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Assessing the Long-Term Groundwater Level Dynamics in Szigetköz, Hungary

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Szigetköz, a large island in the Hungarian Upper Danube, features unique gravel subsoils ranging from 10 to 600 m thick. The region's groundwater levels, profoundly influenced by the Danube's flow, are crucial for drinking water, irrigation, flood retention, and ecosystem functioning. Groundwater levels also impact topsoil moisture, affecting agriculture and forestry. Throughout the 20th century, human interventions, such as river regulation and hydropower plants, disrupted the groundwater balance in Szigetköz. Over the past three decades, water replenishment systems have been implemented to mitigate these effects and restore natural water levels. This study analyses long-term groundwater data from the 1950s until 2022, utilizing over 50 monitoring wells to map fluctuations in groundwater levels. For three periods, decadal, annual, and seasonal groundwater level analyses revealed the impacts of human intervention and the impacts of revitalization. Results of this study show that in the crucial spring and summer seasons, particularly in the vulnerable central regions of Szigetköz, the water table has been elevated by an average of 20-30 cm, recovering more than one-third of the water level reduction caused by the Danube's diversion. However, in the winter period, groundwater levels dropped further in the last 30 y in the upper areas of Szigetköz. These partly unexpected insights highlight the need for further investigations to identify the main drivers of groundwater level dynamics, including studying the effect of bed clogging and the possible consequences of restoring the water levels of the Old Danube.

1. Introduction and literature review

Alluvial aquifers are increasingly important sources of freshwater as global water consumption continues to rise (Fajar et al., 2021), including in regions like Central Europe (Jia et al., 2019). However, water management activities can significantly disrupt the natural hydrological dynamics of river floodplains. River regulation, the construction of flood protection levees, and hydropower installations can drastically alter river morphology, posing potential risks to vulnerable aquifers. Restoration efforts to return these ecosystems to their natural or near-natural states may involve dismantling existing water management infrastructure or implementing engineering solutions to create more favourable hydrological conditions. A well-known example of such transformations took place in Szigetköz (Smith et al., 2002). This 50 km-long island and floodplain area is in the middle of the Danube in Northwestern Hungary. This unique inland delta created by the Danube consists of an intricate system of islands, waterways, and wetlands that sit on top of an extensive quaternary alluvial aquifer, estimated to hold about 5.4 km^3 of water (Erdélyi, 1990). River regulation had already altered the regime of surface and groundwater levels before the 1990s to some extent. However, the diversion of the Danube towards the power channel of the Gabčíkovo Hydropower Plant (HPP) in 1992 necessitated large-scale restoration efforts to preserve this valuable landscape (Ijjas et al., 2010). The aim of the restoration was to return to the characteristic water levels of the 1950s and 1960s for surface and groundwaters as well. Water replenishment systems in the active and historical floodplain were constructed, relying on water withdrawal from the main channel of the Danube and a controlled gravitational system. Hydraulic structures, weirs, and sluice gates help restore the surface water levels in floodplain branches throughout Szigetköz Island. However, surface water levels in the main Danube branch (Old Danube) have not yet been restored despite advanced studies (Széchenyi István University, 2023). Therefore, the Old Danube still drains the shallow groundwaters (SGW). This aquifer is critical for various functions, including water supply, rain-fed and irrigated agriculture, floodwater

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retention, and supporting groundwater-dependent ecosystems. It is essential to assess both the historical and current state of the shallow aquifer. While research has been conducted on short- (Trásy, Garamhegyi, et al., 2018) and medium-term (Kovács et al., 2015) changes in SGW in the Szigetköz region, there is a lack of studies analysing long-term shifts in groundwater levels over decadal timescales. This study evaluates the long-term changes in groundwater levels and assesses the effect of past water management activities. Additionally, it examines the effectiveness of current water replenishment in restoring groundwater levels in the unconfined alluvial aquifer.

2. Method

The study's primary objective is to compare characteristic groundwater level changes to assess the impact of the Danube diversion and subsequent water replenishment measures. Three characteristic periods were established: (1) the Baseline period before the diversion of the Danube (1953-1992); (2) the period after the diversion but before the initiation of floodplain water replenishment (1993-1994); and (3) the period after water replenishment measures were implemented (2003-2022). Within these three periods, decadal and seasonal changes in SGW levels were calculated, with the seasons defined as follows: winter (January-March, Q1), spring (April-June, Q2), summer (July-September, Q3), and fall (October-December, Q4). The changes in SGW levels were evaluated across four cross-sections of Szigetköz Island, as illustrated in Figure 1.

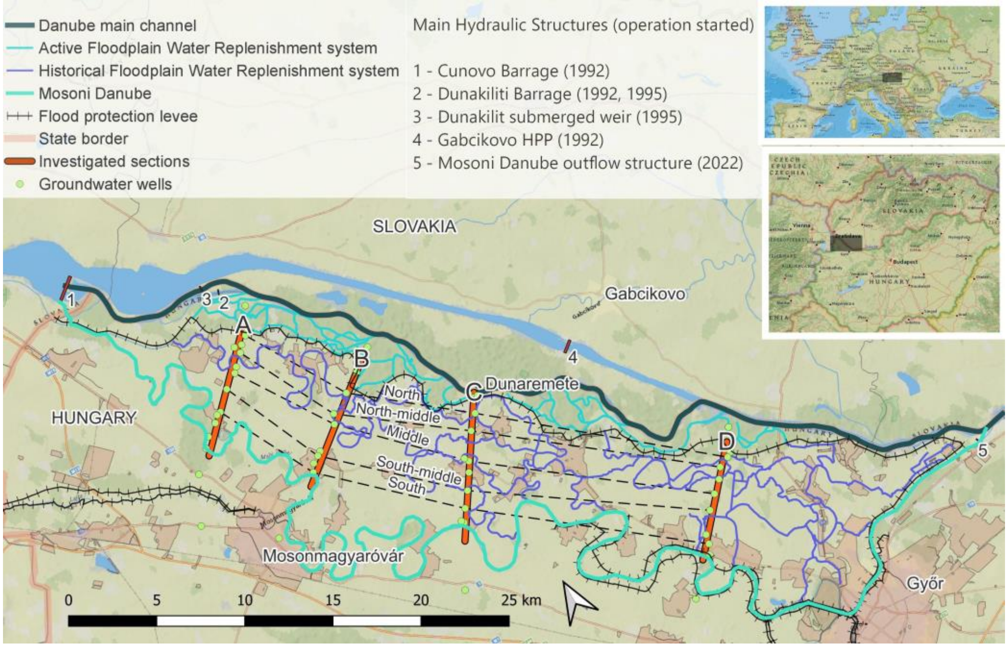


Figure 1: Overview map of Szigetköz area, with four cross-sections and locations of groundwater wells marked. (map created with QGIS, base map: Esri National Geographic World Map)

A daily time series of groundwater level data was obtained from the North-Transdanubian Water Directorate (ÉDUVÍZIG). The data underwent pre-screening to identify any unusual values, which were investigated further. In addition, ÉDUVÍZIG's data quality assessment program regularly monitors and ensures the reliability of the measured data. The selection of monitoring locations was based on two main criteria: geographic distribution and data availability. Geographically, the locations were chosen to cover the upper (A), middle (B and C), and lower (D) regions of the Szigetköz area; the second criterion prioritised areas with the highest data availability, as shown in Figure 1. The direction of the cross-section was determined by selecting the region with the greatest number of well measurements. The active floodplain area (between the Old Danube and the flood-protection levees) has a dense network of branches, yet it is relatively sparsely populated with groundwater monitoring wells. The investigated cross-sections span the historical floodplain, from the Danube flood-protection levee to the Mosoni-Danube. The cross-sections were divided into five regions, with the southernmost section closest to the Mosoni-Danube and the northernmost section near the levee of the Old Danube. Data from 72 shallow groundwater (SGW) wells, with depths ranging from 4 to 18 m and screening intervals between 1 and 15 m, were analysed. Figure 1 illustrates the locations of these wells across each cross-section. Groundwater levels were assessed over multiple decades, focusing on time series data beginning in the 1950s and extending to or near 2022. During pre-processing, time series with significant data gaps were excluded, leaving data from 54 wells for further calculations. The study considers three main driving factors of SGW level changes in Szigetköz. In order of importance: (1) surface water levels in the Danube and Mosoni-Danube, (2) water replenishment in the floodplain branches, and (3) meteorological conditions.

2.1 Danube water levels

The actual level of the Danube River has always been the main driver of SGW level changes in the Szigetköz. Historically, the Danube was the dominant source of recharge for the aquifer, with approximately 7-8 m^3/s infiltrating over the year (Ijjas et al., 2010). The diversion of the Danube in late 1992 resulted in different conditions. About 80 % of the Danube's discharge was diverted towards the Gabčíkovo HPP. Surface water levels reduced by 2-4 m created a situation where the Danube no longer recharged the aquifer but started to drain it. The annual average water levels of the Danube, measured by ÉDUVÍZIG at Dunaremete gauge (see Figure 2), show these changes.

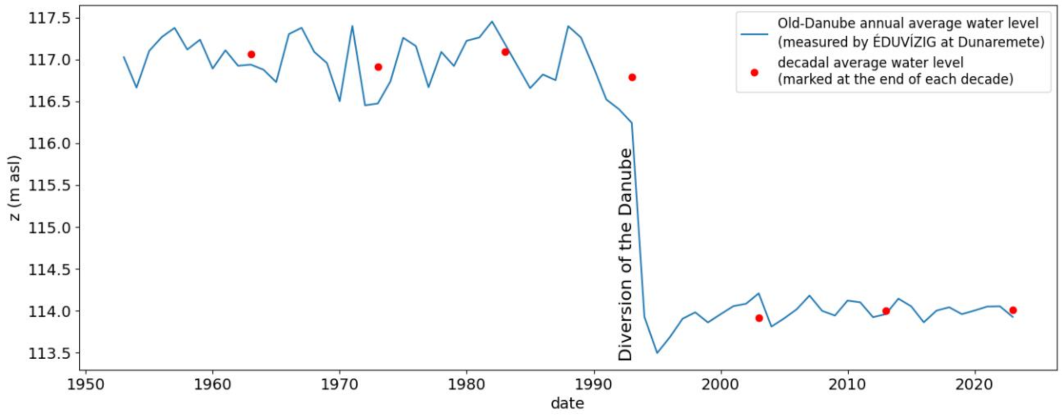


Figure 2: Annual average (blue line) and decadal average (red dots) surface water levels in the Old Danube between (1952 and 2022) measured at Dunaremete by ÉDUVÍZIG

Figure 2 also shows that the diversion of the Danube reduced fluctuations in the decadal-average water levels of the Old Danube. A long time frame to smooth out inter-annual variations was considered to compare characteristic water levels across historical periods. The decadal average water levels, both before and after the diversion, show only minor fluctuations. As a result, decadal average groundwater levels were used for further analysis.

2.2 Floodplain water replenishment

Two and a half years after the diversion of the Danube, a submerged weir at Dunakiliti was built to elevate surface water levels in the upper part of the Old Danube and facilitate a gravitational water replenishment system that restores surface water levels in the active and historical floodplain river branch system (see Figure 1). In this study, cross-sections "A," "B," and "C" will be considered as being influenced by replenishment efforts during the periods 2003-2012 and 2013-2022. Section "D," however, is located downstream from the HPP, so the effects of the diversion were not immediate. However, by the early 2000s, riverbed incision had caused a significant reduction in the groundwater table in the lower areas of Szigetköz (Jakus et al., 2024). Water replenishment in these lower areas began in 2014-2015. For section "D," while the baseline period remains 1953-1992, the period after the diversion considered for calculating the reduction in water levels is 2002-2013, and the effects of water replenishment are examined only in the 2013-2022 decade. The Mosoni-Danube Outflow Structure – restoring surface water levels in the lower parts of the Mosoni-Danube has been in operation since mid-2022. Its operation does not affect this study.

The water replenishment systems are operated on a seasonal basis. Winter discharges (Q4-Q1) from the Old Danube, supplied from the Čunovo dam, are lower than those in spring and summer. The spring period (Q2) often experiences natural or artificial floods. Summer (Q3) is critical for agriculture and natural ecosystems such as groundwater-fed wetlands, meadows, and forests. Consequently, decadal average groundwater levels will be defined separately for each season.

2.3 Meteorological impact

The effect of precipitation and evapotranspiration on the groundwater table is comparatively less critical than the recharge or drainage from the Old Danube and other surface waters. After subtracting evapotranspiration, the net recharge from rainwater was estimated at 0.05 m³/s (Ijjas et al., 2010). While this was a small fraction of the recharge from the Danube before the diversion, it has become more significant since the water table has dropped considerably and continues to be drained by the main branch of the Danube under middle and low-flow conditions. This study considers hydrometeorological variations to have little effect on average SWG levels in a decadal timeframe.

2.4 Evaluation of groundwater level changes

In the first steps, quarterly average water levels were averaged again over seven decadal timeframes: 1953-1962, 1963-1972, 1973-1982, 1983-1992, 1993-2002, 2003-2012, and 2013-2022. Additionally, 1993-1994 were considered separately to represent the "Reduced water levels" (Period 2) during the post-diversion and pre-water replenishment state. For section "D," the period of 2003-2012 is considered to have "reduced water levels" (see explanation in section 2.2). Since the average water levels of the first four decades showed little variance, the "Baseline water levels" (Period 1) were established as the overall average of the 1953-1992 period. "Restored water levels" (Period 3) were calculated as the average water levels of the 2003-2012 and 2013-2022 decades for sections "A," "B," and "C," while for section "D," the 2013-2022 period alone represents the "restored water levels." Cross-sections based on quarterly average water levels for different periods have been compiled for all four seasons across all four cross-sections, resulting in 16 cross-sections. The characteristic groundwater levels for cross-section "C" during Q2 are shown in Figure 3.

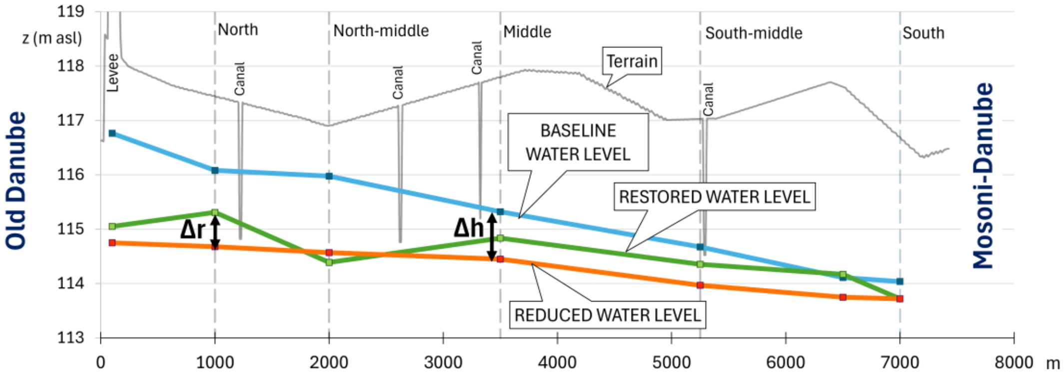


Figure 3: Cross-section "C" with baseline- (1953-1992), post-diversion- pre-replenishment- (reduced 1993-1994), and post-replenishment (restored 2003-2022) groundwater levels for the Q2 (April-June) period. Graphical definitions of Δh *and* Δr *are presented*

To numerically quantify the water level changes in the Szigetköz region, three different parameters were calculated at five locations (North, North-middle, Middle, South-middle, and South) within all four cross sections for every season. These parameters are listed in Table 1, along with their symbols, names, units, and equations.

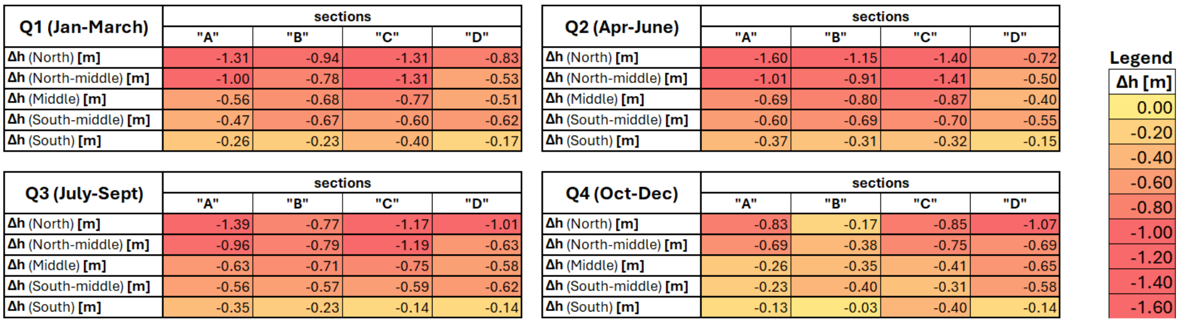
Table 1: Summary of calculated parameters that describe water level changes for three different periods

Symbol	Parameter name	Unit	Equation	
Δh	reduced water level change	[m]	$\Delta \mathrm{h} = \mathrm{z}_{e(\text{Reduced water level})} - \mathrm{z}_{(\text{Baseline})}$	(1)
Δr	restored water level change	[m]	$\Delta \mathrm{r} = \mathrm{z}_{(\text{Restored water level})} - \mathrm{z}_{(\text{Reduced water level})}$	(2)
P	percentage of water level recovery	[%]	$\mathrm{P} = \dfrac{\Delta \mathrm{r}}{-\Delta \mathrm{h}}$	(3)

where $z_{(i)}$ values are average groundwater levels in "meters above sea level" (m asl) for the three distinct periods.

3. Results and discussion

The reduced water level changes (Δh) are shown in Figure 4. The four parts of the figure represent the four quarters of the year, with reduced water levels after the diversion of the Danube indicated in [m]. In the northern sections, the drawdown caused by the Old Danube is most pronounced. Moving southward towards the Mosoni-Danube, the reduction in groundwater levels diminishes as the surface water levels in the upper segment of the Mosoni-Danube are unaffected by the diversion of the Danube. Section D is an exception, as the surface water levels of both the lower parts of the Old Danube and the last section of the Mosoni-Danube are affected by riverbed incision. The magnitude of groundwater level reduction is the smallest in Q4, primarily due to historically low discharges during winter. As a result, the relative reduction in surface water levels following the diversion of the Danube is also minimized during this season.



Q1 (Jan-March)	sections			
	"A"	"B"	"C"	"D"
Δh (North) **[m]**	-1.31	-0.94	-1.31	-0.83
Δh (North-middle) **[m]**	-1.00	-0.78	-1.31	-0.53
Δh (Middle) **[m]**	-0.56	-0.68	-0.77	-0.51
Δh (South-middle) **[m]**	-0.47	-0.67	-0.60	-0.62
Δh (South) **[m]**	-0.26	-0.23	-0.40	-0.17

Q2 (Apr-June)	sections			
	"A"	"B"	"C"	"D"
Δh (North) **[m]**	-1.60	-1.15	-1.40	-0.72
Δh (North-middle) **[m]**	-1.01	-0.91	-1.41	-0.50
Δh (Middle) **[m]**	-0.69	-0.80	-0.87	-0.40
Δh (South-middle) **[m]**	-0.60	-0.69	-0.70	-0.55
Δh (South) **[m]**	-0.37	-0.31	-0.32	-0.15

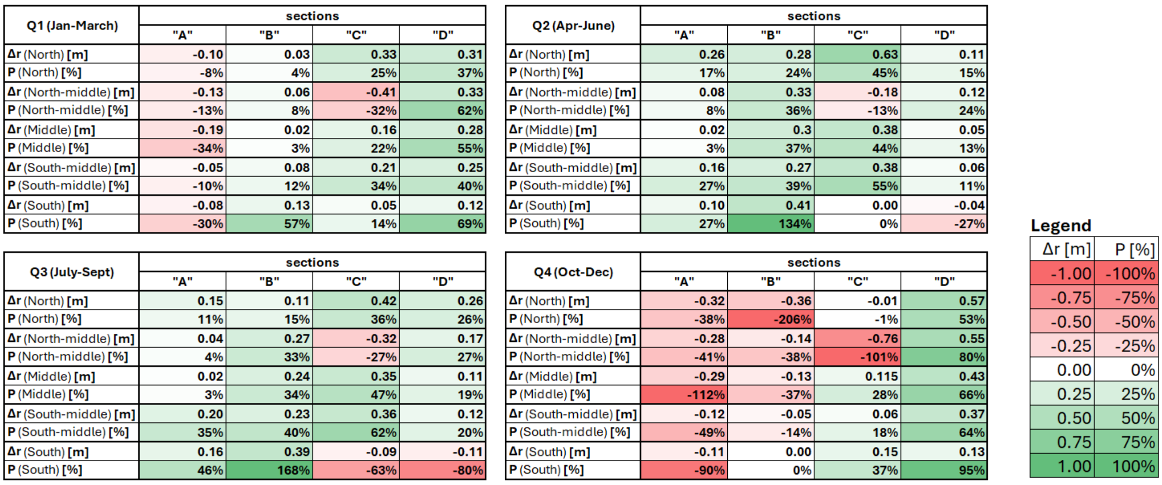
Q3 (July-Sept)	sections			
	"A"	"B"	"C"	"D"
Δh (North) **[m]**	-1.39	-0.77	-1.17	-1.01
Δh (North-middle) **[m]**	-0.96	-0.79	-1.19	-0.63
Δh (Middle) **[m]**	-0.63	-0.71	-0.75	-0.58
Δh (South-middle) **[m]**	-0.56	-0.57	-0.59	-0.62
Δh (South) **[m]**	-0.35	-0.23	-0.14	-0.14

Q4 (Oct-Dec)	sections			
	"A"	"B"	"C"	"D"
Δh (North) **[m]**	-0.83	-0.17	-0.85	-1.07
Δh (North-middle) **[m]**	-0.69	-0.38	-0.75	-0.69
Δh (Middle) **[m]**	-0.26	-0.35	-0.41	-0.65
Δh (South-middle) **[m]**	-0.23	-0.40	-0.31	-0.58
Δh (South) **[m]**	-0.13	-0.03	-0.40	-0.14

Legend

Δh [m]
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60

Figure 4: Reduction in average groundwater levels in different seasons (Q1-Q4) after the diversion of the Danube. Average SWG levels of 1993-1994 compared to baseline levels of 1953-1992. Values for examined wells in sections (A-B-C-D) and distinct locations within the sections (north to south) are placed in the tables



Q1 (Jan-March)	sections			
	"A"	"B"	"C"	"D"
Δr (North) **[m]**	-0.10	0.03	0.33	0.31
P (North) **[%]**	-8%	4%	25%	37%
Δr (North-middle) **[m]**	-0.13	0.06	-0.41	0.33
P (North-middle) **[%]**	-13%	8%	-32%	62%
Δr (Middle) **[m]**	-0.19	0.02	0.16	0.28
P (Middle) **[%]**	-34%	3%	22%	55%
Δr (South-middle) **[m]**	-0.05	0.08	0.21	0.25
P (South-middle) **[%]**	-10%	12%	34%	40%
Δr (South) **[m]**	-0.08	0.13	0.05	0.12
P (South) **[%]**	-30%	57%	14%	69%

Q2 (Apr-June)	sections			
	"A"	"B"	"C"	"D"
Δr (North) **[m]**	0.26	0.28	0.63	0.11
P (North) **[%]**	17%	24%	45%	15%
Δr (North-middle) **[m]**	0.08	0.33	-0.18	0.12
P (North-middle) **[%]**	8%	36%	-13%	24%
Δr (Middle) **[m]**	0.02	0.3	0.38	0.05
P (Middle) **[%]**	3%	37%	44%	13%
Δr (South-middle) **[m]**	0.16	0.27	0.38	0.06
P (South-middle) **[%]**	27%	39%	55%	11%
Δr (South) **[m]**	0.10	0.41	0.00	-0.04
P (South) **[%]**	27%	134%	0%	-27%

Q3 (July-Sept)	sections			
	"A"	"B"	"C"	"D"
Δr (North) **[m]**	0.15	0.11	0.42	0.26
P (North) **[%]**	11%	15%	36%	26%
Δr (North-middle) **[m]**	0.04	0.27	-0.32	0.17
P (North-middle) **[%]**	4%	33%	-27%	27%
Δr (Middle) **[m]**	0.02	0.24	0.35	0.11
P (Middle) **[%]**	3%	34%	47%	19%
Δr (South-middle) **[m]**	0.20	0.23	0.36	0.12
P (South-middle) **[%]**	35%	40%	62%	20%
Δr (South) **[m]**	0.16	0.39	-0.09	-0.11
P (South) **[%]**	46%	168%	-63%	-80%

Q4 (Oct-Dec)	sections			
	"A"	"B"	"C"	"D"
Δr (North) **[m]**	-0.32	-0.36	-0.01	0.57
P (North) **[%]**	-38%	-206%	-1%	53%
Δr (North-middle) **[m]**	-0.28	-0.14	-0.76	0.55
P (North-middle) **[%]**	-41%	-38%	-101%	80%
Δr (Middle) **[m]**	-0.29	-0.13	0.115	0.43
P (Middle) **[%]**	-112%	-37%	28%	66%
Δr (South-middle) **[m]**	-0.12	-0.05	0.06	0.37
P (South-middle) **[%]**	-49%	-14%	18%	64%
Δr (South) **[m]**	-0.11	0.00	0.15	0.13
P (South) **[%]**	-90%	0%	37%	95%

Legend

Δr [m]	P [%]
-1.00	-100%
-0.75	-75%
-0.50	-50%
-0.25	-25%
0.00	0%
0.25	25%
0.50	50%
0.75	75%
1.00	100%

Figure 5: Changes in groundwater levels in different seasons (Q1-Q4) after water replenishment. Δr – post-replenishment restored water level changes in [m], compared to 1993-1994 levels, and P – percentage of water level recovery compared to baseline water levels of 1953-1992

The results for the restored water level changes (Δr) and water level recovery percentage (P) are displayed in Figure 5. The four parts represent different seasons. The impact and effectiveness of water replenishment can be examined from this figure. In Q2 and Q3, groundwater recovery is maximum when water replenishment operates with higher discharges and water levels. During these months, the restored water level is around 15-20 cm on average, representing an approximate 20 % recovery of the reduced water levels. In the spring and summer months, sections "B" and "C" perform best. On the contrary, in section "D," water levels are best restored during the winter half-year. Section "A" shows the poorest performance in recovering groundwater levels, particularly in Q4 and Q1, when SWG levels drop even further than they did shortly after the diversion. There is unusual behaviour in cross-section "C" at the north-middle groundwater well, where recovery is much worse than in nearby wells. Further analysis is needed to determine whether this is due to data errors or some local impact, such as water abstraction, causing this depression throughout the year. This study aimed to quantify the long-term changes in groundwater levels. Limitations of the research include interrelated spatiotemporal and methodological issues. The study method required a multidecadal time series of groundwater monitoring wells. This requirement greatly limited the number of wells and the location of sections that could be included in the analysis. Spatial interpolation methods such as Kriging could be used in later studies to fill data gaps and refine the spatial resolution of results presented here. Another important aspect of SGW level changes in the Szigetköz that needs further research is quantifying the relative importance of driving factors (see sections 2.1, 2.2, 2.3) that affect SWG levels, as demonstrated by Salem et al. (2023). Knowing the amount of net groundwater change due to the surface water level changes in the Old Danube and the replenished floodplain river branches and the resultant effects of precipitation and evaporation can help decide the future steps needed to recover groundwater levels.

4. Conclusion

This study spatially analysed the long-term changes in shallow groundwater (SGW) levels in the Szigetköz region, with special attention to seasonal variations. It quantified the effects of diverting the Danube and the impact of water replenishment efforts on SGW levels. The findings indicate that the Szigetköz water replenishment system has partially restored SGW levels. In the crucial spring and summer seasons, particularly in the vulnerable central regions of Szigetköz (sections "B" and "C"), the water table has been elevated by an average of 20-30 cm, recovering more than one-third of the groundwater level reduction caused by the Danube's diversion. Expected future weather extremes, such as the drought experienced in 2022, underscore the importance of restoring these natural aquifers as resilient storage facilities. However, this study confirms that achieving baseline SGW levels has not yet been accomplished. Therefore, possible solutions such as restoring the surface water levels of the Old Danube (Jakus et al., 2024) do need to be considered. A critical aspect to consider in restoration planning is the role of bed-clogging (Trásy et al., 2018) and its effects on groundwater quantity and quality. A comprehensive evaluation of the potential benefits and drawbacks of different methods to rehabilitate the Old Danube is essential. These broader efforts must consider ecological, societal, and economic sustainability and the prospect of restoring SGW-s.

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