Regional and Business Studies (2016) Vol 8 No 2, 39-63
Kaposvár University, Faculty of Economic Science, Kaposvár

ROLE OF HUMAN IMPACTS ON DRASTIC CHANGES OF INFLOW TO LAKE BALATON – POTENTIAL HYDROLOGICAL AND ECONOMIC CONSEQUENCES – COMPREHENSIVE HYDROLOGICAL STUDY OF LAKE BALATON WATERSHED – ROLE OF HUMAN IMPACTS ON DRASTIC CHANGES OF INFLOW*

Károly KUTICS[1], Gabriella KRAVINSZKAJA[2], György VARGA[3]
[1]K+F Consulting Llc. H-8200 Veszprém Rózsa u. 46.
[2]Central Transdanubian Water Management Directorate, H-8000 Székesfehérvár, Balatoni út 6.
[3]General Directorate of Water Management, H-1012 Budapest, Márvány u. 1/d.

ABSTRACT

Lake Balaton is an important natural and economic asset of Hungary. In the past, similarly to other large lakes, it provided habitat for wild life as well as livelihood and drinking water for the people living in its neighbourhood. In the second part of the last century, water related tourism developed a great deal and Lake Balaton became an important economic factor of the national economy. A necessary condition to maintain or develop the tourism industry in the Lake Balaton Resort Area it is enough to have good quality water in Lake Balaton and a pleasant and rich natural environment in the region. The extended drought period from 2000 to 2004 underlined the vulnerability of the water resources of Lake Balaton to changing hydro-meteorological conditions. It is well known that the water balance of the lake was changing to the worse in the last 3 decades. In this study, human activities affecting the water balance of the lake were investigated. It was found that annually 210 to 230 lake mm of water was deterred from the lake due to human impacts such as the construction/restoration of the Balaton Minor Water Protection System, reservoirs and fish ponds constructed in the watershed, disturbance of the main karstic reservoir by bauxite mining, direct water use from the lake, changes in the land use pattern in the watershed, and already manifested impacts of climate change through decreasing discharges of the tributaries of Lake Balaton. Based on the findings of the study, recommendations were made such as launching a complex water resource preservation program for the whole watershed including rain water management and utilization, land use planning giving priority to water resource management, elimination of illegal water withdrawal, banning the construction of further shallow reservoirs and fish ponds and the improvement of the hydro-meteorological monitoring system.

Keywords: Lake Balaton, human impacts, water balance, climate change

* This article is based on the presentation held at the Conference "100 Year of the Hungarian Hydrological Society - National Wandering Meeting" 6-8 July 2016, Debrecen, [online] <URL: https://www.researchgate.net/publication/312121204_A_Balaton_es_teljes_vizgyujto-teruletenek_atfogo_hidrologiai_vizsgalata_kulonos_tekintettel_a_lefolyasi_viszonyok_drasztikus_valtozasara_es_a_hozza_folyas_csokkenesere

INTRODUCTION

Lake Balaton is a natural asset of Hungary. It is a multiple-use water body: drinking and irrigation and industrial water resource, food resource, a navigation medium, and last but not least, supporter of tourism industry in the region. Lake Balaton region („official" name: Lake Balaton Resort Area, LBRA) is a legal entity consisting of 180 municipalities and the lake surface itself. With more than 6 million commercial guest nights recorded annually, LBRA is the second most important tourist destination after Budapest, both in terms of guest nights and tourism-related income. However, when non-commercial guest nights spent in the more than 70 thousand holiday-houses are counted, LBRA well exceeds the figures of Budapest. For at least two months in summer, Lake Balaton is „the second largest city" in Hungary with an estimated population exceeding 500 thousand.

Tourism related income of LBRA may be estimated at 283,000 million HUF/year (a share of 25% of the national figure) (estimated based on *HCSO*, 2016a and *HCSO*, 2016b). It may be interesting to know what the potential value of the whole Lake Balaton would be as a drinking water resource. The regional price of drinking water is around 500 Ft/m^3. Lake Balaton volume at 100 cm water level is 2,130 million m^3. Therefore, the potential value is 1,065,000 million HUF. It is almost 4 times larger than the tourism income per year. Such calculations can be performed in case of other hypothetical uses, such as irrigation water, fisheries water, and even the case of draining the lake and using as an agricultural area can be (and was!) imagined. All these other uses would provide only a small fraction of the tourism related income.

The good environmental status of Lake Balaton is a necessary condition for the tourism industry to thrive and provide livelihood for the permanent population as well as significant revenues for the local governments.

Lake Balaton is an extremely shallow lake with 3.5 m average depth. Such lakes are very sensitive to environmental changes both in terms of water quantity and quality. Sensitivity of water level to water quantity is caused by natural variability of water budget elements together with changes caused by human interventions to them. Water budget related processes of the last one and a half decades provided several premonitory signs. Mostly due to the more and more extreme meteorological events the extreme water budget condition increase occurs.

In order to track the changes in the water level of Lake Balaton (or any lake) it is essential to have reliable and comprehensive knowledge about the factors affecting water budget.

The water balance of a lake for a certain period of time reads as follows:

$$\Delta B = (PR+IF) - (EV+OF+WU) \quad (1)$$

where

- PR direct precipitation to the lake surface,
- IF inflow from the watershed,
- EV evaporation from the lake surface,
- OF outflow (in case of Lake Balaton controlled outflow through the Sió canal sluice),
- WU water use from the lake,

ΔB change in water budget,
ΔB_N natural change of water budget $\Delta B_N = (PR+IF) - EV$.

In case of Lake Balaton, reliable and verified monitoring data on water budget elements have been available since 1921, resulting in a 94 year long time series (1921-2014).

In *Table 1*, mean, minimum and maximum values of water budget elements are summarized for the entire period.

Table 1

Characteristic values of water budget elements of Lake Balaton

Water budget element	Minimum	Mean	Maximum
	Lake mm/year*		
Direct precipitation (PR)	309	618	929
Inflow (IF)	293	858	1974
Evaporation from the lake (EV)	723	898	1073
Change in natural water budget (ΔB_T)	-281	578	2031
Outflow (OF)	0	558	1791
Water use (WU)**	15	28	51

** 1 Lake mm ~ 600,000 m³ water volume; ** values refer to the 1971-2014period*
It can be concluded that evaporation (EV) shows the least variability while inflow (IF) shows the greatest one.

Long term averages show that Lake Balaton has outflow, i.e. it is an exorheic lake. The annual outflow is approximately equal to the volume of direct precipitation. Outflow from the lake has been controlled since 1863. Discharge and period of outflow are determined by actual demands and the water level control regulations in force.

Changes in the natural water budget mean the algebraic sum of natural water budget elements, i.e. precipitation + inflow – evaporation. This calculated amount (ΔB_N) indicates the impact of natural pressure on the water budget.

Figure 1 shows the time series of the annual values of ΔB_N. It should be stressed that it was positive in every year for the period between 1921 and 1999. However, there were 7 years between 2000 and 2014 when the value of ΔB_N became negative.

In order to explain the changes in the value of ΔB_N in time 30-year averages of precipitation, inflow and evaporation were analysed (in accordance with the recommendations by the World Meteorological Organization, *WMO*, 1983). Results are shown in *Figure 2*.

As it is shown in *Figure 2* the inflow is the budget element that shows strong declines starting from the 1970s. Therefore, it can be concluded that the inflow is the dominant factor controlling the changes in the natural water budget. Based on this finding, inflow to Lake Balaton has been analysed to reveal the causes of the decline in inflow.

Figure 1

Time series of the natural water budget values of Lake Balaton

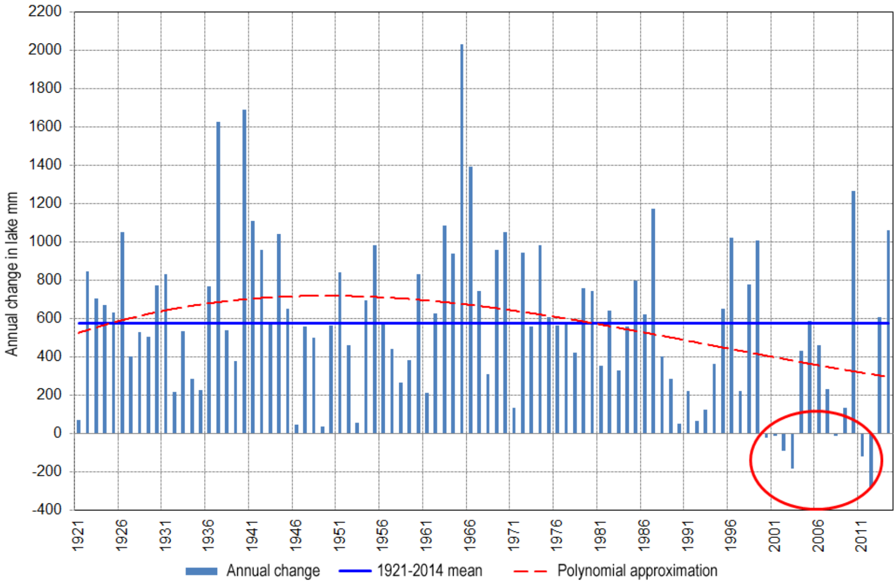
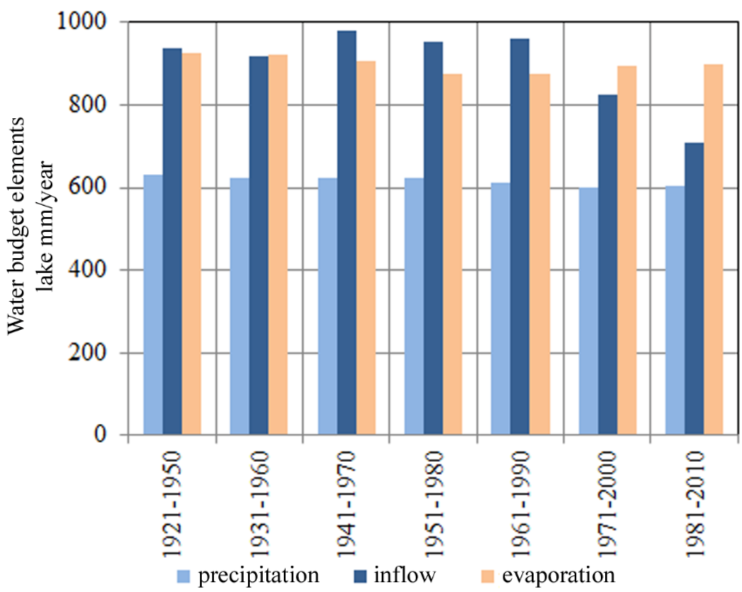


Figure 2

30-year averages of natural elements of the water budget of Lake Balaton



ANALYSIS OF DISCHARGES OF THE TRIBUTARIES OF LAKE BALATON AND BALATON MINOR

Regular hydrological monitoring of the tributaries of Lake Balaton and Balaton Minor („Kis-Balaton" in Hungarian) started in the 1950s. The longest time series of daily mean discharges are available for the Zalapáti section of River Zala. In the second half of the 20th century, more and more tributaries were included in the level/discharge monitoring system. Data used for analysis are shown in *Table 2*.

Table 2

Available discharge data used for the analysis

No.	Tributary/station	Period	Missing data	No. of years
1	Lesence reed field western outflow, Balatonederics	2003-2014		12
2	Lesence reed field eastern outflow, Balatonederics	2003-2014		12
3	Tapolcacreek, Hegymagas	1986-2014		29
4	Eger creek, Nemesgulács	1986-2014		29
5	Burnót creek, Ábrahámhegy	1970-2014		45
6	Örvényesi creek, Örvényes	1970-2014		45
7	Kéki creek, Balatonfüred	1983-2014	1986	31
8	Western belt canal, Balatonkeresztúr*	1992-2014	2011-2012	21
9	Határkülvíz canal, Csömend	1985-2014	1998	29
10	Kőröshegyi creek, Kőröshegy	1979-2014	1983, 1985-86, 1989-91, 2003, 2005, 2007	27
11	Tetves creek, Visz	1964-2014	2000, 2004, 2009	48
12	Keleti Bozót canal, Pamuk	1988-2014		27
13	Büdösgáti creek, Szólád	1967-2014	1980, 1994, 2010	45
14	Boronkai creek, Boronka	1986-2014	1989, 1991-92, 2003, 2010	29
15	Zala river, Zalalövő	1980-2014		35
16	Zala river, Zalaegerszeg	1970-2014		45
17	Zala river, Zalabér	1962-2014	1975	52
18	Zala river, Zalaapáti	1952-2014		63
19	Zala river, Balatonhídvég	1985-2014		30
20	Zala river, Fenékpuszta	1976-2014		39
21	Egyesített-övcsatorna, Fenékpuszta	2005-2014	2014	9
22	Esztergályi creek, Esztergályhorváti	1999-2014		16
23	Orosztonyi creek, Garabonc	2003-2014		12
24	Kiskomáromi creek, Zalakomár	1970-2014	1977	44
25	Zala-Somogyi border ditch, Szőkedencs	1996-2014		19
26	Marótvölgyi canal, Főnyed	1996-2014	2003-2004	17

** For Nyugati övcsatorna, only monthly average discharges are available therefore, only mean discharges could be determined.*

Analysis of the discharge time series

For all tributaries and years shown in table 2 daily average, minimum and maximum discharges were determined for a given year and respective hydrological half years (summer half year (November 1 to April 30) and winter half year (May 1 to October 31). In this way, 228 time series were produced. For all-time series, the linear correlation equation and the respective coefficient of correlation were determined. Pearson's test was performed for the correlation coefficients at three levels of statistical significance (90, 95 and 99%, or p values of .1, 0.05 and 0.01). In addition, signs of the slopes of the correlation equations (or trends of changes) were also analysed. Examples of the results are shown in *Table 3* for River Zala and tributaries of Balaton Minor.

Table 3

Statistical indicators of the discharge monitoring stations of Zala river watershed based on annual medium discharges

Water course/station	N	R^2	R	Changes +/-	Significance level (%)		
					90	95	99
Zala river, Zalalövő	35	0.1093	0.3306	-	+	-	-
Zala river, Zalaegerszeg	45	0.0191	0.1382	-	-	-	-
Zala river, Zalabér	52	0.2086	0.4567	-	+	+	+
Zala river, Zalaapáti	63	0.1251	0.3537	-	+	+	+
Zala river, Balatonhídvég	30	0.0835	0.2890	-	-	-	-
Zala river, Fenékpuszta	39	0.0194	0.1393	-	-	-	-
Egyesített-övcsatorna, Fenékpuszta	9	0.0078	0.0883	-	-	-	-
Esztergályi creek, Esztergályhorváti	16	0.0211	0.1453	-	-	-	-
Orosztonyi creek, Garabonc	12	0.0300	0.1732	-	-	-	-
Kiskomáromi creek, Zalakomár	44	0.1293	0.3596	-	+	+	-
Zala-Somogyi border ditch, Szőkedencs	19	0.0472	0.2173	-	-	-	-
Marótvölgyi canal, Főnyed	17	0.0659	0.2567	-	-	-	-

Statistics were prepared for all discharge indicators of the watershed. Summarizing the results it can be stated that negative (decreasing) trends in the discharges were found in 166 cases out of 228, i.e. in 73.1% of the cases. Positive trends were found only in 61 cases and no change in 1 case.

When statistically significant trends are considered (at least 90% significance level), negative trends dominate even more: 71 (or 84.5%) out of 84 significant trends and as few as 13 trends were positive.

Results of statistical analyses are summarized in *Table 4* and *Table 5*.

Table 4

Number of statistically significant decreasing discharges

Water course/station	**LKQ***			**KÖQ****			**LNQ*****		
	winter half year	**summer half year**	**full year**	**winter half year**	**summer half year**	**full year**	**winter half year**	**summer half year**	**full year**
Lesence reed field western outflow, Balatonederics	1	1	1						
Lesence reed field eastern outflow, Balatonederics									
Tapolcacreek, Hegymagas				1	1	**1**	1		
Eger creek, Nemesgulács									
Burnót creek, Ábrahámhegy	1	1	1	1	1	**1**	1	1	1
Örvényesi creek, Örvényes	1		1	1			1		
Kéki creek, Balatonfüred									
Western belt canal, Balatonkeresztúr									
Határkülvíz canal, Csömend		1							
Kőröshegyi creek, Kőröshegy		1		1	1	**1**			
Tetves creek, Visz		1	1						
Keleti Bozót canal, Pamuk	1								
Büdösgáti creek, Szólád		1			1	**1**			
Boronkai creek, Boronka	1								1
Zala river, Zalalövő	1	1	1	1		**1**			
Zala river, Zalaegerszeg		1	1						
Zala river, Zalabér	1			1	1	**1**	1	1	1
Zala river, Zalaapáti				1	1	**1**	1	1	1
Zala river, Balatonhídvég	1			1					
Zala river, Fenékpuszta	1	1	1						
Egyesített-övcsatorna, Fenékpuszta			1						
Esztergályi creek, Esztergályhorváti	1								1
Orosztonyi creek, Garabonc									
Kiskomáromi creek, Zalakomár	1	1	1	1	1	**1**			
Zala-Somogyi border ditch, Szőkedencs	1								
Marótvölgyi canal, Főnyed	1	1	1						
Total	*13*	*11*	*10*	*9*	*7*	***8***	*5*	*3*	*5*

* LKQ: smallest discharge, ** KÖQ: mean discharge, *** LNQ: largest discharge

Table 5

Number of statistically significant increasing discharges

Water course/station	**LKQ***			**KÖQ****			**LNQ*****		
	winter half year	summer half year	full year	winter half year	summer half year	full year	winter half year	summer half year	full year
Lesence reed field western outflow, Balatonederics									
Lesence reed field eastern outflow, Balatonederics									
Tapolcacreek, Hegymagas			1						
Eger creek, Nemesgulács	1	1	1		1	**1**			
Burnót creek, Ábrahámhegy									
Örvényesi creek, Örvényes									
Kéki creek, Balatonfüred									
Western belt canal, Balatonkeresztúr									
Határkülvíz canal, Csömend									
Kőröshegyi creek, Kőröshegy									
Tetves creek, Visz									
Keleti Bozót canal, Pamuk					1		1	1	1
Büdösgáti creek, Szólád									
Boronkai creek, Boronka									
Zala river, Zalalövő									
Zala river, Zalaegerszeg									
Zala river, Zalabér									
Zala river, Zalaapáti		1	1						
Zala river, Balatonhídvég									
Zala river, Fenékpuszta									
Egyesített-övcsatorna, Fenékpuszta									
Esztergályi creek, Esztergályhorváti									
Orosztonyi creek, Garabonc	1								
Kiskomáromi creek, Zalakomár									
Zala-Somogyi border ditch, Szőkedencs									
Marótvölgyi canal, Főnyed									
Total	*2*	*2*	*3*	*0*	*2*	***1***	*1*	*1*	*1*

* LKQ: smallest discharge, ** KÖQ: mean discharge, *** LNQ: largest discharge

Based on the discharge monitoring data of several decades, it was found that negative trends dominate in the changes of discharges of watercourses in Lake Balaton watershed.

There are two discharge monitoring points on Lake Balaton watershed that have suitably long time series of daily mean discharge values: one on river Zala at the village of Zalaapáti (63 years long) and another on Kiskomáromi canal at the village of Zalakomár (45 years). When these time series were divided into two (approximately) equal periods, and means as well as trends of change were determined, the results shown in *Table 6* were obtained. The linear correlation equations are statistically significant. Discharges for the ends of the periods were also estimated by these equations. For both watercourses, the discharges show significant decrease. The difference for the two periods in case of River Zala is 1.06 m^3/s corresponding to a decrease of 56 lake mm/year.

Table 6

Long term changes in the discharges of River Zala and Kiskomáromi Canal

Zala, Zalaapáti		**Kiskomáromi-csatorna, Zalakomár**	
Period	**KÖQ* mean, m^3/s**	**Period**	**KÖQ* mean, m^3/s**
From measured data		From measured data	
1952-1983	5.56	1970-1992	0.369
1984-2014	4.48	1993-2014	0.325
Change, %	-19.4	Change, %	-11.9
From trendline equation		From trendline equation	
1952	6.01	1970	0.466
2014	3.95	2014	0.325
Change, %	-34.2	Change, %	-30.2

* KÖQ: mean discharge

ANALYSIS OF THE EFFECT OF BALATON MINOR ON THE CHANGES IN THE WATER BUDGET OF LAKE BALATON

Analysis of time series based on hydrological analogy

The Balaton Minor Water Protection System (BMWPS) is a kind of restoration of former wetlands that extended to several tens of square kilometres near the mouth section of River Zala (*Figure 3*). The primary purpose of the restoration was the eutrophication control of Lake Balaton. Stage I. of BMWPS (The 19.6 km^2 surface area Lake Hídvég) was inundated in July 1985. Part of Stage II (Ingó swamp with 16 km^2 area) was inundated in October 1992. Finally, Stage II was finished at the end of 2014 with the construction and inundation of the Lake Fenéki with a surface area of 35.5 km^2. Total surface area of BMWPS is 71.1 km^2, i.e. some 12% of the surface area of Lake Balaton.

BMWPS is situated in the downstream section of River Zala, between the village of Zalapáti and the river mouth. The sub-watershed area of BMWPS is 1094 km^2, belonging entirely to the Lake Balaton watershed.

(Re)construction of BMWPS significantly modified the hydrological processes of the affected area. The open water surfaces created evaporate more water than that (evapotranspiration) of the mostly dry land that had existed there before the inundations.

According to annual water balances calculated for BMWPS evaporation is about 900 mm/year (source: WTDWMA) while, according to literature data (*Nováky*, 1984), evapotranspiration was only 550 to 600 mm/year. This means that the evaporation excess is 300 to 350 mm/year.

In addition to evaporation excess, seepage from the lakes (that are actually reservoirs) to the ground water on the eastern, peaty side of BMWPS may also be important. The seepage may affect (practically increase) the evapotranspiration of the area around BMWPS.

More detailed analysis of the modification effects of BMWPS on the hydrological processes and water budget of Lake Balaton were carried out by two methods described below.

Annual specific runoff of the sub-watershed of River Zala between the Zalapáti water gauge and the river mouth was determined using hydrological analogy based on the discharge data of Kiskomáromi canal (one of the largest tributaries) measured at the Zalakomár water gauge. Processed data of the Hungarian Hydrological Database (MAHAB) were used. Annual runoffs for the sub-watershed (assuming that BMWPS does not exist) were estimated as the products of annual specific runoffs and the area of the sub-watershed.

Results showed that in 23 out of 29 years the difference of measured and estimated discharges for the mouth section of River Zala were negative. The multiannual average is -34 lake mm/year, indicating that BMWPS has a negative impact on the water balance of Lake Balaton. It should be mentioned that there is a great year-to-year variability in the value. The largest deficit is -108 lake mm/year, occurring in 2004.

The negative effect of BMWPS on the water balance of Lake Balaton is most obvious when dry periods with below-average annual precipitation are considered.

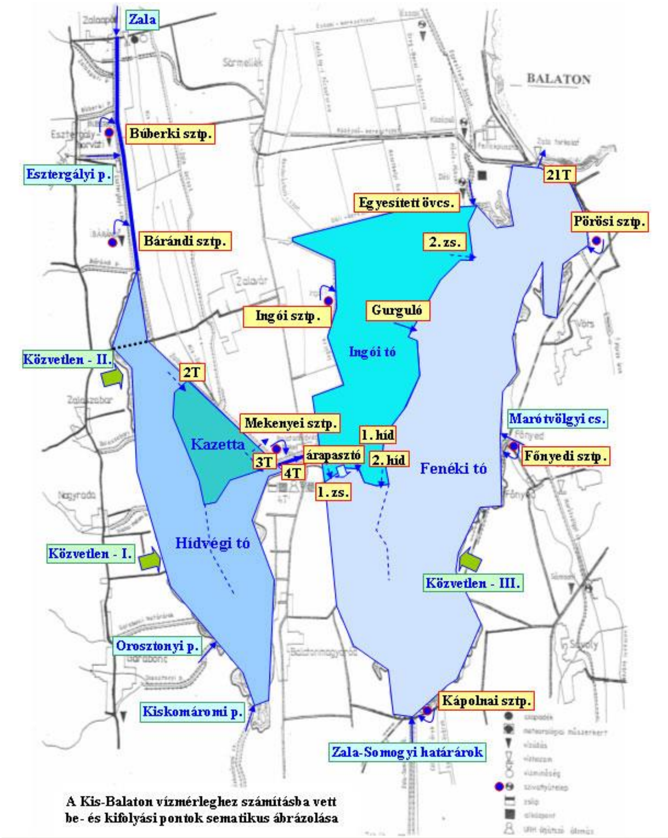
E.g. in the period from 2000 to 2003, the four-year average of annual precipitation was 521 mm/year as compared to the average (660 mm/year) of the whole period examined (29 years from 1986 to 2014). Although in year 2004 there was 6% more precipitation than the average, the water abstraction effect was twice of the average (-67 lake mm/year) for the 4 years.

Analysis of runoff based on multiannual averages and area delineation

After the inundation of Phase I (19.6 km^2) of the BMWPS in 1985, its water surface changed in three steps. The total water surface increased to 35.6 km^2 in 1992 and to 71.1 km^2 in 2014. Water balances have been done for Balaton Minor (BM) every year since 1986, though with changing methodology that resulted in inconsistent results and made year-to-year comparison difficult. Therefore, these annual water balances are not used in this study. Instead, we used a new approach of area delineation to deal with the whole BM area.

Figure 3

A schematic map of Balaton Minor Water Protection System with the objects used for the calculation of water balance



Source: http://www.nyuduvizig.hu/upload/kb_be-kifolyasok-e.jpg

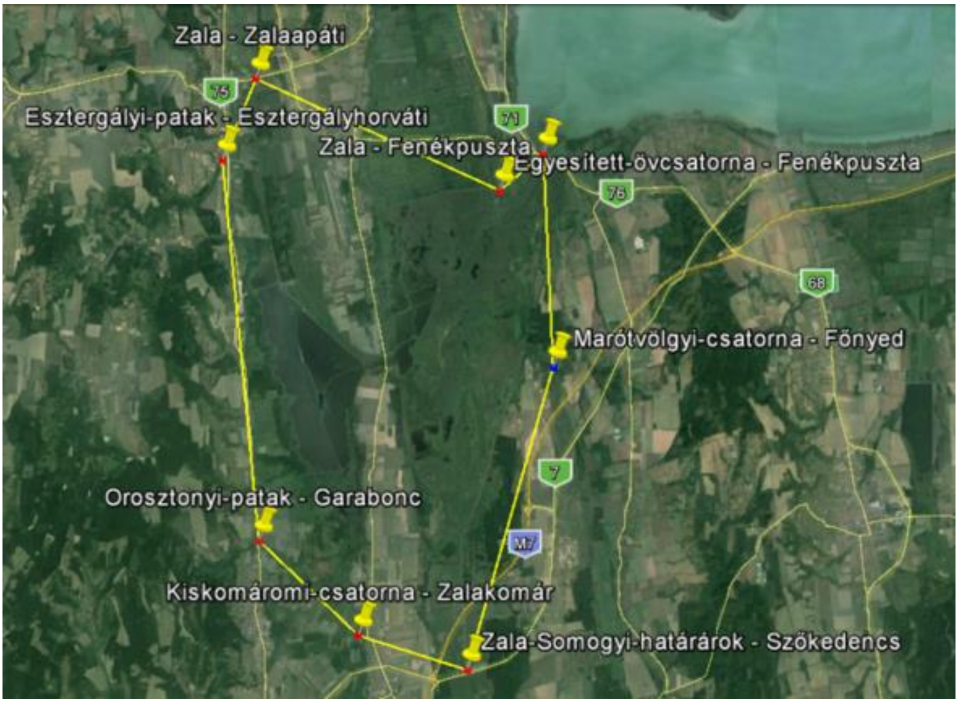
There are 8 discharge monitoring points around the whole area of BM (*Figure 4*). The polygon determined by these 8 points encloses an area being considerably larger than the area of the BMWPS. Therefore, natural internal flows between Phase I and Phase II as well as discharges of pumping stations inside the polygon did not have to be dealt with. Steps of the method are as follows:

1. The polygon enclosing the area was determined based on the geo-coordinates of the discharge monitoring stations.
2. Direct watersheds as well as watersheds of small watercourses located outside the polygon were determined (altogether 8 "outlying" areas).
3. The average specific runoff was calculated for 7 sub-watersheds based on the inflow discharge data of the monitoring stations for the 1986-2014 period.
4. For the "outlying areas, the average specific runoff was calculated as the weighted average of the two neighbouring sub-watersheds.

5. The average specific runoff for the polygon was determined as the weighted average of the known data of the 7 sub-watersheds.
6. The predicted discharge of river Zala at the mouth of river Zala (outflow of the polygon, and inflow to Lake Balaton) was calculated using the specific runoff data of the 7 known sub-watersheds and the 8 "outlying" areas, and the predicted figure was compared to the monitoring data of the station at the river Zala mouth.

Figure 4

The polygon enclosing Balaton Minor
(tips are the discharge monitoring points)



This estimate of the discharge of River Zala is considered as a "conservative" one since the specific runoff data of River Zala (calculated from the data of the Zalaapáti monitoring station) were also included in the estimation of the runoff of the polygon. Since the runoff figure of Zalaapáti is smaller than that of the smaller tributaries of BM, the calculated "theoretical" discharge at River Zala mouth is smaller than it would be by the omission of the Zalaapáti data.

In order to study the sensitivity of the estimated discharge to the method used, two estimations were carried out with slightly modified methods. As one modification, the runoff of the polygon was estimated as the weighted average of 4 medium watercourses (Kiskomáromi Canal, Zala-Somogyi Border Ditch, Marótvölgyi Canal és Egyesített Belt Canal). This is considered to be the "maximum" scenario in terms of the discharge estimate at Zala mouth. The other modification was based on the specific runoff of Kiskomáromi Canal, a medium sized watercourse. The runoff of this watercourse is smaller than the other medium sized watercourses, so this estimate was considered as "minimum" (*Table 7*).

Table 7

Estimation of the effect of Balaton Minor on the discharge of River Zala and on the water balance of Balaton Minor and Lake Balaton

Quantity	Conservative	Maximum	Minimum
Calculated discharge, m^3/s	8.00	8.10	7.81
Measured at Zala mouth, m^3/s	7.04	7.04	7.04
Deficit, m^3/s	-0.96	-1.06	-0.77
Deficit as BM water level (71.1 km^2) lake mm/year	-428	-469	-342
Deficit as Lake Balaton water level (600 km^2) lake mm/year	**-50.7**	**-55.6**	**-40.6**

Based on the estimations by these methods, it can be concluded for the 29 year period studied that the annual average deficit caused in the water balance of Lake Balaton by Balaton Minor is some 40 to 60 mm /year in terms of Lake Balaton water level.

The two different methods (annual analysis based on hydrological similarity as well as multiannual analysis based on territorial delineation and hydrological similarity) resulted in estimates of 34 to 51 mm/year as deficits in terms of Lake Balaton water level.

EFFECT OF RESERVOIRS AND FISH PONDS ON THE LAKE BALATON WATERSHED ON THE WATER BUDGET OF LAKE BALATON

Reservoirs and fish ponds in the watershed

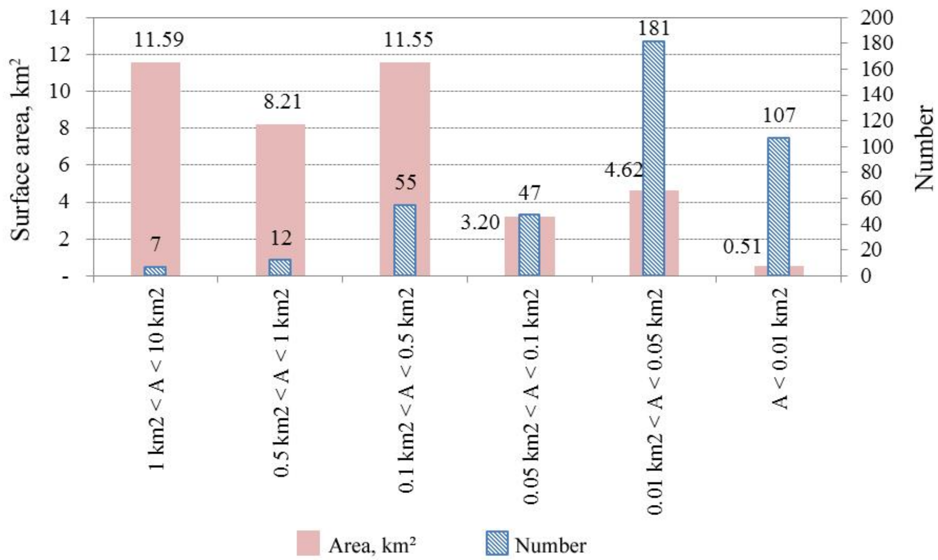
Based on data of year 2015, the number of reservoirs and fish ponds exceeding the 1,000 m^2 area is 405 with a total water surface area of 37.2 km^2. The distributions of these water bodies by size and number are shown in *Figure 5*.

These free water surfaces constructed on the water courses of the watershed are extremely shallow and they increase evaporation (water temperatures exceeding 30 °C are not rare in summer) as compared to the evaporation of small rivers and creeks. The excessive evaporation appears as deficit in the water budget of Lake Balaton.

The excess in evaporation of these water bodies was estimated as the difference in the evaporation of free water surfaces and that of grass covered (meadow, pasture) areas. The long term multiannual (from 1951 to 2014) average was 8 mm/year in terms of Lake Balaton water level. When the period of the existence of BMWPS is considered (from 1986 to 2014), the deficit caused by these water bodies is 10 mm/year. The year-to-year figures show great variability (e.g. 1 mm in 1996 and 21 mm in 2000).

Figure 5

Distribution of number and surface area of reservoirs and fish ponds in the Lake Balaton watershed (without Balaton Minor)



The average water deficit caused by the BMWPS and all the other stagnant surface water bodies is estimated as some 44 to 61 mm/year.

During the extended drought period from 2000 to 2004 the stagnant surface waters alone (including the BMWPS) caused as much as 406 mm deficit in the water budget of Lake Balaton. This figure compares to the 3500 mm average depth of Lake Balaton.

Climate change scenarios referring to Lake Balaton predict increasing temperatures and evaporation (both from the lake and the watershed). In multi-decade lookout, it is probable that the frequency and length of periods with water deficit increase. These findings suggest that the creation of new stagnant water surfaces in the watershed is definitely not recommended.

ANALYSIS OF WATER USE FROM LAKE BALATON

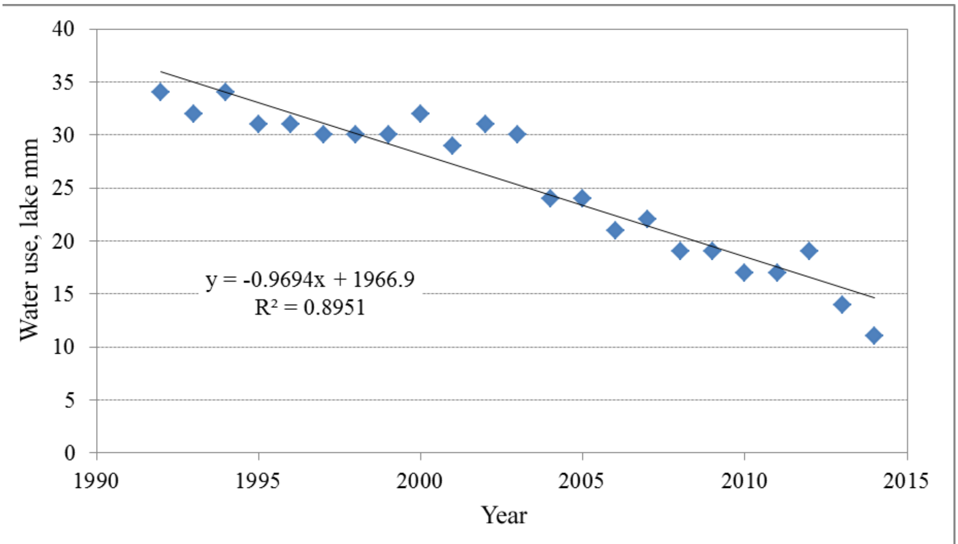
Water withdrawal now and its expected future change

Water use is the difference of withdrawn (drinking, irrigation, industrial, cooling water) and returned (treated effluents, used cooling water, etc.) water volume.

Reliable data for water use from Lake Balaton have been available since 1971. The greatest figure was 51 mm/y in 1989 while the smallest one was 11 mm/y in 2014. Trend of water use in the last 23 years is shown in *Figure 6*.

Figure 6

Trend of water use from Lake Balaton



An important reason for the decreasing trend is that while the consumer price index increased "only" 7.3 times during the period (*HCSO*, 2016c), the drinking water and sewer prices increased 16 times. The high water service price is a strong incentive to water saving. At the same time, environmental awareness may also play some part in the reduction of water use. While water use in the Lake Balaton watershed was 180 litre/person/day in 1997-1999 (in JICA project), it decreased to less than 100 litre/person/day by 2014.

The installed water withdrawal capacity of the Transdanubian Regional Water Works (DRV) corresponds to 41 lake mm/year, but it uses only a fraction of it, i.e. 9 to 11 lake mm. The company plans to switch its water base from Lake Balaton to karstic water wells.

The Water Framework Directive of the European Union states that the principle of the recovery of water service costs should be taken into consideration. Therefore, it is not expected that water prices would decrease in the future, and as a consequence, water use would not increase either. The dissemination of environmental and climate awareness as well as the corresponding programs of municipal governments also have an effect to reduce water use.

Act CXII. of 2000 on the Regional Development Plan of Lake Balaton Resort Area (so called "Lake Balaton Act") prefers environmental and nature protection to industrial development, so it is not expected that industrial water withdrawal would increase to any significant level.

The lack of funds in agriculture at the beginning of 1990 resulted in radical drops in the use of irrigation water and fertilizers. However, in the last decade, fertilizer use increased moderately (*Kutics*, 2015). It is expected that irrigation water demand would slightly increase in the next decades.

In summary, water withdrawal is not expected to increase, and it probably stays in the 10 to 20 mm range.

Water returned into Lake Balaton in the form of treated sewage effluent is 19,098 m^3/day (2014) corresponding to 11.6 lake mm.

The total water withdrawal hardly exceeds the amount of returned water, so water use from the Lake results in a mere 6 to 7 mm deficit in the water budget of Lake Balaton.

EVALUATION OF THE EFFECT OF THE INTRODUCTION OF WATER WITHDRAWN FROM MINES

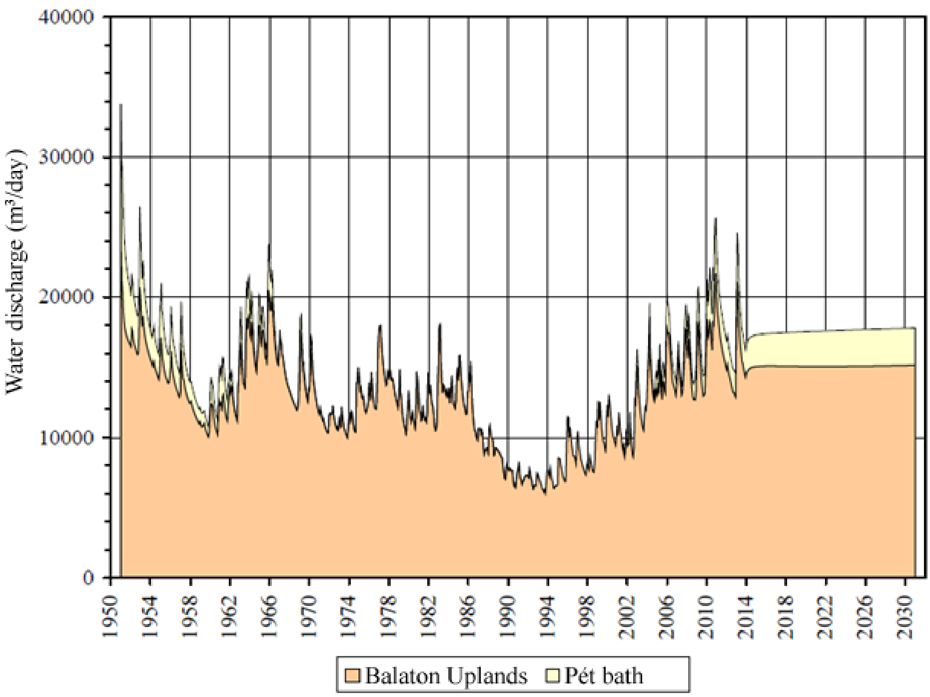
The most important subsurface water storage formation of Lake Balaton region is the main karstic water reservoir of the Transdanubian Mountain Range. Of the anthropogenic impacts on the reservoir bauxite mining is the most influential one. Most of the bauxite deposits at the north-western edge of Bakony Mountains were positioned below the original (natural) karst water level constituting a threat to the mining activities. Since 1963, the mining company applied the active water level reduction technique in the mining area around the villages of Nyirád and Nagytárkány. Water withdrawal from the main karstic water reservoir affected the water level in a wide area at the north-western part of the northern sub-watershed of Lake Balaton. Karstic water level dropped significantly (in some areas as much as 150 m) and the subsurface flow direction of karstic water changed (*Lorberer et al.* 1980). Several springs dried up or their discharges were reduced radically. Some smaller water courses dried up seasonally or even for longer periods (Világos creek, Lesence creek, Eger creek) so the mining activities fundamentally modified the surface water runoff as well (*Kravinszkaja*, 1986). The water withdrawal from the mines around Nyirád village exceeded as much as 5 m^3/s (i.e. some 70% of the discharge of River Zala, the largest tributary of Lake Balaton. Most of the withdrawn water was discharged into another watershed (River Marcal), but a still significant part (in the order of 1 m^3/s) was discharged into the Kétöles creek, a small tributary of Lake Balaton.

Bauxite mining and water withdrawal from the mines came to an end in 1990, and introduction to the withdrawn water to the tributary of Lake Balaton was radically reduced, though some fractional amount from the wells around the mines were introduced to Kétöles creek up to 2009. The introduction of mining water into Lake Balaton was completely stopped in that year.

After ending water withdrawal from the main karstic water reservoir, a natural regeneration process started and this process has been going on since then in front of our eyes. In some areas the karstic water reached the level that was typical before the human interventions, but the regeneration process has not been finished yet (*Figure 7*). However, the depletion and recharge processes differ in terms of duration, intensity and amount.

Figure 7

Calculated and predicted karstic discharges of the Transdanubian Mountain Range from 1951 to 2030



Source: *Hidrosys,* 2014

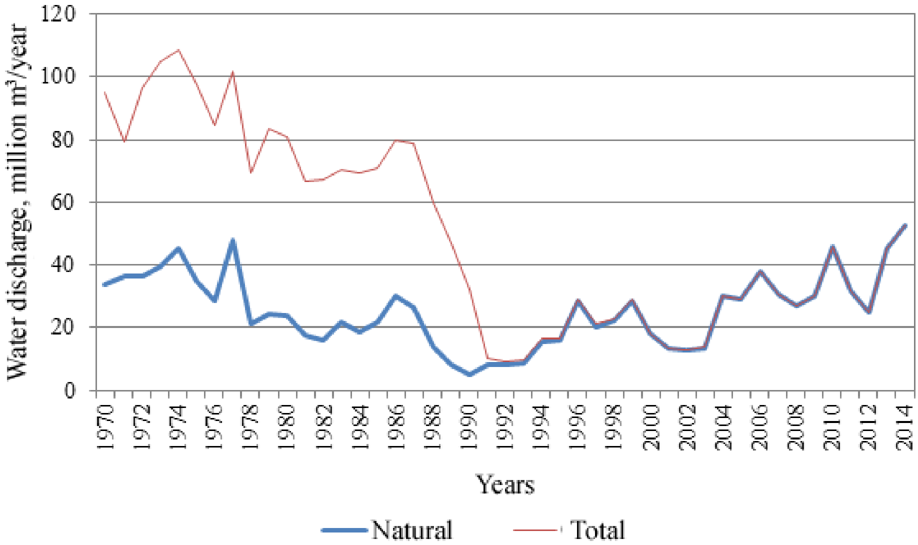
Mining activities influenced mostly the water courses and springs of the Tapolca Basin (NW of Lake Balaton). "Natural" (i.e. free from the effects of mining) runoff time series of the Tapolca Basin were estimated for the 1970 to 1990 time period, as well as for the 1991-2014 time period (actual monitoring data). The results are shown in *Figure 8*.

The two separate natural runoff time series were analysed statistically and average rates of decrease and increase of runoffs were determined. The rate of decrease was found to be -1.44 million m^3/year, while that of the increase was 1.38 m^3/year.

The increasing natural runoff reached the 40 million m^3/year value in 2014, equalling to the figure of 1970. However, in 1970 some 60 million m3/year water withdrawn from the mines added to this figure. This latter amount, corresponding to about 100 lake mm is missing from Lake Balaton's water budget at present.

Figure 8

Total and natural runoff of Tapolca Basin



IMPACTS OF CHANGES ON LAND USE

The most significant changes in land use in the Lake Balaton watershed was the increase of the area of forests in the last 4 decades. The reasons of change are erosion control and abandoned tillage and vineyard following political changes in 1990 and subsequent reprivatisation of land confiscated during the communist period. Since forests retain precipitation and increase evapotranspiration, excessive forestation may have a negative impact on the water balance of the Lake. Effect of land use change was analysed by the DIWA hydrological simulation package (*Szabó*, 2015). Results showed that the impacts of changes in land use on runoff were almost negligible. The deficit caused is some 3 to 4 mm/year in Lake level, close to the uncertainties of the figures of meteorological and hydrological monitoring stations (*Table 8*).

Table 8

Change of land use in the watershed of Lake Balaton (data in per cent)

Category	1977	2006	Change
Tillage	38.0	36.0	-2.0
Forest	23.4	28.3	5.0
Meadow, pasture	15.1	12.3	-2.8
Vineyard, orchard	6.1	3.9	-2.2
Water surface	10.5	11.1	0.5
Other	6.9	8.4	1.5
Total	100.00	100.00	0.00

CLIMATE CHANGE IMPACTS ON THE WATER BUDGET OF LAKE BALATON

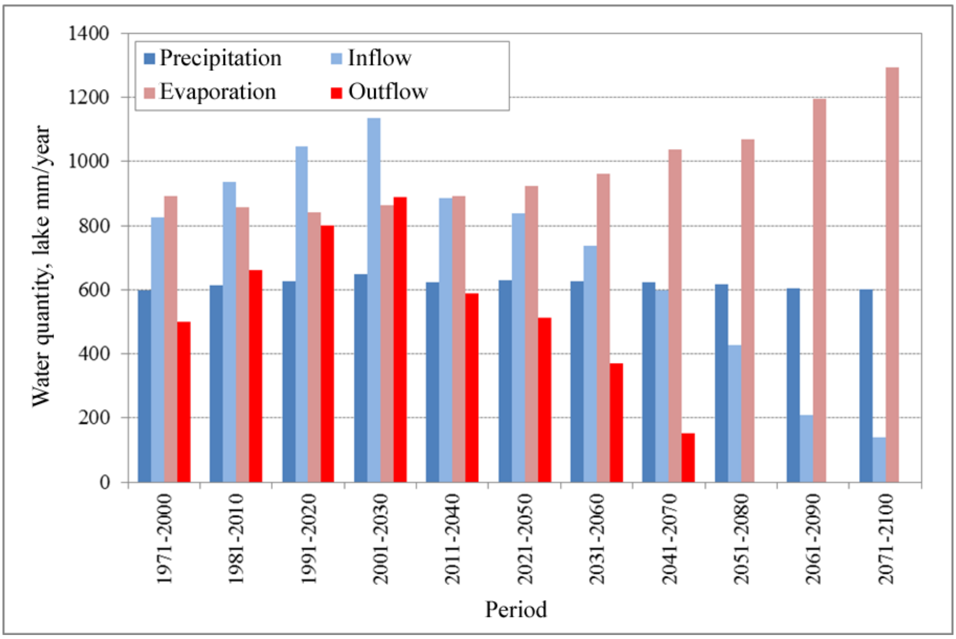
Lake Balaton Development Coordination Agency, the operative arm of Lake Balaton Development Council dealt with the problem of climate change and its impact on Lake Balaton (Lake Balaton Adaptation Project, UNDP-GEF, 2006-2008, EU-Lakes Project "010-2012, Lake Admin Project, 2011-2014).

The objective of the EU-Lakes Project was to study the impacts of climate change on European lakes. A high resolution regional climate change model was developed by one of the project partners (*Züger and Knoflacher*, 2011, 2012) that provided meteorological data for the 21st century for the Lake Balaton watershed. Data of this model were used to predict changes in the water budget of Lake Balaton.

Results of the predictions on the elements of the water budget are shown in *Figure 9*. The graph indicates that inflow is expected to be greatly reduced and Lake Balaton may become an endorheic lake in the second part of the century. It should be stressed that such modelling carries a great deal of uncertainties, but the results suggest that precautionary measures should be planned on the long term.

Figure 9

Changes of water budget elements of Lake Balaton in the 21st century. Results of climate change simulations based on scenario A1b



Source: *Kravinszkaja and Varga*, 2015

Results of climate change impact predictions are not included in the evaluation of human impacts, since the objective of this study was to uncover the human impacts that have already been manifested.

In summary, recognized effects of human influence on the water budget of Lake Balaton are shown in *Table 9*.

Table 9

Effects of human activities on the water budget of Lake Balaton

Human activities	Water resources reduction Lake mm/year
Restoration/Creation of the Balaton Minor Water Protection System	- (34-51)
Formation and operation of fishponds	-10
Changes in land use (forestation)	-(3-4)
Diversion of STP effluents to other watersheds	-(6-7)
Discontinuation of the introduction of water extracted from mines	-100
Significant reduction of the discharges of River Zala and Kiskomáromi Canal	-59
Total	**-(212-231)**

SUMMARY AND RECOMMENDATIONS

Long time series of discharges for whole years as well as summer and winter hydrological half years were produced and trends of changes were analysed for the tributaries of Lake Balaton. Trend of change was found to be decreasing in 73.1%, increasing in 26.5% of the cases. There was no change in 0.4% of the cases. Pearsons tests were performed and it was found that out of the statistically significant ($p < 0.05$) trends, 84.5 % were decreasing ones. In case of River Zala discharge monitoring stations (River Zala carries some 60% of all discharges into Lake Balaton), as much as 93.8 % were decreasing and a mere 6.2% were increasing trends at $p < 0.01$ level. For the two monitoring stations (River Zala at Zalaapáti and Kiskomáromi Canal at Zalakomár) having the longest time series of daily discharge monitoring data, the time series were divided into two, approximately equal length, series and it was found that in the last 31 years the annual mean discharge of River Zala at Zalapáti was 19.4% smaller than in the preceding 32 years. In case of Kiskomáromi Canal, the time series was only 45 years long, and it was found that in the last 23 years the annual mean discharge was 11.9% less than in the preceding 22 years.

The water budget elements of Lake Balaton were analysed for the 1921 to 2014 period (94 years). No statistically significant trend was found in direct precipitation onto the lake surface. However, it should be mentioned that both the greatest and smallest annual precipitation sums occurred in the last 5 years. In the water budget, decrease of inflow is the most serious negative factor. As far as the output side of water budget concerned, statistically significant trend was not found in evaporation time series. Changes in the water budget of the Lake show warning signals. On one hand, frequency of unusual/extreme meteorological conditions has increased. On the other hand, in 7 of the last 15 years the natural water budget (direct precipitation + inflow – evaporation) was negative, while such figure never occurred in the previous 79 year period from 1921 to 1999.

The effect of the Balaton Minor Water Protection System on the water budget of Lake Balaton was analysed by two methods. It was found that the BMWPS reduced the inflow into the Lake. The long term average figure is -34 to -51 mm/year in terms of Lake Balaton level. Consecutive years with drought conditions may result in several times higher values than the averages.

Artificial stagnant surface water bodies (reservoirs and fish ponds) result in 8 lake mm/year deficit for the whole period that could be analysed while the figure is 10 mm/year for the 1986 to 2014 period.

Water use from the Lake, defined as the difference of withdrawn and returned water volume, is not significant as compared to other elements of the water budget. The figure is 6 to 7 lake mm/year, and it is not expected to increase in the future.

The introduction of water withdrawn from bauxite mines into Lake Balaton had a serious influence of the water budget of Lake Balaton. Both introduction and stoppage were abruptly decided and carried out. Reliable discharge data for the water courses and springs affected by mining are not available for the period before mining (and water withdrawal) activities started, therefore a genuine background value for runoff of the affected area is not known. It can be concluded, however, that the natural runoff of the area was 40 million m^3/year in 1970. It was reduced to about 8 million m^3/year by 1990 (when mining was stopped), and increased again to 40 m^3/year by 2014. However, some 60 million m^3/year (100 lake mm/year) of "mining water" (in fact, drinking water quality karstic water) was introduced into the Lake during the 1970 -1990 period that is missing from the water budget at present.

The found impacts on the water budget of Lake Balaton either directly originate from human activities or the manifestations of the global climate change. The deficit caused by human activities in the water budget of Lake Balaton is roughly 210 to 230 mm/year in terms of Lake Balaton level, or 126 to 138 million m^3/year (for comparison, Hungary's total potable water production is 600 million m^3/year). Based on the results of this study our recommendations are as follows:

1. Discharge monitoring on the whole watershed should be developed both quantitatively (more stations) and qualitatively (telemetric, continuous monitoring) in order to increase reliability of the elements of water budget.
2. Construction of artificial shallow surface water bodies (i.e. reservoirs and fish ponds) should not be allowed in the watershed. Expired licences should be revised, extensions should either be refused or strict water management conditions should be required.

3. Manifested direct human impacts and the expected future impacts of climate change indicate that a complex water resources preservation program should be started in the Lake Balaton watershed. The elements of the program are: development of rain water management/utilization on individual and municipality level; improvement of the technical and safety conditions of water storage in the Lake (i.e. maintaining higher water level to alleviate the impacts of droughts); increase the level and efficiency of the activities of water authorities; elimination of illegal water withdrawals; regulation of land use giving priority to water resources management considerations.

ABBREVIATIONS

BM	Balaton Minor
BMWPS	Balaton Minor Water Protection System
DIWA	Distributed Watershed
DRV	Trans-Danubian Regional Water Works
EULAKES	Project - European Lakes under Environmental Stressors
HCSO	Hungarian Central Statistical Office
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
KDT VIZIG	Central Trans-Danubian Water management Authority
STP	Sewage Treatment Plant
UNDP-GEF	United Nations Development Programme – Global Environmental Facility
US-EPA	United States Environmental Protection Agency
VITUKI	Research Centre for Water Sciences
WMO	World Meteorological Organization
WTDWMA	West Trans-Danubian Water Management Authority

REFERENCES

Hungarian Central Statistical Office (HCSO) (2016a): Turizmus-szatellitszámlák, 2014–2015, [online] <URL: http://www.ksh.hu/docs/hun/xftp/idoszaki/turizmszatt/turizmszat14.pdf>

Hungarian Central Statistical Office (HCSO) (2016b): Fókuszban a főszezon – a Balaton idegenforgalmi régió vendégforgalma, Statisztikai Tükör, 2016. nov. 21., [online] <URL: https://www.ksh.hu/docs/hun/xftp/stattukor/regiok/veszpremidforg/ veszpremidforg1608.pdf>

Hungarian Central Statistical Office (HCSO) (2016c): Egyes termékek és szolgáltatások éves fogyasztói átlagára (1996–), [online] <URL: http://www.ksh.hu/docs/hun/xstadat/xstadat_eves/i_qsf003a.html?down=1487.>

Kravinszkaja, G. (1986): A Balaton északi parti vízfolyásainak hossz-szelvény vizsgálata 1985-1986, KDT VIZIG, Székesfehérvár

Kravinszkaja, G., Varga, Gy. (2015): Változások és szélsőségek a Balaton vízháztartásában, A Magyar Hidrológiai Társaság XXXIII. Országos Vándorgyűlése, 2015. júl. 1-3, Szombathely, ISBN 978-963-8172-34-1, [online] <URL: http://www.hidrologia.hu/vandorgyules/33/dolgozatok/word/0327_varga_gyorgy.pdf>

Kutics, K. (2015): The History of Human Interventions in the Environment of Lake Balaton – Downs and Ups –. In: Molnár, G., Kutics, K., Farkas, S. (Eds.): Interaction of Natural and Social Processes in Shallow Lake Areas, Kaposvár University, Kaposvár, p. 21-44, ISBN 978-963-9821-965 (Printed edition), ISBN 978-963-9821-97-2 (Electronic edition)

Lorberer, Á., Lorbererné Szentes I., Mike K. (1980): A Balaton vízgyűjtő földtani kialakulása, felépítése és vízföldtani viszonyai. VITUKI

Nováky, B. (1984): Csapadék, párolgás,Vízgazdálkodási Intézet, Budapest, pp. 107.

Szabó, J.A. (2015): in Kutics et al.: A Balaton és teljes vízgyűjtő-területének átfogó hidrológiai vizsgálata, különös tekintettel a lefolyási viszonyok drasztikus változására, és a hozzáfolyás csökkenésére. Tervtanulmány, 6. Fejezet, 66-67. p., KEOP- 7.11.0./14-2015-0003 Projekt.

West Trans-Danubian Water Management Authority (2016): Annual Water Balances for Balaton Minor (in Hungarian), [online] <URL: http://www.nyuduvizig.hu/index.php/vizrajz/kis-balaton-tavmero-rendszer-vizmerleg>

World Meteorological Organization (1983): Guide to Climatological Practices. Second edition, WMO-No.100, Geneva, ISBN 92-63-12100-1

Züger J., Knoflacher M. (2011): Regional climate change scenario – Scenario selection and preliminary results. Deliverable 4.3.2, Project EULAKES Ref. No. 2CE243P3: European Lakes under Environmental Stressors (Supporting lake governance to mitigate the impact of climate change). [online] <URL: http://eulakes-model.eu/outputs/index.html>

Züger, J., Knoflacher, M. (2012): Climate Change Scenarios Simulation and Exploration. Deliverable 4.3.3, Final Report4.3. Uncertainties of scenarios: Regional climate change scenario Project EULAKES Ref. No. 2CE243P3: European Lakes under Environmental Stressors (Supporting lake governance to mitigate the impact of climate change). AIT Austrian Institute of Technology GmbH. [online] <URL: http://eulakes-model.eu/outputs/index.html>

OTHER LITERATURES

Antal, G. (1994): A lefolyási viszonyok változása a Balaton vízgyűjtőjén 1994., MHT XII. Országos Vándorgyűlés, Siófok

Baranyi, S. (1975): A Balaton hidrológiai jellemzői 1921-1970, VITUKI Tanulmányok és kutatási eredmények 45. Budapest

Baranyi, S. (szerk.)(1975): A Balaton kutatási eredményeinek összefoglalása. Vízügyi Műszaki Gazdasági Tájékoztató 112.sz., Budapest

Bendefy L. (1968): A Balaton vízszintjének változásai a neolitikumtól napjainkig. Hidrológiai Közlöny 48. 6. 257-263. p.

HYDROSYS (Víz- és Környezetvédelmi Fejlesztő Szolgáltató Kft.) (2014): A Dunántúli-középhegység főkarsztvíz-tárolójának 2013. évi állapotértékelése. Kutatási jelentés, KDT Vízügyi Igazgatóság, Székesfehérvár

IPCC (Intergovernmental Panel on Climate Change) (2000): IPCC Special Report, Emissions Scenarios, 2000. [online] <URL: https://ipcc.ch/pdf/special-reports/spm/sres-en.pdf>

KDT VIZIG (2015): A Balaton vízgyűjtő vízgazdálkodási terve (FÖMI, CORINE CLC50 alapján) Székesfehérvár, 2015.

KDT VIZIG BVK (2006): A balatoni vízeresztés vízrajzi tapasztalatai. Témajelentés, Siófok, 2006. Február.

KDT VIZIG:(1993…2016): A Balaton vízháztartási mérlegei. Témajelentés, Siófok.

Kertész, Á. (2011): A földhasználat változása a Balaton vízgyűjtőn egy évszázad során, különös tekintettel az erdőkre, A Miskolci Egyetem Közleményei, A sorozat, Bányászat, 82. 167-170. p.

Környezetvédelmi és Vízügyi Minisztérium (2008, 2014): Nemzeti Éghajlatváltozási Stratégia 2008-2025. [online] <URL: http://www.kvvm.hu/cimg/documents/nes080214.pdf>

Kravinszkaja G. (1989): A Balaton északi parti vízfolyások és a Lesence nádasmező vízkészlet változásának vizsgálata. Székesfehérvár

Kutics, K. (2013): Development and running of EULAKES water Quality model, Phase B, Final report. Project EULAKES Ref. No. 2CE243P3 European Lakes under Environmental Stressors (Supporting lake governance to mitigate the impact of climate change) K+F Consulting Kft. 110. p. [online] <URL: https://www.eulakes-model.eu/media/files/EuLakes-Water-Quality-Model.pdf>

Major, P. (1974): Síkvidéki erdők hatásának vizsgálata a talajvízpárolgás és a tényleges beszivárgás folyamataira. Hidrológiai Közlöny, 54. 6. 281-288. p.

Mészáros E.-Schweitzer (szerk.)(2002):-Magyar Tudománytár 1. kötet; Föld, víz levegő. Kossuth Kiadó, 512 p.

Nakicenovic N., Swart R. (Eds.) (2000): IPCC Special Report on Emissions Scenarios. Cambridge: Cambridge University Press 570 p. [online] <URL: https://www.ipcc.ch/pdf/special-reports/emissions_scenarios.pdf>

PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) (2005): Final Report. (EVK2-CT2001-00132) [online] <URL: http://prudence.dmi.dk/public/publications/PRUDENCE Final report.pdf>

Roeckner, E., Lautenschlager, M., Schneider, H. (2006): IPCC-AR4 MPI-ECHAM5_T63L31 MPIOM_GR1.5L40 SRESA1B run no.1: atmosphere 6 HOUR values MPImet/MaD Germany. World DataCenter for Climate. DOI:10.1594/WDCC/EH5-T63L31_OM-GR1.5L40_A1B_1_6H.

Soja, A.-M., P. Kinner, G. Soja (2012): Project report: 4.2.1 Impacts on Lake Hydrology and Water Quality. Project EULAKES Ref. No. 2CE243P3: European Lakes under Environmental Stressors (Supporting lake governance to mitigate the impact of climate change). [online] <URL: http://eulakes-model.eu/outputs/index.html>

Szilassi P (2006): A területhasználat változás főbb tendenciái a Balaton vízgyűjtőjén Kertész Á, Dövényi Z, Kocsis K (szerk.) III. Magyar Földrajzi Konferencia: absztrakt kötet + CD-ROM. 238 p. Budapest: MTA Földrajztudományi Kutatóintézet

Szlávik L. (szerk.) (2005): A Balaton. Vízügyi Közlemények, Különszám, 87. 1. 477. p.

Tervező és Tanácsadó Agrober Rt. (1995): Balaton vízgyűjtő vízminőségvédelmi, komplex meliorációs és erdősítési tanulmány. Budapest: Földművelésügyi Minisztérium

US EPA (2015): Addressing Climate Change in the Water Sector. [online] <URL: https://www.epa.gov/climate-change-water-sector>

Virág Á. (1997): A Balaton múltja és jelene, Eger: Egri Nyomda Kft. 904 p.

Virág Á. (2005): A Sió és a Balaton közös története (1055-2005). Budapest: Közlekedési és Dokumentációs Kft.550 p.

VITUKI (1977): Vízrajzi Atlasz sorozat, 21. Kötet: Balaton, Budapest

VITUKI (1980): A Balaton kutatása és szabályozása, VITUKI Közlemények 27. Budapest, 1980.

VITUKI (2002): A Balaton ideiglenes vízszint-szabályozási rendjével kapcsolatos hatások és tapasztalatok elemzése II. ütem. Témajelentés, tsz.: 714/1/5371-01, Budapest

VITUKI (2003): A Balaton vízpótlásának szükségessége: hidrológiai elemzések végzése. Témajelentés, tsz.: 721/1/6131-01, Budapest

Corresponding author:

Károly KUTICS
K+F Consulting Llc.
H-8200 Veszprém, Rózsa u. 46.
Tel.: +36 20 313-0538
e-mail: kutics.karoly@chello.hu