwater and quantify the groundwater discharge into the lake. To assess future lake level changes until 2050, six lake level simulations were run based on three different regional climate models and two global warming scenarios (RCP2.6 and RCP8.5).
New hydrological insights for the region: Our results showed that groundwater inflow accounts for up to 12 % of the total annual inflow into Lake Velence. It has been numerically shown that precipitation and evaporation are the primary drivers of lake level changes, meaning that the variation of these two parameters will impact the lake's future. As for the future lake level changes, the RCP2.6 scenario resulted in an increase of 11 cm, while the RCP8.5 scenario led to a decrease of 30 cm compared to the observed annual average lake level until 2050. Our results emphasize the importance of integrating soda lakes into topography-driven groundwater flow systems to develop climate change adaptation strategies.

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https://doi.org/10.1016/j.ejrh.2024.101961
Received 4 July 2024; Received in revised form 30 August 2024; Accepted 31 August 2024
Available online 17 September 2024

1. Introduction

Soda lakes represent a distinctive category of saline water bodies characterised by the prevalence of Na^+ ions alongside HCO_3^- and CO_3^{2-} ions that foster specialized biogeochemical processes and support unique species (Boros and Kolpakova, 2018; Boros et al., 2017; Felföldi, 2020; Hammer, 1986; Schagerl and Renaut, 2016). The water budget of these lakes is primarily driven by the ratio of precipitation and evaporation, which increases the exposure of these unique lakes to climate change (Felföldi, 2020; Lengyel et al., 2020;

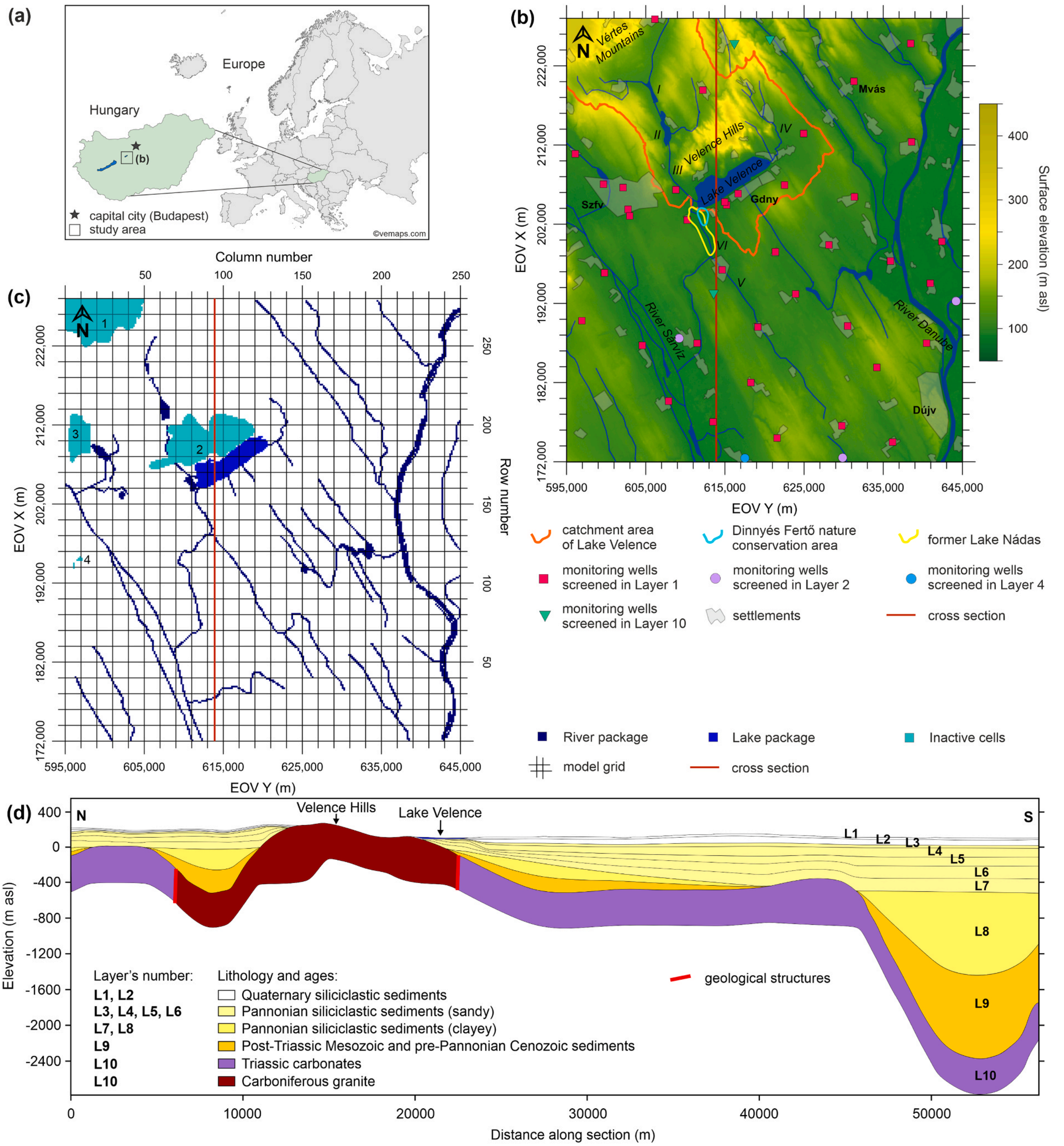

Fig. 1. (a) The location of the study area. (b) The location of the monitoring wells whose groundwater level time series were used for the calibration of the model. Roman numbers indicate the main surface water bodies related to Lake Velence: I - Zámoly reservoir; II - Pátka reservoir; III - Császár-víz; IV – Vereb-Pázmánd watercourse; V - Dinnyés-Kajtor channel; VI – former Lake Nádas. (c) Spatial discretisation of the model domain. Inactive cells in Layer 1 represent the outcrops of the crystalline basement: 1 – Vértes Mountains; 2 – Velence Hills; 3 – Moha; 4 – Szár-hegy. (d) A cross-section of the model domain marked with a red line in (c) displaying the ten model layers.

Oduor and Kotut, 2016). Although their water chemistry's origin is attributed to the influence of upwelling groundwater (Felföldi, 2020; Linhoff et al., 2010; Simon et al., 2008; Simon et al., 2011), groundwater conditions within these environments remain relatively understudied, leading to a knowledge gap in how groundwater can be a buffer against climate change induced changes in the lakes' water budget. For this reason, it is imperative to integrate these lakes into the topography-driven groundwater flow systems, evaluate the properties of these flow systems and interpret the results on a basin scale rather than just an aquifer scale or focusing only on the lake (Mádl-Szőnyi et al., 2023; Simon et al., 2023).

A comprehensive understanding of groundwater conditions and their connection with these lakes can help in determining how these lacustrine ecosystems will respond to climate change and other anthropogenic activities (Amanambu et al., 2020; Havril et al., 2018; Simon et al., 2023; Yihdego et al., 2017). According to the Tóthian topography-driven groundwater flow system theory (Tóth, 2009), groundwater flow has an organised subsurface movement. These systems are vulnerable to changes to varying degrees depending on the type of the hydraulic regime (i.e., recharge, through-flow, and discharge areas) and the hierarchically nested flow system (i.e., local, intermediate, and regional flow system) (Carrillo-Rivera and Cardona, 2012; Kurylyk et al., 2014; Tóth et al., 2016; Trásy-Havril et al., 2022; Xiao et al., 2022).

For instance, local flow systems are particularly vulnerable to the effects of climate change due to the short residence time of groundwater, resulting in rapid responses to alterations in recharge rates and recharge mechanisms (Brouyère et al., 2003; Kumar, 2012; Kurylyk et al., 2014). Recharge areas, compared to discharge areas, are characterised by a groundwater deficit and are, therefore, more susceptible to any changes. On the other hand, the longer the residence time (i.e. in the case of discharge areas or intermediate/regional flow systems), the more likely that the effects of climate change will be attenuated (Chen et al., 2004; Xiao et al., 2022; Zhou et al., 2020). These changes in groundwater flow systems, in turn, would have implications for surface water bodies and groundwater-dependent ecosystems. As they are integral components of the groundwater flow systems, their water and nutrient balance are influenced by the subsurface processes (Barron et al., 2012; Candela et al., 2012; Earman and Dettinger, 2011; Kløve et al., 2014; Lewandowski et al., 2015).

To examine the future groundwater conditions and lake level changes resulting from climate change, numerical simulation of groundwater flow systems is a powerful tool (Ghazi et al., 2021; Green et al., 2011; Havril et al., 2018; Scibek and Allen, 2006; Trásy-Havril et al., 2022). Among others, Visual MODFLOW, a commercial software has reportedly been used to quantify groundwater discharge into lakes in 3D (Ayenew, 2001; Yidana et al., 2019) and project climate change impacts on lakes (Khadim et al., 2023; Walker et al., 2008).

The presented research targeted Lake Velence, one of the westernmost occurrences of soda lakes in Eurasia situated in Central Hungary, and its surroundings (Fig. 1). Its shallow depth (average 1.2–1.4 m referenced to a gauge zero level of 102.62 m asl) makes the lake and its ecosystem extremely vulnerable to weather conditions, which resulted in a record-low minimum lake level (0.53 m referenced to a gauge zero level) in September 2022. This necessitates an urgent evaluation of Lake Velence and the associated groundwater flow systems, in order to explore the processes influencing the changes in the lake's water budget and to find the most suitable adaptation strategy.

Due to the lack of data and studies regarding the relationship between groundwater and Lake Velence, the authority (Central Transdanubian Water Directorate) responsible for the lake's management has not taken the groundwater component into account during water budget calculations so far (Central Transdanubian Water Directorate's Annual Report, 2022). However, recent groundwater flow mapping based on observed groundwater level data of wells revealed that Lake Velence is in the discharge area of local flow systems known to be the most sensitive among the topography-driven groundwater flow systems to any changes (Baják et al., 2022). As both the lake and the connected groundwater sources seem to be vulnerable to climate change, the question arises of how climate change will impact the groundwater levels and Lake Velence's water levels in the future. This question is crucial for the long-term survival of the lake and the related unique ecosystem.

The presented research aimed to expand our available knowledge by quantitatively investigating the interconnection between Lake Velence and groundwater using numerical groundwater flow simulation. To achieve this aim, a transient groundwater flow simulation was carried out by Visual MODFLOW 2011, covering a 32-year-long period from 1990 to 2021. The calibrated model was then used for the projection of lake level and groundwater level changes under two different climate scenarios until 2050 to i) understand the contribution of various lake water budget components, ii) reveal the influencing factors of lake water level changes; iii) understand climate change effects and iv) draw conclusions for possible water and land use management adaptation options.

2. Material and methods

2.1. Study area

The study area was outlined based on the results of previous groundwater mapping carried out in the vicinity of Lake Velence (Baják et al., 2022). It encompasses the lake itself and its wider surroundings, bordered by the main water divide, Vértes Mountains, on the northwest and by the regional erosion base, River Danube, on the east (Fig. 1a,b). This area of approx. 2800 km^2 is located ca. 50 km southwest of Budapest (the capital of Hungary) and delineated by the following 'EOV' coordinates ('EOV' is the 'Uniform National Projection system) EOV Y_{min}=595,000, EOV Y_{max}=645,000, EOV X_{min}=1720,00 and EOV X_{max}=228,000. The highest points of this area are located in the Velence Hills (352 m above the Baltic Sea level, hereinafter referred to as "m asl"). Areas with the lowest elevation are characteristic along the Danube (approx. 90–100 m asl).

This region exhibits a warm and dry climate with precipitation all year around (Péczely, 1998). The annual mean temperature is around 10.5–11°C in the region. The average annual maxima vary between 33.8 and 34°C, whereas the annual minima fall between

−16 and −17°C (Bihari et al., 2018). Annual precipitation is between 550–650 mm, whereas the potential evapotranspiration rate measures between 660–700 mm, according to the National Adaptation Geo-information System (NAGiS) (National Adaptation Geo-information System, 2023). Consequently, the aridity index (the ratio of evapotranspiration to precipitation) exceeds 1, indicating an arid climate in this area (Dégen, 1972).

2.2. Geology and hydrogeology

In the studied region, the pre-Cenozoic basement has two main outcrops, in the forms of carbonate rocks in the Vértes Mountains and granitic rocks in the Velence Hills. Otherwise, it is covered by a thick Neogene-Quaternary siliciclastic sequence (Fig. 1d) (Haas and Budai, 2014). The crystalline basement is composed of Paleozoic formations (low-grade metamorphites (slate), plutonic rocks (granite batholith), terrestrial siliciclastic formations (sandstone), shallow marine carbonates (anhydrite and dolomite)) in the northwest and Mesozoic formations (shallow marine carbonates (limestone) and siliciclastic rocks (marl, sandstone, siltstone)) in the southeast and in the foreland of the Vértes Mountains (Gyalog and Horváth, 2004). These pre-Cenozoic formations are covered by a thick (500–3000 m) Neogene (dominantly Pannonian)–Quaternary siliciclastic sedimentary sequence deposited in various depositional (fluvial, lacustrine, eolian, eluvial, deluvial, and proluvial) systems (Gyalog and Horváth, 2004). These siliciclastic sediments serve as the main drinking water reservoirs in this region, tapped by relatively shallow wells (0–100 m depth) screened between 50–100 m asl. Two main aquifer systems can be distinguished: i) Quaternary loess-sand layers and fluvial gravel assemblages along surface watercourses serve as unconfined aquifers. Of particular note is the alluvium along the Danube, which is produced by an extensive series of bank-filtered wells. ii) The confined aquifers consist of Quaternary, Upper Pliocene floodplain and fluvial sand formations, and Pannonian alluvial plain sand-clay formations. The thickness of unconfined aquifers can be some 10 m, while the confined aquifer system is characterised by a 300–1000 m thickness. These aquifers get their recharge directly from precipitation; thus, the water table follows the course of the topography and groundwater flow systems are driven by the topographic-related groundwater table differences (Baják et al., 2022).

Two main rivers, the Danube and the Sárvíz, flow across this region, fed by numerous small streams and creeks (Fig. 1b). The Danube is the main erosion base in the wider region. In the central part of the study area is Lake Velence, a shallow soda lake, which is the third-largest natural lake in Hungary with a surface area of 24.2 km^2. Its average water depth is between 1.2–1.4 m, and its water level varies between 103.15 and 105.06 m asl (53–244 cm relative water level observed at a gauge zero level of 102.62 m asl) (Szabó, 1997). The lake is located in a long, narrow depression in the southern foreground of the Velence Hills (Gyalog and Horváth, 2004). Based on the mineralogical and pollen analyses of lakebed sediments, Lake Velence has existed for more than 10–15 ky (Ádám, 1955; Bendefy, 1972; Sümeghy, 1952).

From historical records, it is known that Lake Velence is prone to drying out and, thus, can be considered an astatic lake (Bendefy, 1972; Padisák, 2005; Szabó, 1997). Its water balance is mainly driven by precipitation and evaporation; the role of surface waters appears to a lesser extent (Szabó, 1997). Due to the lack of data and studies, the groundwater component has not yet been properly calculated and was considered to be insignificant (Szabó, 1997). The lake has two main surface inlets, the Császár-víz from the west and the Vereb-Pázmánd watercourse from the east (Fig. 1b). In order to avoid extreme changes in the lake's water level, two reservoirs were created along the Császár-víz: the Zámoly and the Pátka reservoirs. The lake practically has no outlet because the artificial Dinnyés-Kajtor channel at the southwestern end of the lake is only opened after extended wet periods due to the usually low water level in the lake (Szabó, 1997).

The water of the lake is of the Na(Mg)–HCO_3 type, with a high SO_4^{2-} concentration and organic matter content (Baják et al., 2022; Boros et al., 2014; Reskóné and Borsodi, 2003). Due to its unique chemical composition, Lake Velence can be considered a soda lake and is one of the many saline ecosystems that occur in Hungary (Boros, 1999). Compared to NaCl and SO_4^{2-} salt lakes, this water type favours more wildlife and higher biodiversity (Boros et al., 2013). According to its special water chemistry and biota, the lake is enlisted on Habitat Directive (92/43/EC) with high protection priority in the Natura 2000 network of the European Union (Boros et al., 2014). Since 1979, Lake Velence has also been protected under the Ramsar Convention (Ramsar Convention, 2024).

2.3. Design of the 3D groundwater flow model

A 3D finite difference model was employed to simulate the groundwater flow conditions and the water budget of Lake Velence under transient conditions. The model was constructed using Visual MODFLOW 2011, a commercial Graphical User Interface of MODFLOW. MODFLOW (Modular Finite Difference Groundwater Flow Model) was developed by the United States Geological Survey in 1984 and is commonly used for modelling and projecting groundwater conditions and simulating the interactions between groundwater and surface water, as demonstrated in numerous studies (Hariharan and Shankar, 2017). In MODFLOW, the variability in groundwater levels in a heterogeneous and anisotropic environment is mathematically represented by the following equation (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities in the *x*, *y* and *z* directions, respectively; *h* is the hydraulic head at position *(x, y, z)* at time *t*; *W* is the groundwater recharge or extraction at position *(x, y, z)* at time *t*; and S_s is the specific storage.

The aim of the transient modelling was to examine what changes the lake has faced over the past decades as a result of climate change and human activity. Therefore, the examined time period covers a 32-year long time period between January 1990 and December 2021 with monthly time steps, resulting in 384 time steps, representing the 384 months (11688 days) of the modelled time interval. Since data collection and input data analysis were completed in 2022, the model does not include data for the years 2022–2024.

The model domain was created to cover the whole studied area of 2800 km^2. A rectangular grid model was chosen rather than the irregular shape typical of surface water models. The rectangular grid includes the entire groundwater and surface watershed of interest. The discretisation of the flow field is generated by primal cell dimensions of 200 m × 200 m, resulting in a mesh net of 280 rows and 250 columns (Fig. 1c). The model was conceived and built as a multi-layer model containing ten layers. Table 1 introduces the petrophysical and hydrogeological properties of these layers. Abbreviations L1 to L10 were used to identify the model layers.

The uppermost two layers, L1 and L2, represent the Quaternary and Upper Pliocene siliciclastic sediments, L3–L8 are assigned as the Pannonian (Miocene) siliciclastic sediments, while L9 and L10 represent the pre-Pannonian sequence that includes post-Triassic Mesozoic and pre-Pannonian Cenozoic siliciclastic and carbonate sediments (L9), Triassic carbonates (L10) and Carboniferous granite and Ordovician slate (L10) (Fig. 1d). There are four areas where the pre-Cenozoic basement outcrops (i.e. Velence Hills, Vértes Mountains, Szár-hegy, Moha). In those areas, cells were set inactive in L1 to L9 (Fig. 1c).

The required hydrogeological parameters for building the flow model were approximated based on literature data. Hydraulic conductivity (*K*) values for each lithology were obtained from Mádl-Szőnyi and Tóth (2009) and Tóth (2018). To allow the spatial variability of both the vertical and the horizontal hydraulic conductivity, the *K* values were modified based on the results of pumping tests obtained from well documentation available in the data repository of the Supervisory Authority of Regulatory Affairs, Hungary. Previously collected hydrogeological data were used to assign the initial values of the hydraulic head distribution of each layer (Baják et al., 2022).

The following flow boundary conditions were set to describe the exchange of the flow between the model and the external system: Recharge, River, Lake, and Pumping well.

Recharge was produced as the difference between observed precipitation and calculated evapotranspiration. Note that if the precipitation was greater than the evapotranspiration, the difference infiltrated the unconfined aquifer, and if it was less, the difference evaporated from the aquifer. Gridded evapotranspiration data was produced using the Morton Method (Morton, 1983). Necessary data, including monthly precipitation sums, mean temperature and mean relative humidity data were available for the study area on a 0.1° grid resolution between 1990 and 2021 from the database of the Hungarian Meteorological Service (Hungarian Meteorological Service, 2022). Gridded global radiation data was available only from 2001 in their database; therefore, this variable was obtained from the E-OBS database on a 0.25° regular grid between 1990 and 2021 (Cornes et al., 2018).

The two main watercourses that flow through the study area (Danube and Sárvíz) and the numerous small creeks that appear scattered throughout the studied area were added to the model as River package (Fig. 1c). The actual influence of these watercourses on the groundwater conditions is unknown, so the input parameters (conductance, riverbed thickness, riverbed vertical conductivity) were approximated and refined during model calibrations.

Lake package was applied to simulate the water budget changes of Lake Velence and quantify the share of groundwater (Merritt and Konikow, 2000). This package requires the following input parameters: atmospheric recharge, evaporation and runoff. The latter includes overland runoff, withdrawal and replenishment. Due to the transient nature of the simulation, the time series of these parameters were generated as input data. Precipitation data was available from the meteorological station of Agárd, a settlement located on the southern bank of the lake, in the database of the Hungarian Meteorological Service (Hungarian Meteorological Service, 2022). Lake evaporation data was produced using the Morton Method (Morton, 1983). Overland runoff, withdrawal and replenishment data were provided by the Central Transdanubian Water Directorate.

Water abstraction is extensive in this region and is mainly concentrated around larger settlements and agricultural areas. There are a total of 1749 wells in the study area, including waterwork wells, company wells and private wells. The water abstraction data were obtained from the database of the General Directorate of Water Management for the period between 1990 and 2021. However, the data were only available on an annual basis. Each well was added to the model as a pumping well, and the annual amount of the abstracted water for each well was divided equally between the 12 months. Therefore, seasonal changes in water abstraction (e.g. in the case of irrigation wells) could not be taken into account.

Table 1
The petrophysical and hydrogeological properties of the model layers. Abbreviations L1 to L10 were used to identify the model layers.

Number of layers	Lithology and ages	Horizontal (x,y) hydraulic conductivity (m/d)	Vertical (z) hydraulic conductivity (m/d)
L1	Quaternary siliciclastic sediments	0.05–2	5×10^{-5}–1
L2	Quaternary-Upper Pliocene siliciclastic sediments	0.005–2	1×10^{-4}–0.02
L3,L4,L5, L6,L7, L8	Pannonian siliciclastic sediments	0.05–2	5×10^{-5}–0.02
L9	Post-Triassic Mesozoic and pre-Pannonian Cenozoic sediments (undivided)	0.05–2	5×10^{-5}–0.02
L10	Triassic carbonates	2–5	0.02–0.5
L10	Carboniferous granite and Ordovician slate	0.005	1×10^{-4}

2.4. Calibration

The model was calibrated manually by comparing the groundwater levels calculated by Visual MODFLOW with observed groundwater levels since the observed data types that are most valuable for model calibration include level changes over space and time (Khadri and Pande, 2016). Observed groundwater level times series of 46 monitoring wells were involved. Among them, 39 monitoring wells were screened in the Quaternary unconfined aquifer system (L1–2), while 7 monitoring wells were screened in either the Pannonian (Miocene) or the pre-Cenozoic confined aquifer system (L4 and L10). To evaluate whether the model computes Lake Velence's water budget correctly, the observed lake level time series was also included in the calibration phase.

Results show that the simulated groundwater levels are in good agreement with the observed levels. The simulated groundwater levels show a good correlation (r^2>0.75) with the observed ones at the start and end of the modelled time period (r^2=0.895 and 0.804, respectively) (Fig. 2). As for the simulated lake level, r^2=0.58 indicates moderate reliability, though the model was able to capture the trends of the lake level dynamics with an average deviation of 0.14 m (up to 0.45 m) from the observed lake level.

However, the model has some limitations that arise from the data availability. Primarily due to the lack of monitoring wells screened in L3, L5–L9, the model's calibration relies especially on observation wells screened in L1. Therefore, the uncertainty of the model results increases with depth.

2.5. Climate models

After calibration, the 3D numerical simulation was utilised to project future changes in groundwater levels and Lake Velence's water level to evaluate the effects of climate change on these water resources under different global warming scenarios by 2050.

For future analysis, we assessed variables of mean temperature, precipitation, global radiation, and relative humidity as monthly outputs of three regional climate models (RCMs). These variables were used to calculate the recharge rate for the future by the Morton Method (Morton, 1983). RCMs are the best tools to capture the impacts of climate change at the regional level as they have a sufficiently good horizontal resolution, and they accurately depict the physical processes of the climate system with nonlinear processes and feedback.

We used RCM data from the EURO-CORDEX database (Kotlarski et al., 2014), on a horizontal resolution of 0.1° and driven by boundary conditions of three different global climate models (GCMs). Since the GCM fundamentally determines the RCM simulation outputs, we selected the GCM-RCM pairs with as diverse GCM and RCM options as possible (Table 2). Hereinafter, we will not use the full name of the 3 RCMs but simply use model-1, model-2 and model-3 instead. The simulated data covers the period of 1990–2005 from the historical runs (using historical emissions) and the period of 2006–2050 from the scenario runs using two different Representative Concentration Pathways (RCP), RCP2.6 and RCP8.5. The RCP2.6 assumes an immediate reduction of greenhouse gas emissions to stay within the "2 degrees" warming following the Paris Agreement, while the RCP8.5 scenario is a non-mitigation, business-as-usual scenario (van Vuuren et al., 2011). This small ensemble of RCM simulations and the two scenarios could allow us to capture the uncertainties inherently part of the climate simulation results (Szabó and Szépszó, 2016).

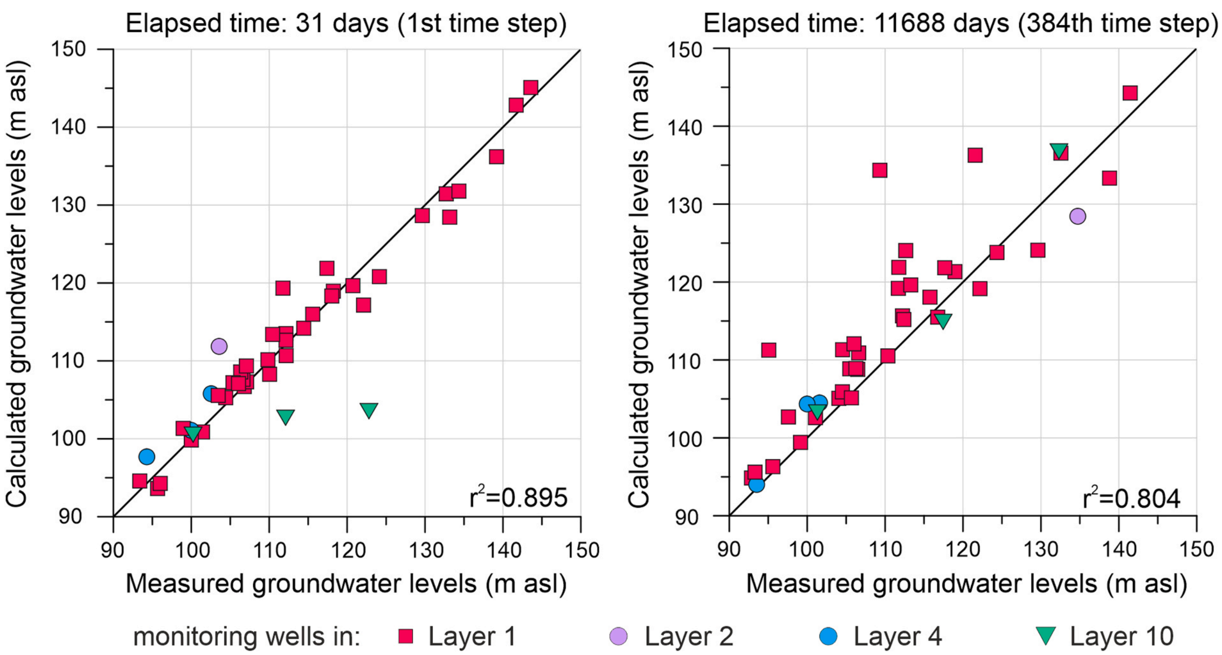

Fig. 2. Calibration of the model by comparing the observed and simulated groundwater levels.

Table 2
RCM simulations used in the study with their respective GCM.

GCM↓ / RCM→	ALADIN63	HIRHAM5	RCA4
EC-EARTH		✓	
CNRM-CM5	✓		
NorESM1-M			✓
Reference article of the RCM	(Nabat et al., 2020)	(Christensen et al., 2007)	(Samuelsson et al., 2015)
Referred as	model−1	model−2	model−3

It is known that both GCM and RCM results inherently have systematic biases compared to observations emerging from various sources (Kotlarski et al., 2019). Since these errors are different to a certain degree for the different climate variables, bias adjustment for the future was not applied for the aforementioned four input variables individually: mean temperature, precipitation sums, global radiation, and mean relative humidity were not bias-corrected one by one before being used by the Visual MODFLOW model as it might ruin the physical consistency between them. Consequently, we did the bias correction for the outputs of the hydrogeological model. For this purpose, we utilised the observations of lake water level and the bias adjustment method of standardization (Wilby et al., 2004), which uses both the mean and the standard deviation of the sample over the reference period of 2002–2021.

3. Results and discussion

3.1. Groundwater discharge into the lake

Previous researchers found that groundwater discharge into Lake Velence is insignificant. Hence, the groundwater component has been neglected in the water budget calculation for the lake (Cserny, 2001; Szabó, 1997; Central Transdanubian Water Directorate Directorate's Annual Report, 2022). However, extremely low lake levels observed recently drew attention to the importance of the exact assessment of all water components that enter the lake. Our previous work revealed that Lake Velence is in the discharge area of local flow systems characterised by shallow penetration depth and short residence time (Baják et al., 2022). The simulated groundwater flow directions in L1 support this concept as groundwater flows from SW-S-SE toward the lake (Fig. 3). Groundwater flow from N toward the lake is not likely to occur because of the presence of the granitic outcrop of the Velence Hills, characterised by very low hydraulic conductivity (10^{-8} to 10^{-3} m/d, Freeze and Cherry 1979). The same groundwater flow pattern could be observed in L2 and L3, while groundwater flow toward the lake is less characteristic in L4 and becomes in the opposite directions (toward SW-SE from the lake) in L5–L10, indicating that groundwater flow systems entering the lake has shallow penetration depth.

Generally, the groundwater component of lakes' water budget varies widely, with percentages ranging from almost 0 % to nearly 95 % for inputs to lakes (Rosenberry et al., 2015; Schmidt et al., 2010; Yihdego et al., 2017). However, in the case of lakes that are

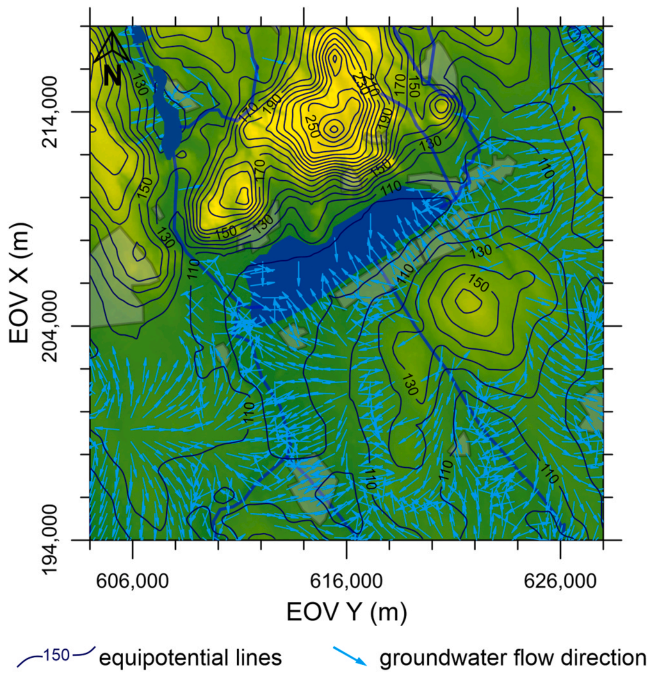

Fig. 3. The simulated groundwater flow direction distribution in L1.

larger than approximately 1 km^2, groundwater typically constitutes less than 40 % of the lake's water budget (Rosenberry et al., 2015). Our results showed that the amount of groundwater that enters the lake ranges from 279 to 11572 m^3/day with an average of 3095 m^3/day, which accounts for an average contribution of 47 lake mm with a range of 13–86 lake mm per year (Fig. 4). This amount of water is contributes to an average share of 5 % in the lake's annual inflows with a minimum of 1 % and a maximum of 12 %. Compared to the recharge coming from precipitation (26–72 %) and inflowing streams (20–72 %), the share of groundwater in the lake's water budget is less significant.

The relatively small amount of groundwater entering the lake can be explained by three factors, which are the type of lake sediments, the geometry of the lake and its catchment, and the hydraulic gradient between the lake and the adjacent aquifers (Schmidt et al., 2010).

The bottom of the lake is completely covered with organic matter-rich silt characterized by low hydraulic conductivity and permeability (Cserny, 2001; Freeze and Cherry, 1979), which slows down the rate of groundwater discharge into the lake, making its measurement and observation difficult.

Furthermore, the catchment area of Lake Velence is 602.3 km^2, which is 25 times larger than the lake's surface area (24.2 km^2), enhancing surface runoff instead of groundwater discharge (Schmidt et al., 2010). However, it has to be mentioned that, based on tritium measurements, the Császár-víz and the Vereb-Pázmánd watercourse receive a significant amount of groundwater discharge (Baranyi, 1973), resulting in an indirect groundwater contribution to the lake's water budget. Based on the analogy of the nearby Lake Balaton (Tóth et al., 2023) and a global review done by Beck et al. (2013), the surface streams have an average baseflow index of 63–77 % in this region, i.e. roughly three-fourths of the discharge is provided by groundwater. If we recalculate the share of each component in the lake's recharge assuming a 75 % groundwater discharge (calculated by Tóth et al., 2023) into the inflowing streams, groundwater would get a 23–56 % share in the lake's recharge, whereas 'real' surface water would contributes only 5–18 %.

Lastly, due to the presence of the Velence Hills, the hydraulic gradient is higher in the north than in the south of the lake, which would enhance groundwater discharge into the lake from the north. However, the low hydraulic conductivity of the granitic rocks outcropping in the Velence Hills resulted in a local discharge of groundwater in the form of cold springs, thus enhanced surface runoff dominates in that northern hilly area (Baják et al., 2022).

In light of our results, the previous theories about the formation of Lake Velence can also be reinterpreted. Although groundwater is typically not the primary driver of lake formation, it can play a role in it, hence intensified groundwater upwelling can enhance lake formation (Gebremichael et al., 2022; Wang et al., 2002).

According to the most accepted theory, the lake was formed in the early Holocene, about 10–15 thousand years ago, under the cool and wet climate of a sub-boreal period, when the shower streams originated from the Velence Hills flowed through and swelled in the tectonic depression in the southern foreground of the Hills (Ádám, 1955; Bendefy, 1972; Sümeghy, 1952). The wet climate could have fostered the functioning of local flow systems in the southern part of the lake, which could have filled the depression together with surface streams.

The groundwater outflow was also calculated by the model and can be considered negligible, being an order of magnitude smaller than the groundwater discharge into the lake. Groundwater seepage most likely occurs toward the Dinnyés Fertő, a marshy area adjacent to the western corner of Lake Velence, where the surface topography (103.15–105.06 m asl) has a similar value as the lake's water level (103–105 m asl) (Fig. 1b). This would align with the results of the previous groundwater flow mapping and the simulated groundwater flow pattern (Fig. 3), which also identified the Dinnyés Fertő area as a discharge area (Baják et al., 2022).

The above-presented results of the numerical groundwater flow simulation can be further supported by the similar hydrochemical characteristics of the lake and the groundwater. Numerous studies have dealt with the uniqueness of the soda lakes' water chemistry, including Lake Velence's (Boros and Kolpakova, 2018; Boros et al., 2014; Boros et al., 2017; Schagerl and Renaut, 2016), revealing the

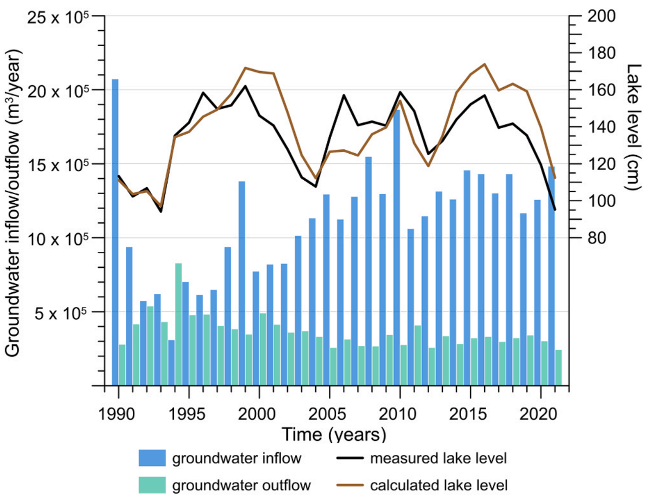

Fig. 4. The calculated amount of groundwater inflow and outflow and the observed and simulated lake level changes of Lake Velence.

role of groundwater inflow as an essential driving force of the lakes' water chemistry evolution (Boros et al., 2017; Grant et al., 2006; Grant, 2004; Schagerl and Renaut, 2016; Simon et al., 2008; Simon et al., 2011). Discharging groundwater whose bicarbonate concentration is more than two times higher than its Ca concentration enhances the formation of soda lakes. Groundwater samples collected in the vicinity of Lake Velence clearly indicate the predominance of bicarbonate, with an average concentration of 478 mg/l, as compared to calcium (averaging 46 mg/l) and magnesium (averaging 47 mg/l). This is in accordance with an excess of bicarbonate (1448 mg/l) over calcium (13 mg/l) in the lake water (Baják et al., 2022).

3.2. Evaluation of the water budget of Lake Velence

To assess the main determining factors in Lake Velence's water budget and lake level changes, the contributors to the lake's water budget (using the groundwater in- and outflows calculated by the calibrated model) were evaluated over time between 1990 and 2021 (Fig. 5a,b and c). Fig. 5a shows the changes in the lake level over the 32-year long interval. A ca. 10-year long period could be observed three times (1993–2004, 2004–2012, 2012–2021) during which an increasing trend is followed by a decrease in the observed lake

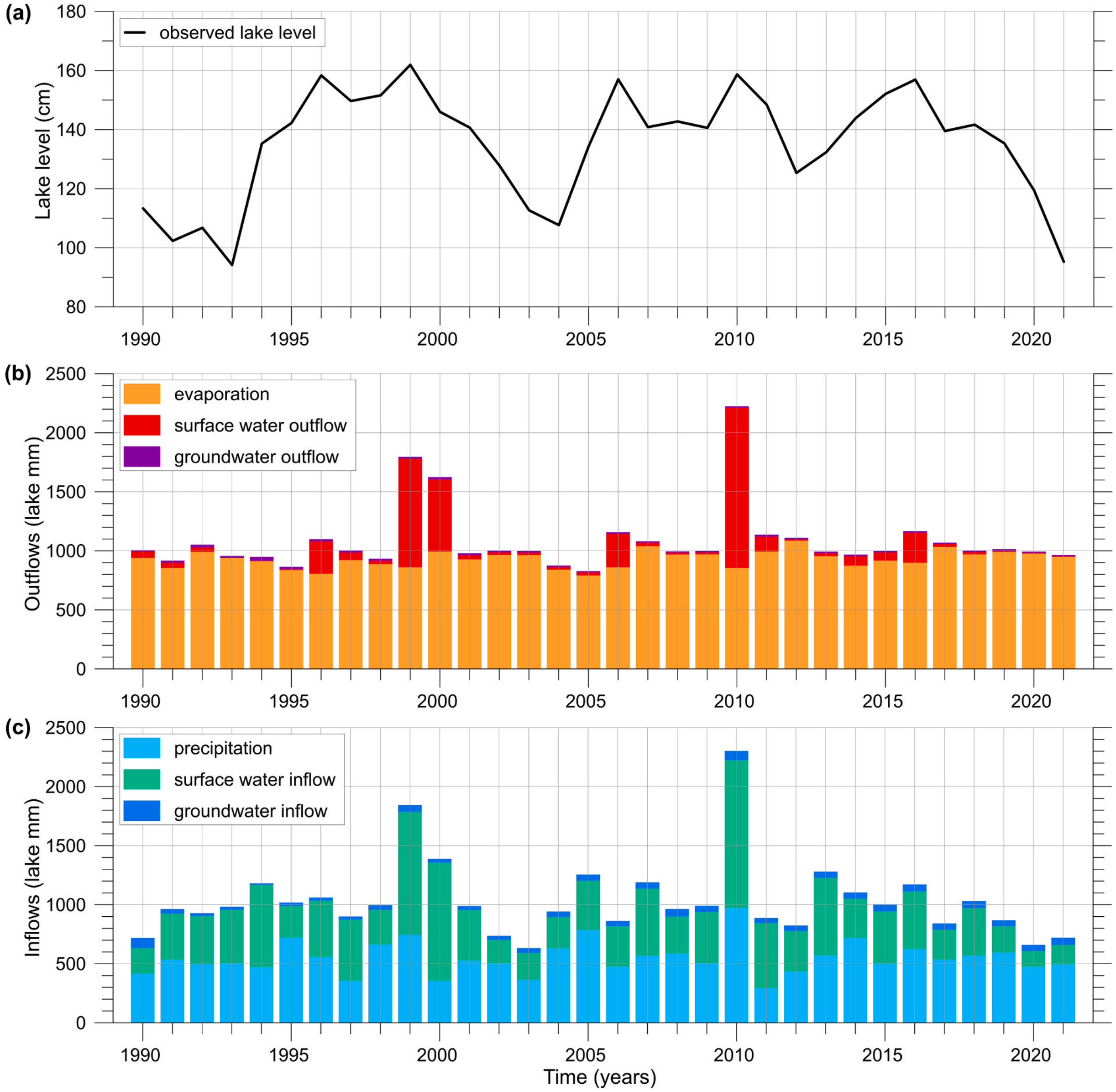

Fig. 5. (a) Observed lake level changes of Lake Velence between 1990 and 2021; (b) the lake loses water via evaporation, surface and groundwater outflows and (c) receives water from precipitation, surface and groundwater inflow. The groundwater in- and outflow values were calculated by the calibrated model.

level. All the outflows included in the lake's water budget calculations are plotted in Fig. 5b, supplemented by the simulated groundwater outflow. Fig. 5b shows that the lake loses water via evaporation, surface water outtake and groundwater seepage. On the other hand, it receives water from precipitation, surface water inflow (including the artificial reservoirs) and groundwater discharge through the lake bottom (Fig. 5c).

The changes in the lake level could primarily be explained by the changes in the amount of precipitation and evaporation since these two components predominated the lake's water budget during the observed 32-year period. Precipitation accounted for an average of 55 % of all inflows into the lake (26–72 %), while among all outflows, evaporation is the most significant with an average share of 89 % (38–99 %). Higher lake levels were observed in those years (1999, 2010), which were rich in precipitation (up to 973 mm compared to the annual mean of 549 mm over the lake) (Fig. 5a,c). On the other hand, the lowest levels were observed in periods (1992, 2000–2003, 2011–2012 and 2017–2021), characterised by warm years with high evaporation (up to 1086 mm) or significantly lower precipitation (as low as 366 mm) (Fig. 5a,b,c). The lake level changes correspond well with changes in the amount of precipitation and evaporation, the other components, such as surface water outtake or groundwater inflow, are much less significant. These findings numerically showed that changes in the lake's water budget are primarily driven by the ratio of these two influence factors. A similar correlation was observed in other saline lakes (Li et al., 2007; Riveros-Iregui et al., 2017). Given that precipitation and evaporation rates change due to climate change, this leads to the conclusion that future changes will heavily impact the lake's very existence without human interference (Woolway et al., 2020).

3.3. Projection of lake levels using different climate models

To project the lake level changes between 2022 and 2050, the recharge rate was calculated by the Morton Method using climate variables obtained from the 3 RCMs (model-1, model-2 and model-3). However, a simplification was made regarding water abstraction and surface water inflow. Based on the observations, the annual average water abstraction and surface water inflow were calculated for the past (1990–2021) and these average values (9321 m^3/day and 28,958 m^3/day, respectively) were used for running the simulations for the future.

Altogether, six simulations were run for the future period because all models (model-1–3) were run by both RCP2.6 and RCP8.5 scenarios. Out of these simulations, we could only verify the results of model-1, where the modelled lake level time series showed a good correlation with the observed lake level between 1990 and 2021 (r^2=0.76) (Fig. 4). Simulations run by variables obtained from model-2 overestimated the recharge rate, resulting in an extreme lake level increase (approx. 3 m) by 2021 compared to the observed lake level. On the other hand, the recharge rates calculated based on variables of model-3 showed negative values, resulting in the lake

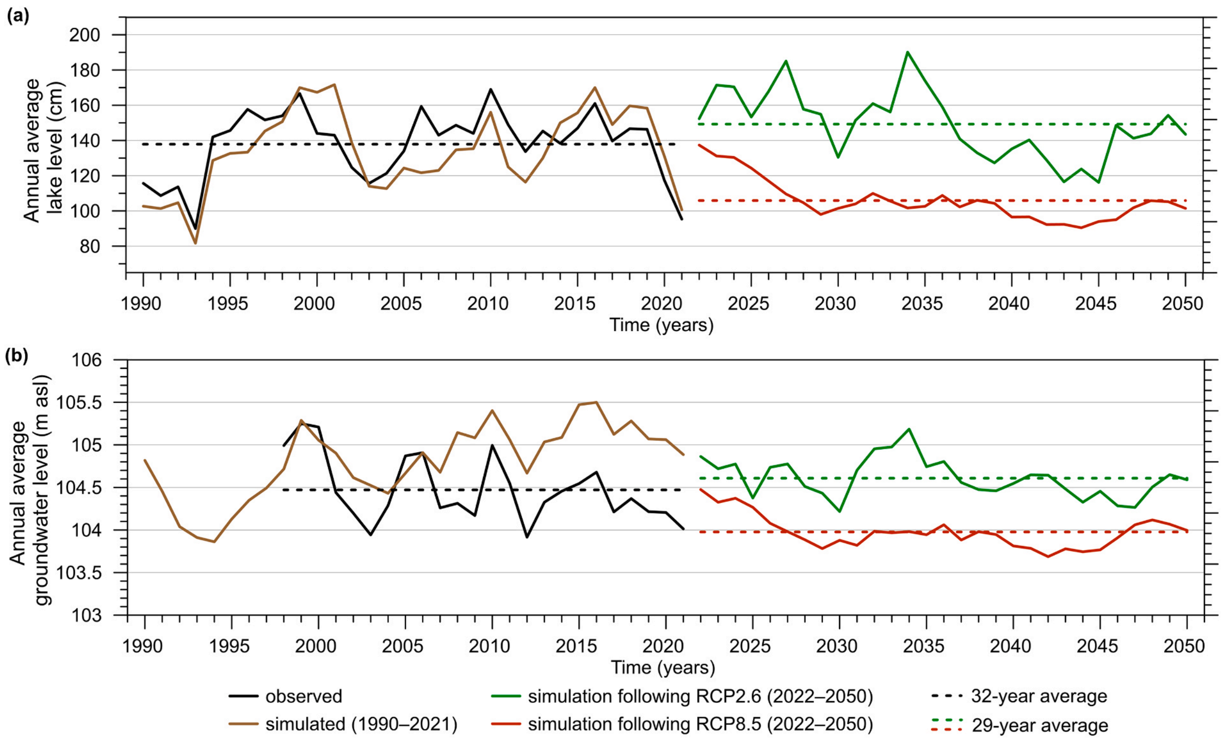

Fig. 6. (a) The annual average lake level of Lake Velence and (b) the annual average groundwater level of Agárd-143969 monitoring well based on i) observations and the simulation run with observations between 1990–2021; ii) simulations of model-1 run with the two different scenarios for the future. The dashed lines represent the average values for the past and future time periods.

drying out by 2021. Consequently, only the results of simulations run by model-1's variables are presented.

The projected lake level time series modelled by model-1's variables following both the RCP2.6 and the RCP8.5 anthropogenic activity showed an average of 0.4 m difference in the simulated lake levels between 2022–2050 (Fig. 6a). The 29-year average lake level that was simulated using the RCP2.6 scenario was 149 cm, while this average value was 106 cm for the simulated lake level using the RCP8.5 scenario.

This difference could be explained by the differences in precipitation and evaporation (Fig. 7). The average annual total precipitation between 2022 and 2050 might be 551 mm for RCP2.6 and 495 mm for RCP8.5. On the other hand, the annual total evaporation could be 943 mm for RCP2.6 and 969 mm for RCP8.5. Compared to the region's observed annual total precipitation between 1990–2021 (535 mm), the RCP2.6 scenario indicated a 3 % increase, whereas the RCP8.5 showed an 8 % decrease. As for evaporation, both the RCP2.6 and the RCP8.5 scenarios showed an increase in its amount (1 and 4 %, respectively) since annual warming stops only a wide decade after greenhouse gas emissions reduction starts. A global review by La Fuente et al. (2024) also showed that following the RCP8.5 scenario will significantly increase lake evaporation over the 21st century.

These changes led to an overall small increase in the annual average lake level of Lake Velence by 2050 (to 149 cm) in the case of RCP2.6 compared to the past observed annual average level of 138 cm (Fig. 6a). On the other hand, the RCP8.5 scenario led to a small decrease in the annual average lake level (106 cm). A similar future trend could be observed for the groundwater level observed in the monitoring well of Agárd-143969, located on the southern shoreline of Lake Velence (Fig. 6b). According to the projected groundwater levels following the RCP8.5 scenario, groundwater resources in L1 and L2 will face a depletion by 2050 in accordance with a decrease in recharge rate (Fig. 6b), emphasising the vulnerability of local groundwater systems (Kurylyk et al., 2014). Due to the lack of monitoring wells in L3–10, the calibration of the model was limited in these layers. Therefore, no groundwater level projection was made for the layers in concern.

4. Conclusion

A 3D transient groundwater flow simulation has been developed and employed to quantify the groundwater inflow into Lake Velence, a shallow soda lake in Hungary. The results provided further evidence that the lake is in the discharge area of local flow systems characterised by relatively shallow penetration depth and short residence time.

Our model demonstrated that groundwater represents an annual average of 5 % (up to 12 %) of Lake Velence's inflows due to the lake's characteristic properties (e.g. catchment area/lake area ratio, type of lakebed sediments, hydraulic gradient). Still, it is of greater importance from a quality point of view because the lake's unique water chemical character (Na(Mg)-HCO_3) can be attributed to groundwater discharge. Considering that the watercourses flowing into the lake drain groundwater as well, the share of groundwater in the lake's water inflow can be as high as 56 %.

The evaluation of the components of the lake's water budget showed that lake level changes are primarily influenced by the changes in the precipitation-evaporation balance. This resulted in the lake's vulnerability to any changes in these two influence factors. However, according to the RCP8.5 scenario, precipitation will decrease by 8 %, and evaporation will increase by 4 % until 2050. These changes were reflected in the declining lake and groundwater levels in the future simulations.

Our study highlights the importance of integrated water management with the application of numerical simulations since lakes and groundwater are inseparable water resources. The lakes' vulnerability to climate change depends on the characteristics of the groundwater flow systems connected to the lakes. Therefore, merely examining the lakes themselves is insufficient. Without understanding their relationships with groundwater flow systems on a basin scale, we will not fully comprehend their processes, and their vulnerability cannot be adequately assessed. Similarly, the effectiveness of mitigation strategies and interventions cannot be achieved without this. By protecting the amount of groundwater, we can ensure the water supply to the lakes from below the surface, which can improve the lakes' water balance and preserve its unique ecosystem.

Author Statement

During the preparation of this work, the author(s) used ChatGPT in order to to check grammar, spelling and references. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Katalin Hegedűs-Csondor: Writing – review & editing, Conceptualization. **Anita Erőss:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **András Csepregi:** Writing – review & editing, Supervision, Software, Formal analysis, Data curation, Conceptualization. **Péter Szabó:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Máté Chappon:** Writing – review & editing, Data curation. **Ádám Tóth:** Writing – review & editing, Supervision, Methodology. **Petra Baják:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

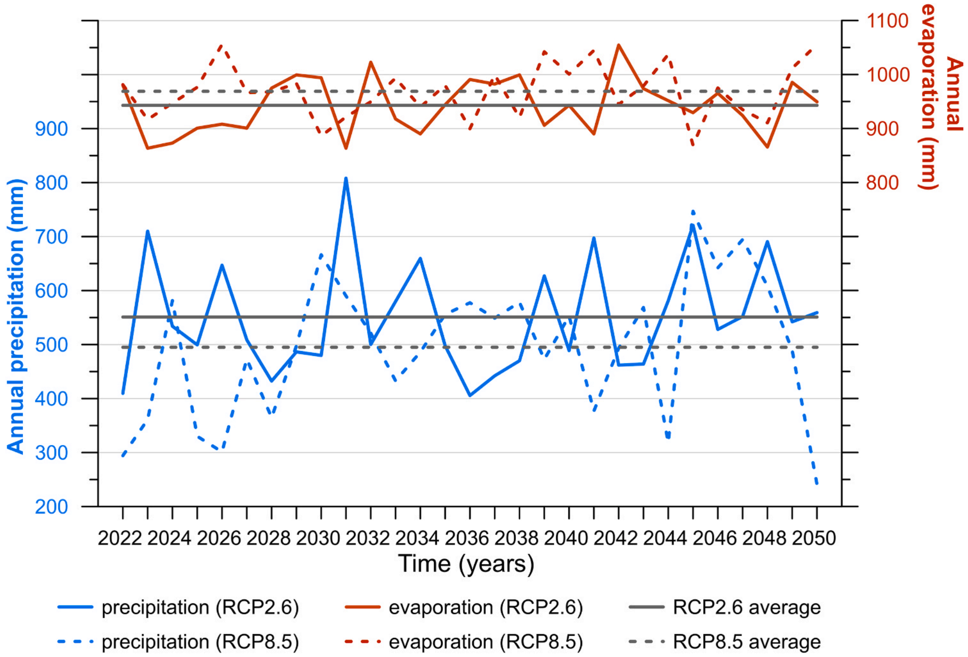

Fig. 7. The annual total precipitation and evaporation for the 2021–2050 period based on climate parameters of model-1. The horizontal (solid and dashed) lines represent the average value for the period.

influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

The research was supported by the ÚNKP-22–3 and ÚNKP-23–4 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund, and by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. The topic is related to research funded by the National Multidisciplinary Laboratory for Climate Change, RRF-2.3.1–21–2022–00014 project. The research was carried out within the framework of the hydrogeology research group of the József and Erzsébet Tóth Endowed Hydrogeology Chair and Foundation. The authors wish to acknowledge the contribution of Emese Gizella Kovács (General Directorate of Water Management) and Péter Szabó (Central Transdanubian Water Directorate) whose help was invaluable during data collection. The assistance of Kinga Gere and Judit Fehér (Supervisory Authority of Regulatory Affairs) in data mining is also highly appreciated.

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