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Comparison of Water Balance Results for Different Operating Conditions of the Ráckeve–Soroksár Danube with Particular Reference to Infiltration

Abstract

The operation of the Ráckeve–Soroksár Danube (RSD) is a complex task for water engineers, as its multiple uses means that there are many different types of water demand in the system. For the economic sustainability of the operation, it is important to know the exact water balance of the RSD, as it is not always the same amount of water that needs to be supplied into the system during low water periods. In this article, the water balances of four operating conditions are analysed and compared, with a special focus on the amount of infiltration. This document also provides a solution for the infiltration amount that should be included in water balance calculations.

Keywords: water balance, infiltration, Danube, operation, RSD

Introduction

The Ráckeve–Soroksár Danube (RSD) is the second longest side arm of the Hungarian Danube. It has gradually lost its natural character over the last 100 years due to anthropogenic influences, with the construction of the Kvassay and Tassi lock gates, and has been transformed into a highly modified, standing water body.[2]

The RSD's proximity to Budapest and its regulated character make it suitable for a wide variety of water management and municipal uses. From a water management

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[2] VITUKI 2019a.

point of view, its most important functions are irrigation water supply, inland drainage, meeting recreational needs and protecting the special areas for conservation within the Natura 2000 framework. The RSD receives treated wastewater too, which leads to more sources of conflict in the operation of the system.[3]

The many (often conflicting) aspects required by the multiple uses must be reconciled in some way to reach a compromise acceptable to the stakeholders in the use. As a result of these factors, the Ráckeve–Soroksár Danube has the most complex tasks of any of Hungary's recreational lakes. Without integrated water resource management, the RSD cannot fulfil its multifunctional role.[4]

During the Danube's low water periods, there are physical limitations to the operation of the pumping station at the Kvassay Water Power Plant, which supplies water to the upper reaches. The low and medium water levels of the Danube, according to the results of the hydrographic measuring of the water levels at the main stations, are decreasing in a trend.[5] The main reason for this is probably the gradual deepening of the Danube riverbed, because the low and medium discharges water levels of the Danube are not showing this trend.[6]

The multifunctional Tassi (Sajó Elemér) diversion structure is also responsible for the safe operation of the RSD and for guaranteeing sufficient water quantity. The construction and operation of the structure has increased the amount of feedwater in the lower RSD reaches, which also means that the operating water level is kept on less extreme level.[7]

In case of pumping at the structures, it is particularly important from a water resource management and economic point of view to have an accurate description of the water balance of the system. The water balance, which based on the discharge measurements, often shows that the amount of water leaving the reservoir is significantly less than the amount entering without any change in the volume of stored water, and therefore presumably has a significant effect on evaporation and infiltration. In this paper, I estimate these types of characteristics of the Ráckeve–Soroksár Danube, which will help to understand the hydrology of the system and to make the management of the system more predictable.

Operational basics of the RSD

The Kvassay structure was built between 1910 and 1962, and located in the 1642.4 river kilometre section of the Danube. Its main function is to ensure the water supply of the RSD, to guarantee the operating water level, to exclude floods on the Danube and to ensure water transport. The Kvassay hydropower station has a dual function, on the one hand to generate hydropower when the Danube water level is sufficiently high, and on the other hand to ensure the flow with fresh water

3 VITUKI 2019a: 44.
4 VITUKI 2019b.
5 Tóth 2021: 31–43.
6 VITUKI 2019b: 13.
7 Közép-Duna-völgyi Vízügyi Igazgatóság 2021.

by operating the turbines in pumping mode during low Danube water levels, when gravity feed into the RSD is no longer possible. The hydropower station is equipped with two turbine-pump units (Kaplan system, reversible vertical axis) installed in 1963. The maximum capacity per unit is 25 m^3/s in turbine mode and 6–15 m^3/s in pump mode, depending on the water level difference.[8]

The Tassi structure, originally built as a group of works, as a joint energy pair with the Kvassay structure, was constructed in the 1586.0 river kilometre section of the Danube between 1926 and 1928. The 1956 ice flood damaged the gate and the hydroelectric power station and it was demolished.[9] The partially renovated structure (of the whole Tassi structure) has been operated since 1956.

In 2021, a multi-functional diversion structure was built to replace the damaged gate and power plant, taking over its functions, north-west of the existing Tassi ship lock, at a distance of about 250 m from it, and integrated into the Danube's first-order flood protection dike. The primary objective of the structure is to ensure a safer regulation of the water flow and water level in the Ráckeve–Soroksár Danube.[10]

The facility, which was inaugurated in June 2021, is a double-arch reinforced concrete structure with two identical openings, each containing a reversible Kaplan turbine with a horizontal axis, a rarity in the world. Thanks to this water engineering equipment, the facility is suitable for both Danube to RSD and reverse flow. It is also capable of generating electricity by exploiting the water potential of the water discharged during normal operation.[11]

The RSD is the permanent or temporary receiving water of the Gyáli, North Danube Valley and Ráckeve (Soroksár) Danube inland water systems connected to its territory. The RSD also functions as an irrigation water base in the area. Figure 1 shows the locations affecting the water balance of the RSD. Blue dots indicate incoming water, red dots indicate outgoing water and yellow dots indicate outgoing and incoming water in the tested operating conditions.

If the water level of the Danube at Budapest, Vigadó Square is below 200 cm, the gravitational water supply of the RSD via the Kvassay lock will be eliminated. As gravity supply ceases and the RSD operating water level decreases, water quality will start to deteriorate due to the inflow of approximately 1.0 m^3/s of treated wastewater from the South Pest Wastewater Treatment Plant (DPSZT on Figure 1.) and the Gyáli stream (Gyáli-patak on Figure 1) into the RSD.[12]

8 VITUKI 2019a: 9.
9 VITUKI 2019a: 14.
10 Közép-Duna-völgyi Vízügyi Igazgatóság 2021.
11 Közép-Duna-völgyi Vízügyi Igazgatóság 2021.
12 VITUKI 2019a: 17.

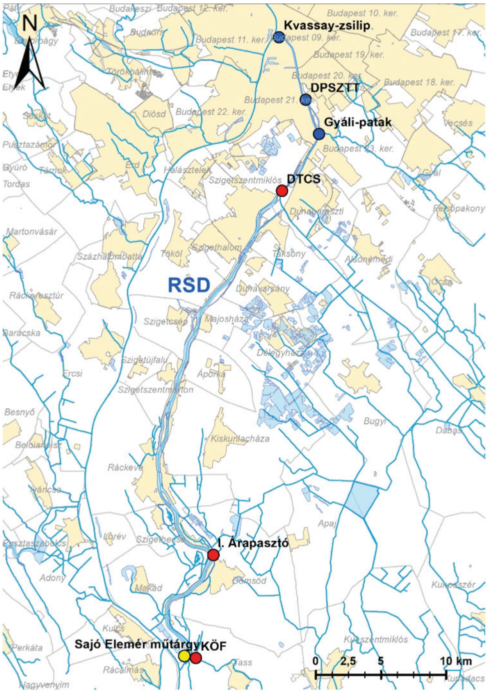

Figure 1: Layout plan of the RSD with the locations affecting the water balance
Source: Compiled by the author.

To mitigate the water quality degradation resulting from the water level decline and to meet ecological and other water needs, the reversible turbines of the Kvassay structure and the turbines of the multi-functional Tassi (Sajó Elemér) diversion structure need to be started up in pumping operation. However, despite the pumped operation, the physical constraints of the pumped operation also require a reduction in the volume of water to be discharged from the system.

The Hydrometeorology Unit of the Central Danube Valley Water Directorate (KDVVIZIG) carries out frequent measurements to monitor the water flow in the system during pumping, and remote sensing of discharge also adds to the knowledge of the hydrologist specialists.

Calculation of the RSD water balance for different operating periods

Water balances are often calculated by hydrologists for the larger lakes of Hungary, but the RSD is a different type of water body.[13] Only the water balance calculated according to the river basin management plan is publicly available.[14]

[13] Kravinszkaja 2022; Közép-dunántúli Vízügyi Igazgatóság Vízrajzi és Adattári Osztály 2022.
[14] Országos Vízügyi Főigazgatóság 2015.

In order to prevent deterioration of the water quality of the RSD and to ensure the ecological water demand of the region, the Central Danube Valley Water Directorate was ordered to pump water into the Danube branch on 13 July 2022, starting at 06:00, as part of a water quality protection alert level III, with the elimination of the possibility of gravity feed. The water quality protection was ordered on the basis of Government Decree 90/2007 (IV.26.) on the Prevention and Remedying of Environmental Damage, due to the obligations to take preventive measures against environmental damage.[15]

During the period of the water quality protection, several discharge and water level measurements were made in the system, so that water balance calculations could be carried out under different operating conditions.

The analyses were based on the water balances of four periods of essentially low water levels (under 200 cm in Budapest) during which KDVVIZIG carried out interventions in the water quality protection:

1. Low water level in the Danube, pumped water supply at the Kvassay and Sajó Elemér structures
2. Low water level on the Danube, gravity feed at the Kvassay structure and pumped at the Sajó Elemér structure
3. Low flood wave (maximum level was 238 cm in Budapest) on the Danube, gravity feed at the Kvassay structure
4. No Danube water supply to the RSD

The flow results are based on actual measurements and the monitoring system of the Water Directorate.[16] For the water balance calculations I used the elements of the hydrological cycle and the major water uses. The water balance had to come out to 0 when the storage was taken into account, so I was able to estimate the unit (m^3/s) of infiltration. The precipitation on the water surface was neglected in the calculation, because there was no rain on the days in the study. I used the following equation for my calculations.

$$\textit{Kvassay} + \textit{SPWTP} + \textit{Gyáli} - \textit{DTCS} - \textit{Árapasztó} - \textit{KÖF} \pm \textit{Sajó Elemér} \pm \textit{storage} - \textit{evaporation} - \textit{infiltration} = 0$$

Low water level with pumped water supply

During the period under review, both water intakes (Kvassay, Sajó Elemér) of the RSD were supplied by pumping. Table 1 shows that on 21 July 2022, in the absence of water level changes (storage), the water flow is assumed to “disappear” in the system by almost 5 m^3/s, which is much higher than the value assumed as a measurement error.

[15] Government Decree 90/2007 (IV.26.) on the Prevention and Remedying of Environmental Damage.
[16] KDVVIZIG: Water flow measurements, 2022.

Table 1: Low water level with pumped water supply, water balance data

21 July 2022		
		m³/s
Kvassay	+	8.450
South Pest WTP	+	0.488
Gyáli	+	0.057
DTCS	–	0.436
Árapasztó	–	2.680
KÖF	–	12.330
Sajó Elemér	+	11.530
waterflow scheme		**5.079**
storage	–	0.000
evaporation	–	0.720
infiltration	–	*4.359*
water balance		**0.000**

Source: Compiled by the author.

The average evaporation calculated by the Meyer method for the month of July is 115 mm/month on the RSD, which can be estimated at 0.7 m^3/s because of the surface area of 15.7 km^2. The Meyer method is used to determine the actual monthly evaporation and allows the determination of actual surface evaporation values using meteorological factors (wind speed, water temperature, air temperature).[17] To the calculated value is added the 20% higher evaporation intensity due to the transpirational evaporation surplus on the water surface covered by approximately 236.15 hectares of reedbed, giving an average evaporation of 0.72 m^3/s. Due to the meteorological conditions on 21 July 2022, I have assumed an average wind speed for the calculation of evaporation, but higher wind speeds may result in a significant evaporation surplus, which cannot be ignored in the daily resolution.

To estimate the infiltration, it was necessary to collect literature values. According to the Csepel–Halásztelek Drinking Water Basin Safety Plan prepared by the KSZI Kft. in 2003, the Csepel Island has a sandy gravel layer of 4–10 m under a sand cover of 4–9 m, which is considered to be a good conductor of water. Based on the water levels measured on 21 July 2022, the groundwater conditions on the Csepel Island are approximate. Figure 2 compares the longitudinal profile of the Danube and RSD water levels for the reference date with the water levels measured in the wells on the island and on the left bank of the RSD.[18]

[17] Koris et al. 1993.

[18] KSZI Kft. 2013.

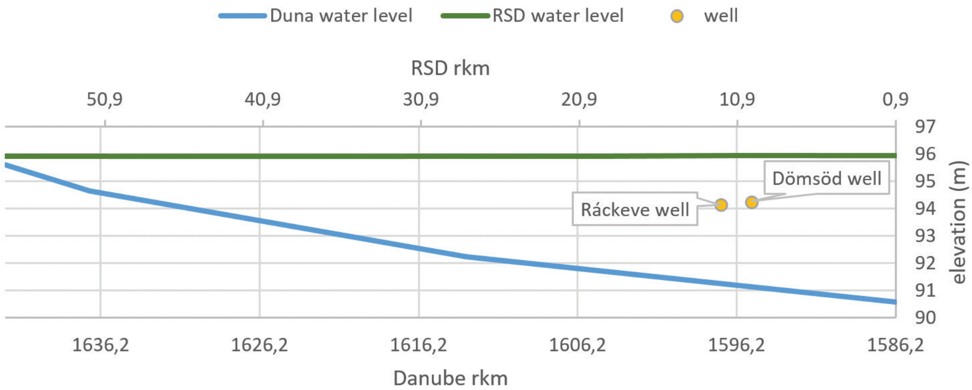

Figure 2: Water levels on 21 July 2022
Source: Compiled by the author.

It can be seen that from the Kvassay structure the water level in the Danube drops by about 5 m to Tass, while the water level in the RSD is nearly constant along its entire length. Compared to the RSD, the water levels measured in the wells were almost 2 metres lower.

Figure 3 shows an estimated cross-section for the Csepel Island (the field level is estimated from a topographic map [without dikes] and the water levels marked with a blue circle are from measurements):

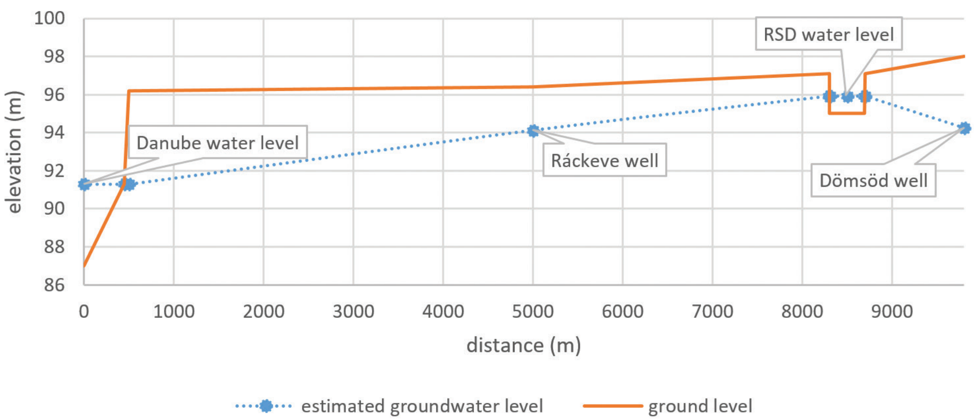

Figure 3: Cross-section (around 1,597 rkm) for Csepel Island on 21 July 2022
Source: Compiled by the author.

The figure shows that the groundwater level in the well-drained soils also decreases towards the Danube and the Sandhills, indicating infiltration from the RSD. By connecting the points, it can be observed that the slope of the RSD–Ráckeve well (55 cm/km) and the Ráckeve well – Danube (63 cm/km) lines are almost identical.

Low water level with gravity and pumped water supply

In the case under study, water was gravity-fed through the Kvassay structure and pumped through the multifunctional Sajó Elemér diversion structure. As shown in Table 2, on 2 August 2022, 3.5 m^3/s was stored in the riverbed, which is estimated from the daily water level rise of 2 cm. Accordingly, based on the water flow, a discharge of nearly 6.4 m^3/s "disappears" in the system.

Table 2: Low water level with gravity and pumped water supply, water balance data

02 August 2022		
		m^3/s
Kvassay	+	18.646
South Pest WTP	+	0.500
Gyáli	+	0.067
DTCS	–	0.828
Árapasztó	–	2.750
KÖF	–	12.320
Sajó Elemér	+	7.320
waterflow scheme		**10.635**
storage	–	3.500
evaporation	–	0.720
infiltration	–	*6.415*
water balance		**0.000**

Source: Compiled by the author.

The average evaporation, calculated by the Meyer method, is still estimated at 0.720 m^3/s per unit, and the longitudinal profile and the cross-section around the wells are shown in the following figures (Figures 4 and 5).

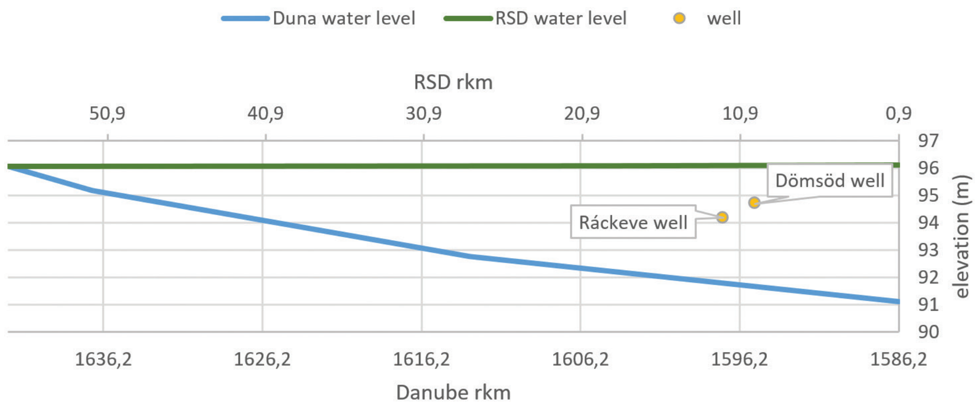

Figure 4: Water levels on 2 August 2022
Source: Compiled by the author.

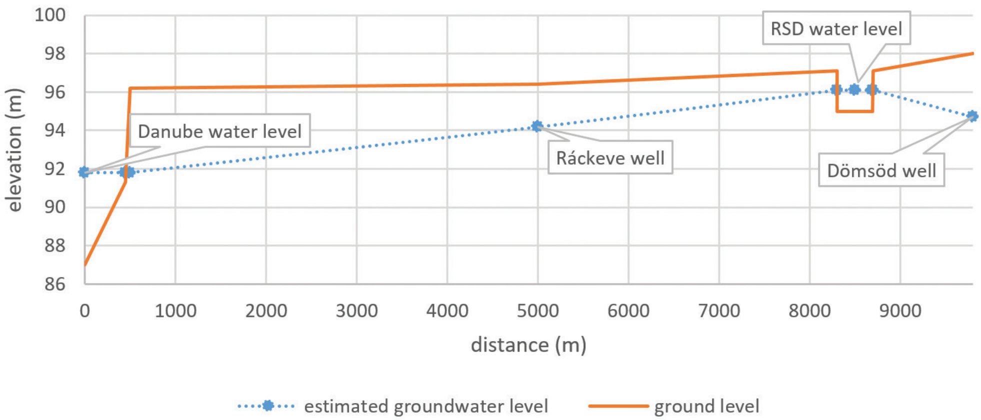

Figure 5: Cross-section (around 1,597 rkm) for Csepel Island on 2 August 2022
Source: Compiled by the author.

The water level of the RSD is permanent in the studied condition, and the groundwater level is visibly decreasing towards the Danube.

Low flood wave on the Danube, gravity feed at the Kvassay structure

In the operational regime under study, gravity feed through the Kvassay structure and no water was required through the multifunctional Sajó Elemér diversion structure, and there was no water discharge due to the filling of the system. As shown in Table 3, on 23 August 2022, 33.2 m^3/s was stored in the riverbed, which is estimated from the daily water level rise of 20 cm. Accordingly, based on the water flow, a discharge of nearly 8.9 m^3/s "disappears" in the system.

Table 3: Low flood wave on the Danube, gravity feed at the Kvassay structure, water balance data

23 August 2022		
		m^3/s
Kvassay	+	52.430
South Pest WTP	+	0.800
Gyáli	+	0.091
DTCS	–	0.251
Árapasztó	–	1.930
KÖF	–	8.270
Sajó Elemér	+	0.000
waterflow scheme		**42.870**
storage	–	33.200
evaporation	–	0.720
infiltration	–	*8.950*
water balance		**0.000**

The average evaporation, calculated by the Meyer method, is still estimated at 0.720 m^3/s per unit, and the longitudinal profile and the cross-section around the wells are shown in the following figures (Figures 6 and 7).

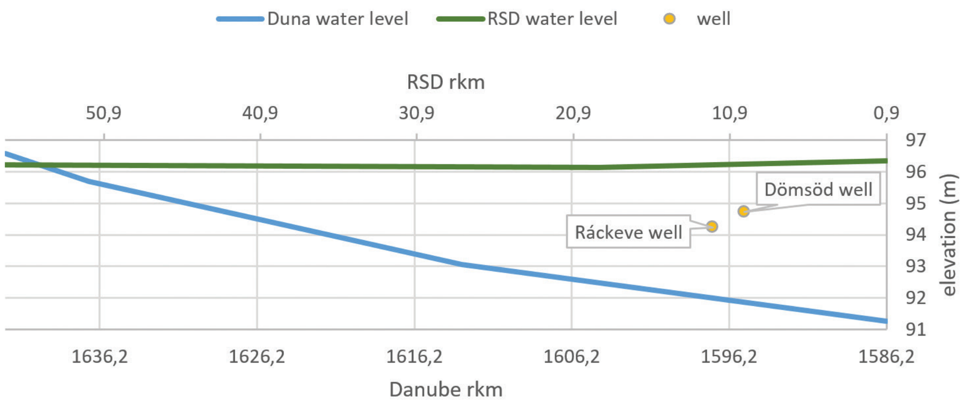

Figure 6: Water levels on 23 August 2022
Source: Compiled by the author.

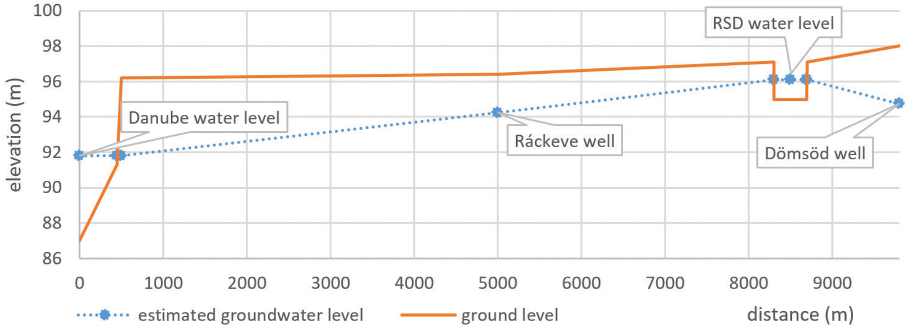

Figure 7: Cross-section (around 1,597 rkm) for Csepel Island on 23 August 2022
Source: Compiled by the author.

At this stage, the Danube water level at the Kvassay structure is higher than at the RSD, and the level at Tass is also higher due to the filling of the reservoir. The groundwater level is decreasing towards the Danube with a nearly equal slope.

No Danube water supply to the RSD

No water is supplied to the RSD from the Danube during the period of operation under consideration. As shown in Table 4, on 23 October 2022, 8.7 m^3 of stored water per second were consumed from the riverbed, estimated from a daily water level drop of 2 cm. Accordingly, based on the water flow, a discharge of nearly 3.38 m^3/s "disappears" in the system.

Table 4: No Danube water supply to the RSD, water balance data

23 October 2022		
		m^3/s
Kvassay	+	0.000
South Pest WTP	+	0.800
Gyáli	+	0.050
DTCS	–	1.000
Árapasztó	–	0.000
KÖF	–	5.000
Sajó Elemér	+	0.000
waterflow scheme	**–**	**5.150**
storage	+	8.700
evaporation	–	0.170
infiltration	–	*3.380*
water balance		**0.000**

Source: Compiled by the author.

The average evaporation calculated by the Meyer method for the autumn period is estimated at 0.170 m^3/s per unit, and the longitudinal profile and the cross-section around the wells are shown in the following figures (Figures 8 and 9).

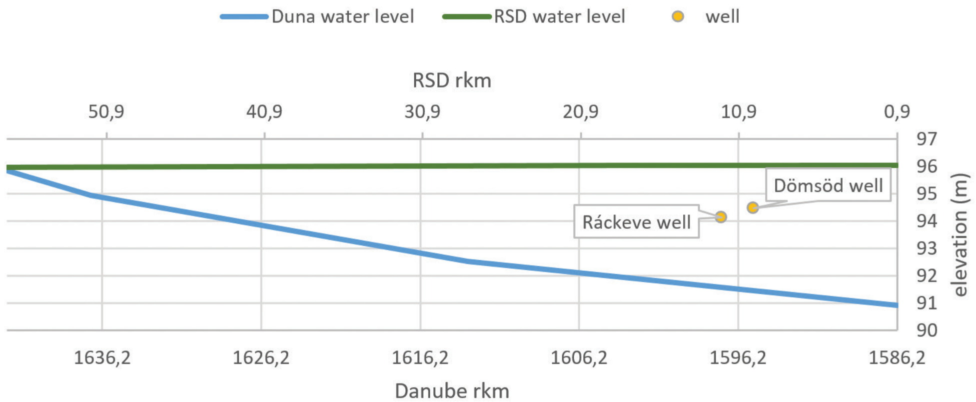

Figure 8: Water levels on 23 October 2022
Source: Compiled by the author.

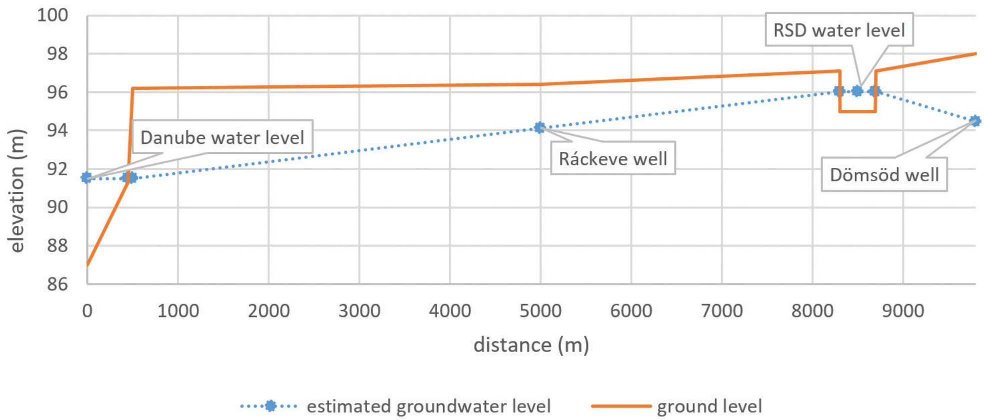

Figure 9: Cross-section (around 1,597 rkm) for Csepel Island on 23 October 2022
Source: Compiled by the author.

In this case, it can be seen that the water level in the RSD is almost unchanged, but water is continuously discharged from the system. It should also be noted that this period is particularly dangerous from a water quality point of view because of the treated wastewater on the system.[19]

[19] Györe 2018.

Conclusion

The Figure 10 summarises the water levels associated with the operating conditions analysed.

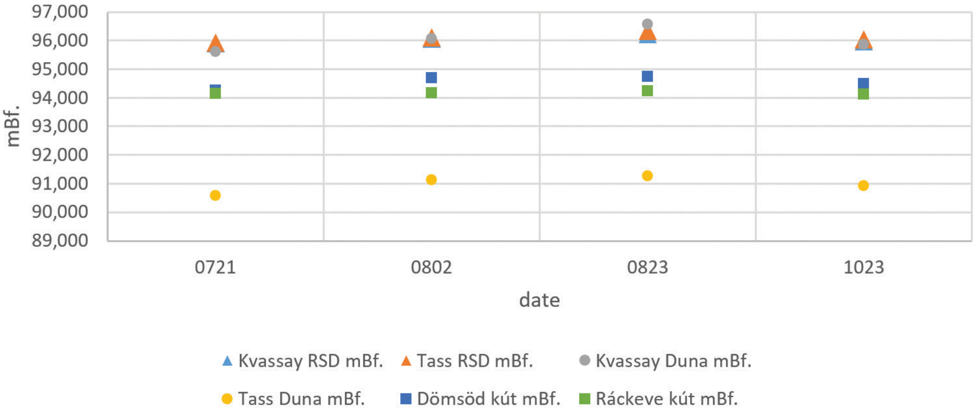

Figure 10: Water levels in the analysed conditions
Source: Compiled by the author.

It can be seen that the water levels measured in the wells are related to the water levels in the Danube and the RSD. A correlation calculation can be carried out to investigate this more specifically.

The closer the correlation coefficient is to +1 or –1, it means that there is a positive (+1) or negative (–1) linear correlation between the arrays. A positive correlation means that as the values of one array increase, the values of the other array increase. A correlation coefficient closer to 0 indicates no or weak correlation.[20]

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

The table shows that there is a strong correlation between the water level in the Ráckeve well, the RSD and the Danube water level, which shows that these values vary together. It is obvious that the water levels (Danube, RSD) are also dependent on each other, which is due to the operating characteristics. If we look at the correlation of the (estimated) infiltration values, we can see that it is highly dependent on the values observed at the Kvassay structure.

[20] CORREL function s. a.

Table 5: Correlation studies between water balance elements

	Kvassay RSD	**Tass RSD**	**Kvassay Danube**	**Tass Danube**	**Dömsöd well**	**Ráckeve well**	**Kvassay supply**	**Tass supply**	**Evaporation**	**Infiltration**
Kvassay RSD	x	x	x	x	x	x	x	x	x	x
Tass RSD	0.990	x	x	x	x	x	x	x	x	x
Kvassay Danube	0.995	0.999	x	x	x	x	x	x	x	x
Tass Danube	0.925	0.920	0.923	x	x	x	x	x	x	x
Dömsöd well	0.897	0.868	0.878	0.984	x	x	x	x	x	x
Ráckeve well	0.965	0.937	0.948	0.802	0.789	x	x	x	x	x
Kvassay supply	0.931	0.912	0.921	0.722	0.693	0.988	x	x	x	x
Tass supply	–0.572	–0.671	–0.640	–0.685	–0.554	–0.374	–0.358	x	x	x
Evaporation	0.357	0.246	0.282	0.101	0.202	0.568	0.576	0.551	x	x
Infiltration	0.940	0.898	0.914	0.770	0.776	0.994	0.978	–0.276	0.648	x

Source: Compiled by the author.

Using a literature value as a benchmark for estimating the exact value of the infiltration, the possible specific infiltration of 13,000 m^3/day/km for the Csepel section of the Danube river as described in the safety plan of the KSZI can be considered a benchmark.[21]

The boundedness of the silt layer deposited in the RSD impedes the infiltration to some extent, but if only two thirds of the specific infiltration of the Danube is considered as being relevant for the RSD, the unit seepage value of 5 m^3/s is still obtained in the summer low water hydrogeological and hydrological situation. The value obtained is supported by water balance studies for different operating conditions.

Without a more accurate model to determine the discharge, this value can only be estimated, but the figures clearly show that when the Danube water level is so low compared to the RSD, it can have a significant suction effect. As shown above, up to a quarter of the injected water volume could then be drained from the RSD. Evaporation during the summer period is also associated with a significant abstraction of water resources on the RSD, estimated at 0.5–1 m^3/s.

There may also be a risk of infiltration from the mine lakes east of the RSD, which have a large evaporation surface area, but whose drainage effect is unknown at present.

[21] KSZI Kft. 2013.

Overall, the Ráckeve–Soroksár Danube is expected to infiltration between 3 and 6 m^3/s during operation, and this should be taken into account when planning the rate of pumped water replacement.

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Legal source

Government Decree 90/2007 (IV. 26.) on the Prevention and Remedying of Environmental Damage