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Master Thesis

Improvement of the estimation of the water balance of the Kis-Balaton lake, Hungary

Submitted by

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Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 2023.02.17 Bruno Barnabás BATKI *(manu propria)*

Preface

This research was prepared with the support of the West-transdanubian Water Directorate (NYUDUVIZIG), Hungary. All data including maps, aerial photos and information about the monitoring system is only and exclusively accessible through this paper and should not used up for other purposes without the permission of the West-transdanubian Water Directorate.

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Abstract

The Kis-Balaton system is a complex reconstructed wetland that consists of three separated lakes. It functions as a water-protection system in the western part of Hungary. Recent studies have shown that there are significant discrepancies in the calculation of the water balance of the Kis-Balaton system. In order to address this issue, the responsible Water Directorate made changes to the input values to improve the calculated water balance, however, there were no clear scientific justifications behind these changes, and the calculations did not yield satisfactory results. In this thesis, a comprehensive study was conducted on the water balance calculation method of the system, with a particular focus on the input elements such as surface discharge, precipitation, and evapotranspiration. The water balance of the three lakes was calculated for the last three years, and different equations regarding evapotranspiration were tested, new storage rating curves were derived, and possible groundwater exchange in the lakes was examined. A sensitivity analysis was also performed for the input elements. The results showed that the main influencing input is surface discharge in every lake, and during the vegetation period, evapotranspiration is also significant, but it is not the main source of error. The old and new storage rating curves were found to have no significant differences, contrary to previous assumptions. Remarkable groundwater exchange was detected in the Ingói-pond, which was also analysed. The Hídvégi-lake was found to be highly sensitive to surface discharge, and accuracy in input values is crucial, as a 5-10% deviation in discharge can cause high closing errors. However, in the case of the Fenéki-lake, there was no clear reason found for the errors, despite being sensitive to deviations in discharge. In most cases, groundwater data was rare and not sufficient to make strong conclusions, so expanding the monitoring system is highly recommended.

Kurzfassung

Das Kis-Balaton-System ist ein Feuchtgebiet bestehend aus drei Seen und dient als Wasserschutzsystem in Ungarn. Die Berechnung des Wasserhaushalts des Systems war in der Vergangenheit ungenau, trotz der Versuche der Wasserdirektion, dies zu verbessern. In dieser Studie wurde der Wasserhaushalt der Seen über drei Jahre hinweg berechnet und verschiedene Input-Elemente analysiert, einschließlich Oberflächenabfluss, Niederschlag und Evapotranspiration. Die Ergebnisse zeigten, dass der Oberflächenabfluss der Haupteinflussfaktor in jedem See ist und dass eine Genauigkeit der Eingabe-Werte von entscheidender Bedeutung ist. Ein bemerkenswerter Grundwasseraustausch wurde im Ingói-Teich festgestellt. Die Ergebnisse zeigen auch, dass das Überwachungssystem erweitert werden sollte, um die Qualität der Daten zu verbessern. Es gab keine eindeutigen Gründe für Fehler im Fall des Fenéki-Sees.

1. Introduction and objectives

This thesis is about a special water management issue related to a unique water body, namely the Kis-Balaton lake. It is a “multifunctional” system since this lake (or sequence of lakes) plays important role in the quality and the quantity of Hungary’s biggest touristic destination, the Balaton-lake, but it is also a unique wetland for many endangered species. The importance of this system is well known in Hungary. However, the calculation of its water balance still has limitations. Recent years showed significant closing errors in the calculation of the Kis-Balaton system. To solve this problem the responsible Water Directorate changed the input values in order to improve and close the calculated water balance. However, there were no clear scientific reasonings and conclusions behind these changes and the calculations did not yield satisfactory results, i.e. a closure of the water balance. Although an extensive monitoring system is in operation, no investigations regarding the systematic deviations exist until now. This thesis aims to identify and address the possible sources of error in the estimation of the water balance, with a focus on their elimination.

1.1. Study area: The Kis-Balaton

Kis-Balaton system is a reconstructed wetland of approx. 70 km² situated slightly upstream of lake Balaton, with an average water depth of 1.2 m. Situated in the western part of Hungary in the delta of the river Zala, lake Balaton and the Kis-Balaton system is of notable socio-economic and ecological importance, being under constant monitoring of water resources and water management (Honti et al. 2020). The area supports remarkable biodiversity in the region, the shallow waters are an important spawning ground for fish, and the swampy meadows and reed beds provide breeding and migration habitat for endangered species (RSIS 2016). Kis-Balaton performs the function of being a protection system for Lake Balaton diverting and thus "slowing down" the inflow of the river Zala into lake Balaton. Also, Kis-Balaton aquatic vegetation filters nutrients (mainly phosphorus and nitrate) and plays an important role in capturing sediment increasing the quality of the water entering lake Balaton (Pomogyi 1993).

Kis – Balaton with its catchment area of 2622 km^2 provides 45% of the Balaton’s water supply. While the catchment of Zala river is mostly hilly, the area of the Kis-Balaton lake is rather flat, bounded by small hills. In the area of the lake in the narrower sense, the height of the terrain is 101-110 meters above the Baltic Sea level (mBf.). Regarding geology and soils the area of the lake is mostly peatland and alluvial deposits, with sand and loess (MBFSZ, 2023). The climate of the Kis-Balaton is temperate continental climate modified by oceanic and Mediterranean influences. The long-term average temperature is 10.25 °C, and the average annual rainfall is 772 mm according to 100 years long-time data of Keszthely meteorology station (OMSZ: www.odp.met.hu). Summer is typically hot and rainy, while winter is rather cold and dry. The annual temperature fluctuation exceeds 20 degrees Celsius.

The Kis-Balaton system consists of three main units, Hídvégi, Fenéki and Ingói. The system is maintained by weirs and dikes. Hídvégi is a hypertrophic lake, with a surface area of 18 km² and mean depth of 1.1 m. Lower Fenéki Lake has a surface area of 35 km² with a mean depth of 1.2 m. Ingói is a mosaic of shallow open water and reeds with approximately 16 km² (Tátrai et al. 2000; Boros et al. 2016). Figure 1 shows the Kis-Balaton system that receives water from the Zala River, which flows into Lake Balaton and has its outlet in the Sió River.

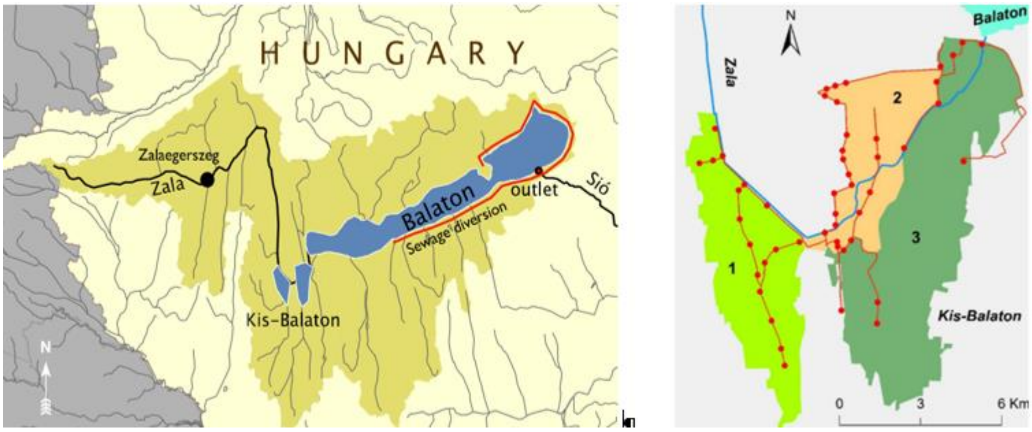

Figure 1: Position of the Kis-Balaton wetlands within the Lake Balaton catchment (left). Kis-Balaton system: (1) Hídvégi-Lake, (2) Ingói-pond and (3) Fenéki-Lake (right) (Boros et al. 2016; Honti et al. 2020).

1.2. History of the lake

Kis-Balaton has a particularly rich history. Geological researchers claim that there was contiguous water body in the area already during the late Pleistocene age approximately 50 000-60 000 years ago. However, at that time they were together with today's Balaton which was more like a marsh. (Almádi et al., 2001).

In the 18th century the land use on the Zala basin changed. There were significant deforestation activities and agricultural use became more important. As a consequence, sediments from the fields accumulated in the Zala river. To solve this, the river was regulated to a straight channel. With time this sediment accumulated in the area of Kis-Balaton. At the beginning of 20th century there were only 2 smaller lakes, which were fully drained in the 1940's. From that time the Zala flowed directly into the Balaton.

In the 1970's water specialists recognized that the quality of the water in the Balaton was continuously deteriorating. This was mostly due to the increased nutrient load (phosphorus and nitrate) which originated from the agricultural fields in the Zala basin. The Keszthely-bay of Balaton was affected the most as the water barely fulfilled the minimum quality for bathing at that time. Researches showed that if this process will go on, the Balaton will be fully eutrophicated in 20 years (Vilmos, 2022)

In the late 1970's the West-transdanubian Water Directorate (WD) planned the I. phase of Kis-Balaton system. The purpose was to prevent the accumulation of nutrients in the Balaton, so to place these processes before it reaches the Keszthely-bay. Within the relatively shallow impounded area – which is now known as Hídvégi-lake– the nutrient load arriving via the Zala will be captured by the proliferated aquatic vegetation. The construction started in 1981 and finished in 1985. The Hídvégi-lake has an area of 18 km^2, 17 % categorized as wetland, 77 % as open water and 6 % as land.

As a result of the operation of the Hídvégi-lake the total dissolved solids (TDS) load decreased by more than 30%, the total phosphorous (TP) decreased by more than 35% and the total nitrogen (TN) decreased by more than 20% in the mouth section of the Zala River until 1992 (Vilmos, 2022) .Despite the good results, experts knew that it was not enough, so they planned the II. phase of the system. Due to financial difficulties, the construction was carried out in two parts. In the first part the so-called Ingói-pond was impounded in 1992. This state is visible on Figure 2. It is a really shallow water body of 16 km^2 approximately 80 % categorized as wetland, 17 % as open water and 3 % as land (NYUDUVIZIG). After Ingói started operating in 1993, the TDS, TP and TN values in the mouth section of the Zala river decreased even more (Figure 3).

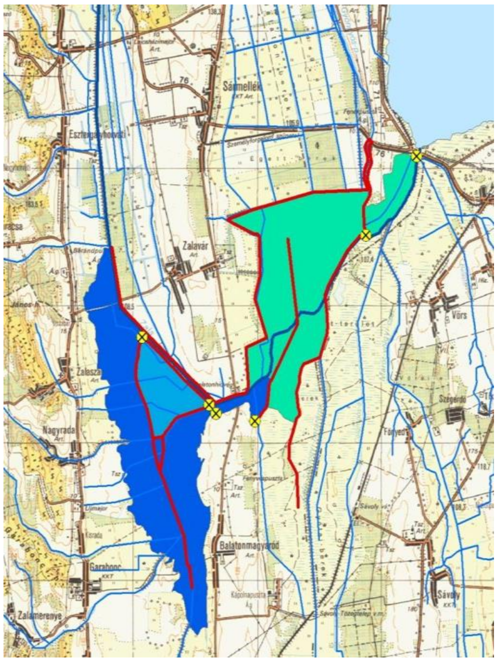

Figure 2: Kis-Balaton between 1992 and 2014. Blue: Fenéki-lake finalised in 1985, Green: Ingói-pond (finalised 1993) (NYUDUVIZIG)

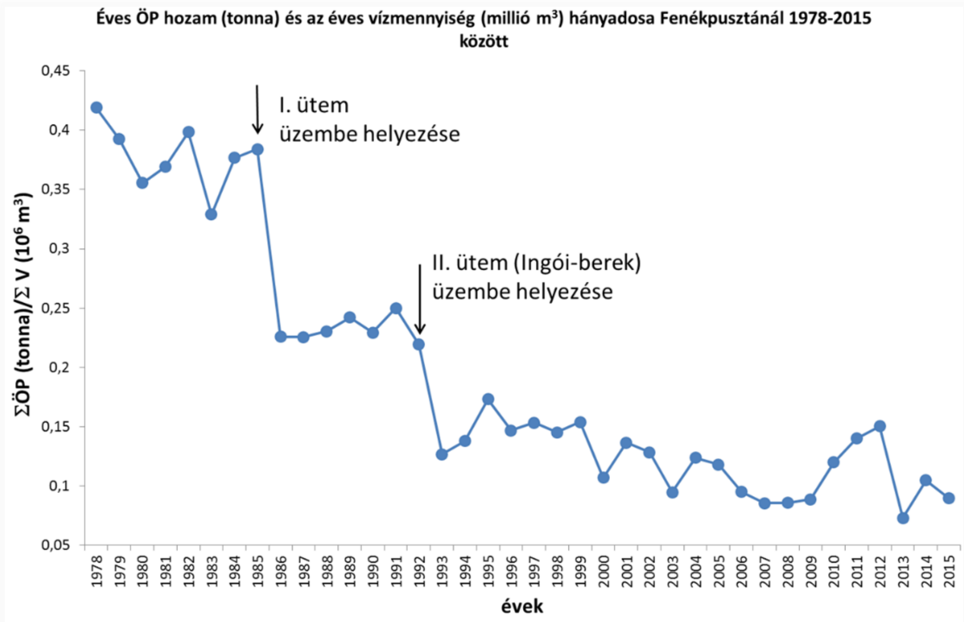

Figure 3: Total phosphorous load in the mouth section of Zala between 1978 and 2015. The arrows indicate the starting of operation of the I. phase (Hídvégi) and the II. phase (Ingói) (NYUDUVIZIG)

It needed more than 20 years for the experts to find financial resource to finish the II. phase with the construction of the lower Fenéki-lake. This part was finished in 2014. The Fenéki-lake has an area of 35 km^2, 86 % categorized as wetland, 10% as open water and 4 % as land. Figure 4 shows the final state of the system and the way of waterflow inside that.

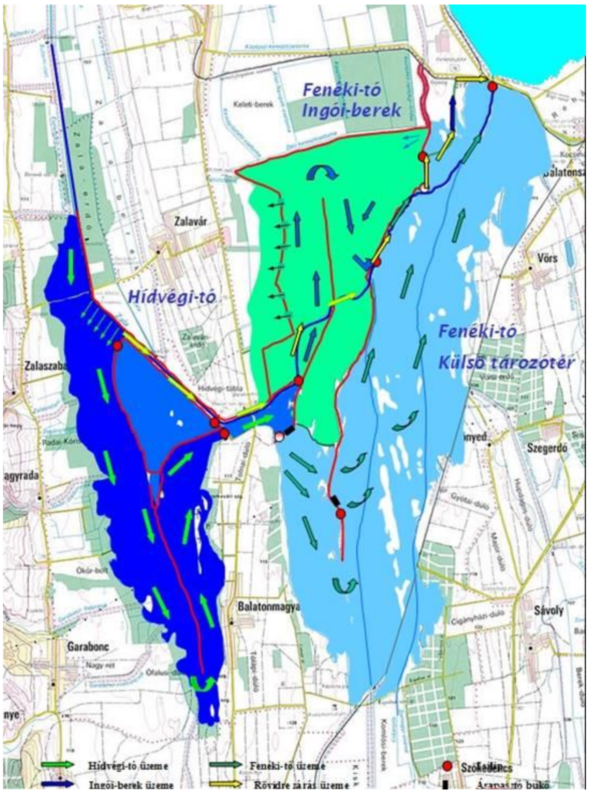

Figure 4: Final state of the Kis-Balaton system; light-blue: lower Fenéki-lake finalised in 2014 (NYUDUVIZIG)

It is indisputable that the system greatly improved the water quality of Lake Balaton. Comparing to the original state (1976 – 1985) TDS load has decreased by 82 %, TP has decreased by 70 % and TN decreased by 60 % in the mouth section of Zala river until 2019 (Figure 5.). Figure 6 shows the annual means for the respective periods of input - output ratio of TDS, TP and TN in the system in tons per year .

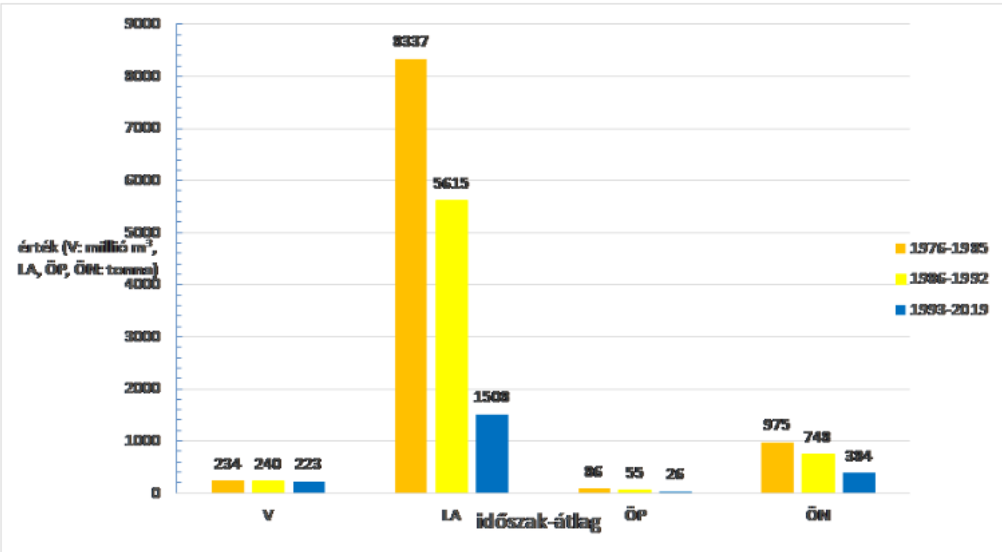

Figure 5: Mean Discharge volume (V), mean TDS load (LA), mean TP (ÖP), mean TN (ÖN) at the mouth section of Zala River in different periods (orange: 1976-1985; yellow: 1986-1992; blue: 1993-2019) (NYUDUVIZIG, 2022)

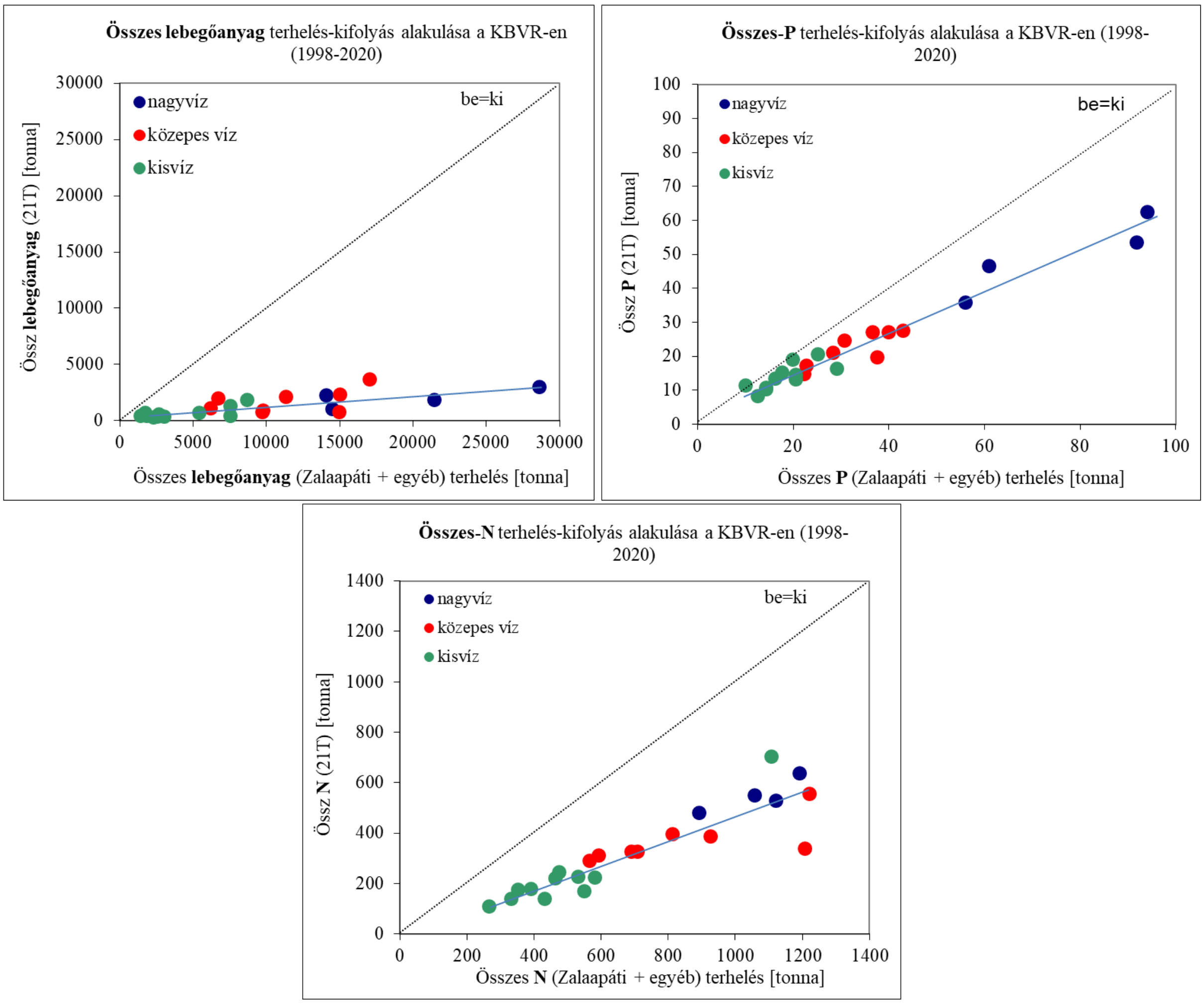

Figure 6: Ratio of the inflow and outflow of TDS, TP, TN loads in the Kis-Balaton system; horizontal axis: inflows, vertical axis: outflow. The blue dots refer to floods and high-water situations, the red dots refer to mean water and the green dots refer to low water conditions. (Department of Water Protection and Watershed Manag, 2021)

1.3. Hydrological monitoring system

A well-functioning monitoring system is very important for such a water body. Therefore, the hydrological data collection of the area goes back a long time. At the inlet Zalaapáti and the outlet Fenékpuszta section, water level and discharge data have been available since the 1970s. Of course, due to several alteration of the system the monitoring had changed. Here the current state of the hydrological monitoring is presented. Currently the following types of monitoring stations operate in the Kis-Balaton:

Table 1: Overview of the hydrological monitoring stations across the Kis-Balaton

	Surface water		Groundwater		Hydrometeorology	
	All	Automatic	All	Automatic	All	Automatic
Water level	61	61				
Discharge	14	6				

Groundwater level			22	5		
Precipitation					13	9
Evaporation					1	-
Relative humidity					4	4
Wind speed					4	4
Air temperature					4	4
Measured elements altogether (automatic)					123	93 (76%)

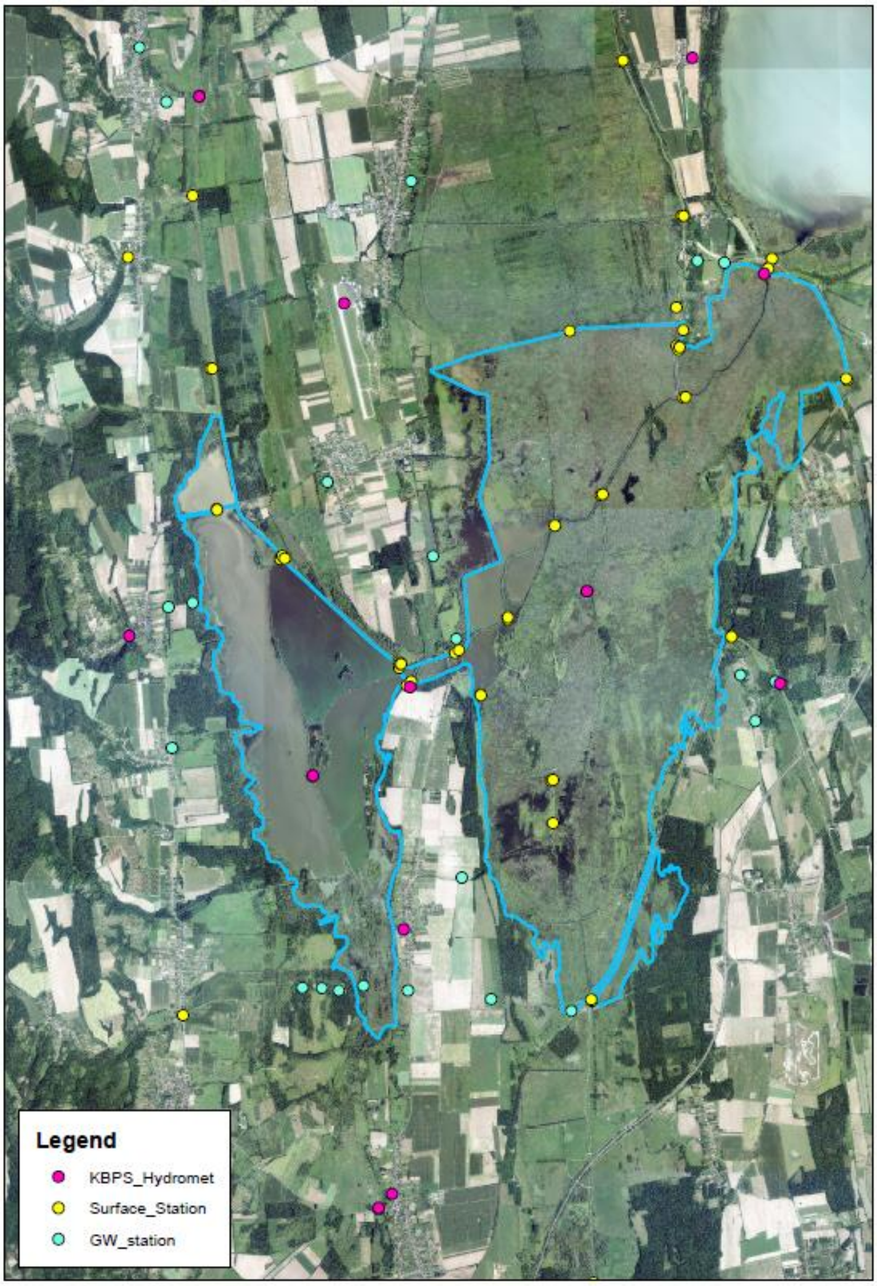

Figure 7: Position of the hydrological monitoring stations in the Kis-Balaton (NYUDUVIZG)

Figure 7 shows a dense observational monitoring network. According to Table 1 the automatization rate is 76 % for all types of stations. These measured values go into the directorate’s telemetry system called WebSCADA. This telemetry system contains all automatized station on the Kis-Balaton catchment. There is an overview of these stations on Figure 8. The less automatized categories are surface water discharge and groundwater. The automatization of discharge measuring stations is urgent as this is one of the main factors in water balance calculation.

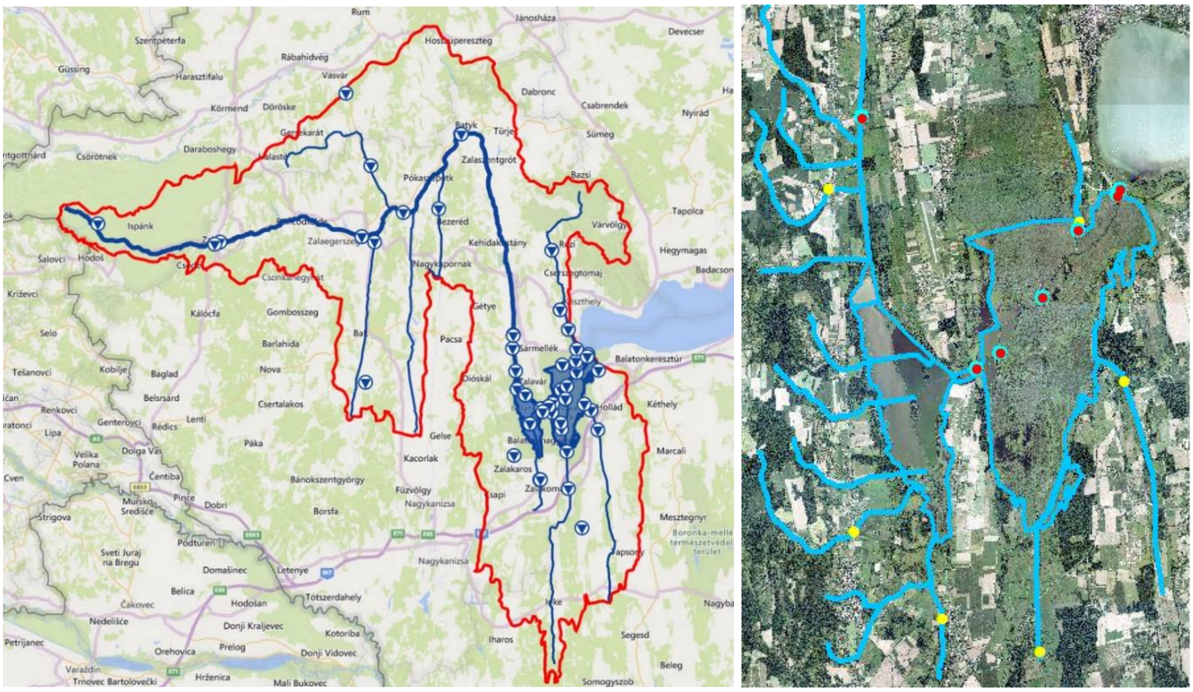

Figure 8: Left: Overview of automatized stations on the Kis-Balaton catchment (source: WebSCADA telemetry system); Right: Discharge measuring stations across KB (Red dots: Automatized; Yellow dots: Rating curve method and occasional measurements)

The lack of discharge automatization mostly affects the tributaries. There are Teledyne Channel Master H-ADCPs at the weirs and on the Zala itself, but on the smaller streams there are only periodic flow measurements either with propeller current meters or via moving boat ADCP’s. Then the directorate derives discharge rating curves from these measurements and then calculates the input discharge from the water level time series. On the right-hand side map of Figure 8 the discharge measuring stations according to the measurement method are depicted. It is visible that there are many tributaries, where there is not any monitoring station at all. The automatized H-ADCP devices requires calibration so the WD has a measurement plan to regularly check the functioning of these devices by moving boat ADCP flow measurements. These control measurements showed that the automatized devices do not operate always properly. A closer investigation of these automatic devices is also addressed in the paper.

1.4. Current water balance calculation method

The WD as the responsible operator of the system calculates the annual water balance of the lake. The calculation is made separately on a monthly basis for the 3 part-lakes. That means that for every month they calculate the input-output ratio for the Hídvégi-lake, the Ingói-pond and the Fenéki-lake. It is due to the reason of operation, because these parts maintained separately and they cannot be treated as a whole. For instance, if there is a flood event on the southern tributaries, holding back the water solely in the Fenéki-lake is possible without affecting the two other reservoirs. Since they are physically separated there could be very significant differences in storage,. The schematic representation of the main elements of the calculation can be seen on Appendix A. The calculation takes into account the input (precipitation, inflow) and the output (evaporation, outflow). The balance of the lakes is calculated based on Equation 1. (illustration on Figure 9.):

Equation 1.: Water balance calculation formula

$$\mathbf{P + R_{Ri} + R_{Gi} - R_{Ro} - E - R_{Go} = \Delta S}$$

Where:

- P: Precipitation on the area of the lake
- R_{Ri}: Inflow from surface waters
- R_{Gi} and R_{Go} : Groundwater exchange
- R_{Ro}: Surface water outflow from the lake
- E: evaporation from the area of the lake
- ΔS: change in storage

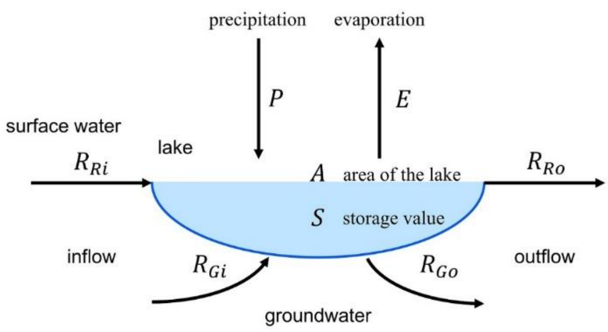

Figure 9: Elements of water balance in a lake (Water balance lake, 2019)

As is visible in equation 1, the calculated value is the storage change. However, this change is calculated in another way which is based on the existing water level-storage rating curves. It gives the volume of water inside the lake as the function of the mean water level. This storage change signed as $\mathbf{\Delta S_V}$. This value can be obtained by examining the characteristic curve as a function of the water level at times t1 and t2, and then subtracting the corresponding volumes. The accuracy of the calculated water balance is rated based on the difference of ΔS and ΔS_V. This is the so-called closing error (e). Equation 2 shows how to calculate it :

Equation 2.: Water balance closing error formula

$$e\ [\%] = \frac{\Delta S - \Delta SV}{\Delta \mathrm{SV}} \times 100$$

Of course, the calculation is more accurate if this error is as close as possible to 0%, but in no case should it exceed ± 50 mm in a month. The annual closing error is the sum of the monthly errors and this also not allowed exceeding this ± 50 mm limit. Unfortunately, however, with the current calculation approach the error is almost always higher than this limit when calculating the balance with unchanged input values. It is maybe due to the inaccuracy of the volume rating curves, or due to inappropriate input values, or both. Whatever the main reason is, the revision of the whole calculation process is urgent as well as the check of the measured values accuracy.

1.5. Objectives & Research Questions

Given this background, the overall goal of this thesis is to find and eliminate the possible error sources in the water balance of the last 3 years: Data from 2020, 2021 and 2022 is used to analyse the problem. The entire process, from data collection and processing to calculation, is undertaken for all three part-lakes. Both the original and new methods for evapotranspiration estimation are tested, and daily water balances are calculated for the year 2022, while monthly values are calculated for the remaining two years. RStudio (RStudio Team, 2020) was used for the calculations, and Microsoft Excel was utilized for the data analysis.

As an elaboration of the main objective, 3 concrete research questions are defined:

1. What effect has the evaporation method and the crop factors on the calculated water balance and the closing error?
2. What effect has the volume and area rating curves on the calculated water balance and the closing error?
3. What other effects can cause high errors in the water balance?

2. Methods

2.1. Data collection and processing

The data collection can be divided into two parts. For 2022 only raw data was available. For the previous years (2017-2022), processed monthly data from the WD was available.

The process of collecting data for the year 2022 was initiated by gathering relevant information such as water levels, surface discharges, meteorological variables, and precipitation data. To ensure the accuracy of the data, measures were taken to remove missing or falsified values from the datasets. The input precipitation data was obtained through the application of the Thiessen polygon method and sourced from the WD and the Hungarian National Meteorological Service. The discharge data was obtained solely from the Water Directorate and was comprised of raw values, some of which were measured automatically and others that were derived from the water level using Q-H rating curves. The accuracy of the Q data was confirmed through control measurements obtained from the Water Directorate. The calculation of evaporation required the collection of meteorology data, including relative humidity, wind speed, and air temperature, which was obtained from automatic stations in the centers of the lakes, as well as direct ETp data from the NMS for the surrounding area. Finally, the groundwater level data was sourced from the Water Directorate.

2.2. Precipitation

The precipitation data from ten monitoring stations, including those operated by the Water Directorate and the Hungarian Meteorological Service (OMSZ), were used to estimate actual rainfall amounts for each part of the lake using the Thiessen polygon method. The polygons and monitoring stations are illustrated in Figure 10. Proportions of the precipitation gauge data were calculated for each corresponding lake, with two versions available for the Hídvégi-lake (1st lake; green and yellow in Figure 10) when the "Kazetta" (yellow in Figure 10) was closed or open, which will be further explained in the calculation section. The corresponding rainfall amount for each lake was then calculated based on the Thiessen polygons.

table 2: Precipitation gauging stations near the Kis-Balaton

Operator institute	ID	NAME	EOVx	EOVy	Device
WD	4381	Balatonmagyaród tópart 4T	144 785	506 650	SEBA RG50
WD	4535	Zalaszabar	145 714	501 570	Hellmann
WD	4536	Balatonmagyaród	140 385	506 539	Hellmann
WD	166003	Balatonmagyaród - Fekete sziget	143 179	504 895	SEBA RG50
WD	166046	Zalaapáti vm.	155 488	502 835	OTT Pluvio2
WD	166047	Zalakomár vm.	135 339	506 083	OTT Pluvio2
WD	166048	Balatonmagyaród - Almás sziget	146 516	509 852	SEBA RG50
OMSZ	6343	Keszthely-Tanyakereszt	156 189	511 766	OTT Pluvio2
OMSZ	26514	Sármellék repülőtér	151 734	505 457	OTT Pluvio2
OMSZ	6890	Főnyed	144 844	513 357	OTT Pluvio2

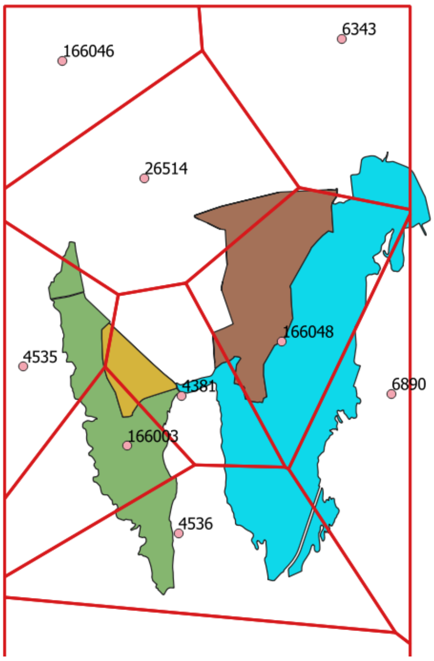

Figure 10: Thiessen-polygons

table 3: Proportions of precipitation gauges according to Thiessen-polygon method

ID	Station name	Proportion	ID	Station name	Proportion
4381	4T	0,17	4381	4T	0,05
166003	Fekete-sz.	0,40	166003	Fekete-sz.	0,45
4536	Balatonm.	0,18	4536	Balatonm.	0,21
26514	Sarmellek	0,01	26514	Sarmellek	0,02
4535	Zalaszabar	0,23	4535	Zalaszabar	0,27
Hídvégi with "Kazetta"			**Hídvégi wo. "Kazetta"**		

ID	Station name	Proportion
26514	Sarmellek	0,14
166048	Almas-sz.	0,86
Ingói-pond		

ID	Station name	Proportion
6343	Keszthely -Tk	0,08
6890	Főnyed	0,14
4381	Bmagyarod 4T	0,12
4536	Balatonm.	0,20
166048	Almas-sz.	0,47
Fenéki-lake		

2.3. Evaporation and transpiration

For the evaporation calculation the following input meteorology data had to be collected: relative humidity, wind speed and air temperature. These values came from automatic stations in the center of the lakes (166003: Fekete-sz. and 166048: Almás-sz.). Direct evaporation data from the OMSZ were also available for Sármellék (26514), Főnyed (6890) and Keszthely-Tk. (6343) stations.

Basically the reference evaporation was calculated via Antal-formula modified (Timár, 2014) (in the followings Antal-formula) which is visible as Equation 3. This formula was developed for the Neusiedlersee and it became the standard calculation method for Kis-Balaton (Anda, Nagy , Soos, & Kucserka, 2015). On the other hand direct evaporation data from OMSZ was available, which was calculated by them from their direct measurements. Furthermore, A-pan evaporation values from April to October were used in the calculations. These measurements were carried out in an A-pan by the WD at Balatonmagyaród 4T station (4381).

Equation 3: Antal formula modified (Timár, 2014)

$$E = 0{,}42\left(e_{s_a} - e\right)^{0{,}9}(1 + \alpha_t T)^9 (1 + 0{,}015 \cdot u)^2 \; [mm\, nap^{-1}]$$

In Equation 3 above ***E*** is potential evaporation in mm/day, $(e_{sa} - e)$ is the water vapor pressure deficit of the air, α_t is a constant with a value of 1/273, **T** is the daily mean air temperature and **u** is the daily mean wind speed.

However it is not enough to calculate only with the evaporation, since Kis-Balaton is largely covered by aquatic vegetation, mostly reeds. Reed can greatly influence water evaporation by its transpiration in the vegetation period. Therefore, crop factors (Kc) for reed were used on the area where the lake is covered with it. WD used the Kc factors developed for Neusiedlersee (Antal et.al., 1982). In addition to using these Kc factors, new values from a recent study were also incorporated in the calculations. In the study “Evapotranspiration and crop coefficient of common reed at the surroundings of Lake Balaton, Hungary.” (Anda, da Silva, & Soós , 2014)the authors investigated the evapotranspiration in a common read planted A-pan at Keszthely for years and they determined new Kc factors for reed. They separated years with different climate according to TI (Thornthwaite) index. Based on that new Kc factors had been determined for cold, normal and hot climate. The original and the new Kc factors are illustrated in table 4.

Table 4: Kc factors for reed ((Anda, da Silva, & Soós , 2014); (Antal et.al., 1982))

Cold	Normal	Hot	Month	Original
0.8	1.05	1.15	04	1.02
0.6	1.20	1.40	05	1.11
0.7	1.40	1.50	06	1.20
0.8	1.50	1.60	07	1.26
0.8	1.00	1.40	08	1.21
0.6	0.80	1.20	09	1.13
1.0	1.00	1.00	10	1.11

Final potential evapotranspiration (ETP) values were then derived by multiplying the reference evaporation with Kc factors and weighting with the area of reed coverage in the lake. Equation 4 shows this, where E0 is the reference evaporation, Aw is the area of free water surface, Ar is the area of reed coverage in the lake and Kc is the reed crop factor.

Equation 4.: ETP calculation

$$ETP\ [mm] = \frac{(E0 \times Aw) + (E0 \ \times Kc \ \times Ar)}{Aw + Ar}$$

To utilize Equation 4 as an analytical tool, an assessment of the reed coverage within the lakes was necessary. For that purpose Sentinel-2 images (European Space Agency, Copernicus Applications, 2023) for the year 2022 (Figure 11.) were downloaded from https://efold.gov.hu/. This is a government-operated platform designed for the purpose of gathering publicly available satellite imagery for Hungary. I used ESA SNAP software (European Space Agency, SNAP - ESA Sentinel Application Platform, 2023)and ArcGIS ArcMap 10.8.2 (ESRI, 2012) for clustering the images. I validated the clusters by aerial photos, however these aerial images are from 2018. Still, they gave me info about which pixel should be obviously reed or water or grassland etc. I found that the reed coverage has not changed significantly to those values which I got from the Directorate. Table 5 summarizes the results for the 3 parts.

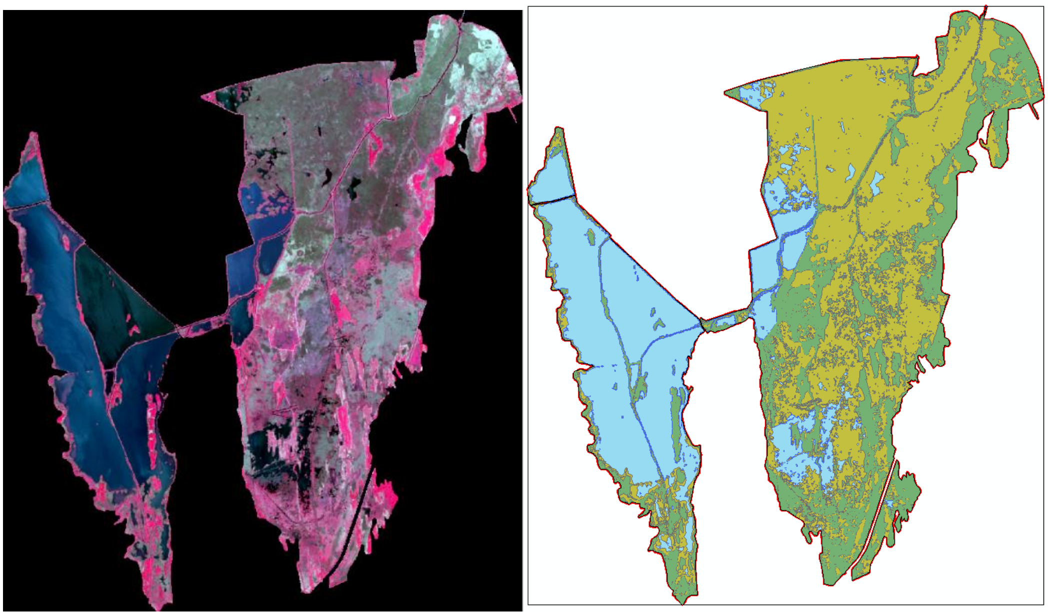

Figure 11: Left: Near-infrared image from Sentinel-2 satellite for 01.06.2022; Right: Clusterized map of the left hand-side image (blue: open water surface; yellow: reed; green: grassland)

Table 5: Percentage of reed coverage in the 3 parts of Kis-Balaton

	Reed (%)	Free water surface (%)
Hídvégi-lake	18	82
Fenéki-lake	85	15
Ingói-lake	82	18

2.4. Volume and area rating curves

To start to calculate the water balance the derivation of new volume and area rating curves was needed. For that purpose, recent survey results were used up. In 2019 there was a Lidar survey in the area and in 2020 the WD made a sonar survey in the lakes. Using these two the DEM of the area was created using ArcGIS (Figure 12. left hand side). The lakes were separated according to storages and the storages were subdivided according to typical water level in each part (Figure 12. right hand side). This separation was necessary because there can be remarkable differences in water level even in the same storage. For example in the Fenéki-lake there is an average difference of 1 m between the westernmost and easternmost part in the typical water level. Therefore the Fenéki-lake was split into 4 parts (5 ,6, 7, 8 on Figure 12.), the Hídvégi-lake into 3 parts (1, 2, 3 on Figure 12.) and only the Ingói-pond remained as a whole (4 on Figure 12). Then for these separated parts the "Cut & Fill" tool was applied and the DEM had been "inundated" by these artificial surfaces which representing the water table in the lake. This process was done for all parts by raising the inundation level by 20 cm until the maximum operational water level was reached. As a result of this process new volume and area rating curves had been determined for each part lake. This was a key step for the new calculations not just because this is the basis for error calculation, but because the old rating curves from WD were derived in the time of the construction of the parts and of presumably, there have been changes in the bed of the lake. The table of the updated rating curves is available in Appendix C of this paper.

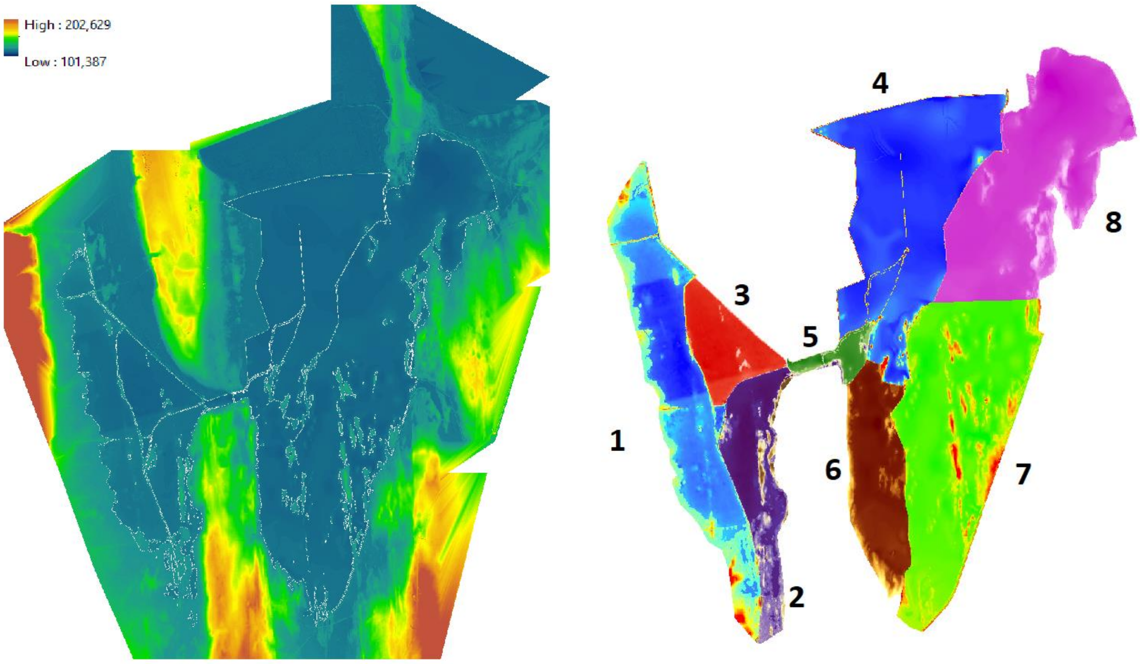

Figure 12: Left: DEM based on Lidar and sonar survey (units: mBf.); Right: Splitted parts for new rating curves

2.5. Surface discharge

For the surface discharge the data of 12 stations were used. The characteristics and the connections with the lakes are summarized in Table 6. The position of the stations is illustrated on Figure 13. The station numbers presented in Table 6 correspond to the stations shown in Figure 13. The connections between each station and the three part-lakes (Hídvégi, Ingói, Fenéki) are marked with different colors in the table, and the method of discharge determination is also indicated. The water network appears to be relatively dense, particularly in the western part of the study area. However, it should be noted that many tributaries are not measured. The Water Directorate's experience suggests that these tributaries often dry out and have a negligible impact on the water balance.

Table 6: Discharge measurement stations in the Kis-Balaton system

No.	Name	Water body	Inlet for	Outlet for	Method
1.	Zalaapáti	Zala-river	Hídvégi-lake	-	automatic
2.	Esztergályhorváti	Esztergályi-creek	Hídvégi-lake	-	Q-H curve
3.	Garabonc	Orosztonyi-creek	Hídvégi-lake	-	Q-H curve
4.	Zalakomár	Kiskomáromi-chanel	Hídvégi-lake	-	Q-H curve
5.	Balatonhídvég	Zala-river	Fenéki-lake	Hídvégi-lake	automatic
6.	24 T weir	Kis-Balaton	Ingói-pond	Fenéki-lake	automatic
7.	25T weir	Kis-Balaton	Fenéki-lake	Ingói-pond	automatic
8.	Fenékpuszta	Egyesített-chanel	Ingói-pond	-	manual meas.
9.	Szőkedencs	Zala-Somogyi ditch	Fenéki-lake	-	Q-H curve
10.	Főnyed	Marótvölgyi-chanel	Fenéki-lake	-	Q-H curve
11.	21T weir	Kis-Balaton	-	Fenéki-lake	automatic
12.	Fenékpuszta	Zala-river (mouth)	-	Fenéki-lake	automatic

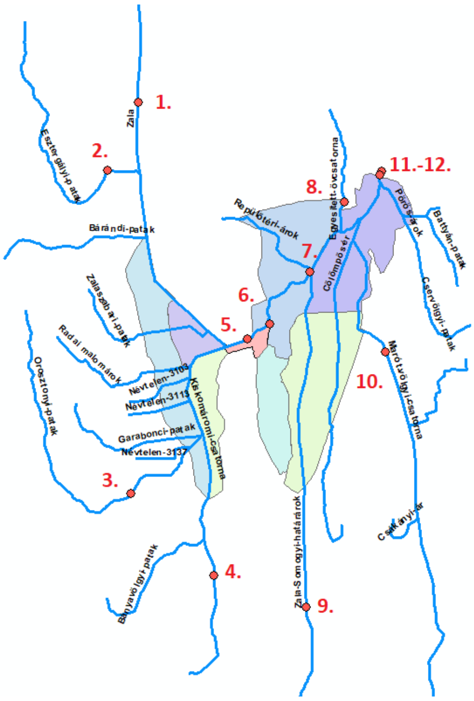

Figure 13: Water network and discharge measurement stations in the Kis-Balaton system

For the year 2022, only raw data was obtained from the WD. To ensure accuracy of the data, control measurements were conducted and the results of the automatic stations were checked and corrected where necessary. Due to the complexity of the task, involving numerous NA values and discrepancies between automatic and control measurements, a detailed description of the correction process is beyond the scope of this paper. The method involved identifying data pairs, where the automatically measured value was compared to the corresponding control measurement in order to detect any systematic deviations. Where a strong correlation was observed, raw values were corrected using the equation of the correlation line. An example is shown on Figure 14. which applies to 1. Zalaapáti station. There we can see that in the case of low flow the automatic device underestimated and during high flow it overestimated the discharge. Given the strength of the correlation, the time series was adjusted by substituting the automatically measured discharge for the independent variable 'x' in the correlation equation, resulting in the computation of the actual discharge values.

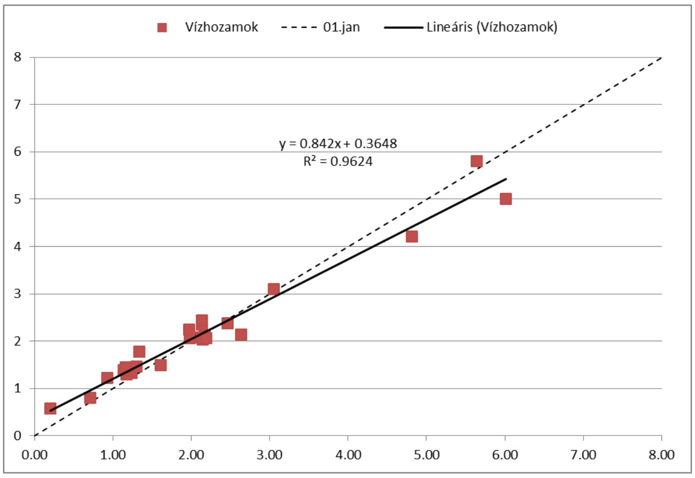

Figure 14: Correlation of automatically measured discharge (x axis) and control measurements (y axis) [m^3/s]

2.6. Water balance calculation

As mentioned earlier the daily balance was calculated for 2022, however the results were aggregated by month as well. For 2021 and 2020 only monthly values were available, therefore monthly balances were calculated. It was impossible to calculate more years, because from 2019 only "corrected" input values are available, which means that the WD changed these values in order to minimize the closing error.. For each calculation, the comparison of the calculated water balance and the storage change was performed, which resulted in values of the closing error for the periods. The water balance calculation was made in RStudio.

For every lake part basically 6 calculations were carried out where the changes affected only the evapotranspiration:

1. Antal E + Antal Kc (standard)
2. Antal E + ANDA Kc
3. OMSZ E + Antal Kc
4. OMSZ E + ANDA Kc
5. A-pan E + Antal Kc
6. A-pan E + ANDA Kc

Some calculation for each lake is available as a .Rmd result file in Appendix B. There are comments in the files to make each step easier to understand. However, there are some acknowledgments that must be clarified before moving on to the results.

- For Hídvégi-lake the inflow from the western tributaries is derived from No 3. Orosztonyi-creek – Garabonc data. The topography and geology of the catchments are quite similar and there were some manual measurements on the small creeks which showed that the summarized discharge of the tributaries is around 30% of the Orosztonyi-creek's discharge. Therefore there is an input element in the calculation named "Own catchment" which is calculated by this way.
- The "Kazetta" is a separated part of the Hídvégi-lake. It can only gain or lose water if the respective weirs are open. It is used for the isolation of pollution and floodwater. Normally, it does not participate in the flow. Therefore a logical dataset had been built in with 0-1 to indicate when the "Kazetta" operated. This is the reason why this part must be calculated separately in the case of characteristic curves and when determining precipitation and the

area of evaporation. The model was built up in a way that if the "Kazetta" is closed the model does not count it into the lake area, and the volume change because it was hermetically separated from the other parts of the lake. It affects both precipitation, evapotranspiration and storage change. This is a new approach that has not been used before by the WD.

- There are pumping stations which pump the undrained excess water from outside into the Hídvégi and the Fenéki-lake. Although their operation is temporal, the effect of the pumping stations had been built into the model. However, the daily values of the pumped water volumes were available, there is no guarantee that they are correct, because there is no option for control.
- Regarding the ETP and Anda Kc values, the distinction between cold, warm and normal climates was determined based on air temperature differences to longtime air temperature. If the mean air temperature in corresponding month was higher by 10% compared to the long-term values, a "hot" Kc factor was used. When it was lower by 10% the "cold" and if it was between ±10% a "normal" Kc factor was used. The long-term data of Keszthely meteorology station was used for the comparison. The data series goes back to 1951.

3. Results and Conclusions

This chapter presents the results and conclusions for each part-lake of the Kis-Balaton.

3.1. Hídvégi-lake

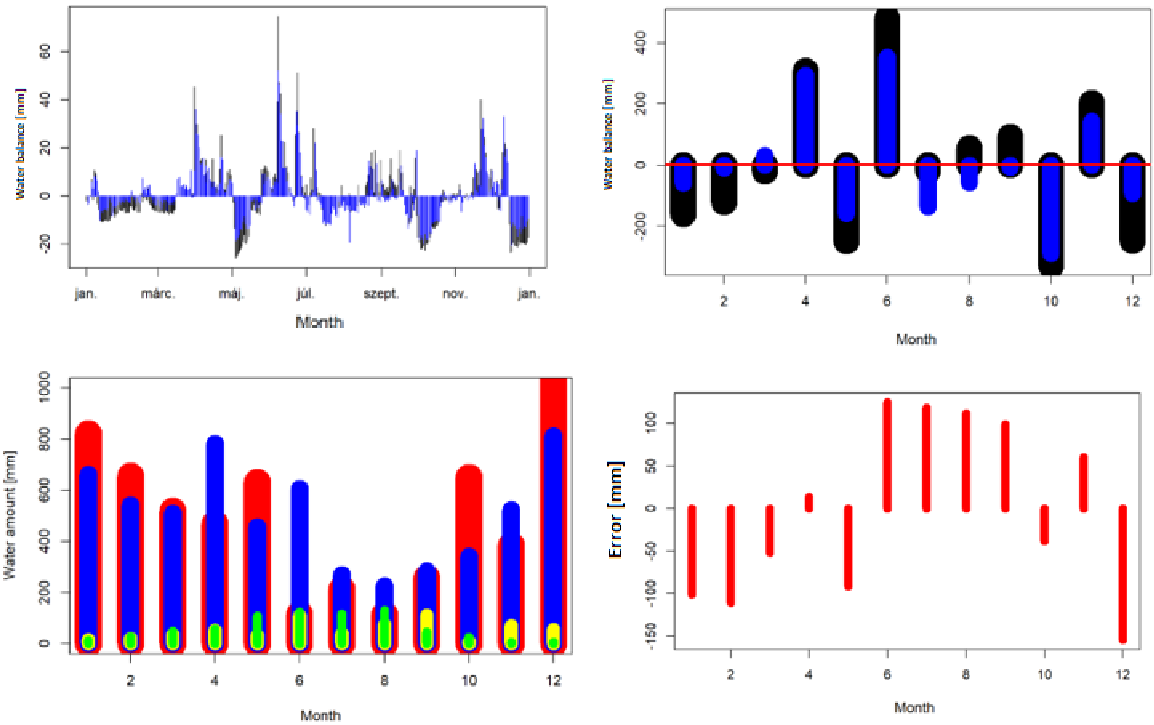

Figure 15: Water balance results of Hídvégi-lake; upper left: daily balance for 2022 [blue: storage change; black: calculated]; upper right: daily balance for 2022 aggregated to monthly values; lower left: input elements in the calculation for 2022 [blue: inflow, red: outflow, green: ETP, yellow: Prec.]; lower right: monthly closing errors in mm for the calculation “Antal E + ANDA Kc” for 2022.

After all the 6 versions were calculated for each year, it was clear that the calculated balance showed enormous differences compared to observed storage changes. Figure 15 above represents the version: Antal E + ANDA Kc for 2022. However, all methods showed large errors. Figure 16 below illustrates the errors for Hidvegi-lake in all versions for the whole research period. This figure represents that errors of ±100 mm or even ±200 are not uncommon either. Negative errors mean that the calculated balance is more negative than the volume change in the lake.

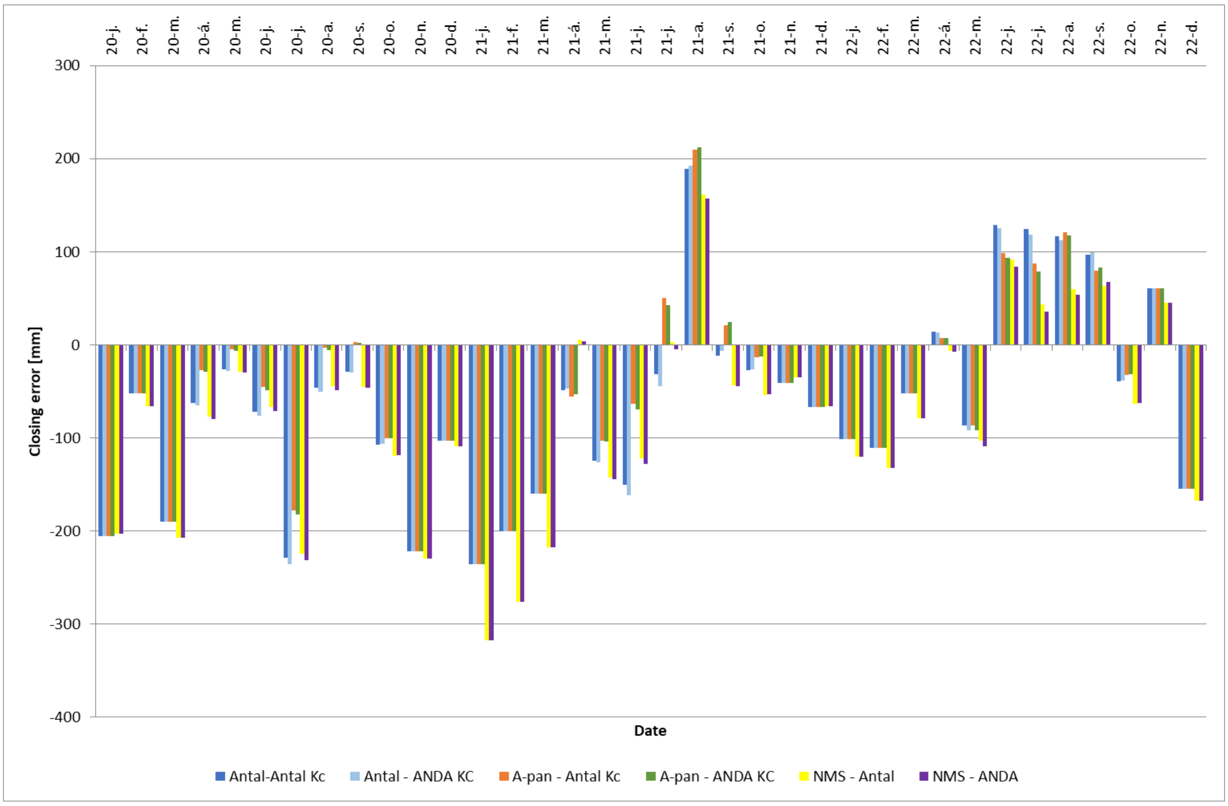

Figure 16: Closing errors for Hídvégi-lake, all versions

3.1.1. Influence of evapotranspiration

Since the different versions only affected evapotranspiration, which is only significant in the vegetation period, it is therefore worthwhile to compare the differences between the versions taking into account only the vegetation period. This period was defined from April to October. A closer investigation of these months including their: mean, absolute mean, sum/year, absolute min, absolute max, and number of months in limit (%). For the latter, the limit is ± 50 mm. Figure 17 shows these statistics for all the 6 versions.

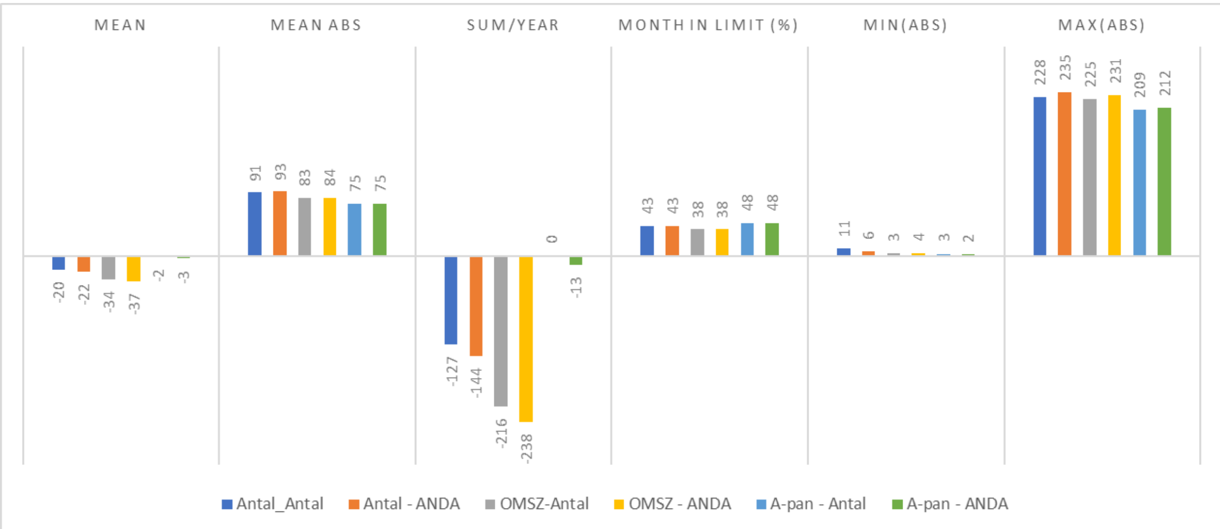

Figure 17: Summarized statistics of ETP methods for Hídvégi-lake

It turned out that all methods gave more or less the same result regarding the mean and the absolute mean, min and max deviations. Remarkable difference can be seen only in the summarized deviations where the A-pan methods gave the best and the only applicable results. It is obvious that ETP is close to A-pan evaporation since 82% of the Hidvégi-lake’s area is free water surface. This also means that the Kc factors have relatively small influence on the results. Despite the usage of A-pan evaporation showed really good summarized error values, the absolute mean and the abs max deviations and the month in limit are almost as bad as the other methods. This suggests that something, other than evapotranspiration caused these high errors. To find that out, sensitivity of the balance for ETP was checked. Figure 18 demonstrates that there can be around 30 – 90 mm difference in the vegetation period depending on which ETP method was used. This means that in the summer period errors up to this amount could be caused by ETP method.

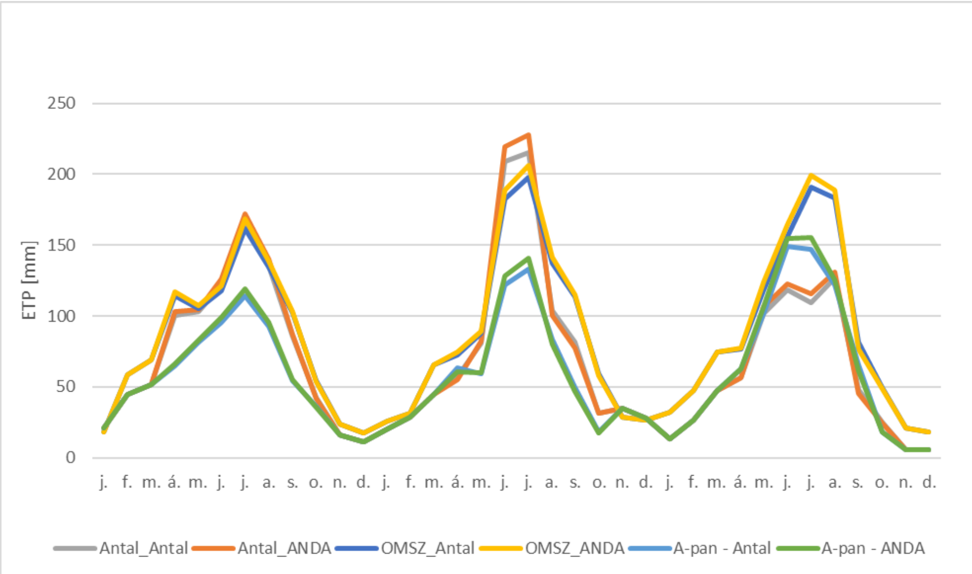

Figure 18: Monthly ETP sums for Hídvégi-lake

However, to define the real influence of the ETP method the significance of this input element must also be considered. Analysis was made to determine the percentage contribution of each element to the overall water transport during each month. Based on the observations from Figure 19, it is evident that the inflow and outflow (Qi+Qo) of surface water play a dominant role in the water balance of Hídvégi-lake. Even during the vegetation period, in a season of intense drought, surface water inflow and outflow contributed more than 50% of the total water transport. This proportion increases to 90% outside the vegetation period, thereby providing an error margin of no more than 10% in the absence of any inaccuracies in these discharges. The evapotranspiration (ETP) is only significant during the summer months and can contribute a maximum of 30%, depending on the prevailing climatic conditions. The influence of precipitation (P) is around or most of the time under 10%. The orange line on Figure 19 represents the closing error.

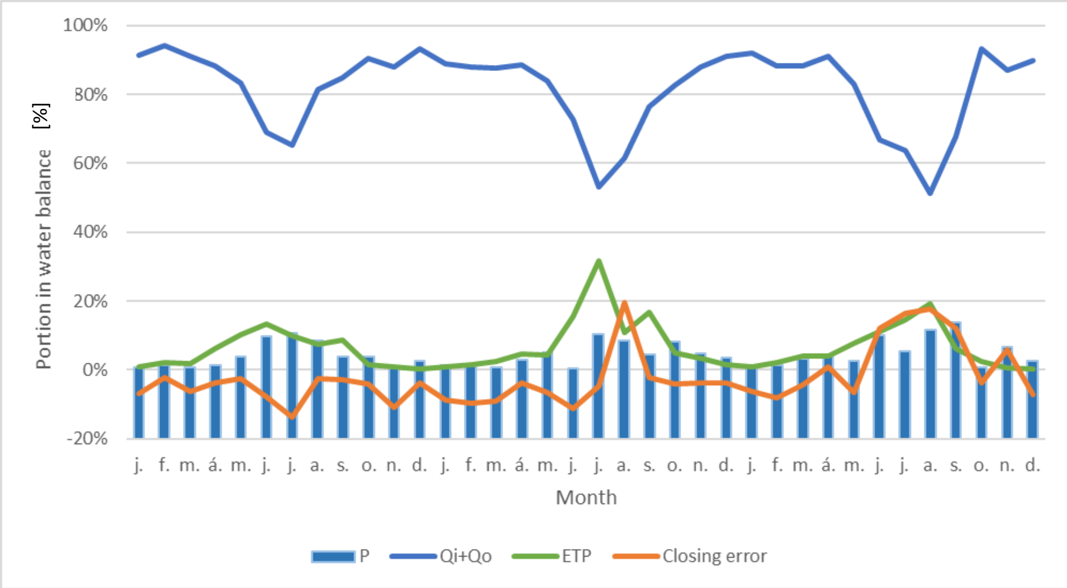

Figure 19: Influence of input elements in the water balance of Hídvégi-lake (2020-2022)

Regarding the error, it is visible that the errors can be positive only during low flows and high ETP. Positive error means that we assumed more output from the system than in reality. In terms of ETP this means an overestimation. However positive error affected only 6 months of the total 36. In most of the months there were negative error and this gives rise to two assumptions. One is that there is a constant inflow to the system which was not considered. The other one is that there is a constant error in the input elements.

If there is just one thing what is good about that the water balance for 2022 was calculated on a daily basis is the possibility to investigate the correlation between the calculated balance and the daily storage change. On the left side of Figure 20 this correlation plot is visible. The 81% correlation can be considered as a really good fit. The right-hand side graph shows the calculated daily values between January and April. It is clear that the two lines move together, but the calculated one has a constant negative difference to the blue storage change line. It also raises the assumption that there must be some inflow to the system which has not considered (just a reminder: in case of negative error we assume something on the input side because output is much higher than input and that caused the negative error).

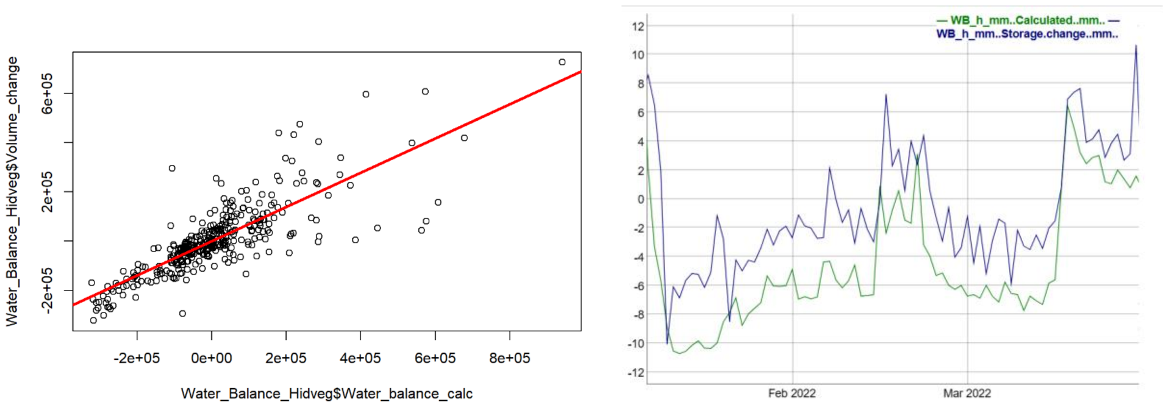

Figure 20: Left: Correlation between calculated daily balance and daily storage change; Right: time series for calculated balance (green) and storage change (blue)

3.1.2. Analysis of groundwater exhange

The assumption of a constant groundwater inflow to the system was made, and as a means of validating this assumption, the level of groundwater in surrounding monitoring wells was monitored.The left graph on Figure 21 shows the monitoring wells near the Hídvégi-lake. Unfortunately, some wells have not been in operation for years, still investigation of the data of 10 wells was possible. Following a thorough examination of the groundwater levels in relation to the mean water level of the area, it was determined that 2 wells (identified by the red circles in Figure 21) provide significant information. These are the most closely operating wells to the lake, namely Zalaszabar 3/4 and Garabonc 6/5. The time series of other wells did not show connection with the closing errors. On the right side of Figure 21 there are the groundwater level of these 2 wells (purple and brown) and the water level of the western part of the lake (blue). The closing errors are also highlighted with green bars on the diagram.

Figure 21: Left: Map of observation wells around Hídévi-lake; Right: Groundwater level time series and closing errors

The graph on the right-hand side of Figure 21 led to the following observations: positive errors occurred exclusively when the groundwater levels were lower than the lake water level, reflecting the expected groundwater recharge mechanism. However, it should be noted that a lower groundwater level does not always lead to a positive error. To minimize the effect of evapotranspiration, data from the summer months was excluded. Next, a correlation analysis was performed between the errors and both groundwater levels and the difference between the lake water level and the groundwater levels. The correlation plots are presented in Figure 22. Data from months with an ETP influence greater than 10% was excluded from the analysis.

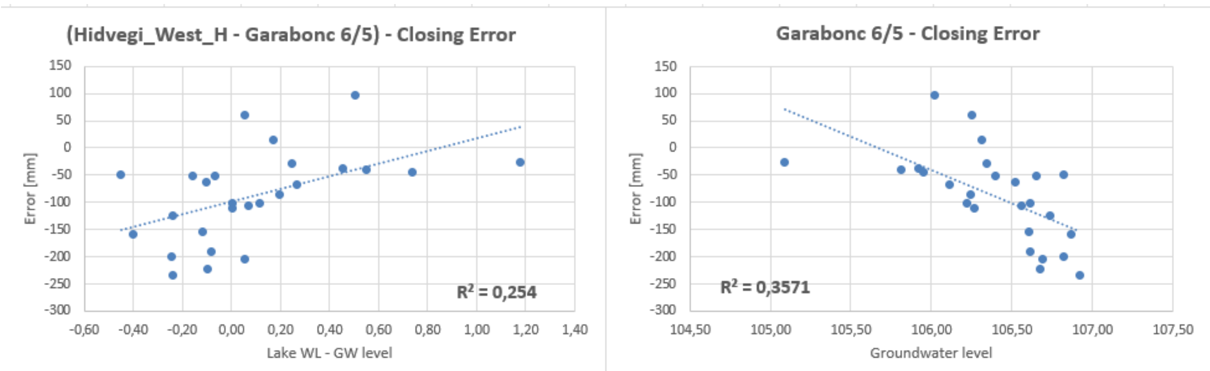

Figure 22: Relationship between lake & groundwater levels and closing errors in the water balance

Results from the correlation analysis did not indicate a significant association in either case. However, the relationship observed for the Garabonc well suggests that a higher water level in the surrounding area is associated with a larger negative error, indicating possible groundwater inflow. Nevertheless, the data also showed substantial deviations, such as the point at 106.60 mBf, where a -230 mm error and a - 50 mm error can be observed. Based on the available data, it can be concluded that there is likely to be some groundwater exchange, but the extent of this exchange cannot be determined with a high level of confidence.

3.1.3. Influence of updated rating curves

In the next step the influence of the new rating curves was checked. Figure 23 meant to show the old (red) and the new (blue) values for storage volume and area. Again, the Kazetta was treated separately. While there is no significant difference in volume in the main part of the lake, there is some difference regarding lake area above 106.00 mBf. water level. There is a considerable difference in the Kazetta both in volume and area.

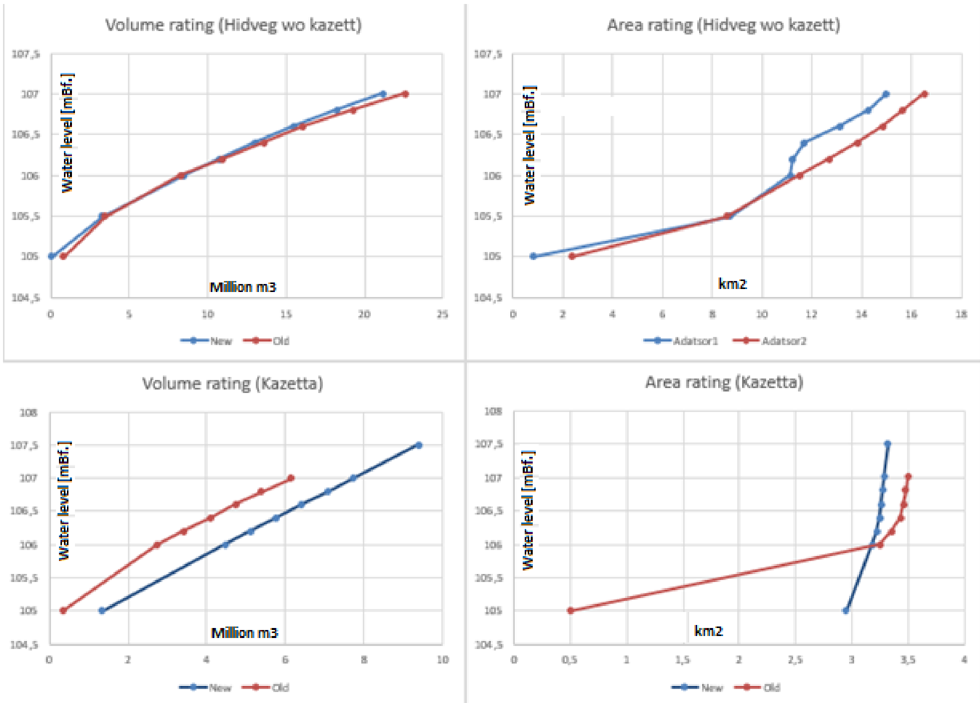

Figure 23: Volume and area rating curves for Hídvégi-lake

Next step was the investigation of what influence these differences have on the water balance calculation. Table 7 shows the old and the new values and the difference of volumes in percentage and in mm. Not counting the 105.00 and the 107.00 water levels, it is visible that differences range from – 18 mm to 72 mm. The right Table shows the values for the Kazetta. Here huge differences can be observed of partially more than 500 mm.

Table 7: Absolute differences for storage volume, Left: Hídvégi-lake; Right: Kazetta

Stage	Vnew	Anew	Vold	Aold	diff %	diff mm
105	0,1	0,8	0,8	2,4	1107	936
105,5	3,3	8,7	3,5	8,6	5	17
106	8,5	11,1	8,3	11,5	-2	-18
106,2	10,7	11,2	11,0	12,7	2	20
106,4	13,0	11,7	13,6	13,8	4	47
106,6	15,5	13,1	16,1	14,8	4	48
106,8	18,2	14,3	19,3	15,7	6	72
107	21,2	15,0	22,6	16,5	7	95
107,5	28,9	15,8	NA	NA	NA	NA

Stage	Vnew	Anew	Vold	Aold	diff %	diff mm
105	1,3	3,0	0,4	0,5	-74	-336
106	4,5	3,2	2,8	3,3	-39	-541
106,2	5,1	3,2	3,4	3,4	-33	-532
106,4	5,8	3,2	4,1	3,4	-29	-511
106,6	6,4	3,3	4,7	3,5	-26	-515
106,8	7,1	3,3	5,4	3,5	-24	-508
107	7,7	3,3	6,2	3,5	-20	-478
107,5	9,4	3,3	NA	NA	NA	NA

Analysis of the curves and the difference between consecutive volumes reveals a notable decrease in differences, suggesting that changes in storage have no significant impact on the water balance.. This is represented in table 8 (left: Hidvegi-lake without kazetta, right: Kazetta). Overall, the maximum effect of the new storage curves is ± 30 mm, which is within the standard margin of error (± 50 mm).

Table 8: Difference of new and old storage curves according to increment, Left: Hídvégi-lake; Right: Kazetta

Stage	Vnew	Vold	diff %	diff mm
105			NA	NA
105,5	3,2	2,7	-18	-67
106	5,2	4,8	-7	-32
106,2	2,2	2,7	19	38
106,4	2,3	2,6	14	28
106,6	2,5	2,6	3	6
106,8	2,7	3,2	15	28
107	2,9	3,3	14	27
107,5	28,9	NA	NA	NA

Stage	Vnew	Vold	diff %	diff mm
105			NA	NA
106	3,1	2,4	-23	-230
106,2	0,6	0,7	1	3
106,4	0,6	0,7	8	16
106,6	0,7	0,6	-3	-6
106,8	0,7	0,7	2	5
107	0,7	0,8	14	29
107,5	9,4	NA	NA	NA

3.1.4. Relationship of closing errors and discharge measurements

Given the persisting large negative errors, a correlation analysis was conducted to investigate the relationship between closing errors and individual input variables, including surface inflow, surface outflow, precipitation, evapotranspiration, and water level. The analysis revealed no significant correlation between the errors and any of the variables, except for surface outflow. Surprisingly, a strong correlation (R^2 = 0.66) was observed between outflow and error, as shown in Figure 24. This is strange since there is only one outflow of the first lake namely the Zala – Balatonhídvég automatic discharge measurement station. This is one of the most stable operating station of the WD. The raw data had been previously adjusted to the control measurements, but the differences were not significant. Based on the high level of confidence in the accuracy of the 2022 outflow values, a correlation analysis was conducted using the 2022 data only, as illustrated in Figure 24. Surprisingly the correlation was even stronger (R^2=0.9).

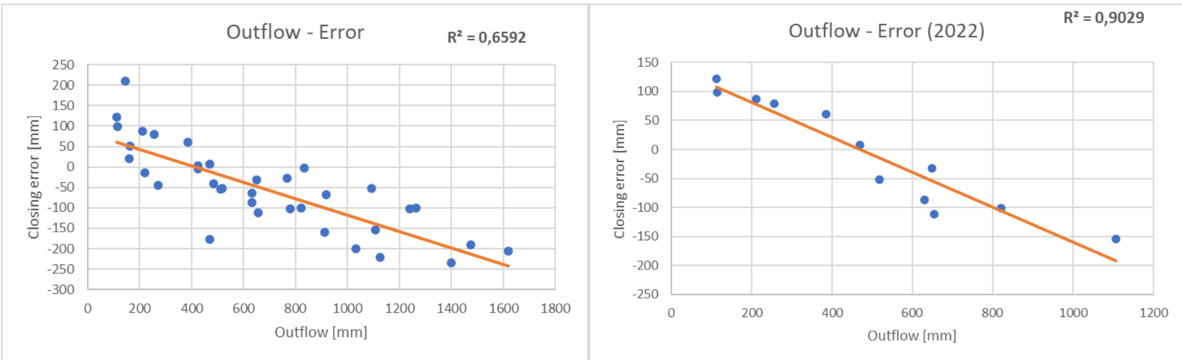

Figure 24: Correlation plot for Outflow and error, Right: 2020-2022; Left: 2022

The results were also converted to m^3/s for a better comparison as visible in Figure 25. According to the trend line the case is the following: When there is high discharge at the outflow section there are negative errors in the calculated balance. When there is low discharge there are positive errors. To be understandable, it suggests that at high discharge the automatic station measures more than the real and at low discharge it measures less than the real flow rate.

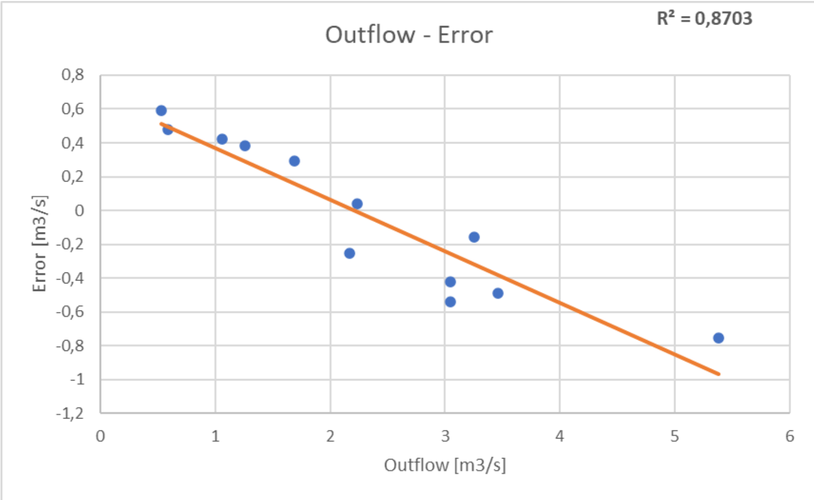

Figure 25: Correlation for Outflow and error in m^3/s, 2022

A further examination was conducted of the raw and processed discharge values for the station in question. Figure 26 displays the correlation between the control measurements and the automatically measured discharges for 2022, with the raw values adjusted using the linear correlation equation. Figure 27 displays the resulting discharge time series, which indicates a reduction of low discharges and an increase of high ones.

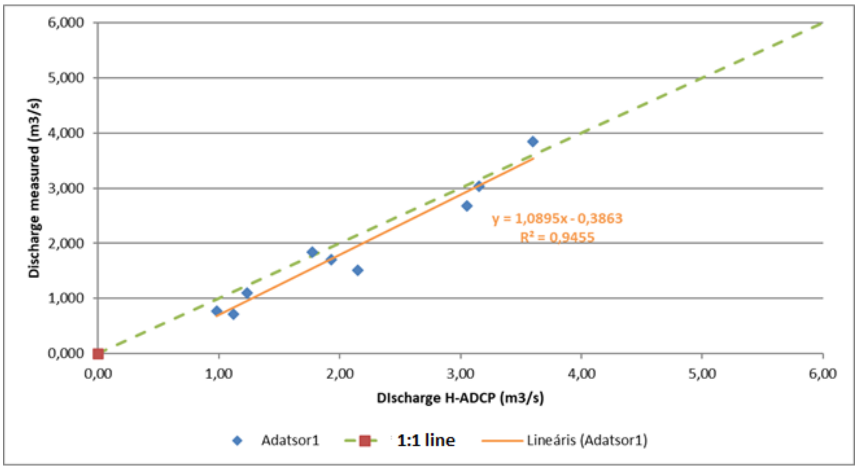

Figure 26: Correlation of automatically measured (H-ADCP) and control discharges at Zala - Balatonhídvég station, 2022

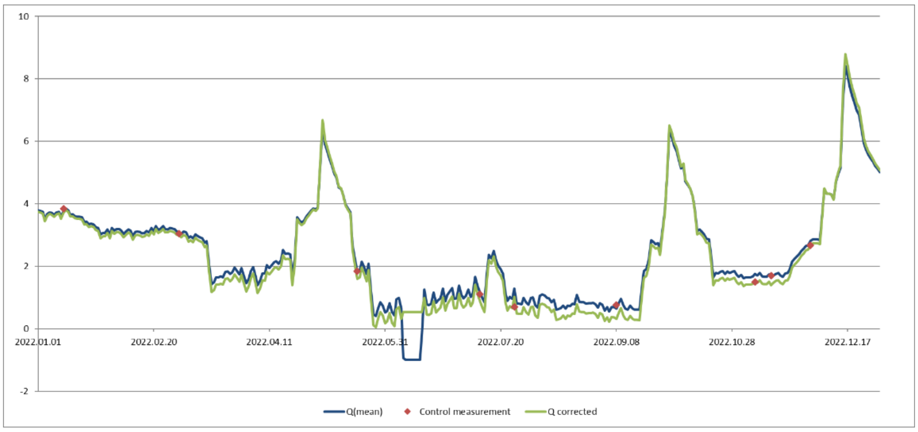

Figure 27: Original and corrected daily mean discharge time series for 2022 at Zala-Balatonhídvég station (x axis: Date, y axis: discharge in m^3/s)

Although this approach contradicts the findings of the previous analyses, I investigated the performance of this method in previous years by incorporating control measurements from 2021 and 2020 in the plot (Figure 28). Despite the near-perfect fit with an R2 value approaching 1, the correlation line remains below the 1 to 1 line even at high discharges. Accordingly, I used this correlation equation to adjust the values for 2022, as indicated by the purple line in Figure 29.

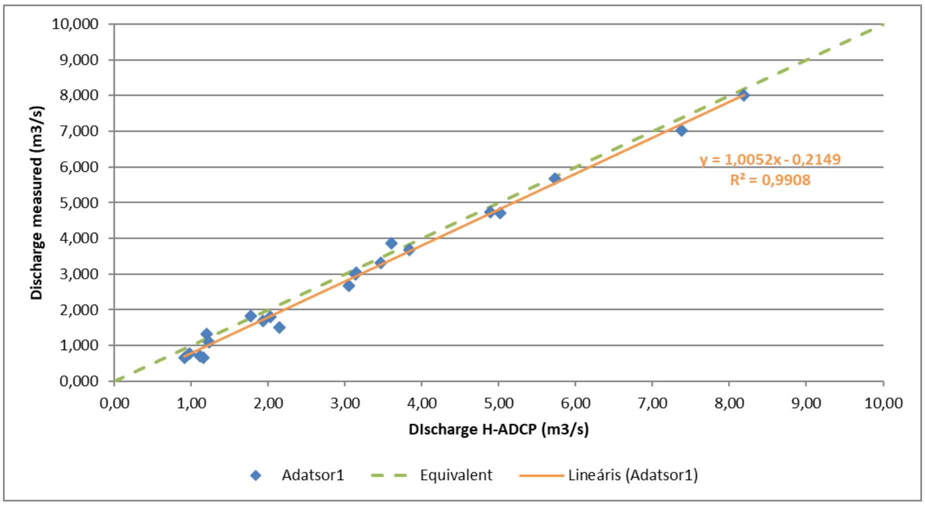

Figure 28: Correlation of automatically measured (H-ADCP) and control discharges at Zala - Balatonhídvég station, 2020-2022

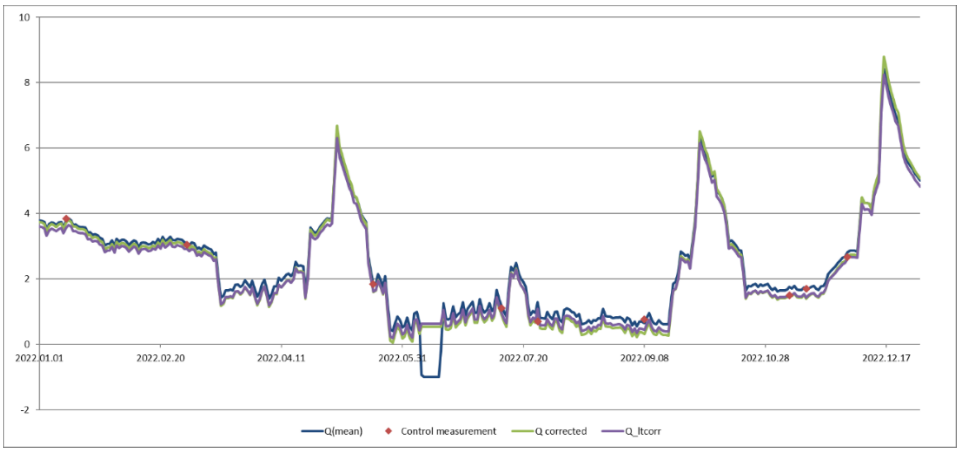

Figure 29: Original and re-corrected daily mean discharge time series for 2022 at Zala-Balatonhídvég station (x axis: Date, y axis: discharge in m^3/s)

The re-correction resulted 0.2 – 0.5 m^3/s differences to the first correction. This small change seemed insignificant, in light of the fact that there were 2 to 8 m3/s discharges originally. Therefore, a sensitivity analysis was made to investigate the influence of inaccuracy in the surface discharges on the closing error. The results can be seen in Table 9 below. The process was the following: errors from 5 cm to 30 cm were created with an average mean area of 13 km^2 (this is the area of the lake at around 106.6 water level which is a really common case). In the fourth column the annual mean ofthe summed monthly inflows and outflows are indicated in m^3/s. In the 3rd column the values indicate how much m^3/s inaccuracy in monthly mean discharge can cause the closing error of this magnitude indicated in the first column. In Table 9 it means that 0.2 m^3/s constant difference in all the inflow and outflow discharges can cause 5 cm closing error in a month. The fifth column meant to represent what percentage of error has to be in the measurements at this discharge rate (4.5 in the example) to have the error in the first column. So in this example when the sum of all the monthly mean outflow and inflow discharges is 4.5 m^3/s in reality, it is enough to make inaccuracy of 5% when measuring discharge and it will result 0.2 m3/s deviation which can cause 5 cm difference between the real storage change and the calculated change. The surface discharge sensitivity analysis showed that the water balance of the Hídvégi-lake is very sensitive to inaccuracy in surface discharges.

Table 9: Discharge sensitivity of Hídvégi-lake

Hidvegi-lake closing error due to surface discharge inaccuracy				
Closing error in cm	Mean area [m^2]	Deviation in Q [m^3/s]	Annual mean Q [m^3/s]	Error in Q measurement [%]
5	13000000	**0,2**	4,5	5%
10	13000000	**0,5**	4,5	11%
15	13000000	**0,7**	4,5	16%
20	13000000	**1,0**	4,5	22%
25	13000000	**1,2**	4,5	27%
30	13000000	**1,5**	4,5	32%

The margin of error even in the control flow measurements is 5 %. An automatic discharge measurement station can easily under or overestimate discharge by 10%. . Given that small discrepancies between measured and actual discharge can result in substantial closure errors, and that the margin of error in automatic and control flow measurements is sufficient to account for such discrepancies, it is strongly advised to identify the primary source of error in the input surface discharge.

Considering the importance of minor deviations in surface discharge on the closing errors, the water balance for 2022 was recalculated using re-corrected outflow values.The results can be seen on Figure 30.

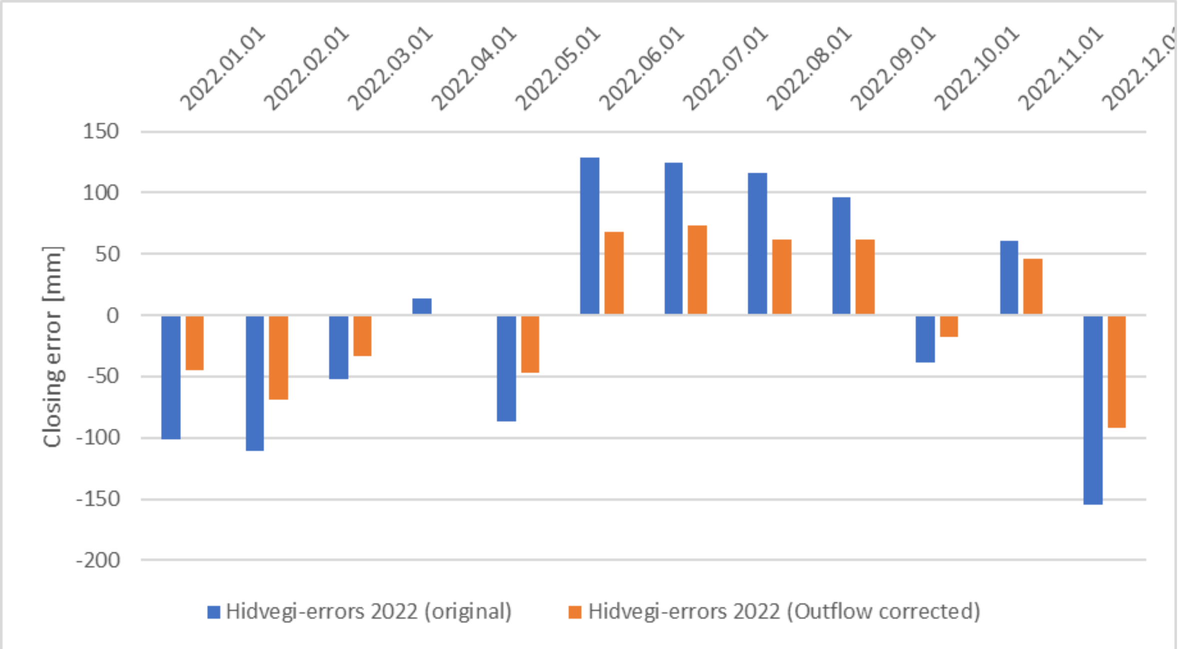

Figure 30: Original and corrected closing errors of Hídvégi-lake for 2022

It clearly turned out that even these small changes can reduce the errors by almost 50%. Most of the errors are inside the ± 50 mm threshold or close to it. The final error (sum of all the deviations) is 8 mm. The absolute mean deviation is 51 mm, before the outflow re-correction the best result was 90 mm.

3.1.5. Summary for Hídvégi-lake

The Hídvégi-lake is very sensitive for small deviations in surface discharges. An error of 0.2 – 0.5 m3/s can cause 50 to 100 mm error when closing the balance.

The available data suggests the presence of groundwater exchange, albeit the extent and certainty of this inference remains ambiguous. Therefore, further investigations are required to ascertain the nature and magnitude of any such potential exchange.

Precipitation is not the main driving force of the lake's water balance, therefore small inaccuracies in precipitation measurements do not result in significant closing errors.

The new rating curves did not affect the balance significantly. However there is a difference to the old ones around ±30 mm.

Regarding evapotranspiration, it does not have a primary influenceon the calculated balance, even in vegetation period the ETP was around 20%.. There were 30 to 90 mm differences between ETP methods in the vegetation period, so when the evaporation is high the selected method can be crucial for the closing errors. Still the main driver are potential errors in measurement of surface discharge.

3.2. Ingói-pond

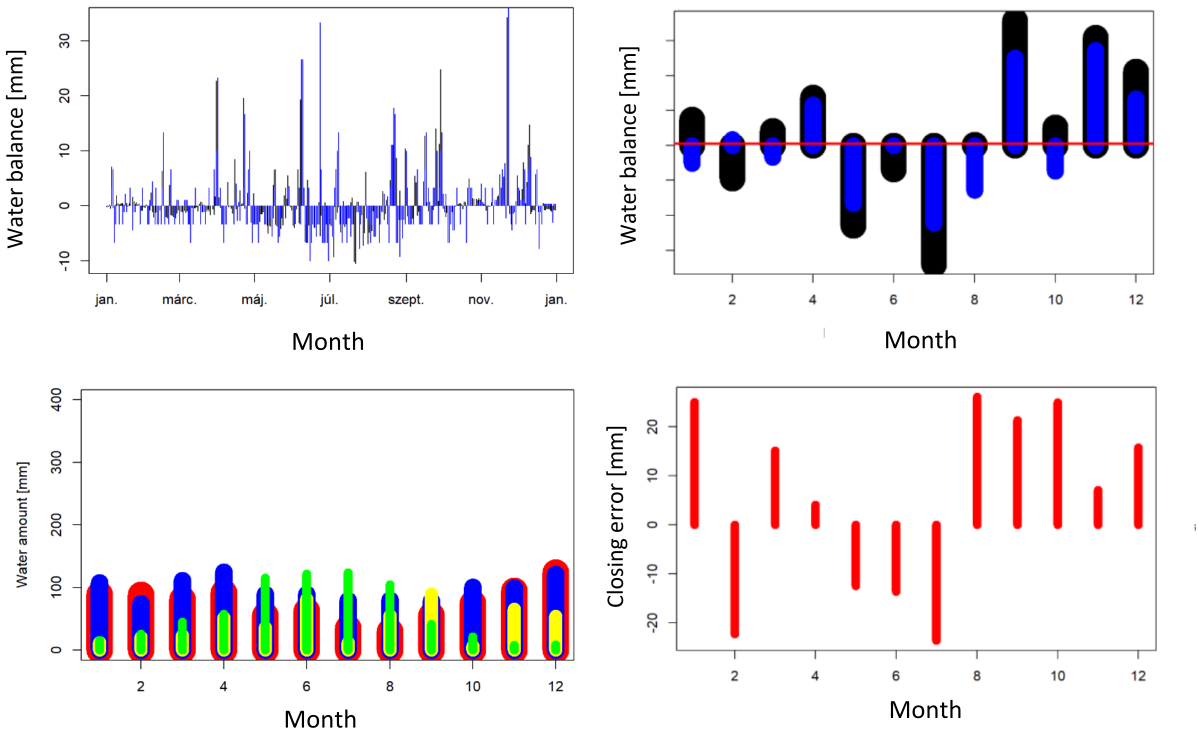

Figure 31: Water balance results of Ingói-pond; upper left: daily balance for 2022 [blue: storage change; black: calculated]; upper right: daily balance for 2022 aggregated to monthly values; lower left: input elements in the calculation for 2022 [blue: inflow, red: outflow, green: ETP, yellow: Prec.]; lower right: monthly closing errors in mm for the calculation

For the Ingói-pond the same 6 versions for evapotranspiration method were calculated. Figure 31 above represents the version Antal E with Antal Kc factors for 2022. We can see on the lower-right graph that the monthly differences are remained inside the ± 50 mm error threshold. The daily balance was not good, the correlation of the storage change and the calculated balance is only 30%, still the differences in the monthly aggregated values are adequate. This is because there is no automatic discharge measurement at the main inflow section (Egyesített-channel – Fenékpuszta station) and therefore the daily input surface Q is not precise. It is also visible on the lower-left graph of Figure 31 that the ETP is significant in the vegetation period and this was the main element of the water transport in that period. Even though the results for 2022 were really good regarding monthly errors, there were still huge errors in the previous years. Figure 32 below represents the closing errors for all the 6 ETP versions for the whole study period. Looking at the graph we can see huge negative errors in 2020 and 2021. Most of these large errors occurred outside of the vegetation period, which suggests that not the evapotranspiration caused them. However there were differences between the methods in the summer months, even though they mostly remained inside the error threshold. Therefore, the vegetation period was again examined separately.

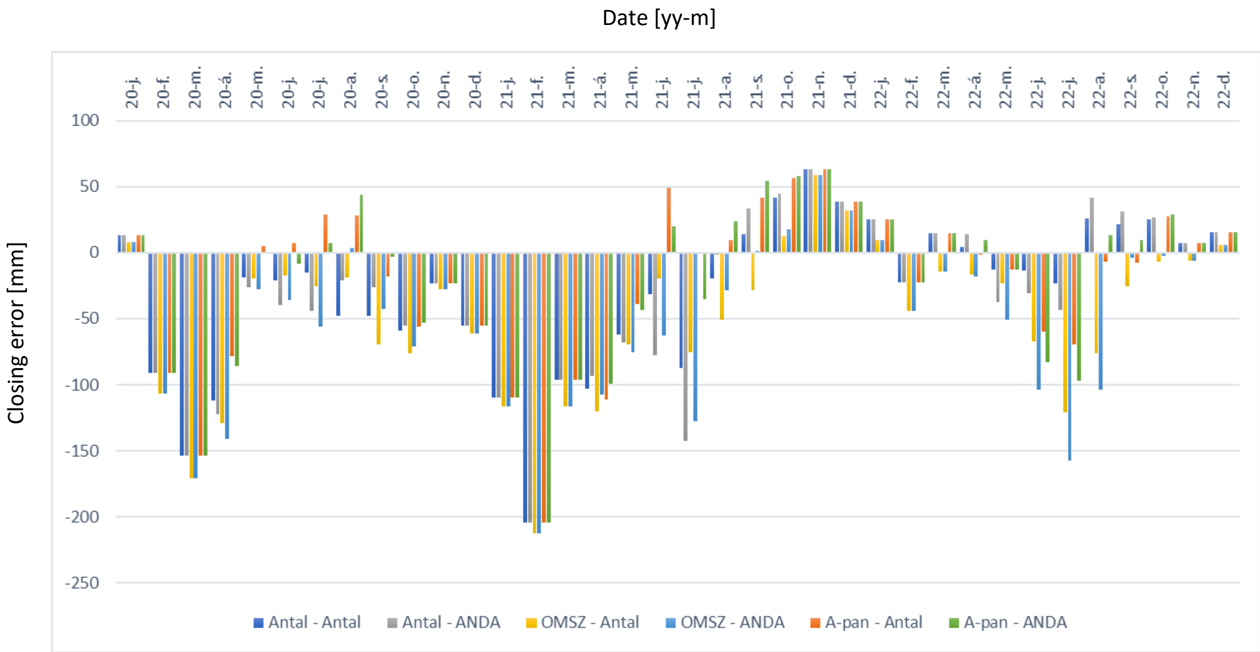

Figure 32: Closing errors for Ingói-pond for all 6 ETP version; 2020-2022

3.2.1. Influence of evapotranspiration

Figure 33 below meant to show the statistics of the 6 ETP methods during the vegetation periods. As Figure 33 suggests the worst results came from the OMSZ reference evaporation. The A-pan and the Antal formula gave slightly different but similar results. With the Antal formula 3/4 of the monthly balances remained inside the error threshold in the vegetation period. The A-pan method gave the best summarized errors, still they are outside the threshold. Negative means and summarized errors suggests that all methods overestimates the rate of ETP, however we saw that there were negative errors outside of the vegetation period too, so they were probably caused by other effects.

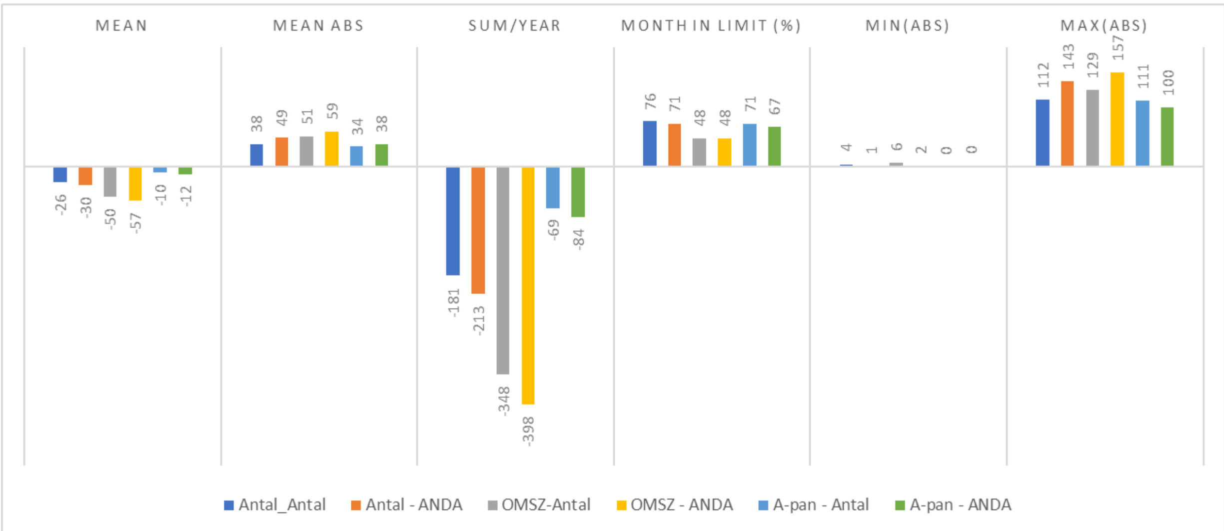

Figure 33: Summarized statistic of ETP methods in the vegetation period (2020-2022)

The monthly ETPs of all the 6 methods are illustrated on Figure 34. This graphs indicates that differences up to 150 mm (!) occurred depending on which reference evaporation and Kc factors were used. A good example of this influence observed in Figure 32 looking at the errors of June

2021, when the Antal – ANDA Kc method gave -75 mm error, while the A-pan – Antal Kc gave + 50 mm.

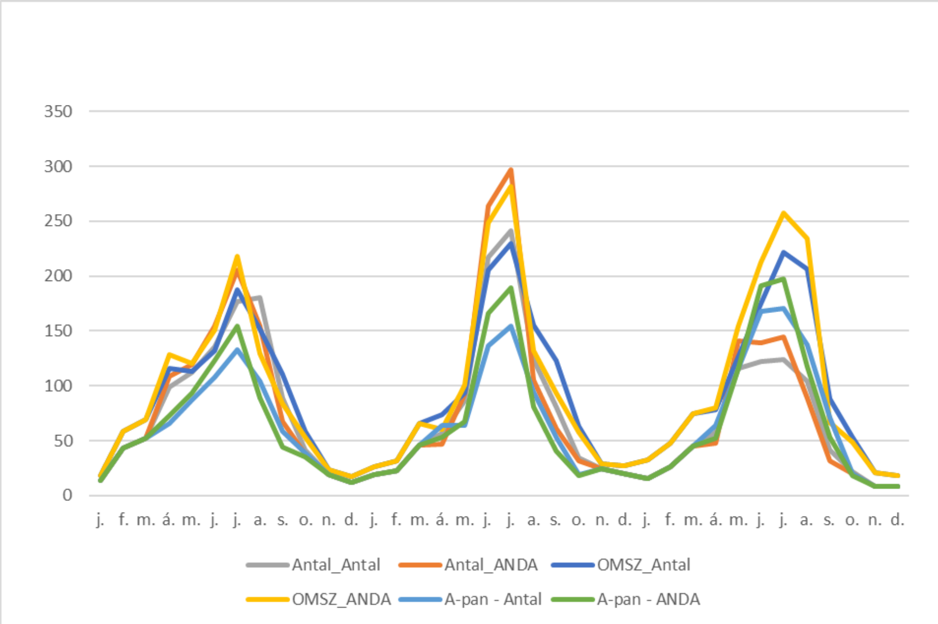

Figure 34: Monthly ETP sums for Ingói-pond (2020-2022)

Looking at the influence of the different input elements we can have a better picture about what is the main driver of the water balance in the Ingói-pond. Figure 35 below shows this influence in percentage of the sum of all elements of the balance, including the error too. This graph demonstrates that in the winter periods the main driver was the surface inflow and outflow (Qi+Qo), but the contribution of them reduced rapidly to 10-30 % in the summer months. Without a doubt the evapotranspiration (ETP) was the main driver at the peak of the vegetation period, with around 30-50 % contribution. Precipitation (P) is not negligible either with its 30-40 %, especially when there are low flow conditions. The orange line again represents the error. Considerable errors up to 20-30 % occurred mostly outside of the high ETP periods.

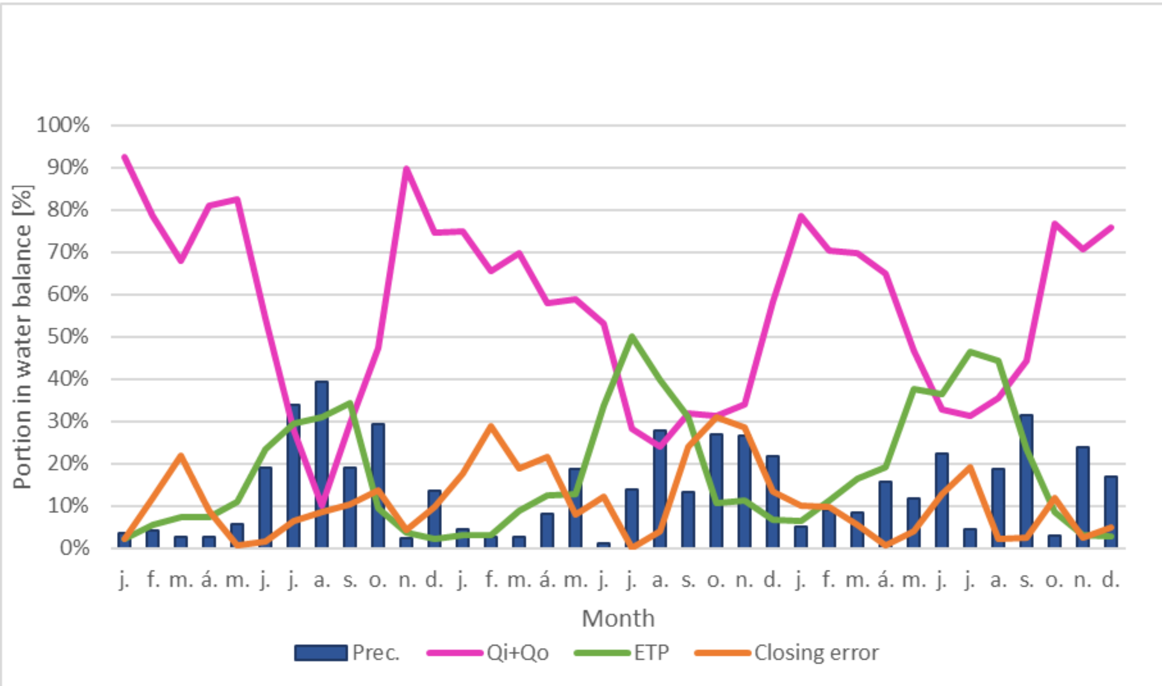

Figure 35: Influence of input elements in the water balance of Ingói-pond (2020-2022)

3.2.2. Analysis of groundwater exhange

Investigation of the groundwater level in the nearby monitoring wells carried out with a purpose of finding the reason for high errors. There are many observation wells around the Ingói-pond, but only 5 of them are still operating. Upon examining the groundwater levels of the monitored wells and the water level in the pond, a strong correlation was observed between the errors and two wells, specifically Sármellék 35/1 and Fenékpuszta 12/4. These wells have been identified and marked with a red circle on the left map of Figure 36.

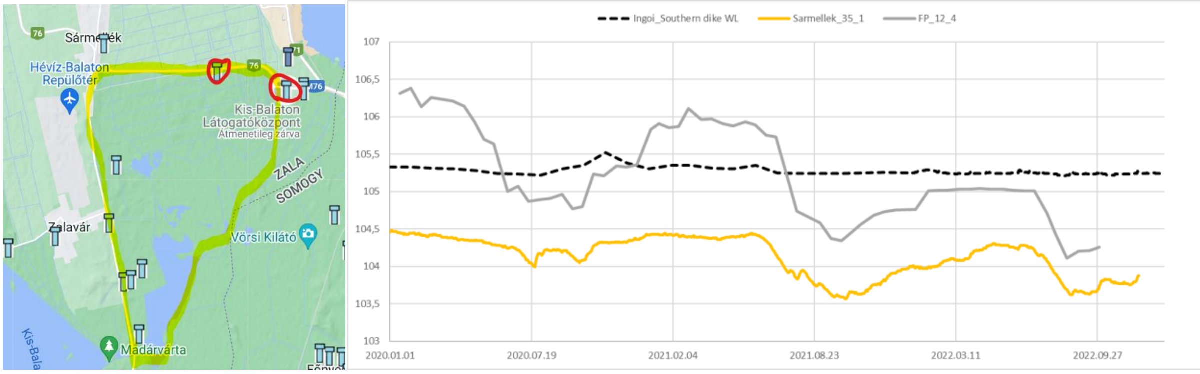

Figure 36: Left: Map of observation wells around Ingói-pond; Right: Groundwater level in the wells and Ingói-pond water level (black dashed line) [Period: 2020-2022; units: mBf.]

The groundwater level of these wells are indicated on the right-hand side diagram of Figure 36. The dashed black line indicates the water level inside the Ingoi-pond. This is not the mean water level, but this station was chosen because there are 3 gauges in the pond and only this one (Southern-dike) is far from any weir which can rapidly influence the water level. It is interesting that the level in FP12/4 was sometimes higher than the water level in the lake, while the groundwater level at SM 35/1 remained constantly under the pond water table. The monthly mean groundwater level in these two wells and the monthly closing errors of ETP version Antal – Antal Kc are shown in Figure 37. The graph suggests that the higher the groundwater level the more negative the closing error and the lower the groundwater level the error moves more to positive range. Considering this we can assume water exchange between the Ingói-pond and the surrounding groundwater.

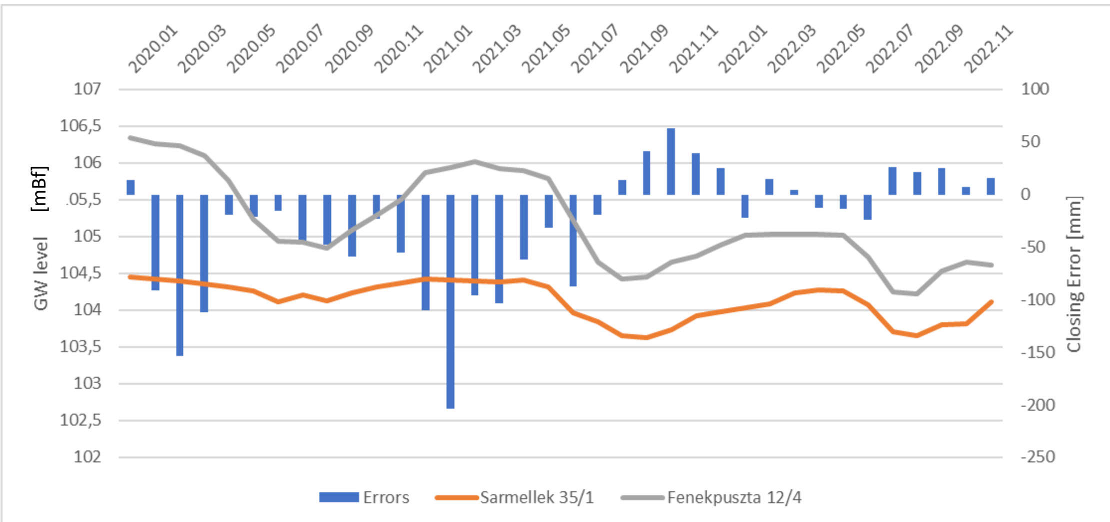

Figure 37: Groundwater level time series and closing errors

In the next step the correlation between the closing error in million m^3/month and the groundwater levels were examined. To exclude the effect of ETP, only the months when the ETP influence was less than 20% were considered. The correlation plots can be seen in Figure 38. All the 3 diagrams show that there is a relationship between groundwater and errors with an R^2 around 0.6. It turned out that the higher the groundwater level in the area, the more negative the closing error. That rises the assumption that during high groundwater level, the water flows into the lake. Converting the monthly closing error to million m^3 and relating this to the average monthly groundwater level a conclusion can be given on the amount of monthly groundwater exchange. Taking the mean of the two observation wells resulted the best connection, therefore equation 5 had been built in the water balance model. This equation represents groundwater exchange rate in the pond, where $\mathbf{Q_{GWx}}$ is the monthly groundwater exchange in million m^3 and **GWLx** is the monthly mean groundwater level in the two wells in mBf.

Equation 5.: Ingói groundwater exchange

$$\mathbf{Q_{GWx} = (1.634 \times GWLx) - 170.69}$$

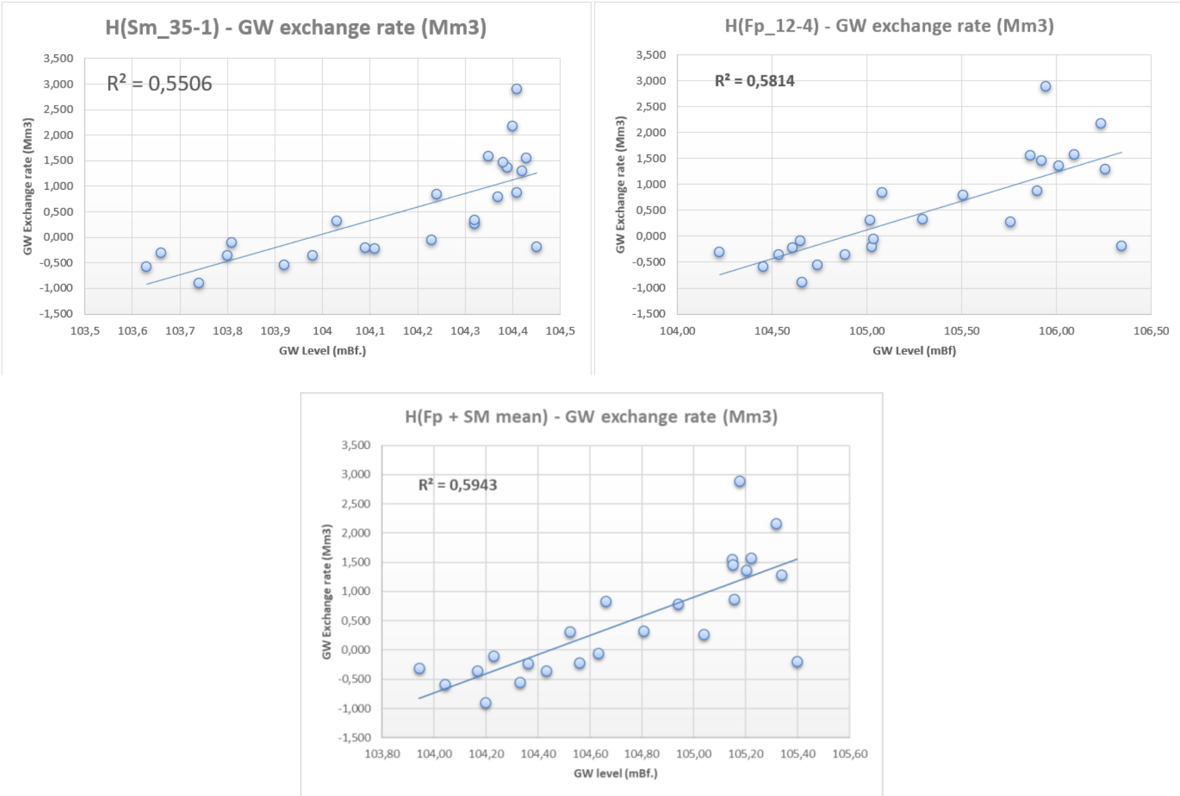

Figure 38: Correlation plots of groundwater level and water exchange rate

The groundwater exchange corrected closing errors can be seen on Figure 39 below. The graph demonstrates that the closing errors have improved a lot, since only 3 of the total 36 months exceeded the ± 50 mm limit. There were 2 winter months with + 122 and -122 mm error. The summarized errors are 5 mm, -233 mm and -34 mm for the three successive year. It can be also seen from the new results that the use of the groundwater exchange model did not deteriorate the already good 2022 values.

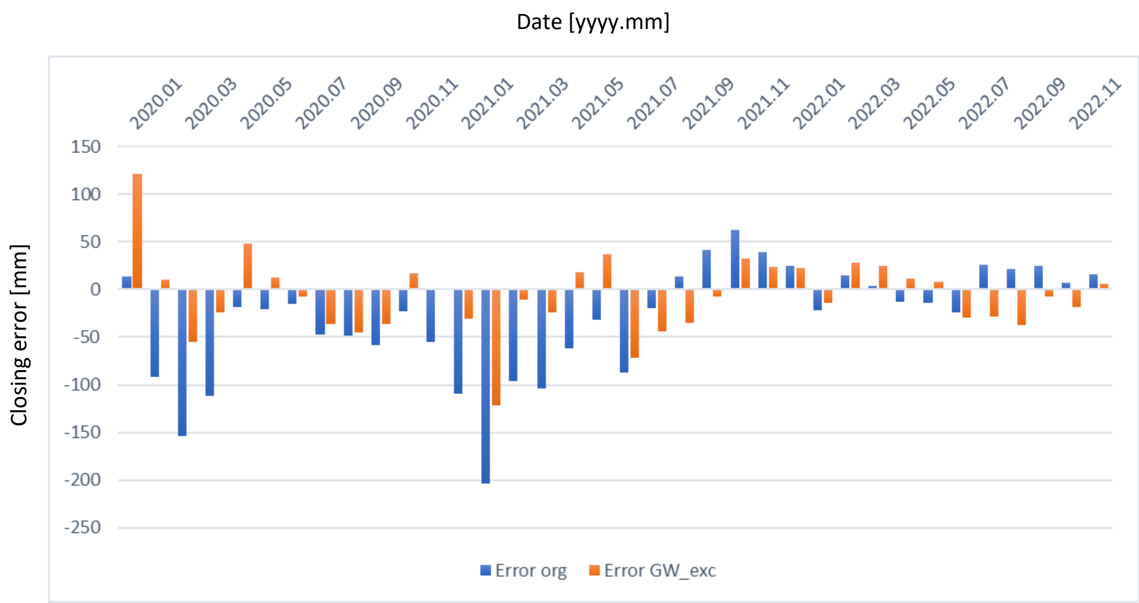

Figure 39: Closing errors for Ingói-pond with the original (blue bars) and the groundwater exchange corrected (orange bars) calculation (2020-2022)

3.2.3. Influence of updated rating curves

The next step was to check the volume and area rating curves. The old and new curves can be seen on Figure 40. As we can see there are considerable differences in both volume and area. Regarding volume, the inclination of the two curves are quite similar so the volume change between different stages is more or less the same. However, for area there are differences up to 1-2 km^2 and that can affect both precipitation and ETP. Table 10 summarizes the effect of the rating curves in mm. As the last column tells us, the significance of which rating curves are in use is very low. Differences ranging between -7 and +5 mm are negligible. Actually, the absolute differences are also believable since the old rating curves were defined more than 30 years ago and the lake probably filled up with sediment during this time. Overall, it is recommended to use the new rating curves because they are more up-to-date.

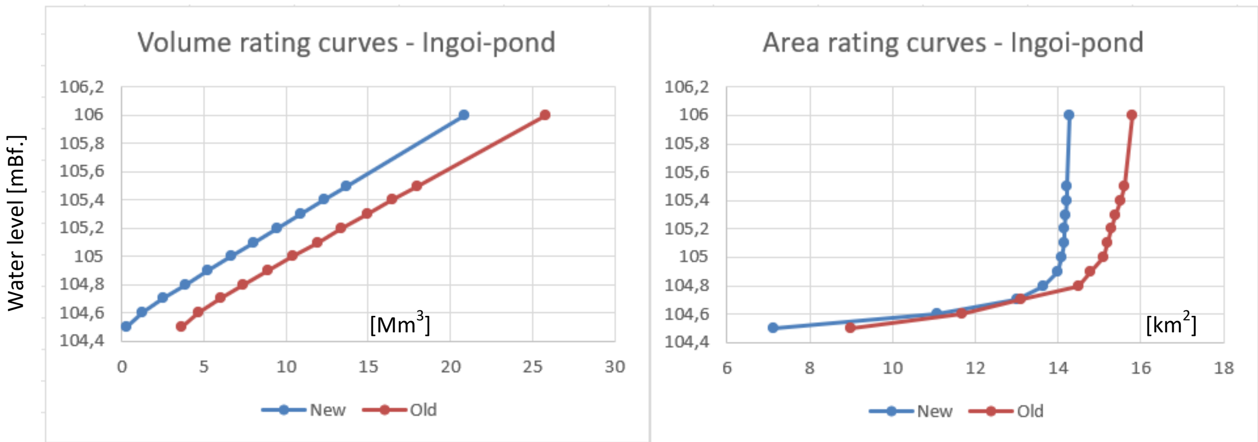

Figure 40: Old and new volume and are rating curves for Ingói-pond

Table 10: Error effect of new and old storage curves

Stage [mBf.]	V_new [Mm^3]	A_new [km^2]	V_old [Mm^3]	A_old [km^2]	Δ Vnew [mm]	Δ Vold [mm]	Δ (new-old) [mm]
104,5	0,3	7,1	3,6	9,0	-	-	-
104,6	1,3	11,1	4,7	11,7	87	94	**-7**
104,7	2,5	13,0	6,1	13,1	95	103	**-8**
104,8	3,8	13,6	7,4	14,5	98	93	**5**
104,9	5,2	14,0	8,9	14,8	99	101	**-2**
105	6,6	14,1	10,4	15,1	100	99	**0**
105,1	8,0	14,1	11,9	15,2	100	99	**1**
105,2	9,5	14,2	13,4	15,3	100	98	**2**
105,3	10,9	14,2	15,0	15,4	100	101	**-1**
105,4	12,3	14,2	16,5	15,5	100	100	**0**
105,5	13,7	14,2	18,0	15,6	100	96	**4**
106	20,9	14,3	25,8	15,8	499	494	**5**

3.2.4. Relationship of closing errors and discharge measurements

To examine the sensitivity of the pond for surface discharge the previously presented method was applied. The mean pond area was taken as 14 km^2 which represents a normal operation. Annual mean surface discharge for inflows and outflows was 0.8 m^3/s, but raising of that to 1.4 m3/s was reasonable because in 2022 there were really low flow conditions and that latter discharge is better suited to long-term values. It is visible in Table 11, that 0.3 m^3/s error causing 5 cm closing error and that means almost 20% error in the measurements when the sum of surface discharges is 1.4 m^3/s. These percentage values for larger errors are way higher and that 20% error in the flow measurements is really unlikely too. Periodic measurements are currently the only available data for the main inflow section (Egyesített-channel – Fenékpuszta station). However, due to the potential for inaccuracies when simply interpolating between two measurements, it is imperative to implement automatic discharge measurement at this station. Despite this limitation, it can be concluded that the Ingói-pond is not particularly sensitive to inaccuracies in surface discharge data, given the relatively low annual surface discharges and large area of the lake.

table 11: Sample errors and discharge sensitivity of the Ingói-pond

Ingoi-pond closing error due to surface discharge inaccuracy				
Closing error in cm	Mean area [m^2]	Deviation in Q [m^3/s]	Annual mean Q [m^3/s]	Error in Q measurement [%]
5	14000000	**0,3**	1,4	19%
10	14000000	**0,5**	1,4	37%
15	14000000	**0,8**	1,4	56%
20	14000000	**1,0**	1,4	75%
25	14000000	**1,3**	1,4	93%
30	14000000	**1,6**	1,4	112%

3.2.5. Summary for Ingói-pond

The main problem with the water balance calculation of the Ingói-pond was that the groundwater exchange was not considered before. There was a relatively strong correlation between 2 groundwater observation wells and the closing errors. Based on that relation it was possible to correct the calculated values and as a result of that 92% of the closing errors remained inside the ±50 mm error limit.

Evaporation methods and reed factors have a strong influence on the results in the vegetation period of up to 150 mm differences. The original method, Antal E with Antal Kc provided the best fit and OMSZ direct E values definitely overestimated the evaporation.

The new volume and area rating curves have almost no influence on the storage change calculation. However, there are considerable absolute differences which suggest that the lake bed has filled up with sediment to some extent during the decades.

The surface discharge sensitivity test revealed that the large errors were probably not due to normal errors in discharge measurements.

3.3. Fenéki-lake

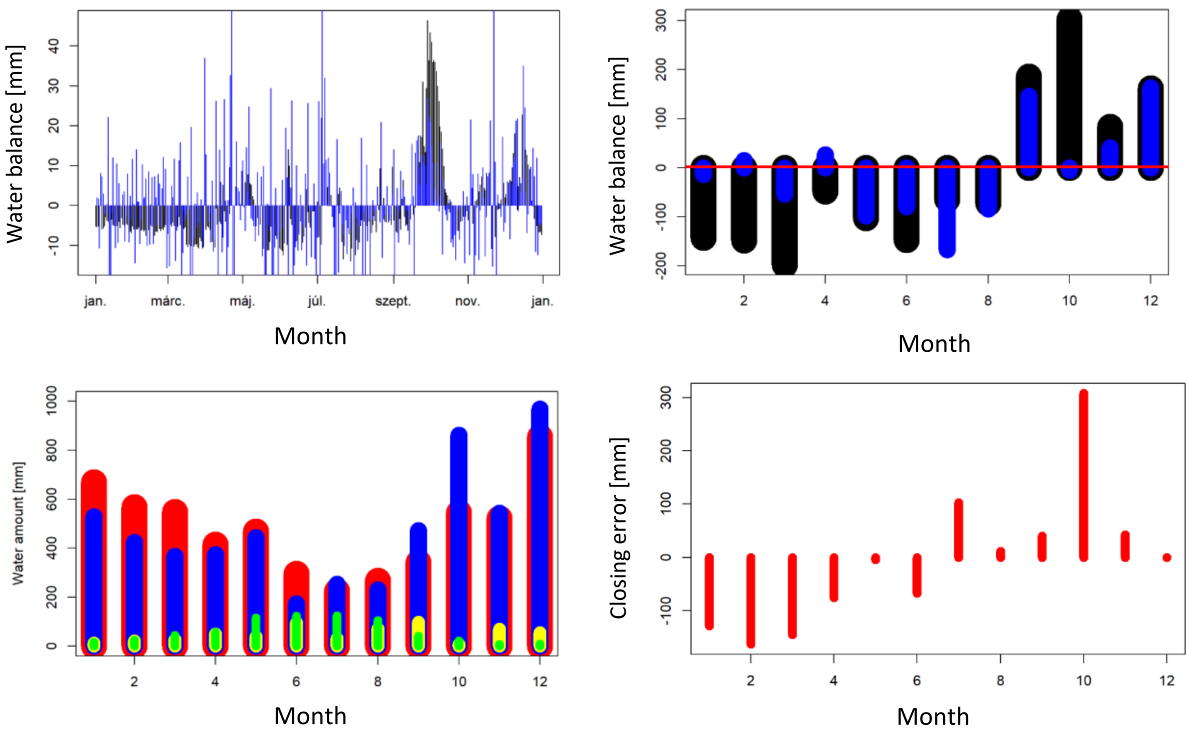

Figure 41: Water balance results of Fenéki-lake; upper left: daily balance for 2022 [blue: storage change; black: calculated]; upper right: daily balance for 2022 aggregated to monthly values; lower left: input elements in the calculation for 2022 [blue: inflow, red: outflow, green: ETP, yellow: Prec.]; lower right: monthly closing errors in mm for the calculation

For the Fenéki-lake the same 6 versions were calculated for evapotranspiration. Figure 41 above represents the version Antal ET0 with Antal Kc factors for 2022. The lower-right graph represents the monthly differences, which ranging from -160 to +300 mm. Only 5 months have lower closing errors than ±50 mm. The daily balance was really inaccurate, this can be seen on the upper left graph. The blue bars represents the daily storage change and it is visible that values jump up and down rapidly. Meanwhile the calculated balance (black bars) seems that it has a normal tendency. As presented on the lower left graph of Figure 41 the surface inflow and outflow were the most significant driver of the water balance even in the vegetation period.

The accuracy of the 2022 results is questionable and does not meet the required error criteria. To address this, the water balance was also calculated for 2021 and 2020. Figure 42 illustrates the closing errors for all six ETP versions over the entire study period, with consistently high errors observed across all versions in both positive and negative directions. These errors did not exhibit any seasonality, occurring in both summer and winter periods.

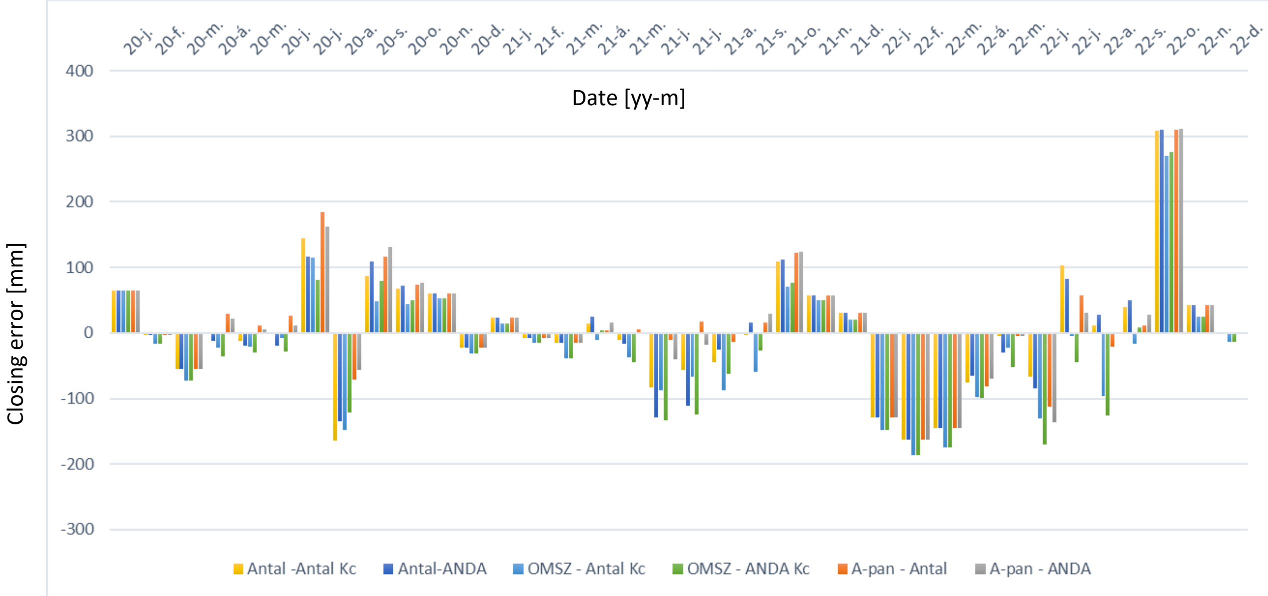

Figure 42: Closing errors for Fenéki-lake for all 6 ETP version; 2020-2022

3.3.1. Influence of evapotranspiration

Before examining the impact of ETP methods, a preliminary investigation was conducted to assess the significance of individual elements in the water balance. This analysis is presented in Figure 43, which shows that surface inflow and outflow were the dominant drivers throughout most of the study period, with ETP emerging as the most significant input element only during the summer of 2021.

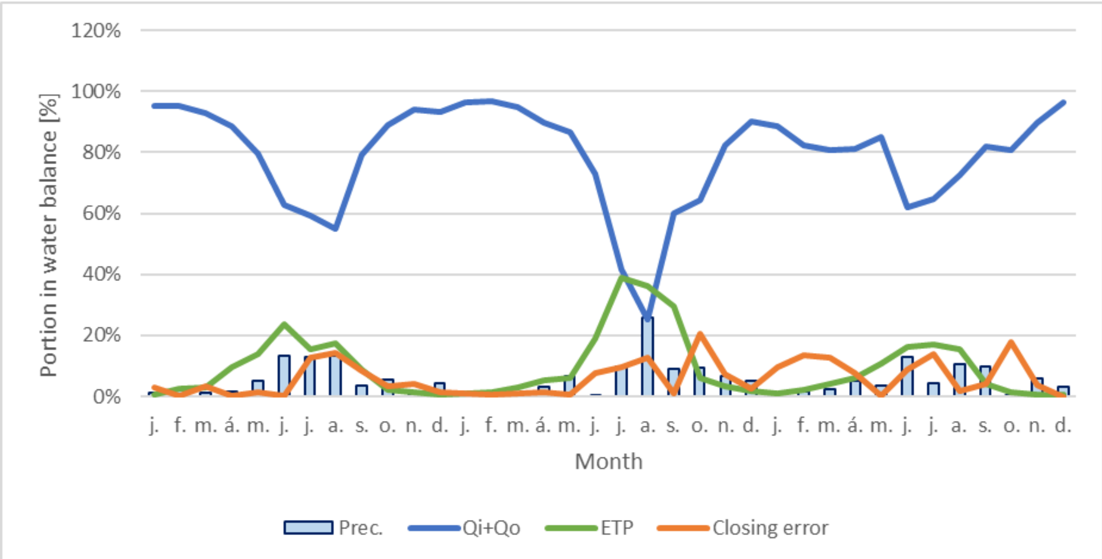

Figure 43: Influence of input elements in the water balance of Fenéki-lake (2020-2022)

Therefore, the effect of ETP methods was studied for that period alone, covering a span of six months from April to September. Figure 44 displays the statistical results obtained from this investigation, which revealed that the OMSZ methods led to overestimation of evaporation and poor statistical performance. In contrast, the Antal E method and the A-pan values exhibited the best fit, with A-pan outperforming Antal E on most criteria. Regarding the effect of reed factors, the higher the ET0 the higher the effect of Kc factors obviously. However from that few values it cannot be determined which Kc factor is better.

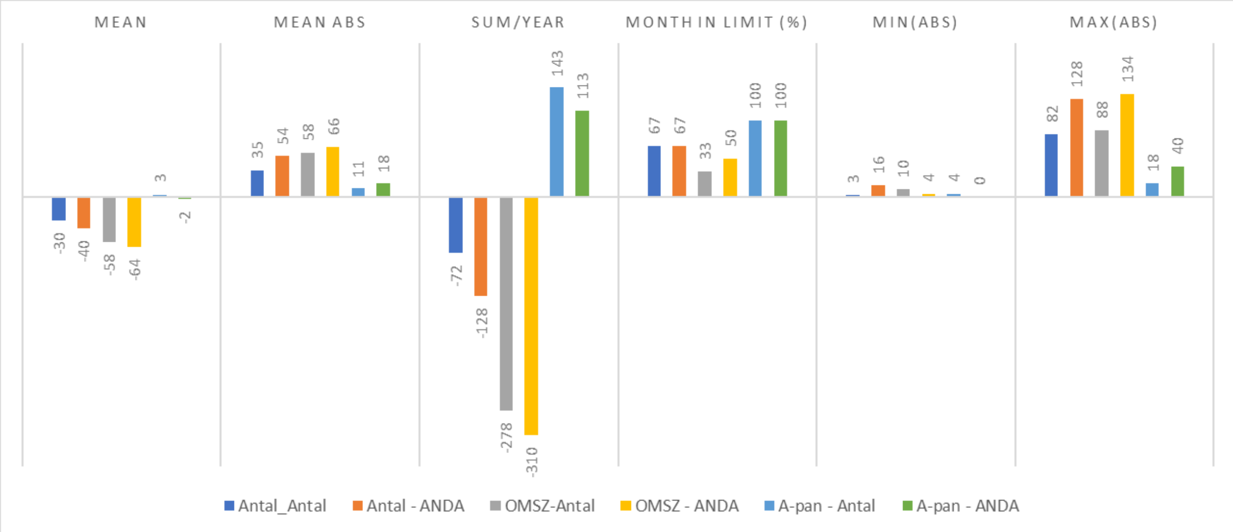

Figure 44: Summarized statistic of ETP methods in the vegetation period (2020-2022)

According to Figure 45 a closer examination of the ETP values and their effect on the results revealed that the methods can result in an error of up to 150 mm (!) at the peak of the vegetation period. If the absolutely overestimating OMSZ method was not taken into account, there are differences of around 80 mm between the Antal and A-pan methods.

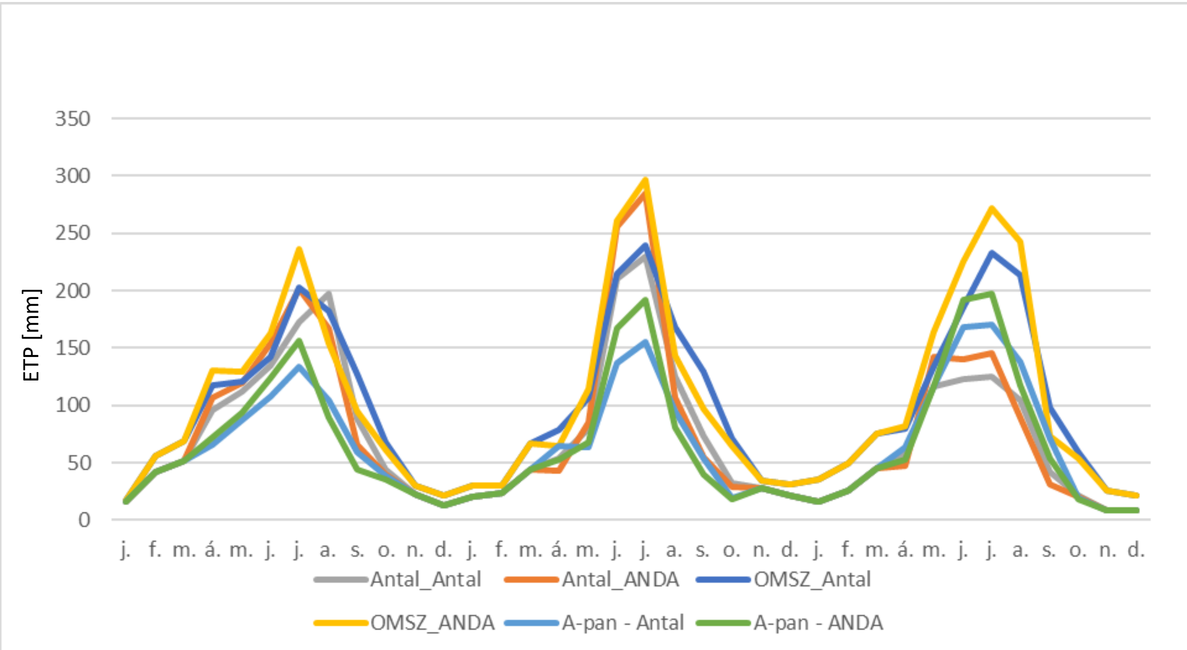

Figure 45: Monthly ETP sums for Fenéki-lake (2020-2022)

3.3.2. Analysis of groundwater exchange

To investigate the source of the significant closing errors observed, an analysis was conducted to examine the groundwater levels in the surroundings. Despite the presence of numerous observation wells in the area, only eight were currently operational, as indicated by the red circles in Figure 46.

While the groundwater levels at each of these wells were carefully examined, no correlation was found between the observed levels and the closing errors. Further attempts were made to explore potential links between the differences in groundwater and lake water levels and the errors, but no such relationships were observed. Based on the available data, it can be concluded that no significant groundwater exchange could be detected.

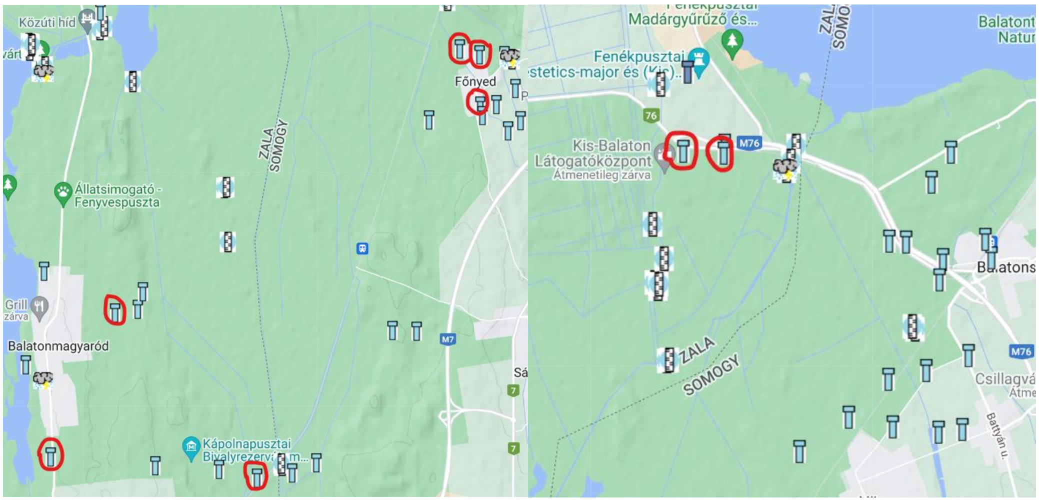

Figure 46: Groundwater observation wells around Fenéki-lake

3.3.3. Influence of updated rating curves

The investigation of the volume and area rating curves was continued, and as shown in Figure 47, differences were observed between the old and new curves. It is important to note that the previous rating curves were applied for the entire lake, whereas the new curves were created for four distinct units (5, 6, 7, 8), as detailed in Chapter 2.4. These units were necessary due to the significant differences in water levels within the lake. To compare the new and old curves, the unit values were summed. In reality, it is unlikely that water levels would be the same across the entire lake. Nevertheless, relevant volume and area values were compared, as outlined in table 12.

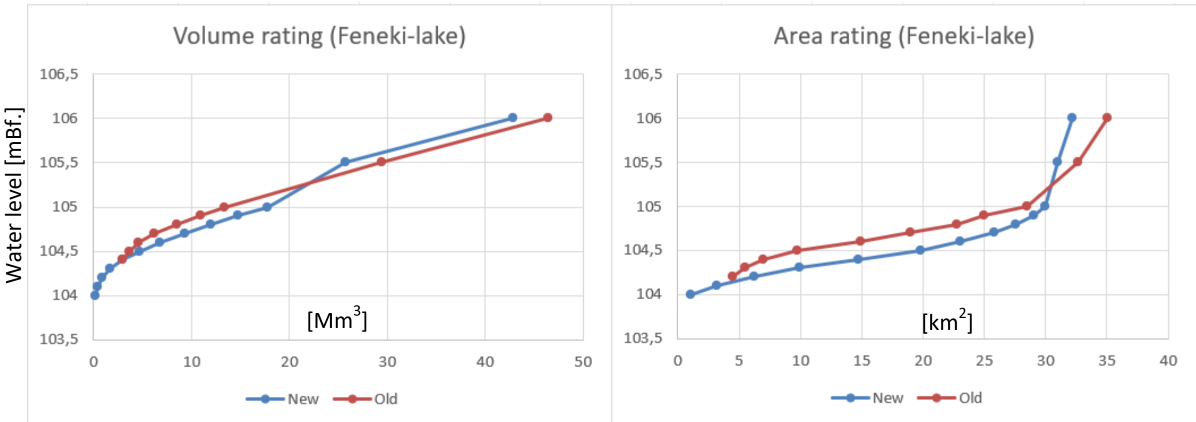

Figure 47: Old and new volume and area rating curves

table 12: Error effect of new and old storage curves

Stage [mBf.]	V_new [Mm^3]	A_new [km^2]	V_old [Mm^3]	A_old [km^2]	Δ Vnew [mm]	Δ Vold [mm]	Δ (new-old) [mm]
104	0,2	1,1	-	-	-	-	-
104,1	0,5	3,2	-	-	-	-	-
104,2	0,9	6,2	-	4,5	-	-	-
104,3	1,7	9,9	-	5,5	-	-	-
104,4	3,0	14,7	3,0	7,0	83	-	-
104,5	4,7	19,8	3,7	9,8	87	72	**15**
104,6	6,8	23,0	4,6	14,9	94	60	**33**
104,7	9,3	25,9	6,2	19,0	95	84	**11**
104,8	12,0	27,6	8,5	22,8	97	101	**-4**
104,9	14,8	29,0	11,0	25,0	98	100	**-2**
105	17,7	30,0	13,4	28,5	99	84	**14**
105,5	25,8	31,0	29,5	32,7	259	493	**-234**
106	42,9	32,2	46,5	35,0	530	486	**45**

As visible in the last column of table 12, there can be -2 to +33 mm differences between 104.5 and 105 water level, depending on which rating curve was used. However there is a considerable difference at 105.5 water level. To check the effect of this difference, a period with this high average water level was considered between July and November in 2020. During this time there was very high water level in the lake even at the lowermost part. A red circle indicates this period on Figure 48, where the closing errors were high too.

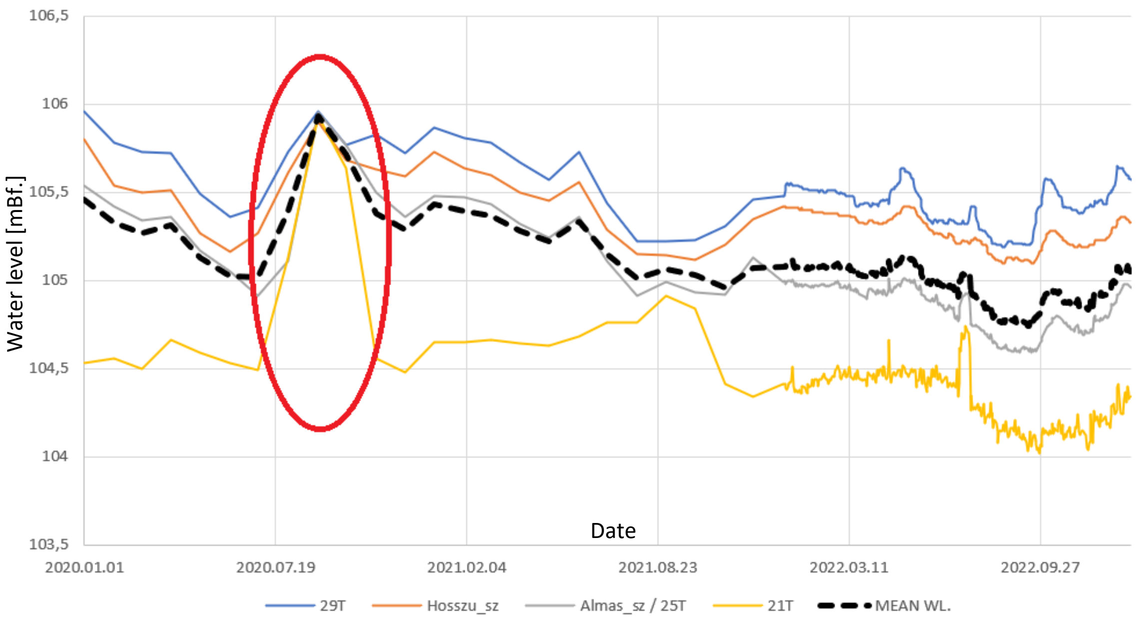

Figure 48: Water levels in Fenéki-lake (2020-2022)

The water balance of 2020 was recalculated using the old rating curves to check if the errors improve. The A-pan reference evaporation version was used since that method seemed to be the best earlier. Figure 49 represents the differences. Despite that the errors improved, they are still too high at that period. Only October showed remarkable improvement. We can also see that below this water level it does not really matter which curve is being used, since errors are in the same order of magnitude. This suggest that above 105.5 water level the new rating curves are incorrect, however the old one is inaccurate too.

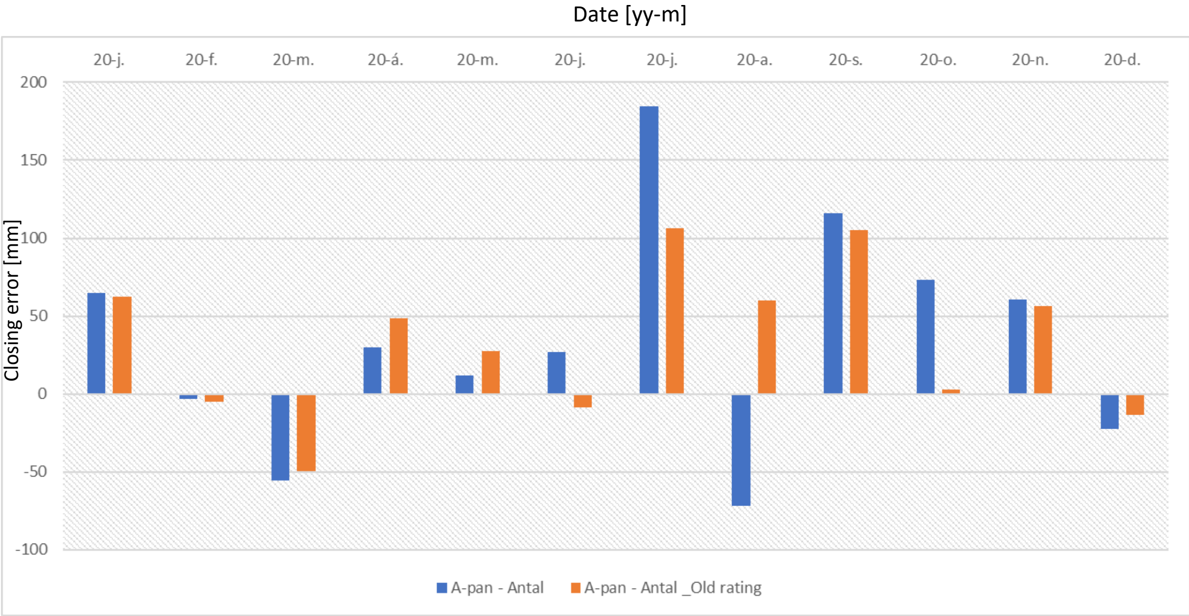

Figure 49: Closing errors in 2020 with the use of new (blue bars) and the old rating curves (orange bars)

3.3.4. Relationship of closing errors and discharge measurements

As the cause of the errors remained unknown, a sensitivity analysis was conducted to investigate the effect of surface discharges. Sample errors with hypothetical input variables were created again every 5 cm. Since the discharges can vary in a wide range there were 2 different sample discharge used: 7 m^3/s for low flow and 20 m^3/s for high flow conditions. The two versions can be seen in table 13. The mean area was chosen for 105 mBf. mean water level in both cases. We can see that at low discharges 8% inaccuracy in the flow measurements can cause 5 cm, 16% inaccuracy can cause 10 cm closing error and so on. These values at high discharges are 3% and 6% respectively. In the case of high discharge even 11% inaccuracy can cause 20 cm error. Here, it has to be mentioned that automatic flow measurement is a really hard task in the Kis-Balaton area due to low channel slope and backwater effects. These effects are also sensible during control measurements which means that sometimes it is hard to keep the 5% margin of error even during control flow measurements. In addition, the installed automatic discharge measuring devices show a classic behavior of working well in a certain range, but malfunctioning in other ranges. Taking this into account, it becomes evident that flow measurements can easily result in a 10% error, which can explain the periodic variations in the closing error of the water balance.

table 13: Sample errors and discharge sensitivity of Fenéki-lake, Left: normal flow conditions; Right: high flow conditions

Feneki-lake closing error due to surface discharge inaccuracy				
Closing error in cm	Mean area [m^2]	Deviation in Q [m^3/s]	Annual mean Q [m^3/s]	Error in Q measurement [%]
5	28000000	**0,5**	7	7%
10	28000000	**1,0**	7	15%
15	28000000	**1,6**	7	22%
20	28000000	**2,1**	7	30%
25	28000000	**2,6**	7	37%
30	28000000	**3,1**	7	45%

Feneki-lake closing error due to surface discharge inaccuracy				
Closing error in cm	Mean area [m^2]	Deviation in Q [m^3/s]	Annual mean Q [m^3/s]	Error in Q measurement [%]
5	28000000	**0,5**	20	3%
10	28000000	**1,0**	20	5%
15	28000000	**1,6**	20	8%
20	28000000	**2,1**	20	10%
25	28000000	**2,6**	20	13%
30	28000000	**3,1**	20	16%

To try to find if there is a certain range where the input discharges caused the errors a correlation analysis was made between the closing errors and the inflows and outflows. Surprisingly, there was no correlation between them. This suggests that not every time the inaccurate input discharges caused the high errors.

3.3.5. Summary for Fenéki-lake

The Fenéki-lake is sensitive for ETP method. The OMSZ method did not provide usable values as it overestimated the reference evaporation. Antal E and A-pan values seemed to be the best methods to use to determine reference evaporation. However, notable closing errors occurred outside the vegetation period which means that not the ETP method is the primary source of errors.

There was no evincible groundwater exchange from the results.

There is difference between the old and the new rating curves, although it is only significant above 105.5 mBf level. Although the old rating curves appeared to perform slightly better at high water levels, their use did not provide a solution to the problem.

It turned out that surface discharge can be a considerable source of error, but there was no correlation between surface discharge and error. The most likely explanation is that the closing errors result from the accumulation of minor errors from different sources. That would explain the irregular temporal occurrence of the closing errors.

4. Summary and conclusions

4.1. Main findings

The Kis-Balaton system which consists of 3 separated lakes, the Hídvégi-lake, the Ingói-pond and the Fenéki-lake, is a very complex water management unit. This researched confirmed this statement. This chapter briefly summarizes the answers to the 3 research questions established in this research:

1. **What effect does the evaporation calculation method and the crop factors have on the calculated water balance and the closing error?**
    - 3 types of reference evaporation methods and 2 types of Kc factor methods were tested. The OMSZ method gave the poorest results for all 3 lakes, since it overestimated the evaporation. There were considerable differences between Antal and measured A-pan reference evaporation, still there were periods with adequate results for both. Regarding Kc factors, the larger the portion of reed covered area, the greater the effect of Kc factors. Therefore, Kc factors have importance in Ingói-pond and Fenéki-lake.
    - The effect of potential evapotranspiration (ETP) is only significant at the peak of the vegetation period mainly from June to August. Overall ETP is least significant in Hídvégi-lake and most significant in the Ingói-pond. Different ETP methods resulted 30-90 mm differences in the case of Hídvégi-lake and up to 150 mm in Ingói and Fenéki. The ETP method is a considerable source of error but only affects 3-5 months in a year and not the ETP is the main source of error in neither part-lake.
2. **What effect has the volume and area rating curves on the calculated water balance and the closing error?**
    - New storage curves were derived for the 3 parts from recent surveys in the area. Except Ingói, the lakes were sud-divided into smaller parts according to the typical water levels. Regarding Ingói and Hídvégi the new rating curves did not affect the results notably. In the case of Fenéki there is a remarkable difference above 105.5 mBf. Level, where the old storage curves seemed to be better.
    - Examination of the differences between the new and old rating curves revealed that the high level of errors observed could not be solely attributed to the previously assumed inaccuracies in the rating curves. While they may contribute to the overall error, their contribution is primarily limited to the margins of the error limit.
3. **What other effects can cause high errors in the water balance?**
    - The Hídvégi-lake is very sensitive to inaccuracy in surface discharge values.. A constant error of 0.2 - 0.5 m^3/s in surface discharge can cause 10 centimeters of closing error in the water balance estimation. So, the accurate measurement of surface discharge is crucial. Therefore, the automatized measurement of all inflows, but at least doing regular measurements on the smaller creeks is highly recommended.
    - In Ingói-pond there was an unequivocal connection between groundwater and errors. Due to typically low surface flow and large area, the pond is sensitive for groundwater exchange. A relatively strong connection could be established between the nearby observation wells and the deficit or surplus in the lake, as a result it was possible to correct the balance according to groundwater exchange.
    - Fenéki-lake is sensitive for inaccuracy in surface discharge, however due to large area and many inflows this is the most complex lake of the three, so there was no detectable and clear connection between the inputs and the errors. Neither was any correlation

with the groundwater levels noticeable. Overall, the errors probably caused by the summation of many smaller error. This also explains the irregular temporality of errors.

4.2. Recommendations for the future

Since it turned out that inaccuracy in the measurement of surface inflow and outflow is a remarkable source of error in the water balance estimation, it is highly recommended to improve and extend the hydrological monitoring system. Small deviations can cause large closing errors especially in the case of Hídvégi and Fenéki lakes. In order to prevent these inaccuracies it is reasonable to increase the frequency of the control measurements at automatic discharge measurement stations. It is also recommended to analyze the deviations between automatically measured and manually measured discharges from time to time and when experiencing larger deviations in a given range then increase the control measurement frequency even more. To minimize the portion of estimated surface discharge carrying out regular water flow measurements on every inflow (including the smaller creeks) is also recommended. In the case of Ingói the main inflow (Egyesített-channel – Fenékpuszta station) is still non automatized and the use of Q-H curve method is also limited due to regular backwater effects. Therefore the automatization of the discharge measurement at this station is urgent.

Regarding groundwater exchange in the lakes, the quantity of available data remains insufficient to establish conclusive findings. However, it turned out that groundwater exchange is relatively significant in Ingói-pond and connection between the groundwater level of two monitoring wells (Sármellék 35/1 and Fenékpuszta 12/4) and monthly groundwater exchange rate was possible. It is suggested to use the Equation 5 to estimate the rate of groundwater exchange in Ingói-pond however, further research on the subject is advised. It is also recommended to replace the rare manual groundwater level measurements with pressure probes or any other accurate and automatized method in these observation wells. This is true for the observation wells around the other two lakes, where possible groundwater exchange was also assumed, but have not proved yet.

In case of evapotranspiration further conclusion can be drawn only after minimizing all the other sources of error. However, it turned out that the reference evaporation of the OMSZ is overestimated, so the use of this method is not recommended. Antal-modified (Neusiedlersee formula) and A-pan values can be used in the calculations but with caution. Regarding reed coefficients (Kc) further researches necessary to prove which one fits the best to the water balance calculation.

The use of new rating curves are also suggested, because they are more up-to date, however regarding storage change there are mostly negligible differences to the old ones which used by the WD. Due to better segmentation (the lakes divided into smaller parts according to typical water level), errors due to water level differences in the same lake can be avoided by using the new rating curves. Nevertheless, resurvey of the area is highly recommended with more state of art technology e.g. Lidar for shallow water bodies (de Jongh, 2023).

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List of abbreviations

Abbreviations used in the paper:

OMSZ: National Meteorology Service of Hungary (Országos Meteorológiai Szolgálat)

WD : West-transdanubian Water Directorate (NYUDUVIZIG)

MBFSZ: Mining and Geological Survey of Hungary

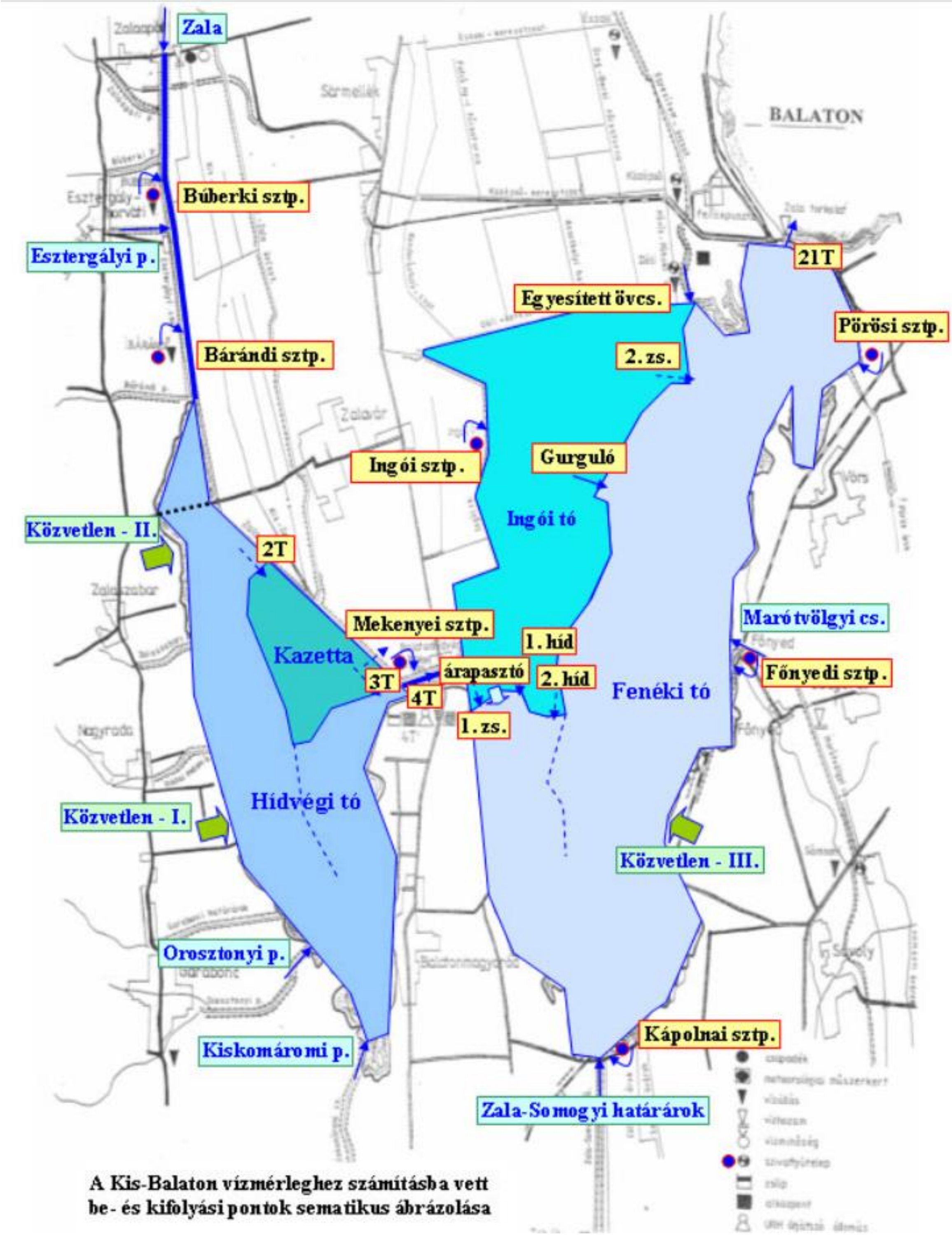
E: Reference evaporation

ETP: Evapotranspiration

mBf.: meters over Baltic Sea level

Mm^3 : million cubic meters

Appendix A: Schematic representation of the main elements of the water balance calculation



Appendix B: Water balance calculations

The following calculations are only available virtually as an .Rmd result file:

- Hídvégi-lake: Antal ET0, Antal Kc factors, daily balance 2022 (after re-correction of outflow)

  Hidveg_Fsz_A_NsdsKc.html
-
- Hídvégi-lake: Antal ET0, Anda Kc factors, daily balance 2022 (original outflow)

  Hidveg_Fsz_A_A.html
-
- Ingói-pond: Antal ET0, Anda Kc, daily balance 2022 (without GW model)

  Ingoi_Alm_Ant_Anda.html
-
- Ingói-pond: Antal ET0, Antal Kc, monthly balance 2020 (GW model included)

  Ingoi_20_org_KcAnt_GW.html
-
- Fenéki-lake: Antal ET0, Antal Kc, daily balance 2022

  Feneki_Almas_Ant_NsdsKc.html
-
- Fenéki-lake: Antal ET0 and A-pan values, Anda Kc, monthly balance 2021

  Feneki_21_org_A-pan_KcAnt.html
-

Appendix C: Table of updated rating curves

Hídvégi-lake:

	Hídvégi-west		Hídvégi-east		Kazetta	
Stage	**V [Mm3]**	**A [km2]**	**V [Mm3]**	**A [km2]**	**V [Mm3]**	**A [km2]**
105	0	0	0,0663	0,78415	1,34	2,95
105,5	2,31535	5,9557	0,9841	2,7645	2,906	3,0667
106	5,93534	7,9001	2,5462	3,2472	4,472	3,1834
106,2	7,5251	7,9607	3,1958	3,2524	5,1126	3,222
106,4	9,12	8,0763	3,8751	3,6123	5,7602	3,24922
106,6	10,82478	9,018	4,6481	4,0932	6,4114	3,2628
106,8	12,72008	9,8777	5,5009	4,4064	7,0652	3,2751
107	14,75224	10,3958	6,4009	4,5786	7,7213	3,2858
107,5	20,11273	10,9553	8,7602	4,8324	9,3717	3,3185

Ingói-pond:

	Ingói-pond	
Stage	**V [Mm3]**	**A [km2]**
104,5	0,318584	7,133892
104,6	1,27676	11,06968
104,7	2,50726	12,99778
104,8	3,845351	13,63664
104,9	5,229104	13,98722
105	6,635069	14,09974
105,1	8,047298	14,14084
105,2	9,462676	14,166
105,3	10,88024	14,18322
105,4	12,29946	14,20213
105,5	13,72071	14,22319
106	20,8515	14,29261

Fenéki-lake

Fenéki-lake "A"			Fenéki-lake "B"			Fenéki-lake "C"		
Stage	**V [Mm3]**	**A [km2]**	**Stage**	**V [Mm3]**	**A [km2]**	**Stage**	**V [Mm3]**	**A [km2]**
104	0	0	**104**	0	0	**104**	0,000504	0,005529
104,5	0,015114	0,122963	**104,5**	0,061433	0,698728	**104,5**	0,08036	0,828321
104,6	0,033073	0,244183	**104,6**	0,168422	1,517227	**104,6**	0,229582	2,375725
104,7	0,066566	0,448151	**104,7**	0,367296	2,322026	**104,7**	0,569318	4,372415
104,8	0,118287	0,569905	**104,8**	0,623916	2,781138	**104,8**	1,129568	6,8087
104,9	0,179401	0,654968	**104,9**	0,927129	3,29481	**104,9**	1,910408	8,729298
105	0,248314	0,714686	**105**	1,287633	3,908769	**105**	2,863866	10,2013
105,1	0,321273	0,73779	**105,1**	1,697933	4,215359	**105,1**	3,936978	11,22072
105,2	0,395531	0,74692	**105,2**	2,126478	4,348036	**105,2**	5,093469	11,8906
105,3	0,470582	0,753719	**105,3**	2,566693	4,452083	**105,3**	6,313077	12,433
105,4	0,546247	0,759433	**105,4**	3,015766	4,5214	**105,4**	7,572654	12,72803
105,5	0,62242	0,763938	**105,5**	3,469582	4,554106	**105,5**	8,855287	12,91332
106	1,016295	0,855489	**106**	5,7844	4,698217	**106**	16,72324	13,52627

Fenéki-lake "D"		
Stage	**V [Mm3]**	**A [km2]**
104	0,183527	1,064688
104,1	0,313291	1,537454
104,2	0,492457	2,06012
104,3	0,730125	2,752426
104,4	1,079561	4,551458
104,5	1,652944	7,150188
104,6	2,425192	8,204903
104,7	3,330898	9,688676
104,8	4,34468	10,58091
104,9	5,441108	11,37095
105	6,615033	11,97957
105,5	12,84448	12,79653
106	19,34731	13,13738