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Multimethodological Revisit of the Surface Water and Groundwater Interaction in the Balaton Highland Region—Implications for the Overlooked Groundwater Component of Lake Balaton, Hungary

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Abstract: The hummocky Balaton Highland is located in western Hungary and is part of the Transdanubian Mountains, the most extensive carbonate aquifer system in Hungary. The study region also encompasses Lake Balaton, the biggest lake in central Europe, which is to the south of Balaton Highland. The surface water–groundwater interaction in the Balaton Highland–Lake Balaton region and the groundwater contribution to Lake Balaton are revisited in this paper. Hydrostratigraphic classification was performed first; then, groundwater flow directions by hydraulic head distribution were analysed, and baseflow indices of surface watercourses were calculated. Regarding hydrochemical characterisation, general hydrochemical facies were identified, natural tracers of temperature, chloride and uranium were applied, and the stable isotopic composition of oxygen and hydrogen was determined. Finally, groundwater flow and heat transport were simulated in a 2D numerical model. A high level of hydraulic interaction was evidenced between surface water and groundwater and the sub-regions of Bakony Mountains, Balaton Highland and Lake Balaton by physical and chemical parameters, numerical simulation and groundwater-flow-related natural manifestations, revealing hydraulic continuity in the study region. Based on the results, the division of legislative water bodies can be reconsidered, especially that surface water and groundwater should be regarded as interconnected, and Lake Balaton can be considered a groundwater-dependent ecosystem in any water-use planning in the region.

Keywords: hydrostratigraphy; hydraulic head; baseflow; uranium; stable isotopes; numerical simulation

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1. Introduction

The springs of the Balaton Highland have been providing high-quality karst water for centuries [1], as exemplified by several archaeological sites, primarily Roman ruins, in the vicinity of the springs. The groundwater of excellent quality serves as the drinking water resource for the local residents; some mineralised springs have long been used for drinking cures, and the groundwater is also bottled as mineral water [2]. For sustainable water management, the recharge area of the groundwater, the path travelled underground, and the amount of water extracted are essential to be determined. At the same time, Balaton Highland is under protection and is part of the Bakony–Balaton UNESCO Global Geopark. Balaton Highland is bound in the south by Lake Balaton, which has an outstanding natural conservation value as the largest freshwater lacustrine wetland in central Europe. From the viewpoint of the subsistence of Lake Balaton and the surrounding wetlands in light of climate change, it is particularly crucial to understand their water budget and supply, both in terms of the extent of the drainage basin and the temporal variability of water budget components. This topic is aligned with the implementation of the European Union Water Framework Directive [3].

Studies from all over the world have proven vital surface water–groundwater interaction [4–8], and these two types of water form an interconnected resource [9,10]. Meanwhile, the surface waters of Hungary, including Lake Balaton, remain groundwater-intact and are handled as separate entities without a single mention of groundwater in their budget [11,12]. However, several authors have hypothesised and claimed the opposite. Szádeczky-Kardoss [13] conceptualised a hydraulically continuous hydrogeological system for the entire Transdanubian Mountains, where groundwater is discharged around the foothills and accumulated as surface water, such as in the case of Lake Balaton. Groundwater discharge in Lake Balaton has also been reported: in addition to lakeshore springs, sublacustrine seepage occurs through the lake sediments in a diffuse way and along the tectonic lines under the lakebed [14–19]. Furthermore, it can also be assumed that the watercourses of the Balaton Highland are supplied by groundwater, which is why these do not freeze in the winter [13,18].

Therefore, the main goals of this paper are to revisit (1) the surface water–groundwater interaction in the Balaton Highland–Lake Balaton region, and (2) the groundwater contribution to Lake Balaton. Firstly, the physical parameters and proofs are analysed: (a) hydraulic head distribution as an indicator of groundwater flow directions, and (b) baseflow indices of surface watercourses as a direct indicator of surface water–groundwater interaction. Then, secondary hydrochemical characterisation is performed: (c) general hydrochemical facies, (d) natural tracers of temperature, chloride and uranium, and (e) the stable isotopic composition of oxygen and hydrogen of springs, creeks and Lake Balaton. These samples are studied to understand the groundwater processes of recharge and discharge and to trace the groundwater flow paths. Finally, (f) a 2D numerical model of groundwater flow and heat transport is presented to connect the findings and facilitate joint interpretation. The structure of this paper might be irregular as the methods and materials, results, interpretation and comparison are discussed technique by technique (a–f), chapter by chapter.

2. Study Area

The Balaton Highland is located in western Hungary and is part of the Transdanubian Mountains, the most extensive carbonate aquifer system in Hungary (Figure 1) [20]. The region is abundant in naturally discharging springs of various temperatures, creeks and wetlands. Groundwater is the primary natural resource in the Transdanubian Mountains, and it is used mainly for public water supply, healing and heating purposes and bottled as mineral water [2]. However, the region is also rich in bauxite and brown coal found in the saturated zone; therefore, mine dewatering was required during the production period (1950s–1990s). As a result, the groundwater abstraction reached an enormous amount and caused a significant water level decrease of up to 100 m [21]. A popular tourist destination, the biggest lake in central Europe, Lake Balaton, lies south of the Transdanubian Mountains in a shallow depression (average depth is 3.14 m, maximum 11 m) and has a surface area of 593 km^2 [22]. The 10–15 km wide region to the north of Lake Balaton is called the Balaton Highland, and it is separated from Bakony Mountains via an intramountain basin (Figure 1).

The hydrogeological processes (including recharge, flow pattern, dynamics, storage and discharge) are governed by the hydrogeologic environment: topography (which serves as the main driving force via water table differences), climate (which provides the replenishment) and geology (which determines the geometry of flow paths and intensity of groundwater flow) [23]. Therefore, these components are presented here.

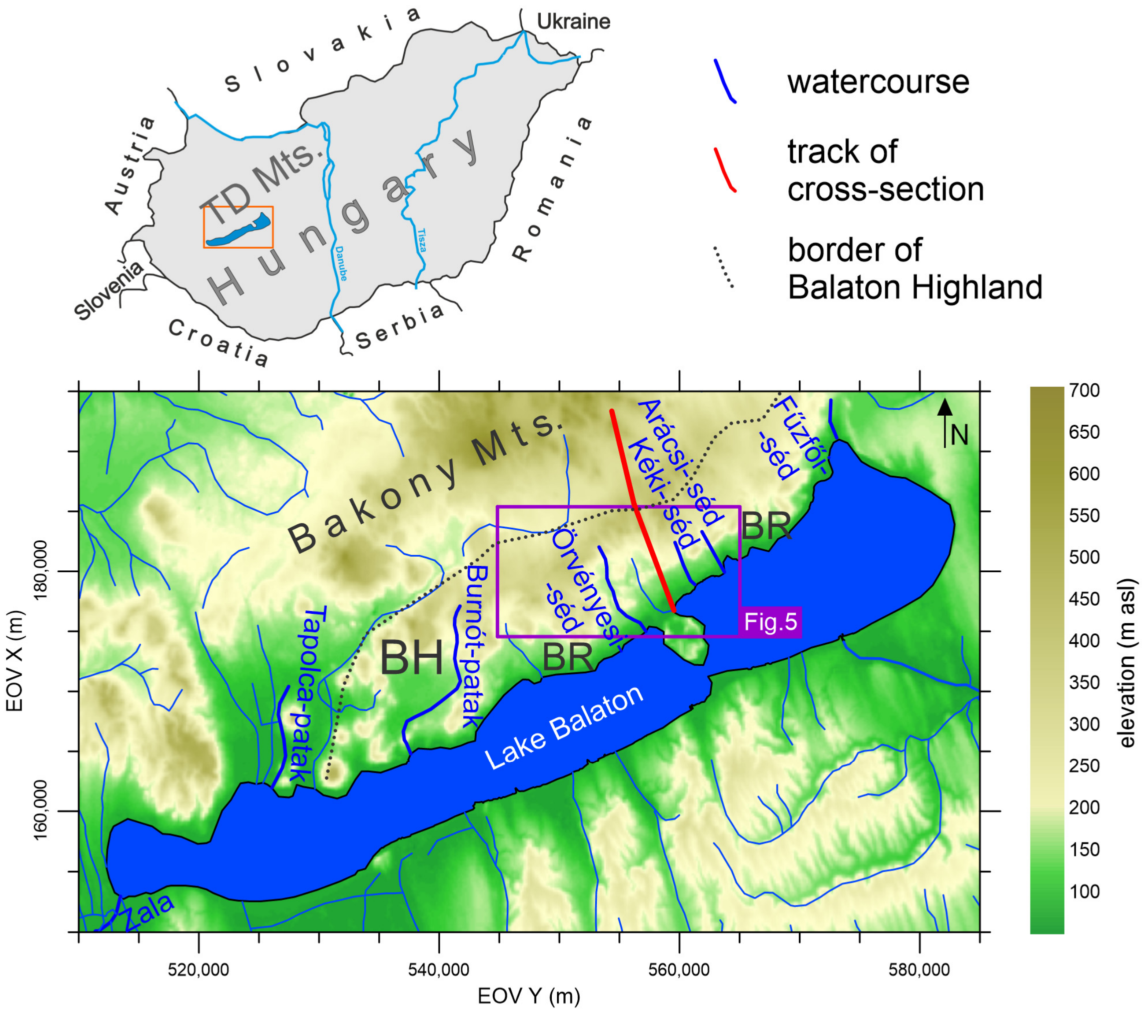

Figure 1. Location of the study area. TD Mts.—Transdanubian Mountains, BH—Balaton Highland, BR—Balaton Riviera (EOV is the Hungarian National Grid, a transverse Mercator projection, in which a positive X indicates north and positive Y indicates east. The numbers refer to metres).

The Balaton Highland dips gradually from the highest northern points of ~350 m asl toward Lake Balaton, which has an average water level of ~104 m asl. The littoral zone is just a couple of metres above the lake and is called Balaton Riviera. Several short creeks (the region-specific term is "séd") transect the Balaton Highland and feed Lake Balaton (Figure 1).

A humid continental climate characterises the area, but the effects of the Mediterranean influence can be detected in the sunshine duration and annual mean temperature (11 °C). The amount of precipitation, which falls predominantly in the form of rain, is 500–600 mm/year. However, due to the high actual evaporation rates, only 20–40% of precipitation can infiltrate and serve as recharge [24–26].

The geological reconnaissance in the Transdanubian Mountains started 200 years ago [27]; a detailed geographical, geological, biological and hydrological monograph of Lake Balaton and its surroundings was published in 1913 [14], and a detailed 1:50,000 scale map and its explanatory book of the Balaton Highland was published in 1999 [28,29]. The Balaton Highland and Lake Balaton are located in the Transdanubian Range Unit, which is part of the ALCAPA Mega-Unit. In terms of its structure, non-metamorphic younger formations are superimposed on Palaeozoic rocks that have undergone a low degree of metamorphosis [30–32]. Above the metamorphic basement, the formations of the Permian–Triassic period dominate the Balaton Highland's geological structure. The Permian Balatonfelvidék Sandstone Formation, formed in a fluvial environment, outcrops in the Balaton Highland [33]. The Lower Triassic predominantly clastic and carbonate–clastic shallow marine formations were deposited by erosion discordance on the Permian sandstone. These were followed by Middle Triassic carbonate ramp sediments, platform carbonates, igneous limestones and volcanics [29,34,35]. In the Upper Triassic sequence, platform carbonate appears in the N and NE, while a thick marl sequence has developed in the SE and E. The Upper Triassic formations become increasingly carbonated upwards, eventually forming a considerable thickness of platform carbonates. The total thickness of the Triassic sedimentary sequence is ~4 km [29,36]. During the uplift at the end of the Cretaceous, the Mesozoic formations younger than the Triassic were eroded [29]. Finally, Pannonian (Mio-Pliocene) detrital sediments developed along the southern part of the Balaton Highland [29,37,38]. See the details of these formations in Figures 2 and 3 in Section 3. The structural elements that most determine the geology of the Balaton Highland were created during the Cretaceous: thrusts and younger-on-older thrusts, accompanied by antiform and synform structures [39–41].

age	formation	lithology	thickness [m]	hydrostratigraphic unit	lgK_{xx} [m/s]	n [%]	λ_m [W/(m·K)]
Upper Miocene–Pliocene	Újfalu Fm., Tihany Mb.	silt, fine- and medium-grained sand, clay	30–120	HsU 7 Mi–Pl Siliciclastic AF	–7	10	1.7
Upper Triassic	Main Dolomite	dolomite	550–750, <2000	HsU 6 Tr Carbonate AF	–5	20	2.5
Upper Triassic	Sándorhegy	limestone, marl, dolomite	<130				
Upper Triassic	Veszprém Marl	marl, clay marl	<500	HsU 5 Tr Carbonate AT	–8	5	2
Upper Triassic	Gémhegy Fm., Kádárta Dolomite Mb.	dolomite, limestone	150	HsU 4 Tr Carbonate AF	–6	15	2.5
Middle–Upper Triassic	Füred Limestone	limestone	~10, <65				
Middle Triassic	Buchenstein	limestone, cherty, siliceous limestone	30–60				
Middle Triassic	Felsőörs Limestone	limestone	35–40				
Middle Triassic	Megyehegy Dolomite	dolomite	80–100, <270				
Middle Triassic	Iszkahegy Limestone	limestone	250–300				
Middle Triassic	Aszófő Dolomite	dolomite	100–250				
Lower Triassic	Csopak Marl	marl, clay marl, siltstone	100–200	HsU 3 Tr Carbonate AT	–8	10	2
Lower Triassic	Hidegkút Dolomite	siltstone, dolomite	60–70				
Lower Triassic	Arács Marl	marl, siltstone	50–70				
Permian	Balatonfelvidék Sandstone	sandstone, conglomerate	100–1000	HsU 2 P Siliciclastic AF	–7	10	1.7
Ordovician–Devonian	Lovas Shale	slate, metasiltstone, metasandstone	<1050	HsU 1 O–D Metamorphic AT	–10	1	2

Figure 2. Hydrostratigraphic units and their characteristics for the Balaton Highland region.

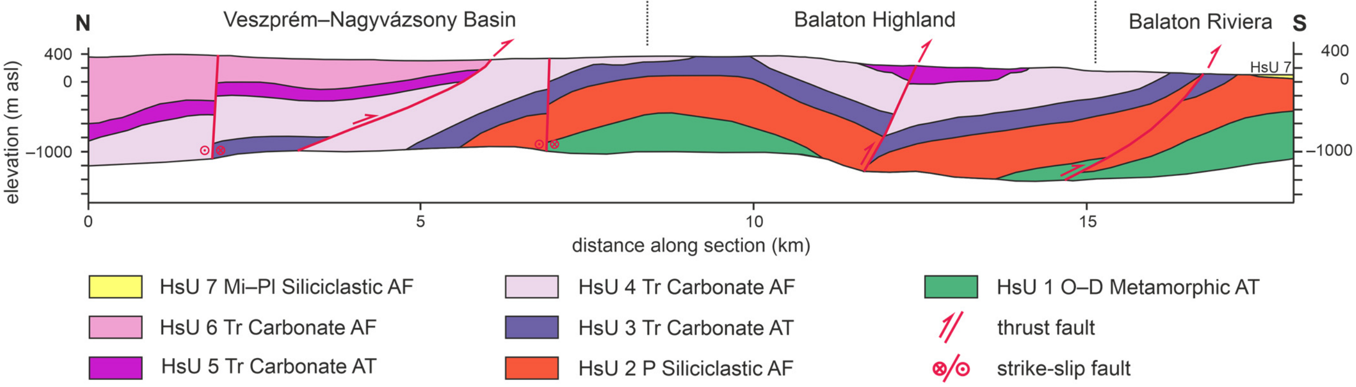

Figure 3. Hydrostratigraphic cross-section of the Balaton Highland (see the track in Figure 1) (after Budai et al. [28]).

3. Hydrostratigraphic Classification

The simplification and uniformisation of geology are required for hydrogeological studies, emphasising those properties that determine and alter groundwater flow. Instead of a detailed palaeontologic, diagenetic, mineralogic and petrographic characterisation, the hydraulic behaviour of rock matrices is essential, governed primarily by hydraulic conductivity and porosity. For this purpose, hydrostratigraphic classification was proposed and introduced, allowing the hydrogeological comparison of any geological unit based on uniform criteria [42,43]. These include the main lithological character, facies, sorting, thickness, extent, presence of fractures, faults, dissolution caverns, and nature of groundwater movement and storage [42]. Hydrostratigraphic units (HsU) serve as a base of classification with the two main types: aquifer and aquitard.

3.1. Methods and Materials

The hydrostratigraphic classification provided input information for the regional-scale numerical simulation of groundwater flow and was necessary for interpreting the results. Therefore, this analysis is based on the 16 geologic formations and members presented in the cross-section (ED) of Budai et al. [28]. The hydrostratigraphic conversion of the units started with a desktop study of the available literature, including lithological and hydrogeological descriptions and international references. The collected pieces of information were: name of formation/member, chronostratigraphy, thickness, facies, and lithological character [29,44,45]; qualitative and quantitative hydrogeological properties, mainly hydraulic conductivity and porosity [46–49]; and the reference values of textbooks [50–52]. The heat transfer simulation also required the thermal conductivity of the rock matrices. Site-specific values and international references were collected for this characterisation [49,53–56].

Sporadically occurring and thin (<10 m) units were merged with the host formations during the hydrostratigraphic classification. Considering the scale of the cross-section and study, only units with similar lithology (e.g., carbonates) and superimposed layers with physical contact were merged into one single hydrostratigraphic unit, keeping the geological variation represented in the hydrostratigraphy (after Maxey [42]). Once the division was set, representative hydraulic conductivity and porosity values were determined based on the available information. The last step was naming the units: ID + age + dominant lithology + hydraulic behaviour (aquifer (AF)/aquitard (AT)). Finally, the hydrostratigraphic units were illustrated using the corresponding colour of the International Chronostratigraphic Chart [57].

3.2. Results

The 16 formations included in the geologic cross-section were classified into seven hydrostratigraphic units (Figure 2). The succession started with a basement aquitard (HsU 1 O–D Metamorphic AT), which determined the depth of the groundwater basin.

This unit was followed by a relatively thick (100–1000 m) sandstone aquifer (HsU 2 P Siliciclastic AF) and a composite aquitard (HsU 3 Tr Carbonate AT). The region's main aquifers, with high storage capacity and hydraulic conductivity (HsU 4 Tr Carbonate AF and HsU 6 Tr Carbonate AF), were separated by an aquitard (HsU 5 Tr Carbonate AT), and these carbonate units were prevalent and dominant in the basin. Finally, a sedimentary cover unit (HsU 7 Mi–Pl Siliciclastic AF) appeared in the southern part of the study area. The variation, thickness, depth and distribution are presented in the hydrostratigraphic cross-section (Figure 3).

The horizontal hydraulic conductivity (K_{xx}) and porosity (n) values reflect the variation of aquitards and aquifers and the differences even within the same category. Regarding the thermal conductivities of the matrix (λ_m), a simple differentiation was applied: 1.7 W/(m·K) for siliciclastic, 2.5 W/(m·K) for carbonate aquifer units, and a transitional value of 2 W/(m·K) in the case of metamorphic and carbonate aquitard units (Figure 2). This hydrostratigraphic classification is the first of this kind for the Balaton Highland and will serve as a basis for the study.

4. Fluid Potential Distribution

As groundwater flow is driven by the differences in fluid potential (from higher to lower values), analysing and visualising fluid potential distribution, which is directly proportional to and measured through the hydraulic head, can reveal groundwater flow patterns [47,58–60]. Therefore, a fluid potential/hydraulic head map can serve as a base for understanding groundwater flow processes and indicate horizontal flow directions.

4.1. Methods and Materials

Traditionally, only one hydraulic head map, also called a potential or potentiometric map, is constructed for a single horizontal confined aquifer. Nevertheless, in practice, several potential maps should be created for various elevation or depth intervals in sedimentary basins to avoid misleading visualisations and interpretations of fluid potential [59,61–63]. However, in hilly or mountainous regions, such as the Balaton Highland, wells are quite rare because of accessibility, construction and production barriers. In these cases, the data set of the measured hydraulic head is limited, but naturally discharging springs can provide additional information about the potential field. Tóth et al. [58] demonstrated the application of springs in hydraulic data processing and derived the methodology by involving spring data. Assuming hydraulic continuity in the subsurface geologic domain [64], which is a valid assumption until the opposite is proven, and considering the morphology of the given range and springs as the primary data source, no interference between the elevation slices and maps is expected. Consequently, a tomographic map series can be stacked into one single potential map in the case of topographically elevated areas, i.e., ranges, hills and mountains.

As a result of the extensive groundwater production due to mine dewatering in this and neighbouring regions [21], only well data before 1962 (the start of pumping) could be considered to represent the natural conditions. Due to this limitation, water level records were available only for 37 shallow wells (<100 m, 15% of total data), and considering their spatial distribution, a potential map for the whole region could not be created. Nevertheless, 196 springs and their archive repository [65] could provide additional data (85% of the total) for the Balaton Highland region (Figure 4a). Their orifice's elevation was considered as the hydraulic head [58]. The hydraulic head map was constructed using the kriging interpolation with the default linear variogram and without extrapolation.

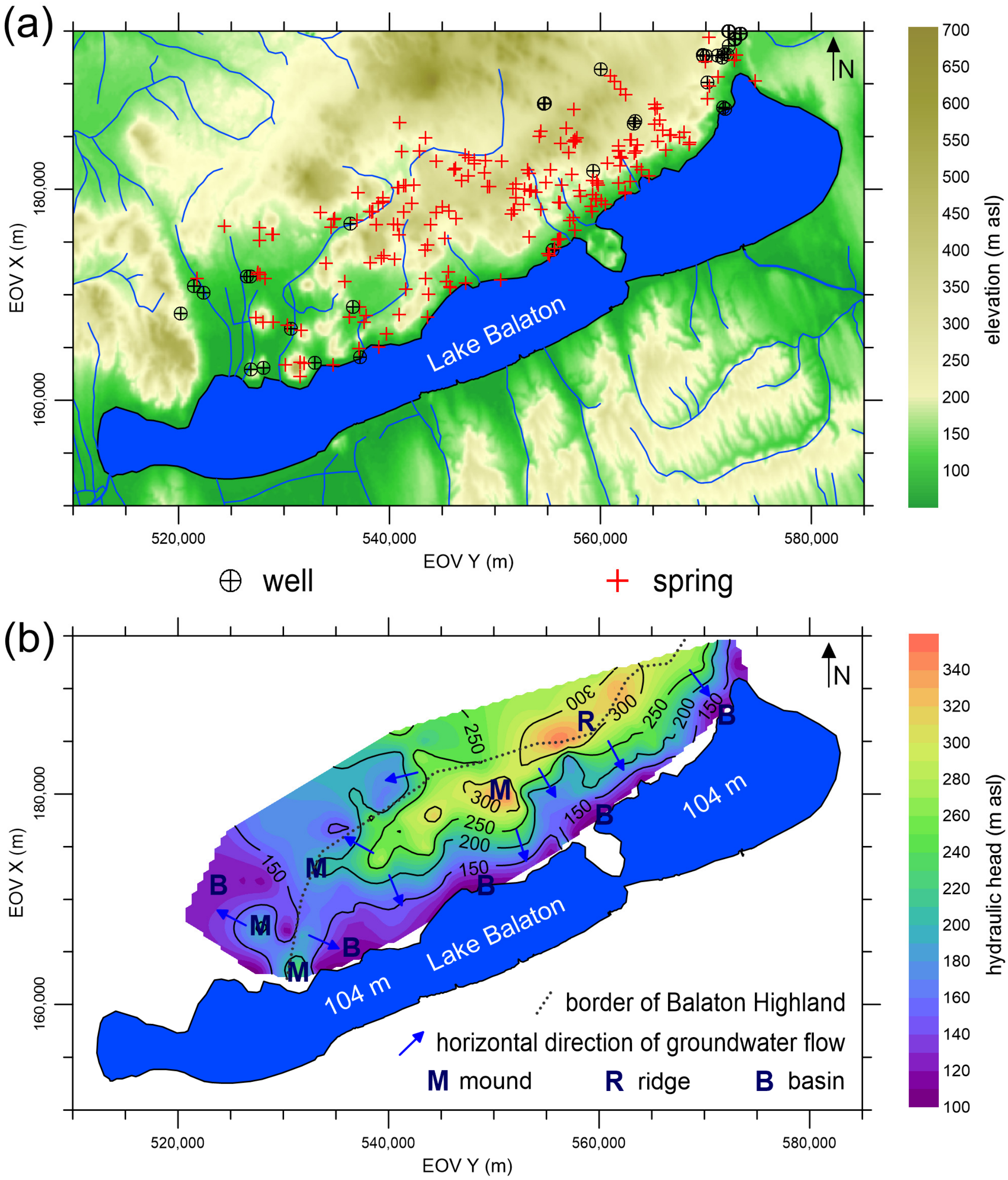

Figure 4. Hydraulic head distribution. (**a**) Topographic map for reference showing the data source and its distribution; (**b**) hydraulic head map with the interpreted horizontal groundwater flow directions and hydraulic features (mound, ridge, basin).

4.2. Results, Interpretation and Comparison

The fluid potential distribution map, which can be considered a water table map, depicts the variation of the hydraulic head and, therefore, the groundwater flow directions, assuming homogeneous isotropic conditions (Figure 4b). The highest hydraulic heads (300–<350 m) were present along the border of the Balaton Highland and Bakony Mountains, forming an elongated fluid potential ridge (R). A smaller hydraulic head mound (M) appeared west of the ridge, but these two traits may form the same potential feature. Additional tiny mounds could be revealed in the western part of the region. The hydraulic head values gradually transitioned toward the potential basins (B) around the Balaton Highland. As hydraulic head differences drive the groundwater flow, the horizontal flow components follow the hydraulic gradients, and arrows indicate the prevailing directions: from the ridge and mounds toward the basins, generally, is the southerly groundwater flow. This hydraulic head pattern generally reflects and mimics the undulation of topography, and the peculiarities of the landscape generate the fluid potential features (see Figure 4a for reference). Regarding the surface water–groundwater interaction, Lake Balaton sits within a fluid potential basin, so groundwater flows toward the lake and must discharge into the lake due to the hydraulic head distribution.

This fluid potential map is not the first for this region, but it is the first of its kind as it integrates spring data and not only sparse well records. VITUKI Environmental and Water Management Research Institute Non-profit Ltd. released the water level maps of the southwestern Transdanubian Mountains yearly until 1995. Gondár-Sőregi and Gondár [66] and Mádl-Szőnyi [46] analysed and interpreted the water level map of 1950, published by Lorberer [67]. At that time, even fewer wells were drilled and operating, but at least the natural conditions were represented. These authors identified similar features (ridge, mounds and basins) in the hydraulic head field and groundwater flow directions. However, the map in this paper could be considered more accurate because it has been created based on more data.

5. Baseflow Index Calculation

The baseflow index (BFI) quantifies the ratio of baseflow to total flow in percentage terms and, therefore, reveals the contribution of groundwater discharge into surface streams [6,9,68]. BFI is an essential indicator of surface water–groundwater interaction and, more precisely, the discharging conditions where surface streams receive groundwater contribution through riverbed seepage.

5.1. Methods and Materials

Several methods for quantifying and predicting baseflow are available [69], but the baseflow is usually calculated from streamflow time series using hydrograph separation [70]. An automated separation technique developed by the University of Calgary (bflow.exe) working with a recursive digital filter, called the Lyne and Hollick filter, was applied to determine baseflow [70–72]. The recursive digital filter passes the daily streamflow data three times: the first pass is forward, the second is backward, and the third pass is forward again [70,72–74]. During the three-phase filtering, with the filter value of 0.925, the amount of baseflow is gradually reduced pass-by-pass [70,74].

Daily streamflow data were provided by the Central Transdanubian Water Directorate for six creeks (Arácsi-séd, Burnót-patak, Fűzfői-séd, Kéki-séd, Örvényesi-séd and Tapolca-patak), and the Western Transdanubian Water Directorate provided the data for a large stream (River Zala), as the daily flow rate was recorded only for these watercourses (see Figure 1 for the geographic locations). The applied software needed the date and flow rate in a specific format for at least one month. Nevertheless, the shortest data series was 29 years long, and the longest contained nearly 51 years of daily mean flow rate values (Table 1). Daily baseflow rates were calculated, but the BFI values were averaged over the entire time series.

Table 1. Length of data series, average flow rate and baseflow index calculation results for the seven investigated watercourses.

Name of Stream	Start of Data Series	End of Data Series	Average Flow Rate (m^3/s)	BFI (%) after 1st Pass	BFI (%) after 2nd Pass	BFI (%) after 3rd Pass	Average BFI (%)
Arácsi-séd	1 January 1988	31 December 2020	0.014	86	79	75	**80**
Burnót-patak	1 July 1970	31 December 2020	0.129	72	58	50	**60**
Fűzfői-séd	1 January 1992	31 December 2020	0.017	69	56	49	**58**
Kéki-séd	1 January 1983	31 December 2020	0.038	83	76	71	**76**
Örvényesi-séd	1 July 1970	31 December 2020	0.073	88	82	78	**83**
Tapolca-patak	1 January 1986	31 December 2020	0.308	88	81	76	**81**
River Zala	1 July 1975	31 December 2020	7.17	82	71	64	**73**

5.2. Results, Interpretation and Comparison

The automated baseflow separation of seven surface streams revealed a high groundwater contribution in the investigated watercourses. In all cases, at least half (>50%) of the total streamflow came from groundwater discharging in the creeks. The individual average BFI was between 58% and 83%, and the overall average of the seven watercourses was 73%. However, the BFI (%) after the first pass is often considered representative of the catchment [70]. Bearing this in mind, the BFI was above ~70%, and the average value of the BFI (%) after the first pass was 81% (Table 1).

Considering the relative importance of the seven watercourses, the average flow rates of the entire time series were also quantified. Arácsi-séd, Fűzfői-séd, Kéki-séd and Örvényesi-séd are short and low-discharge creeks, which are essential for maintaining local ecosystems but represent negligible supply for Lake Balaton (these four creeks altogether equalled ~1%). On the other hand, Burnót-patak and Tapolca-patak are longer and more significant streams flowing in the Balaton Highland region (~4% of the total streamflow). However, most of the streamflow entering Lake Balaton is provided by River Zala, and its share is ~60–70% [12].

The discharging surface water–groundwater condition in the Balaton Highland region was revealed by Tóth et al. [58]. The authors created a fluid potential difference map based on the elevation of springs and creeks. The simple operation (the potential of streams representing surface water minus the potential of springs representing groundwater) could yield preliminary small-scale information on the interaction of groundwater and surface water. The published map showed streams which were fed by groundwater. Only the type of interaction was unravelled, but the amount of groundwater contribution in the streams was not quantified. Our calculated BFI values are similar to those found in Winter et al. [9], especially if we consider similar climatic conditions (e.g., Sturgeon River, MI, and Ammonoosuc River, NH, in the USA). Furthermore, a global review of BFIs in 3394 catchments presented a value of ~70% for the latitude of the Lake Balaton and Balaton Highland region [75]. Based on this discussion and reported values, three-fourths (75%) of the total streamflow in this region could be accounted for by groundwater discharging in the surface streams.

6. Hydrochemical Analyses

Hydrochemical analyses and tracers could provide additional supplementary information about groundwater flow after understanding the physical parameters and properties of it. However, flow pattern interpretation is required first, as local pore-scale fluid–rock interaction may alter the groundwater's hydrochemical character, leading to a misconception of groundwater flow based purely on chemical parameters. Furthermore, in quasi-homogeneous media, the groundwater samples may exhibit a uniform hydrochemical character, and no groundwater flow-related information can be deduced. Therefore, hydrochemistry should be applied secondarily in the understanding of groundwater flow [58,59].

6.1. Methods and Materials

For the hydrochemical characterisation of water samples, hydrochemical facies was introduced by Back [76]. The hydrochemical facies is determined, on one hand, by the rock matrix and properties and, on the other hand, by groundwater evolution along flow lines or differences between groundwater flow systems (local, intermediate, regional) and hydraulic regimes (recharge, through-flow, discharge) [77,78]. The hydrochemical facies—and also the dominant anion and cation—can be read from a Piper diagram, which illustrates the major components ($Na^+ + K^+$, Mg^{2+}, Ca^{2+}, HCO_3^-, Cl^-, SO_4^{2-}) of water samples in the percentage of total equivalent per litre. A Piper diagram allows a quick and easy hydrochemical comparison of many water samples [79,80].

A determination of major components was performed in the laboratory of the Department of Geology at ELTE Eötvös Loránd University: Na^+ and K^+ by flame photometry, Mg^{2+}, Ca^{2+} and HCO_3^- by acid-base titrimetry, Cl^- by complexometric titration and SO_4^{2-} by photometry. For the laboratory analyses, altogether, 24 unfiltered water samples (16 springs at their orifices, 5 creeks, and 3 locations in Lake Balaton) were collected in 1.5 L PET bottles during two field sampling campaigns (summer of 2016 and 2021), refrigerated and preserved by acidification until analysis (Figure 5). Additional in situ parameters were recorded by a YSI Pro Plus multiparameter water quality instrument (Xylem, Rye Brook, NY, USA) in the field during sampling: specific electrical conductivity (EC), temperature (T), pH and redox potential (Eh) occasionally (Table S1 of the Supplementary Material).

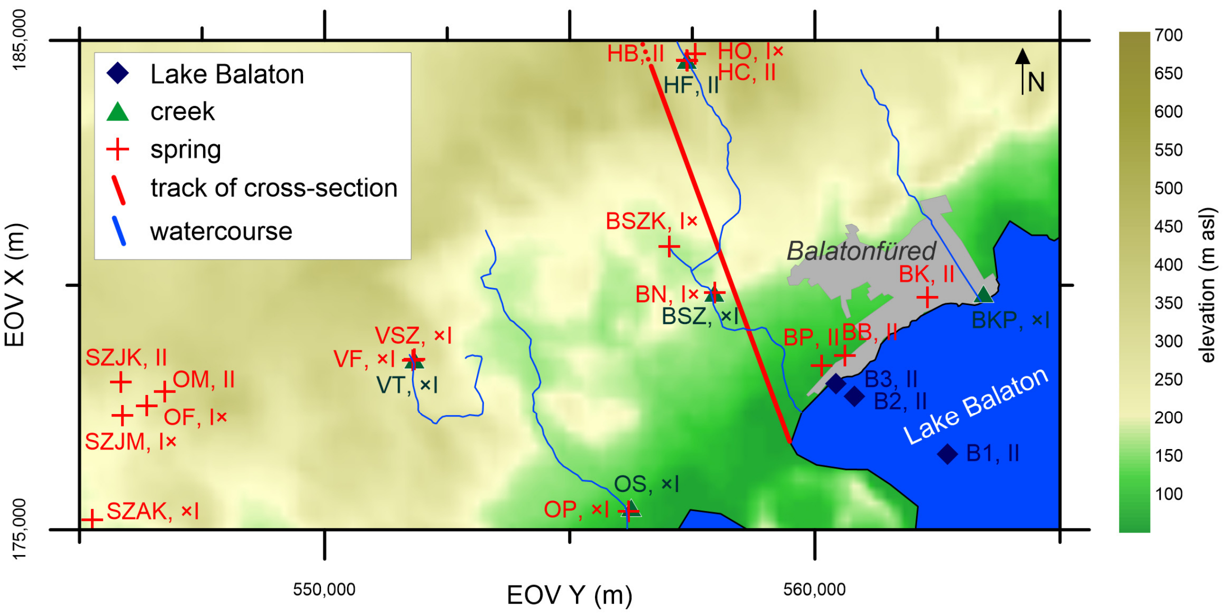

Figure 5. Sampling sites of hydrochemical and stable isotope analyses. Major components of water were determined for all the samples. The two-character code after the sampling ID indicates the uranium (first digit) and stable isotope (second digit) analysis, I: available, ×: not available.

In addition to temperature and chloride as natural tracers [5,81,82], uranium was also applied for differentiating groundwater flow paths and revealing surface water–groundwater interaction [83–85]. Temperature, a physical parameter, can be a tracer of heat sources in deep or surface exposure [5,51,86–88]. As chloride, a conservative natural tracer, enriches along the subsurface flow path due to groundwater–rock interaction, higher concentrations may imply longer flowlines [89]. Furthermore, as the underground dissolution of formations is the source of chloride in water, higher concentrations also indicate groundwater contribution [7]. Uranium may be prospective in this area as there is a uranium-bearing sedimentary phosphatite indication hosted by the HsU 4 Tr Carbonate AF (specifically the Megyehegy and Buchenstein Formations). However, the uranium source is the HsU 2 P Siliciclastic AF (alluvial sandstone), which outcrops near the shore [29,90,91].

Water samples for uranium analysis were collected in 0.25 L PP bottles at fewer sites, altogether 16 sites: 12 springs, 1 creek and 3 locations in Lake Balaton (Figure 5). Total uranium activity, $\Sigma U = {}^{234}U + {}^{235}U + {}^{238}U$, was determined by alpha spectrometry using NucFilm discs (see measurement details in Baják et al. [11,92] and Surbeck [93]).

6.2. Results, Interpretation and Comparison

The hydrochemical facies of different sample types was uniform for all the samples based on the Piper diagram (Figure 6): springs, creeks and Lake Balaton had dominantly Ca + Mg; HCO_3, Cl + SO_4 hydrochemical facies, and a few samples were in the Ca + Mg, Na + K; HCO_3, Cl + SO_4 zone. Regarding the anions, HCO_3^- was dominant in all cases as the host formations were prevalently carbonates. For the same reason, Ca^{2+} and Mg^{2+} were the prevailing cations, and the variation of limestone and dolomite formations could cause the transition. The total dissolved solids (TDS) showed similar values: Lake Balaton 605–615 mg/L, creeks 640–815 mg/L and springs generally 640–930 mg/L except for the three springs of Balatonfüred (BK, BP, BB), which had higher TDSs (1380, 2000 and 2025 mg/L, respectively). This analysis revealed the same hydrochemical character of groundwater and surface water, reflecting their interconnectedness.

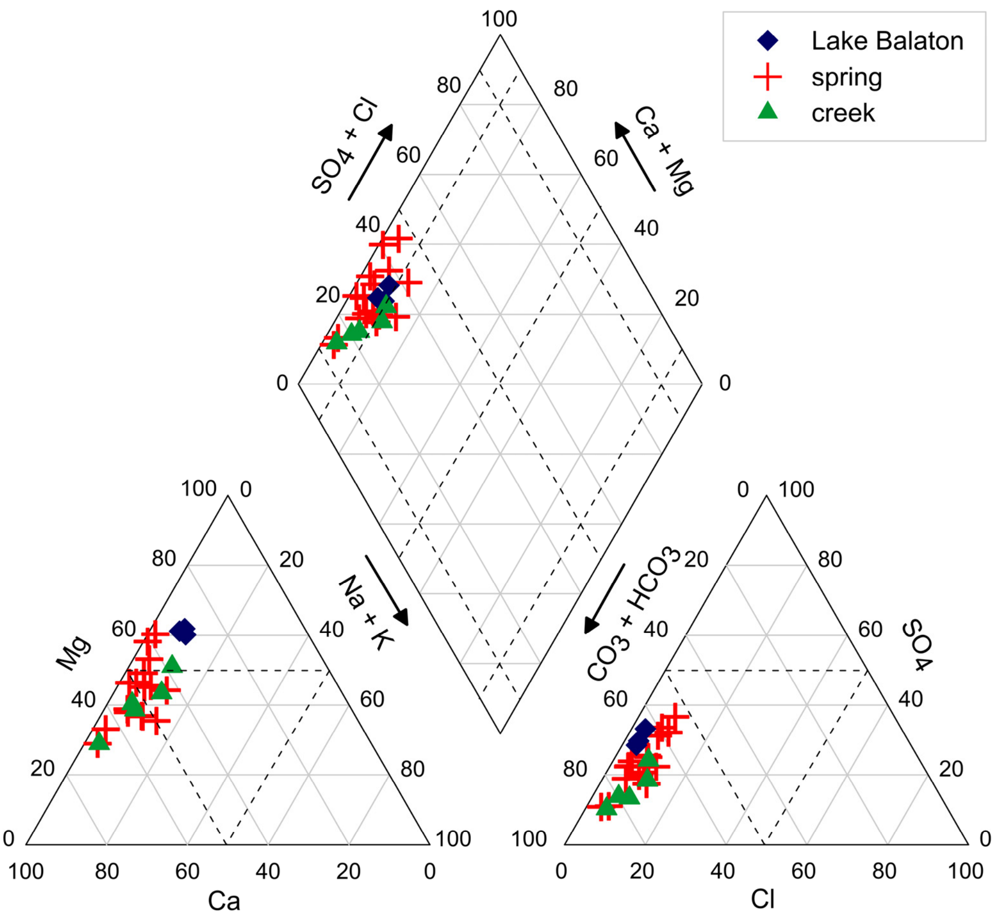

Figure 6. Piper diagram of water samples.

The dominance of Ca^{2+}, Mg^{2+} and HCO_3^- in groundwater and surface water, including creeks and Lake Balaton, and the uniform chemical composition has been presented earlier by Ilosvay [94], Szádeczky-Kardoss [13], Entz [95], Schmidt [96] and Tompa et al. [97]. Furthermore, this hydrochemical character is typical for the entire Transdanubian Mountains [13], resulting from the hydraulic communication and interaction of waters in the whole region [13,98,99].

As a general hydrochemical characterisation could not indicate differences within the water types and samples, natural tracers of temperature (T), chloride (Cl) and total uranium (ΣU) were employed. Cl vs. T and ΣU vs. T plots were created to gain insights into groundwater flow processes and the surface water–groundwater interaction (Figure 7).

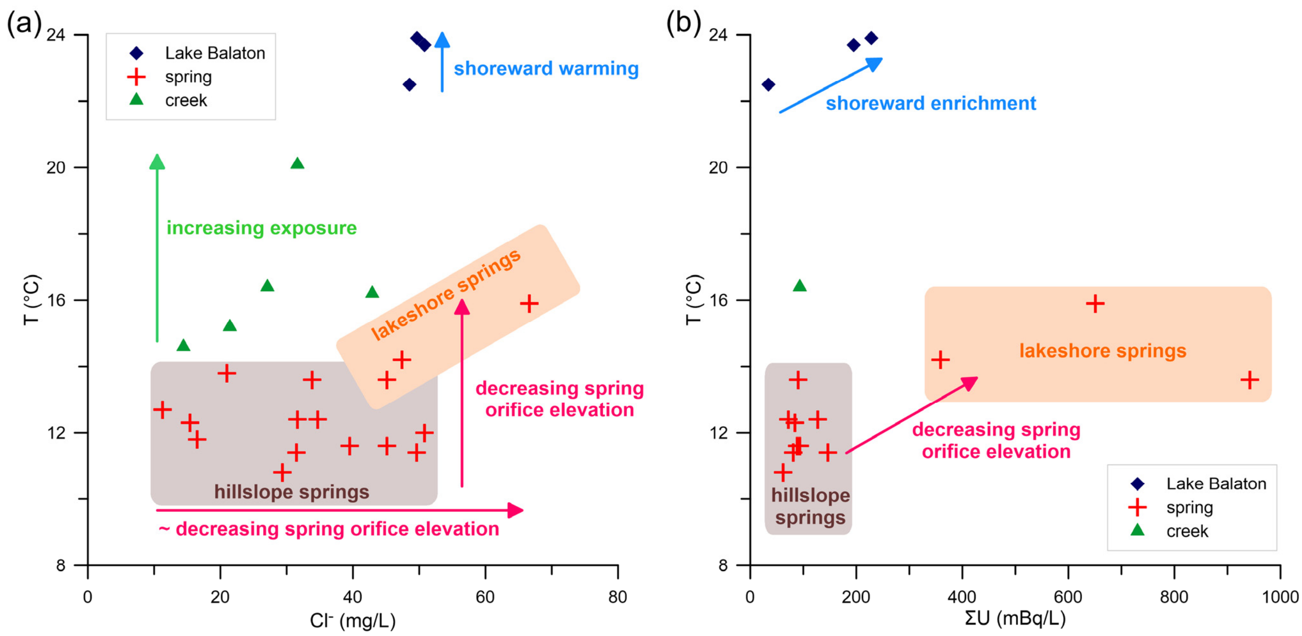

Figure 7. Plots of natural tracers of temperature (T), chloride concentration (Cl) and total uranium activity (ΣU). (**a**) Cl vs. T, (**b**) ΣU vs. T.

The water temperature of groundwater was generally <16 °C, with an increasing trend when moving toward a lower spring orifice elevation, from ~300 to ~110 m asl. Lakeshore springs of Balatonfüred (BP, BB and BK) were slightly warmer than other hillslope springs, reflecting longer underground flow paths. The water running in creeks was warmer (~15 °C < T < ~20 °C), exhibiting increased solar radiation exposure. Because of summertime sampling, the waters of Lake Balaton had the highest temperature (~22 °C < T < ~24 °C) and shoreward warming of the lake was also detected as the shallower water columns toward the shore could heat up faster (Figure 7a). The concentration of chloride varied between 10 and ~65 mg/L. In the case of springs, an increasing trend was found with decreasing spring orifice elevation; therefore, lakeshore springs had the highest chloride concentrations. This trend may also represent longer flow paths toward the shore. Lake Balaton samples contained a higher amount (~50 mg/L) of chloride than the creeks (~15–45 mg/L), and the concentration was in the chloride concentration range of lakeshore springs (~45–65 mg/L) (Figure 7a).

The total uranium activity values formed two main groups: one with lower ΣU (~30–230 mBq/L) and one with elevated ΣU (~350–950 mBq/L). However, plotting ΣU against T revealed additional information on the origin and character of water samples. The highest ΣU values were found in the lakeshore springs, suggesting that groundwater may have interacted with the HsU 2 P Siliciclastic AF and its uranium source as this unit hosted these springs. Within the low ΣU activity cluster, hillslope springs exhibited a distinct group, with <150 mBq/L of ΣU and <14 °C of T. Here, the uranium-bearing indication hosted by the HsU 4 Tr Carbonate AF may have been responsible for the low ΣU activities, and the springs were tapping this aquifer. The only creek sample had 95 mBq/L of ΣU, which should have indicated groundwater contribution as rainwater naturally has a low uranium activity in the ~nBg/L–µBq/L range. Only industrial activities and nuclear explosions can elevate its concentration [100–102]. In the case of Lake Balaton, not only was the shoreward warming of water detected but a shoreward enrichment of ΣU was also found: on the shore, the ΣU activity was 230 mBq/L, and in the open water body, the activity was only 35 mBq/L. The elevated concentrations may have been caused by groundwater discharge carrying water with higher ΣU, likewise for the lakeshore springs (Figure 7b).

Similar trends in temperature and chloride concentration in the function of spring orifice elevation were demonstrated by Mádl-Szőnyi and Tóth [89] and Bodor et al. [103]. However, dissolved uranium in water was applied as a natural tracer in this study area for the first time. As there was a uranium source in the geologic succession, flow paths crossing these uranium-bearing units could be determined. Groundwater discharge was evidenced by the elevated uranium concentrations in Lake Balaton, also showing a shoreward enrichment, which could be explained by the nearly exponential decay in groundwater seepage fluxes when moving away from the shores [6,9,83]. Lake Balaton is a polymictic lake and a gently flowing surface water body, with a retention time of 3–8 years [22,104], so accumulation could not be a plausible explanation for the high ΣU as the lakewater is entirely mixed and exchanged within a couple of years. The combined application of temperature, chloride and uranium activity proved efficient in differentiating surface water and groundwater components and could unravel the fine details of surface water–groundwater interaction. Therefore, Lake Balaton and the creeks receive a groundwater contribution, which is responsible for the elevated chloride concentration and total uranium activity.

7. Stable Isotope Analysis

Processes and reactions during groundwater recharge, storage and discharge, including mixing, evaporation, seasonal variations and high-temperature rock–groundwater interactions, can be characterised by isotopes [105]. δ^2H and δ^{18}O stable isotopes are frequently applied in groundwater studies and also for revealing surface water–groundwater interactions [106–109].

7.1. Methods and Materials

The δ^2H and δ^{18}O stable isotopes show a strong relation between the precipitation and the subsequently infiltrating rainwater recharging shallow groundwater. The isotope characters of these waters bear the relation of $\delta^2H = 8\cdot\delta^{18}O + 10$, known as the global meteoric water line (GMWL) [110]. However, waters exposed to evaporation exhibit a modified isotopic composition as surface waters are enriched in heavier isotopes compared to the original precipitation. Therefore, evaporated waters, such as lakes and rivers, will plot below the GMWL. Waters infiltrated during different climatic conditions, such as deep groundwater, may be depleted in these stable isotopes and reflect a more negative isotope composition [11,105,111,112].

Altogether, 19 water samples were collected for δ^2H and δ^{18}O analyses: 11 springs, 5 creeks and 3 Lake Balaton waters (Figure 5). δ^2H and δ^{18}O measurements were performed by a PICARRO L2130-i $\delta^2H/\delta^{18}O$ Ultra High-Precision Isotopic Water Analyzer (Picarro Inc., Santa Clara, CA, USA), a cavity ring-down spectroscopy (CRDS) instrument of the isotope laboratory of the Geological Survey of Finland (GTK). The results are reported as isotope ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^2H/^1H$) relative differences between the sample and standard. The δ values are measured relative to the international VSMOW (Vienna Standard Mean Ocean Water) standard and expressed in per mill (‰) units [105,110]. The measurement uncertainty is <0.1‰ for oxygen and <0.3‰ for hydrogen.

7.2. Results, Interpretation and Comparison

The traditional δ^{18}O vs. δ^2H plot revealed two main clusters of the samples: Lake Balaton was one, and the springs and creeks formed the other (Figure 8). The latter samples were plotted close to the global meteoric water line, as a local meteoric water line was unavailable for the region, and Barna and Fórizs [113] presented the validity of GMWL for the Lake Balaton area. These samples of springs (groundwater) and creeks (surface water) reflected a direct precipitation origin without evaporation or a minor evaporative effect, with the values of ~−10‰–(~−8‰) for δ^{18}O and ~−70‰–(~−60‰) for

δ^2H. However, the Lake Balaton samples exhibited a fingerprint of intensive evaporation and were consequently plotted under the GMWL, with the values of ~−1‰ for $\delta^{18}O$ and ~−18‰ for δ^2H. A linear function fitted to all the samples could reveal the effect of evaporation and the local evaporation line (LEL).

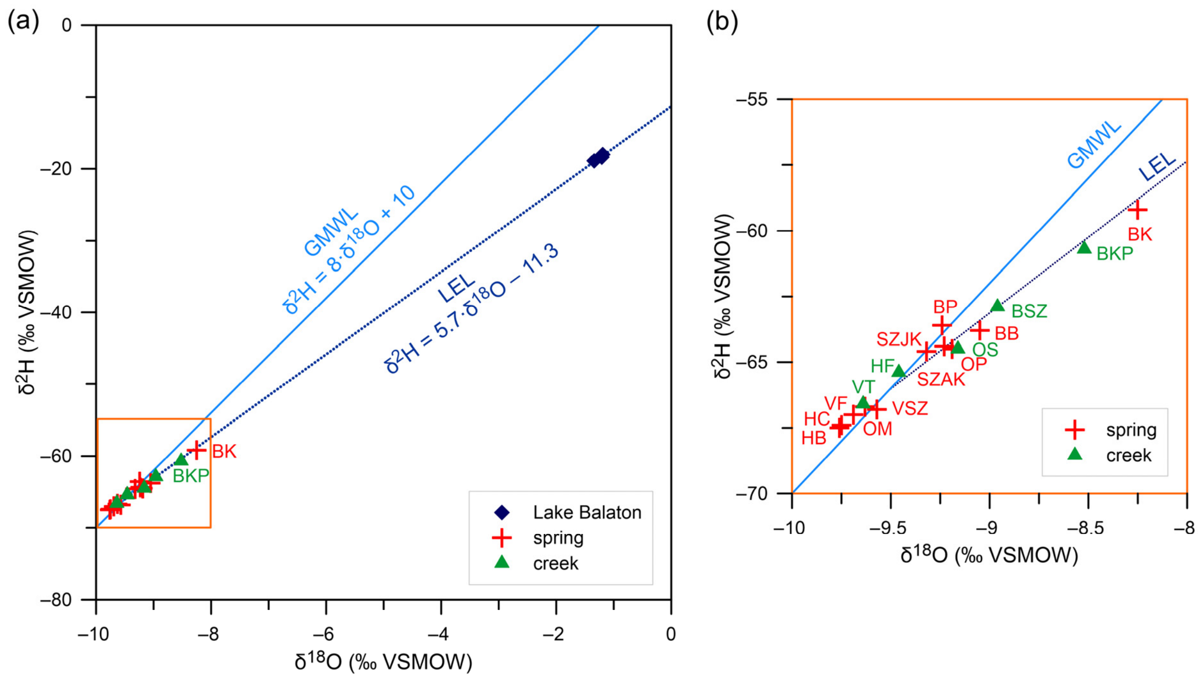

Figure 8. Oxygen and hydrogen stable isotopes plotted with the global meteoric water line (GMWL, Craig [110]) and the fitted local evaporation line (LEL). (**a**) All water samples, (**b**) zooming in on a selected part of the plot.

Among the eleven springs, there were slight differences in the isotopic composition. Two groups and a stand-alone spring were identified: one with the $\delta^{18}O$ values of −9.7 ± 0.1‰, another one with −9.2 ± 0.2‰ $\delta^{18}O$ values and a spring (BK, Kossuth spring) showing the most positive (−8.2‰ $\delta^{18}O$) values among these samples. The two clusters may suggest different recharge elevations and/or seasonal variations in recharge. Regarding the Kossuth spring, partial evaporation (in this case ~10%—based on a simple mixing calculation) prior to recharge may be hypothesised as this sample sits on the LEL. Mixing with surface water may be another possible explanation for this isotope signature, and the previous sections have already discussed a high level of surface water–groundwater interaction. This mixing was evidenced by the $\delta^{18}O$ vs. δ^2H plot, where sample BK was close to BKP (Koloska creek). However, anthropogenic influence must be mentioned as an affecting factor of natural processes and patterns. The Kossuth spring is located within a residential and touristic area of Balatonfüred; therefore, landscaping and the construction of underground artificial reservoirs during the years may have altered the groundwater flow. Water quality issues due to surface contamination were reported several times, and surface water and shallow groundwater contribution to this spring were identified [114].

The effect of evaporation on isotopic composition could be tracked on the five samples of creeks as these lined up along the LEL. The two samples on the GMWL were sampled next to a spring or <1.5 km away from the orifice (HF and VT in Figures 5 and 8). The two samples sitting on the LEL's head were samples ~7–8 km away from the source (BSZ and OS in Figures 5 and 8), and the creeks flowed through forested areas. The most evaporated one has already been discussed; BKP was sampled ~5 km downstream from the source, but this creek flows mostly across an open non-vegetated area. Therefore, the evaporation could have acted more intensively here than in the case of other samples.

The evaporation started in the creeks but culminated in Lake Balaton, exhibiting the most evaporated samples of the open surface water. The fitted LEL was in agreement but slightly different than that reported by Barna and Fórizs [113]: δ^2H = 5.7·δ^{18}O–11.3 vs. δ^2H = 5.2·δ^{18}O–13.8. This deviance may be caused by the seasonal variation of evaporation as the samples of this study were collected during early summer and Barna and Fórizs [113] sampled the lake in late summer. The origin of the lake water could be tracked back by determining the intersection of LEL and GMWL. The two lines met at δ^2H = −64.1‰ and δ^{18}O = −9.26‰, around the spring samples clusters and the amount-weighted average of annual precipitation in Budapest (~100 km away from the study site) in 2016–2018: δ^2H = −62.4‰ and δ^{18}O = −8.86‰ [115].

Deuterium excess (d-excess, = δ^2H–8·δ^{18}O, Dansgaard [116]) may provide a valuable tracer for the groundwater origin and evaporation effect. The theoretical d-excess value of precipitation and groundwater recharged without evaporation is 10‰, and evaporated surface water samples have much less than 10‰ and even negative values [105,116]. The sampled eleven springs had d-excess values of 6.8–10.6‰ (average was 9.6‰), consequently representing groundwater (90% of a global well and spring database have d-excess values >0‰, [105]). Moreover, the five creek samples showed a similar character: d-excess values of 7.5–10.5‰ (average was 9.2‰), meaning that the water in creeks had a groundwater origin. Lake Balaton was distinctly separated from the other samples as the average d-excess value of the lake was −8.5‰.

The stable isotopic investigation revealed that springs and creeks were fed by groundwater, and the watercourses were running even though the sampling campaign was performed after around three months of drought. The isotopic signature of these samples also unravelled the recharge conditions: based on the δ^2H and δ^{18}O values, the infiltration took place recently, which suggests a Holocene recharge of these springs [111,117–119]. The origin of evaporated Lake Balaton samples was also precipitation with the same isotopic composition. Consequently, all waters have the same chemical and isotope hydrologic character, signifying the surface water–groundwater interaction. However, these results were supported by only one sampling campaign.

8. Numerical Simulation of Groundwater Flow and Heat Transport

Groundwater models are inevitable tools for supporting resource-management-related scientific and practical research. Understanding groundwater flow patterns and dynamics, quantifying groundwater processes (recharge, storage, discharge), predicting the effects of future changes and communicating results to the public and decision-makers are among the main goals when applying groundwater models [120]. Furthermore, following a physical and hydrochemical characterisation of a study area, the numerical simulation may provide further insights and link the previous findings.

8.1. Methods and Materials

A 2D numerical simulation of groundwater flow and heat transport was accomplished in COMSOL Multiphysics 5.3a, a finite element-based software package, applying the coupled fluid flow/porous media and subsurface flow/Darcy's law and heat transfer/heat transfer in porous media modules [121]. Darcy's equation and the Fourier–Kirchhoff equation were solved during the calculations for the steady-state (without source and sink) gravity-driven (constant gravitational acceleration) model run. The fluid (water) was incompressible and isothermic, and its dynamic viscosity remained constant. Consequently, only conduction and advection (forced convection) were the forms of heat transfer, and this assumption proved to be valid in shallow domains [122].

The geologic cross-section (~17 km in length and ~1.5 km in depth) of ED in Budai et al. [28], specifically its converted version, was applied for the numerical simulations. The model consisted of the seven derived hydrostratigraphic units (see Section 3) represented by 25 model domains. The hydraulic conductivity, porosity and thermal conductivity values of different porous media were based on the hydrostratigraphic division (see Figure 2).

As a general rule of thumb, vertical hydraulic conductivity was kept one order magnitude less than the horizontal. For the thermal conductivity of water, the default value of 0.6 W/(m·K) was chosen. Heat capacity at constant pressure was 4200 J/(kg·K) for water and 1000 J/(kg·K) for the geologic units, respectively.

For the upper boundary condition, the water table was specified as hydraulic heads, according to the observed water level (see Section 4), which was the subdued, smoothened replica of the topography (Figure 9a). Boundary conditions for flow were prescribed along the sides in the form of a constant hydraulic head of the corresponding water table: 357 m on the left and 104 on the right (Figure 9b). The bottom of the numerical model was an artificial undulating surface where a no-flow boundary condition was set. The heat transport simulation was run with the following boundary conditions: annual mean air temperature (11 °C) along the surface (after Péczely [123]), a constant heat flow of 55 mW/m^2 at the bottom (based on Lenkey et al. [124]) and symmetry on the lateral boundaries, meaning that the temperature gradient across these boundaries was zero (Figure 9d).

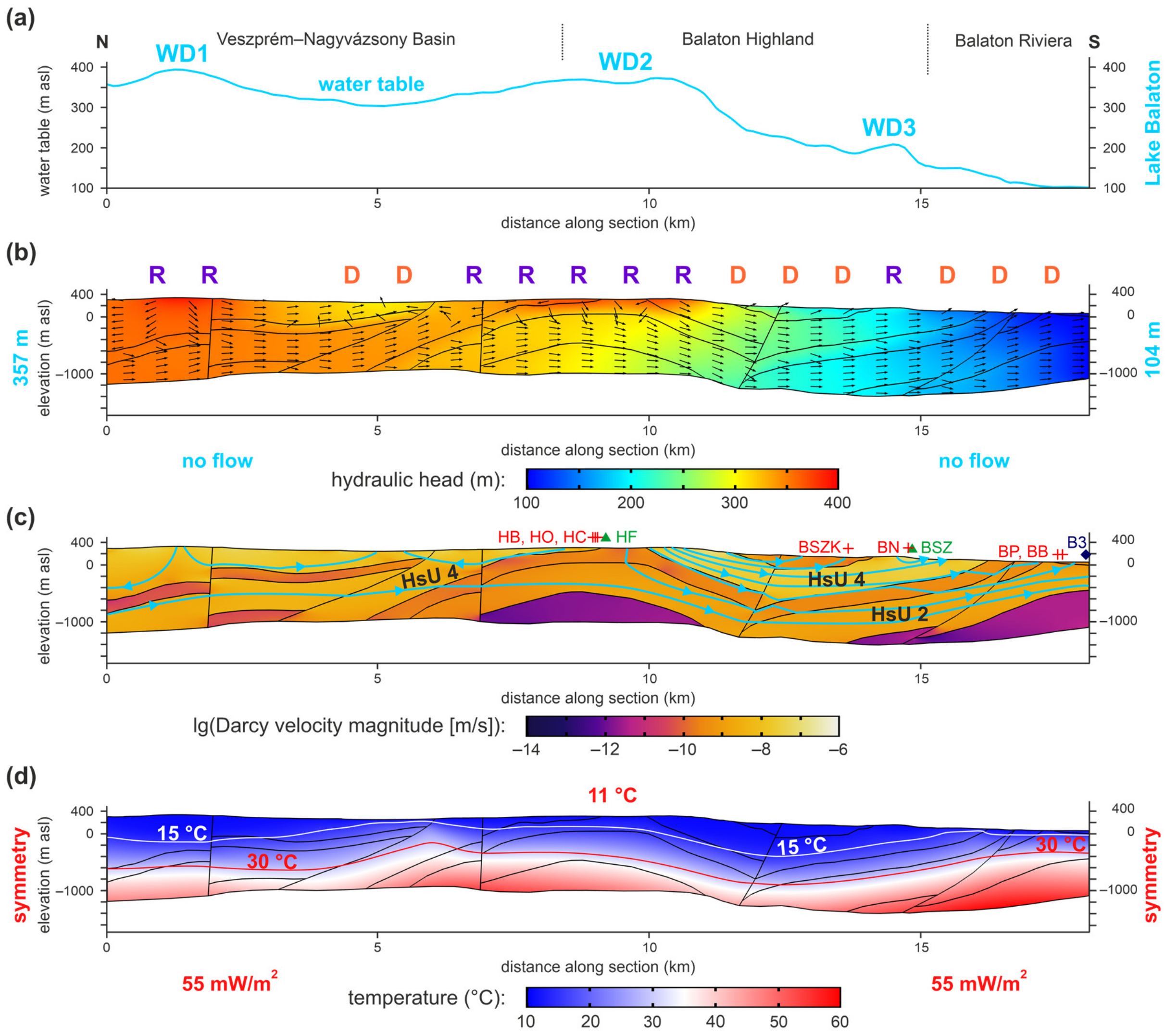

Figure 9. Numerical simulation input and results. (**a**) Water table configuration as upper boundary condition along the surface, indicating water divides (WDs). (**b**) Boundary conditions and the simulated flow pattern showing the hydraulic head and uniform Darcy velocity vector field. R: recharge, D: discharge. (**c**) Base 10 logarithm of Darcy velocity magnitude with characteristic flow lines, sampling sites and uranium-bearing hydrostratigraphic units (HsU 2 and 4). (**d**) Boundary conditions and the simulated temperature distribution with selected isotherms (T = 15 and 30 °C).

The model was discretised by triangular and non-uniform finite elements using a maximum element size of 50 m within the model domain and 25 m along all the inner and external boundaries. Consequently, the mesh contained 84,292 finite elements. The simulation results were presented in three panels: (1) hydraulic head with recharge and discharge areas indicated along the surface and uniform Darcy velocity vectors (non-magnitude controlled arrows) for getting the general picture of groundwater flow directions (Figure 9b); (2) base 10 logarithms of the Darcy velocity field with some characteristic flow lines, sampling sites and uranium-bearing hydrostratigraphic units (HsU 2 and 4) for the intensities of groundwater flows and revealing flow paths behind the sampling sites (Figure 9c); temperature distribution with the isotherms of 15 and 30 °C for tracing the water temperatures (Figure 9d).

8.2. Results, Interpretation and Comparison

Water table variations were the driving force for groundwater flow; therefore, its undulation revealed three water divides (WDs), which determined the near-surface flow directions (Figure 9a). WD1 (~390 m asl) occurs at ~2–3 km along the section and creates both northward and southward (toward Veszprém–Nagyvázsony Basin) flows. WD2 is a wide water table mound (~350–365 m asl) at ~7–11 km around the northern border of Balaton Highland, and this is believed to be the water divide separating the hydrogeological Balaton Highland from the Bakony Mountains to the north [48,66]. Again, groundwater flow is driven to the north (toward Veszprém–Nagyvázsony Basin) and south (toward Balaton Riviera and Lake Balaton). However, the hydraulic gradients are higher southward (~200 m/5 km, 0.04) and are much less northward (~50 m/3 km, 0.0166). Finally, WD3 (~200 m asl) formed around the northern border of Balaton Riviera at ~14–15 km and acts as a small local water divide with a negligible effect.

These water divides outline the recharge areas (R) along the section (Figure 9b). The calculated recharge rate was 238 mm/year, which is in agreement with the previously determined average value of 186 mm/year for the period of 1951–2005 by Csepregi [20]. Groundwater discharge (D) occurred in the Veszprém–Nagyvázsony Basin, at the lower half of the Balaton Highland and Balaton Riviera. Groundwater flowed locally between the adjacent recharge and discharge areas only in the upper part of the section above ~−500 m asl (Figure 9c). However, the simulation revealed the deeper hydraulic head and flow characteristics. A deeper through-flow component comes from the north (Bakony Mountains), flowing under ~−500 m asl toward Balaton Highland, Balaton Riviera, Lake Balaton and even more southward.

The groundwater flow is restricted to the highly permeable, mostly carbonate hydrostratigraphic units because the flow could barely traverse the metamorphic basement (indicated by purple in Figure 9c). Groundwater was forced upwards, elevating flow intensity due to the undulation of the basement surface, especially under the Balaton Riviera. The most intense groundwater flow (10^{-7}–10^{-6} m/s) occurs in the HsU 4 Tr Carbonate Aquifer and the unconfined carbonates of the Veszprém–Nagyvázsony Basin. The variation of aquifers and aquitards is reflected in the Darcy velocity field and compartmentalises the flow field near the surface; however, cross-formational groundwater is present in the deeper part.

The temperature distribution was determined by forced convection due to groundwater flow. The infiltrating cold water prevails in the shallower parts (above ~−200 m asl) and mainly under the recharge areas (Figure 9d). However, heat accumulated in the low-hydraulic conductivity basement and warm water (>30 °C) reach a near-surface position at the discharge zones. As a result, a considerable heat accumulation is formed under the Balaton Riviera close to the surface.

Sampling sites of hydrochemical analyses are presented in Figure 9c to facilitate a joint interpretation and find possible explanations for previous findings, emphasising the natural tracers of heat and total uranium activity. The hillslope samples (HB, HO, HC, BSZK, BN springs, and HF, BSZ creeks) showed low temperatures (~11–13 °C) and total uranium activities (70–120 mBq/L). The simulated flow and temperature fields could clarify these qualities: the flowlines cross HsU 4, which indicates the presence of uranium, and stay within the near-surface cold zone. However, lakeshore samples of BP and BB exhibited water temperatures of 14–16 °C and uranium activities of 350–950 mBq/L. The closest Lake Balaton sample to the shore (B3) also showed elevated (230 mBq/L) uranium activity. These samples were connected to flowlines passing through the uranium-bearing unit of HsU 2 and were getting the extra temperature from the heat accumulation under the Balaton Riviera. These two types of water have nearly the same recharge zone within WD2, but they seep through different rock matrices due to geological heterogeneities.

Another interesting feature of the flow field was the horizontal flow system across the whole model. Gondárné Sőregi and Gondár [66] and Gondár and Gondárné Sőregi [48] identified WD2 as the main barrier to hydraulic communication between the Balaton Highland and Bakony Mountains. Interestingly, the same authors hypothesised a deeper connection between these areas, but this could not be proved due to a lack of data. However, based on the numerical results, the water divides acted only as surface water/shallow groundwater divides because more regional conditions determine the deeper flow pattern. For that, a basin-scale evaluation is required, highlighting the importance of basin geometry and the asymmetry of driving forces [125].

The simulated temperature field was in accordance with the published temperature maps based on well data: 500 m below the surface, the average temperature was 20–30 °C, and 1000 m below the surface, temperatures of 40–50 °C were reported for the study area [124]. Groundwater flow is responsible for the region's temperature anomalies [126,127]. Due to the extended recharge areas, below worldwide average geothermal gradients could be expected here (~20 °C/km). The geothermal conditions could be more favourable (50–60 °C/km) around the foothills at the discharge zones and the occurrence of lukewarm springs [128–130]. The regions south of Lake Balaton (out of the current study area) could have higher geothermal potential [96,131] due to basin-scale hydrogeologic conditions [125].

9. Discussion

In line with the main goals of this paper, the surface water–groundwater interaction in the Balaton Highland–Lake Balaton region and the groundwater contribution to Lake Balaton are summarised and discussed here. Nevertheless, first of all, the transferability and scalability of the results obtained along a cross-section are examined. Gleeson and Manning [132] published a criterion that helps in choosing the dimensions of the hydrogeological study, especially whether two-dimensional representation is sufficient and valid. If the infiltration/hydraulic conductivity (R/K) ratio is below 0.15, the groundwater flows dominantly in the same direction as the main hydraulic gradient, and the share of perpendicular, transverse groundwater flow does not reach 10% of the total water flow. In such cases, a two-dimensional hydrogeological analysis provides adequate details of the system. However, above a ratio of 0.15, it is necessary to consider the groundwater flow in all directions, and a 3D model is needed. The former applies to the Balaton Highland because the R/K ratio is around 10^{-4}–10^{-3} (R: 200 mm/year, K: HsU 4 and 6 are at the recharge areas [10^{-6}–10^{-5} m/s]). Consequently, the two-dimensional section in this study can represent the hydrogeological processes of the entire system, as the portion of transverse groundwater flow to the regional hydraulic gradient is negligible.

9.1. *Surface Water–Groundwater Interaction and Hydraulic Processes of the Balaton Highland–Lake Balaton Region*

The groundwater table variations loosely follow the topography in a subdued and smoothened way, and groundwater flow occurs as a result of these hydraulic head (fluid potential) differences. Based on the distribution of the fluid potential, groundwater from the water divides mainly flows in a southern direction in the Balaton Highland. The shallower, shorter (maximum 10 km in length) and, thus, local flow systems between the local adjacent recharge and discharge zones are nested in a deeper, longer, basin-scale flow system, which transports groundwater horizontally under the Balaton Highland region. Regional differences in the intensity of the groundwater flow can be related to the variation in the vertical and horizontal hydraulic gradients due to the basin geometry and geological formations with different hydraulic conductivities. The hydraulic communication between the carbonate and siliciclastic hydrostratigraphic units becomes significant in the Balaton Riviera, where groundwater originating from the northern Balaton Highland and Bakony Mountains is forced upwards and may discharge due to the restricted basin geometry caused by thrusts.

The temperature field reflects the effect of topography-driven groundwater flow (forced convection). At the recharge zones, the intensively infiltrating cold water (<15 °C) can reach quite deep parts (~−400 m asl), and warm water (>30 °C) can only be expected even deeper, except for the two near-surface heat accumulations under the discharge zones of the Veszprém–Nagyvázsony Basin and Balaton Riviera. On one hand, they were formed due to hydrostratigraphic reasons, and on the other hand, they can be linked to upward moving and discharging groundwater. Therefore, the occurrence of heat accumulations can be explained by lithological, basin geometry and hydraulic reasons. The overall geothermal potential in these areas is favourable, as all three components (reservoir, temperature and carrier fluid) are available. Shallow geothermal energy utilisation (e.g., borehole heat exchanger systems) is realisable, especially in the Balaton Riviera, where there is an actual demand for geothermal energy.

The hydrogeological boundary between the Bakony Mountains and Balaton Highland was identified as a water divide (WD2) appearing at the border of these two regions [48,66]. However, the hydraulic connection between these regions is twofold: groundwater flows from the Balaton Highland towards the Bakony Mountains in the near-surface domain, and in the deeper region, under ~−500 m asl, groundwater flows from the Bakony Mountains toward the Balaton Highland in the form of cross-basin flow. Hence, WD2 functions as a non-regional, somewhat local subsurface water divide between the investigated regions.

The high-quality surface water and groundwater of the Balaton Highland are used in many ways, including drinking, industrial, agricultural, irrigation, mining and balneological purposes. In order to maintain optimal water management and coordinate extractions and water use aligned with the ecological water needs, the Watershed Management Plan and its Balaton Sub-catchment Watershed Management Plan and Balaton Direct Watershed Management Plan were developed in accordance with the Water Framework Directive of the European Union [3,133–135]. As a result, around six main and several local mountainous groundwater bodies were demarcated in the Balaton Highland–Lake Balaton region, although the investigated area could be a single, continuous water body. Based on the results, the division of water bodies can be reconsidered according to the hydraulic connections and flow systems, especially that surface water and groundwater should be considered interconnected.

The surface water–groundwater interaction was evidenced by the high baseflow indices (~75%) of watercourses and reflected in the hydrochemical character of the water samples: the same hydrochemical character, carbonate-type water (dominance of Ca^{2+}, Mg^{2+} and HCO_3^-), is present in surface watercourses, underground, in springs and in Lake Balaton. Stable isotopes of hydrogen and oxygen also reveal the same origin for all water types and their interconnectedness. The isotopic composition of water samples suggests a recent Holocene recharge. The infiltrated water flows through mainly carbonate aquifers and interacts with chloride- and uranium-bearing units: the high chloride content and total uranium activity of the lakeshore springs indicate the hydraulic interaction of various formations and the deeper and longer flow paths are also reflected by the higher temperatures. These natural tracers evidence the groundwater contribution to Lake Balaton.

9.2. Groundwater Contribution to Lake Balaton

The subsurface component of Lake Balaton's water budget has already been assumed by Lóczy [14] in the form of "lakebed springs". These are called *"hevesek"* (singular: heves;

literally meaning warm, intense and boisterous; sublacustrine spring is used from now on), which are the best to observe in wintertime when the upwelling warm water (10–12 °C) and gas (mainly CO_2) create ice-free spots on the frozen water surface. These were also observed by Cholnoky [136], mapped by Entz [18], sampled by Rádai [15], and detected recently by Pósfai (2017, pers. comm.), and similar features were identified by Visnovitz et al. [17] and Visnovitz [137] on water reflection seismic profiles. Interestingly, these sublacustrine springs appear along only the northern coast (Figure 10). This also explains why the groundwater contribution from the southern shore was not investigated. The absent or rather negligible amount of water coming from the hilly region south of Lake Balaton can be justified by the asymmetric groundwater flow pattern caused by different hydraulic head distributions on the two sides of the lake, revealed by basic-scale numerical simulation [125].

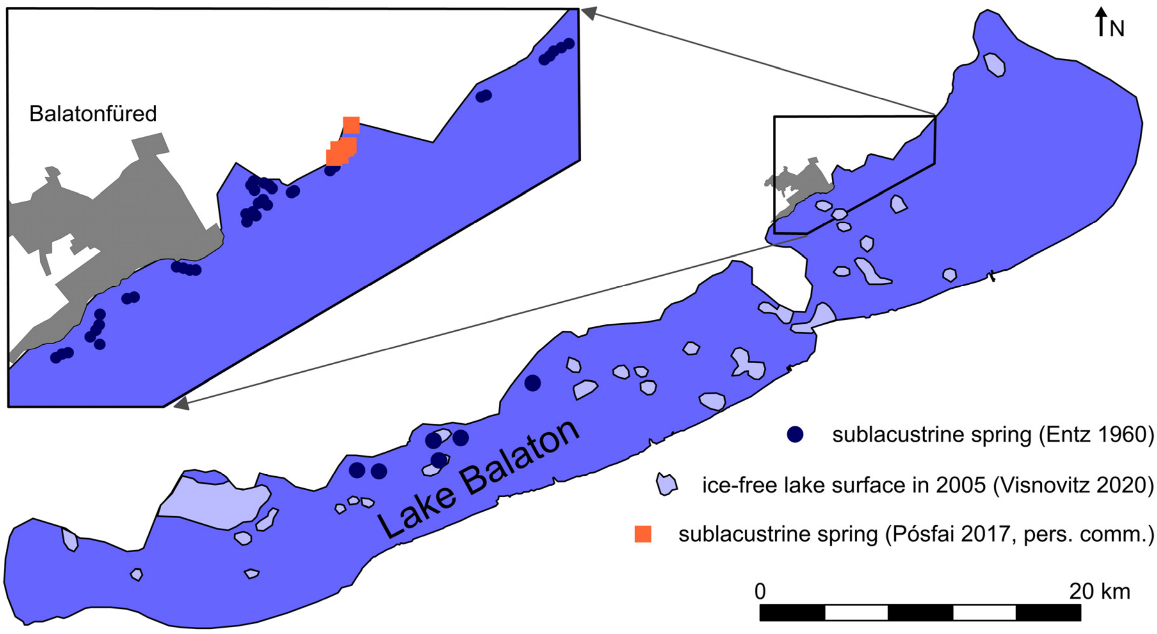

Figure 10. Location of sublacustrine springs ("hevesek") and the ice-free lake surface.

Even though the sublacustrine springs were sampled, their hydrochemical character was not analysed, only the gas content [15]. Therefore, to quantify the amount of groundwater contribution, we need to consider the two ways of discharge: along geological boundaries and structural elements in a discrete manner and diffuse water seeping through the lakebed. Direct determination of groundwater inflow to Lake Balaton may be possible with a seepage meter [138,139]. However, Lake Balaton has an average depth of 3.14 m and only ~2 m of transparency, which may hinder the installation of seepage meters. Furthermore, considering its extent (593 km^2), many measurements would be necessary to obtain presentative values.

The amount of groundwater seeping into Lake Balaton can only be estimated based on numerical simulations and published analogues. Based on the groundwater model, the calculated discharge intensity is 10^{-9} m/s (m^3/m^2/s). Taking one-fourth of the total lake surface (approximated based on Figure 10), the result is $1.8 \cdot 10^7$ m^3/yr, which equals 7–8 lake mm, a commonly applied unit for describing the water budget (1 lake mm = 600,000 m^3). The same value was estimated by Erdélyi [16] based on several assumptions, observations and analogues, meaning <1% of groundwater contribution in the lake budget. The groundwater component of a lake can be minimal and generally decreases as the lake area increases [4]. A global compilation of groundwater portions in lakes is provided, and based on the published graph and trendline, a value of 6–12% can be determined for Lake Balaton as the percentage of groundwater component of the total lake water budget. Similar-in-size lakes of Lake Michigan, USA (580 km^2), and Lake Ziway, Ethiopia (500 km^2), have this portion of 2.6% and 10%, respectively [4,140,141].

However, groundwater reaches Lake Balaton not only through lakebed seepage but also through streamflow. Since the surface watercourses of the Balaton Highland are fed by groundwater, the inflowing surface water can also be considered partly (75%) as groundwater. The average streamflow contribution is 851 lake mm for the 1921–2017 period [142], and three-fourths, 638 lake mm, of this component should be accounted to the groundwater side. Considering the other incoming component, the precipitation, and its average of 617 lake mm [142], the summed share of groundwater in Lake Balaton could reach 44%, including the directly discharging groundwater and the indirectly transported groundwater via surface streams. Compared to the no mention of groundwater in the official water budget [12], this percentage makes an enormous difference. Therefore, this hitherto neglected component contributes significantly to the lake and may also affect the water quality. Furthermore, the continuous replenishment of water with a low solute content may assist the ecological state of the lake (e.g., [6,143,144]). In conclusion, Lake Balaton can be considered a groundwater-influenced ecosystem with a high dependency on groundwater [145,146]. This fact should also be considered in future research and water-use planning related to the lake.

10. Conclusions and Summary

In this paper, the hydraulic connection of surface water–groundwater and Bakony Mountains–Balaton Highland–Lake Balaton and the groundwater contribution to Lake Balaton is revisited and re-evaluated by several techniques, including hydrostratigraphic classification (as a base for numerical simulation), hydraulic head distribution visualisation, baseflow index calculation, and general hydrochemical characterisation, applying natural tracers and stable isotopes and a numerical simulation of groundwater flow and heat transport. The results highlight a high level of interconnection of surface watercourses, groundwater and Lake Balaton and hydraulic continuity in the study area. Furthermore, the largest lake in central Europe can be regarded as a groundwater-dependent ecosystem.

As the effects of climate change intensify, the predicted changes will affect Lake Balaton, firstly, through direct changes in precipitation and evaporation. Secondly, it may also affect streamflow and, in the longer term, groundwater resources as well. Since surface waters react more quickly to climate change, groundwater replenishment will become more and more prominent, which presumably represents a stable contribution to the lake's water budget. However, climate changes can recompose the subsurface flow pattern, thus changing the hydraulic regimes (recharge and discharge), flow systems and dynamics and the amount of discharging water. Therefore, from the viewpoint of water management, evaluating the sensitivity to climate change is also increasingly coming to the forefront, considering the management of aquifer recharge for environmental benefits.

The presented tools and techniques for evaluating surface water–groundwater interaction were applied in a methodological sequence, like a workflow, following the concept of regional groundwater flow, which is primarily driven and determined by physical processes; then, local chemical interactions may secondarily alter the hydrochemical facies and imprint. Techniques tailored to the local characteristics seem particularly useful, such as the natural tracers of temperature, chloride concentration and total uranium activity in this case study. The presented set of methods could be applicable to any study area with similar research questions and provide a comprehensive understanding of the regional hydrogeological conditions and processes.

A general philosophic and semantic discussion may arise related to the following surface water–groundwater interaction: based on what criteria should surface water be considered surface water? In other words, is it surface water because it is open to the surface and flowing on the ground surface? Surface water and groundwater are intertwined in so many ways, and sometimes, their distinction is artificial and, at times, almost impossible due to the same hydrochemical character. In the worst cases, their interaction is entirely neglected, and surface water and groundwater are considered completely disjoint. We, even as professionals, must realise, admit and promote the "groundwater and surface water: a single resource" approach of Winter et al. [9]. This is in line with the motto of World Water Day and the whole year of 2022: "Making the invisible visible". In the spirit of this slogan, we shed light on the overlooked groundwater component of Lake Balaton.

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