IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 114, No. 3, July – September 2010, pp. 187–201

Analysis of precipitation on Lake Balaton catchments from 1921 to 2007

Angéla Anda[*1] and **Balázs Varga**[2]

[1]*Department of Meteorology and Water, University of Pannonia Georgikon Faculty*
H-8360 Keszthely, Hungary; E-mail: anda-a@georgikon.hu

[2]*Agricultural Research Institute of the Hungarian Academy of Sciences, Martonvásár, Hungary*

[*]*Corresponding author*

(Manuscript received in final form November 20, 2009)

Abstract—The aim of this analysis is to provide an overview of the precipitation conditions of the Balaton catchments. Because Lake Balaton has shallow water, it responds sensitively to any change in the environment, including precipitation. The influence of the dry period on the lake's water level in the years 2000–2003 serves as a good example for this. Data series of 25 precipitation gauging stations of catchments, recorded between 1921 and 2007, were investigated in this study.. Annual precipitation sums, monthly distribution of rainfall, and the influence of rainfall on natural change in water storage were studied. The whole catchment area was divided into different parts depending on geographical locations and climatic conditions. We found significant differences in the regional precipitation amounts. The western part of the catchments (half of the Zala River basin) has the highest annual precipitation sum, while going towards the east and in the "cut" of the lake, the amount of rainfall decreases. At the majority of the examined stations the decrease in precipitation was also detectable on the basis of WMO climate means, but we did not find explicit decreasing tendencies in the case of several stations. Surface runoff moved collaterally with precipitation decreases, and its impact on natural change in water storage was even more pronounced. The natural change in water storage of the lake is a good indicator reflecting the drying tendency of the recent past, and it calls attention to the necessity of more deliberated water management of the Lake Balaton. Presumably, the precipitation phenomenon, similarly to the past, will also vary in the future. Analysing the data of the past decades may help in making more established decisions.

Key-words: precipitation, Balaton catchments, natural change in water budget

1. Introduction

Investigations of the water budget of Lake Balaton, the largest lake of Central Europe (46°42’6”–47°3’50” N and 17°14’58”–17°14’58” E, its surface is about 600 square kilometers, and the average depth of it is ~3 m) has been ongoing since the 1870s, because of the construction works of the local southern railway. The scientific investigation of the lake (covering gage measurements) was established in the 1890s. However, reliable data series of water budget are available only from the beginning of the 1920s. Besides the most important water supplier of the lake, the river Zala, there are about 50 watercourses. The inflow to the lake is mainly determined by the amount of precipitation. In the last decade, investigations on a local level have been devoted to precipitation depression as a main issue of global warming (*Bartholy et al*., 2007a; *Kertész* and *Mika*, 1999; *Varga et al*., 2007). According to the latest PRUDENCE simulations, the annual precipitation sums of Balaton watershed are not expected to change (A2 and B2 scenarios) significantly, but it is not valid to seasonal distribution of rainfall (*Bartholy et al*., 2009). Decreases in summer precipitation for 2071–2100 are 35% and 20% at A2 and B2 scenarios, respectively. The increase in winter precipitation is the same as the projected rainfall decline in summer. Earlier results of the authors (*Bartholy et al*., 2001) harmonize with their last projection.

As a result of increased air temperature and precipitation decline, an unprecedented decrease in the water level of the lake was measured around 2000. The former water shortage was restored without any controlled human intervention by the winter of 2003/2004. Similar fluctuations in lake water levels were also observed in other parts of the world (*Gianniou* and *Antopoulos*, 2007; *Mercier et al*., 2002; *Schindler*, 2001; *Winter et al*., 2003). Decreases in lake water levels are not independent of global climate change (*Lenters et al*., 2005). Aspects of climate variability on the lake water level of different sites were reviewed by *Greenland* and *Kittel* (2002).

The most serious problem with handling of Balaton water level is that only reduction of excess water can be controlled, by discharging it through the Sió sluices, but it is not possible to provide a controlled water supply. The inflow to the lake is totally exposed to the precipitation and water amount delivered by surface runoff determined thereby. Any precipitation deficit is immediately reflected by the water level of the lake, like a mirror. *Somlyódi* and *Honti* (2005) projected warmer (0.5–1.5°C) and drier (5–15% less precipitation) climate conditions for Balaton watershed at doubled CO_2 concentration for 2100.

Direction of change in weather of different projections is similar, but the size of change may vary in every scenario. The uncertainty seems to be extremely high regarding the precipitation amount and its distribution.

Antal (1974) determined the multi-year average precipitation amount of the entire watershed as 700 mm in 1951–80. Later it was determined more precisely broken down to sub-basins; according to this, the source region of Zala River has the most precipitation with an annual amount of more than 800 mm, and the "cut" along the lake proved to be the driest with an annual amount of 700 mm. Above the lake this feature is even less: precipitation of about 600 – 650 mm is expected. *Varga et al.* (2006) determined the annual average precipitation of 619 mm based on measurements performed between 1921 and 2005. The differing values can be explained by the differences in the period examined. Analysis of the long-term annual precipitation sums shows negative trend (– 90 mm/100 year) in more than half of the 17 stations of Hungary. The cited precipitation data were homogenized and controlled by the Hungarian Meteorological Service. Without this thorough check-up, the conclusion will not be adequate for later processing.

The aim of this analysis is to provide an overview of the precipitation conditions of the Balaton catchments for the period from the beginning of reliable precipitation gauging (1921) until the end of 2007. These results are more complex, containing more information than the earlier findings regarding the Balaton watershed or the lakeshore alone (*Béll* and *Takács*, 1974; *Bartholy et al.*, 1995). The Balaton watershed and its surroundings is one of the two most vulnerable regions of Hungary. Although the amount and occurrence of precipitation are important measures, our investigation starts with analysis of monthly and annual precipitation sums. Some of the elements of lake water budget influenced by precipitation were also included in the study. We used the simplest statistical method, the linear trend analysis in our work. This procedure results enough information about the spatial and temporal changes in precipitation amounts. The former precipitation observations generally tried to draw a conclusion from shorter time intervals. The change in precipitation that is analyzed can be utilized in the future for local climate change evaluation of lake's watershed or water budget more precisely.

2. Material and methods

The catchment area of Balaton was divided into five sub-catchments (*Table 1* and *Fig. 1*). Besides geographical position of the sub-catchments, their climate was also taken into consideration. Zala River, the main water supplier, enters the lake on the western side of Balaton, providing 55% of the total water input.

The basin of Zala River was divided into two parts due to the difference in the amount of precipitation. Part I is the western sub-basin of the river, the wettest part of the whole region considered, and includes 6 precipitation gauging stations. The eastern sub-basin of the river is closer to the lake and it is warmer and drier than the western sub-basin. The determination of the remaining three sub-basins was performed on the basis of the former classifications. Parts III–V cover the three corners around the lake: the northern, southern, and eastern sub-basins of Lake Balaton, with 5, 6, and 3 precipitation gauging stations, respectively. Since the warmest and driest sub-catchment of the region was the eastern one (part V) it was separated from the other sub-regions. As the number of gages was limited on the fifth sub-catchment, outside gages were also included in the study. The largest distance of the outside stations should not exceed 10 –15 kilometers from the catchment's border. The precipitation of sub-catchment was equal to the average rainfall measured at different precipitation stations.

Table 1. Main information for sub-catchments of Lake Balaton (* based on Climate Atlas of Hungary, 2002)

Name of sub-catchment areas	Number of stations	Area (km^2)	Annual mean temperature* (°C)	Measured precipitation (mm)	Indicator
River Zala, western	6	1678	9.0 – 9.5	650 – 750	I
River Zala, eastern	5	944	9.5 –10.5	630 – 700	II
Balaton, northern	5	820	9.0 –10.5	580 – 660	III
Balaton, southern	6	1272	10.0 –10.5	650 – 700	IV
Balaton, eastern basin	3	36	10.0 –10.5	580 – 620	V

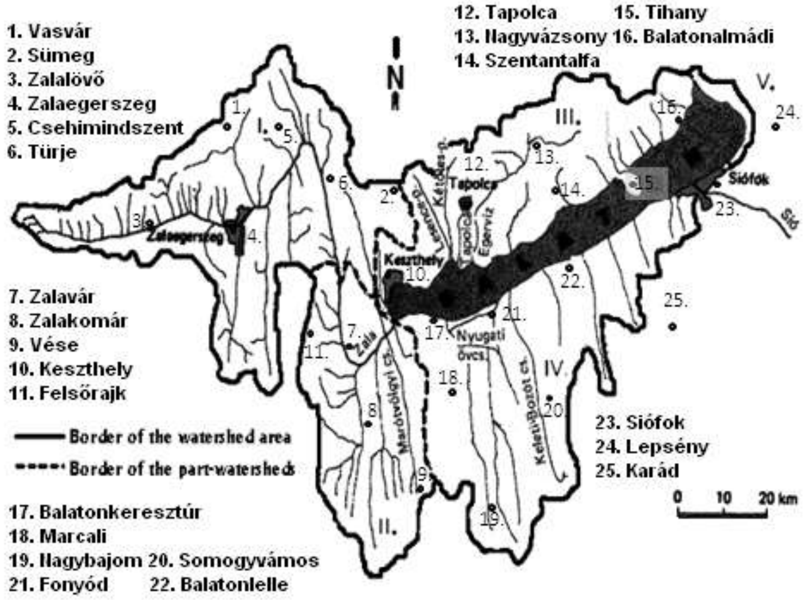


Fig. 1. Catchments of Lake Balaton were divided into five sub-catchments (parts I –V).

The 25 precipitation gauging stations selected for the description of the catchments are part of the precipitation gauging network of the Hungarian Meteorological Service consisting of about 600 stations. At the beginning, gauging stations were equipped exclusively by Hellmann type precipitation gauging units (up to about the middle of the 1990s), that were partly replaced by tipping-bucket automatic devices. The automatic devices were mainly deployed to bigger settlements (Keszthely, Zalaegerszeg, Siófok, Fonyód), and the majority of the stations are still equipped with Hellmann type devices. In the procession, the monthly and annual amounts were derived from the daily amount of precipitation gaged at 07:00 CET.

Regression analysis of long time series was included in the study. The level of significance referred to in the results was less than 0.05. The critical R^2 value for 87 elements was 0.0446 (linear regression). The statistical evaluation was performed by the free version of STATA 5.0 (1996) program package.

Water budget of Balaton balances the flows in (precipitation, surface water, and groundwater inflows) and out (evaporation, surface and groundwater outflows, surface water withdrawal) of the lake, and the natural change in storage of the lake water (ΔS) is:

$$Inflow - Outflow = \Delta S. \tag{1}$$

In the case of artificially regulated lakes as Lake Balaton, the change in natural water storage is

$$\Delta S = (P + I) - E, \tag{2}$$

where P is the precipitation (mm), I is the surface runoff (mm), and E is the evaporation (mm). Change in water storage represents modification in the lake water level. To characterize S, the lake evaporation (E in mm) was calculated by using the classical Meyer formula between 1921 and 1985. Regarding the relatively large error in evaporation estimates, the so-called Balaton formula was introduced after 1985 (*Antal*, 1963). Partial analysis of evaporation was excluded from the study.

The surface runoff was calculated statistically by using the measured discharge of principle streams. More details can be found in *Varga* (1986).

3. Results and discussion

3.1. The annual amount of precipitation over the Balaton catchments

According to the PRUDENCE results for 2071–2100, regional warming with a mean temperature rise of 3.2–4°C is projected in the Carpathian Basin (*Bartholy et al.*, 2009). It is expected that drying will not be even and will be concentrated in the summertime (25–35% decline in the amount of rainfall). In our investigation we reviewed the changes that have already occurred in the amount of precipitation first; for other experts it can serve as a good starting point for establishing future scenarios. Future precipitation prognosis is excluded from our study.

The regional average of the annual precipitation amount calculated for the entire catchment based on the data of the 25 stations for the period of 1921–2007 is 684.4 ± 111.4 mm. The year with the highest amount of precipitation was 1965 with 986 mm. The driest year of the observed period was 2000, with 458 mm. These two extreme values well demonstrate the eccentric precipitation regime of the Carpathian Basin, where the ever measured wettest year may gain three times more precipitation than the driest year.

In spite of consistent negative sign**s** in the regression coefficient of annual precipitation sums, the decline was not always significant at every station. We found a significant decrease in annual precipitation sum (that covered several stations) only in the case of the western sub-catchments of Zala River (part I), where a drop in precipitation (1.1–1.7 mm in annual average) was justifiable during the period from the beginning of gauging to date in the case of four out of six stations (*Table 2*). For the whole investigation period it means 95–146 mm precipitation depression depending on the place of the station. The confidence intervals in *Table 2* have got meaning only when the rainfall change is significant. Values of regression coefficient have to fall in the confidence intervals on 95% probability level.

Table 2. Development of the annual sums of precipitation at stations for 1921–2007. Stations showing significant changes in rainfall are in bold (*station excluded from the watershed)

Station	**Regression coefficient (mm/year)**	R^2	**Confidence intervals**	
			Lower	**Upper**
Vasvár	–0.056	0.000	–1.0902	0.9796
Sümeg	**–1.128**	**0.048**	**–2.2087**	**–0.0477**
Zalalövő	**–1.336**	**0.048**	**–2.6217**	**–0.0519**
Zalaegerszeg	**–1.736**	**0.109**	**–2.8066**	**–0.6668**
Csehmindszent	–1.004	0.039	–2.0752	0.0671
Türje	**–1.103**	**0.050**	**–2.1354**	**–0.0692**
Zalavár	–0.942	0.029	–1.9491	0.257
Zalakomár	–0.771	0.018	–1.9884	0.4457
Vése	–1.049	0.028	–2.3673	0.0269
Keszthely	**–1.480**	**0.073**	**–2.6127**	**–0.3471**
Felsőrajk	–1.020	0.033	–2.2161	0.1753
Tapolca	–0.967	0.037	–2.0257	0.0899
Nagyvázsony	**–1.323**	**0.066**	**–2.3976**	**–0.2493**
Szentantalfa	–0.303	0.003	–1.3639	0.7578
Tihany	–0.787	0.028	–1.7765	0.2019
Balatonalmádi	–0.944	0.038	–1.9609	0.072
Balatonkeresztúr	–0.655	0.015	–1.7728	0.4612
Marcali	–0.071	0.000	–1.3556	1.2141
Nagybajom	–0.383	0.004	–1.6584	0.8908
Somogyvámos	–0.867	0.025	–2.0338	0.3009
Fonyód	**–1.385**	**0.054**	**–2.6252**	**–0.1453**
Balatonlelle	–0.020	0.000	–1.0081	0.9651
Siófok	**–1.404**	**0.087**	**–2.3817**	**–0.4276**
Lepsény*	–0.47	0.010	–1.4403	0.4989
Karád*	–0.392	0.005	–1.5305	0.7469

In the case of the other four sub-catchments (though the regression coefficients of the trend lines are negative), we found a significant decrease in the annual amount of precipitation time series at one station from each (Siófok, Fonyód, Nagyvázsony, Keszthely). At the majority of the stations, in the case of three out of four sub-catchments showing changes in precipitation that cannot be statistically justified – in an interesting way – the only gauging location showing significant decrease was at the lakeshore (Keszthely, Fonyód, and Siófok).

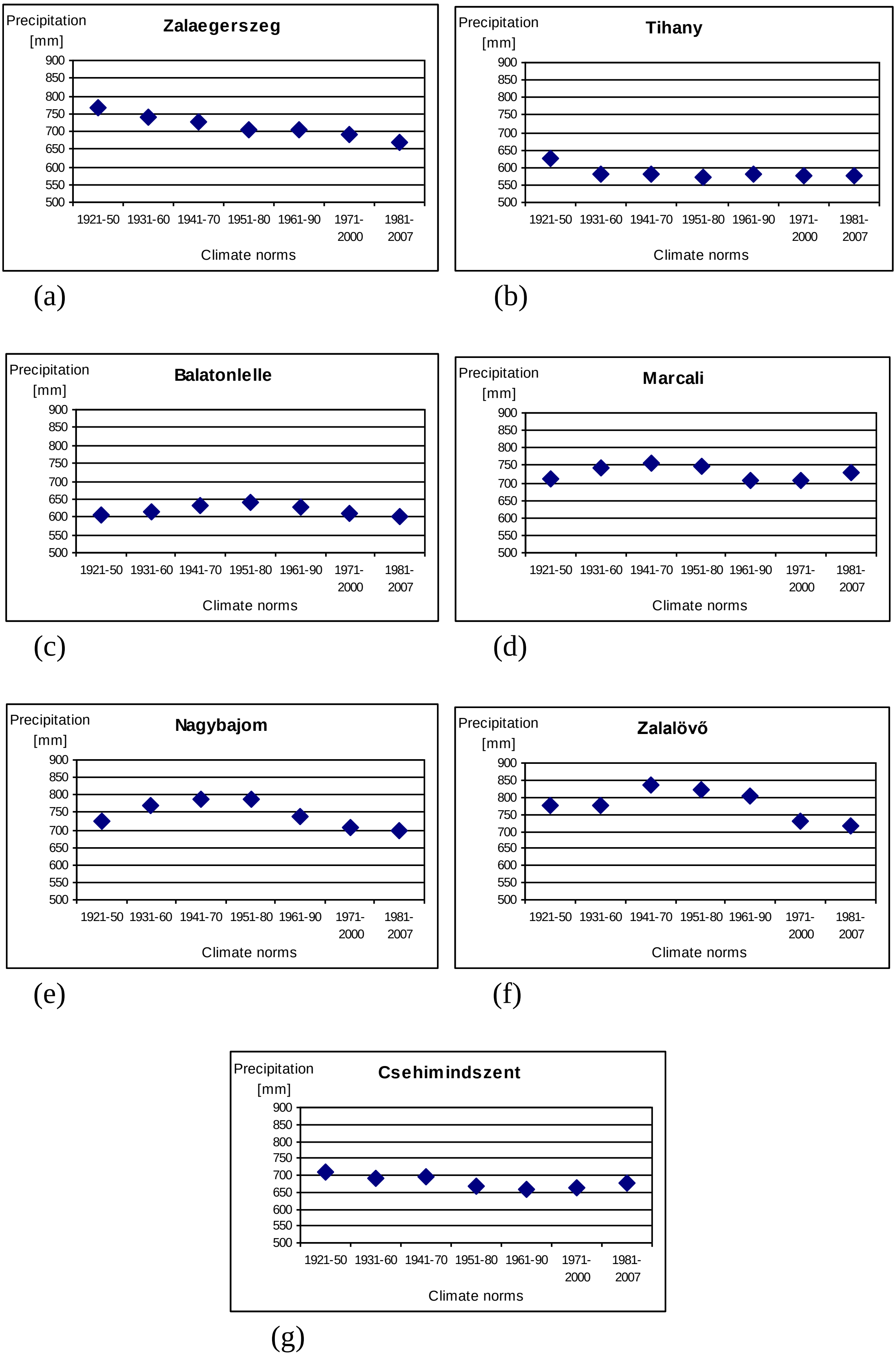
The average rate of precipitation decline computed from the regression coefficients for the whole watershed is 86 mm/100 year. Previous work on precipitation trend of whole Hungary (*Koflanovits-Adámy* and *Szentimrey,* 1986) for the time period of 1901–1984 provided almost the same result (–90 mm/100 year). It is interesting that decline in precipitation of the past two decades did not influenced strongly the regression coefficient. The possible reason might have been the yearly precipitation sums used as a basis in this study.

On the basis of the recommendation of the WMO, we created 10-year running climate norms (*Fig. 2*). In *Fig. 2,* the decreasing precipitation characteristic of the majority of the stations is demonstrated by the data of Zalaegerszeg station located at the centre of the catchments (sub-catchments I) (*Fig. 2a*). All the other sub-figures contain the exceptions. The constant amount of rainfall for Tihany compared to the other stations is remarkable; it is in connection with the geographical location of the gauging station. Tihany is located on the only peninsula pushing out into the lake (*Fig. 2b*). The relatively less yearly amount of rainfall in Tihany is closer to the lower amount of precipitation falling to the lake surface.

The amount of precipitation measured at the other stations show fairly diversified pictures in time, but at 21 out of 25 stations the period between 1921 and 1970 was wetter, followed by a drying period. The abovementioned tendency did not emerge at four stations; 3 of them are located in the southern river basin of Lake Balaton (Balatonlelle, Marcali, and Nagybajom); here there was a modest increase in precipitation in the period up to 1970, then came the decrease lasting up to the present (*Figs. 2c–e*).

There were only three out of the 25 precipitation gauging stations (Marcali, Zalalövő, and Csehimindszent) where the last two climate norms (the period between 1971 and 2007) were not the two driest ones (*Figs. 2d–g*). Looking for the reasons we did not find any change in location or environmental conditions of the stations. The amount of rainfall slightly increased until the 1960s, and from the 1980s to present a decreased tendency manifested. Our multi-year precipitation data for the largest part of the Lake Balaton catchments correspond well to the studies demonstrating this drying tendency of the last decades (*Bartholy et al.*, 2007b; *Kertész* and *Mika*, 1999; *Nováky*, 1991).

The mean rate of precipitation decline for the whole watershed is 83.4 mm/-100 year (*Fig. 3*). Until now, the decrease was not significant at less than 0.05 significance level.



(a) (b) (c) (d) (e) (f) (g)

Fig. 2. Mean annual precipitation sum for 30-year-long time periods at some selected stations of the Balaton catchment area

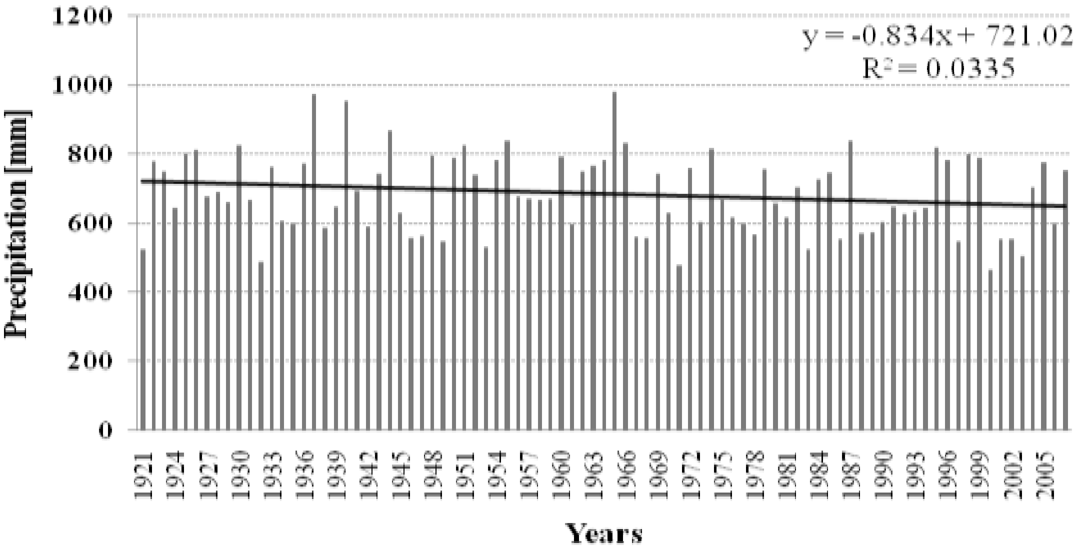


Fig. 3. Variation in yearly precipitation sums for the Balaton catchments (1921–2007)

From the point of view of the development of the lake's water budget, the annual distribution of precipitation is also important. Earlier studies pointed out two maximum points in the annual variation of monthly precipitation sums in the catchments of the lake (*Bartholy et al.*, 2001). The main maximum point is the consequence of wet air inflowing from the Atlantic Ocean at the beginning of summer. The second maximum point is in October-November, owing to the intensifying cyclone activity coming from the Mediterranean basin (*Antal*, 1974). Several studies analyzing Hungary's precipitation conditions found moderate spatial and temporal shift in annual distribution of rainfall sums (*Ambrózy et al.*, 1990). Less than 10% change was observed in the southwestern region of the country, like in the area of the Balaton catchment. *Bartholy et al.* (1995) published that the modification in annual rainfall distribution is one of the local consequences of global warming. Significant decrease in the second peak of precipitation amounts was not confirmed by the precipitation data of the 25 stations located in the catchments of Lake Balaton. On the contrary, in the case of 10 out of the 25 stations (Sümeg, Zalavár, Zalakomár, Vése, Tapolca, Balatonkeresztúr, Marcali, Fonyód, Balatonlelle, Siófok), the ratio of precipitation in August has risen significantly, by 5–10%, compared to the main maximum point in the past 30 years. The uncertainty of the precipitation in the winter months and the higher variability of the amount of precipitation can be experienced. Our observations correspond to the outcomes published to Balaton watershed by *Bartholy et al*. (1995) and *Varga et al*. (2004).

3.2. Water budget elements closely related to precipitation: surface runoff and release through the Sió sluices

Among the two referred elements, the release is intensively affected not only by the rainfall, but by the amount of evaporation. The aim of our investigation was the study of precipitation and strongly concerned elements as surface runoff and release in the vicinity of Lake Balaton. Knowing the importance of evaporation in lake water budget, we took it into account where it was necessary, but we did not focus on it, discussion of evaporation is excluded from this work.

Watercourses deliver the larger part (about 60%) of the entire lake water acquisition. In the period studied, the annual average surface runoff was 873.9 ± 300 mm (*Fig. 4*) with the maximum of 1974 mm measured in 1965, and the minimum of 293 mm determined both in 2002 and 2003. There were 26 out of 87 years of the whole time series (about one-third) when the surface runoff exceeded 1000 mm, and only two of them were after the year 2000 (dry spell). The average runoff fell back to 501 mm in 2000 and remained on this value until 2004. The moderate decrease in precipitation leads to higher depression in surface runoff. Even in the case of non-significant precipitation changes, 42.7% reduction in runoff seriously affected the lake water level in the beginning of the 2000s. Recovery of the lake water level was late. This is in contrast with other semi-arid regions, where surplus water after drought is mostly used for infiltration and replenishment of groundwater resources, and the surface runoff to the stream-network appears only at a later stage (*Varga et al.*, 2007). The authors mentioned that despite the humid years of 2004 and 2005, the runoff depression still was one third of the average.

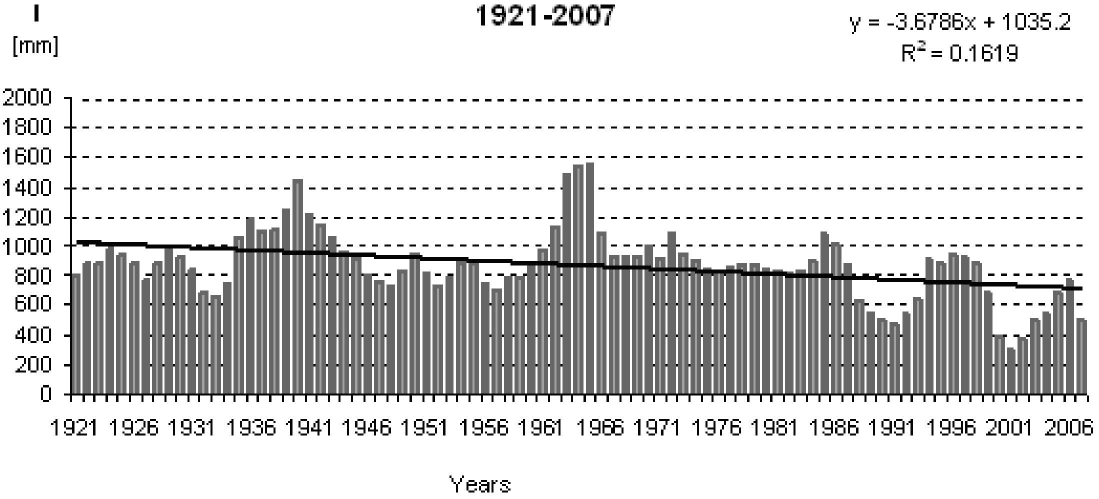


Fig. 4. Annual variation in inflow (*I* mm) for the investigation period (based on data provided by the VITUKI). The change is significant at less than 0.05 significance level.

Signs of change in the annual variation of surface runoff were the same as for precipitation, and water depression was even significant at less than 0.05 significance level. From the beginning of measurements (1921) to the present, the surface runoff has fallen by 315.6 mm (*Fig. 4*). Similar results were published by *Nováky* (1991).

Because of the precipitation pattern and crop cover modifications in Hungary, the runoff has special seasonal variability (*Table 3*).

Table 3. Monthly averages of runoff in the Balaton region. Months having significant change below the 0.05 significance level are in bold

Month	**Average runoff (mm/month)**	**Direction of change**	**Degree of change (mm/year)**
January	81.6	not changed	0.008
February	**99.2**	**decreasing**	**–0.481**
March	121.1	not changed	–0.637
April	96.4	not changed	–0.297
May	**74.5**	**decreasing**	**–0.312**
June	**64.4**	**decreasing**	**–0.411**
July	**54.7**	**decreasing**	**–0.400**
August	44.7	not changed	–0.222
September	43.0	not changed	–0.126
October	49.6	not changed	–0.092
November	66.7	not changed	–0.037
December	78.0	not changed	0.044

The highest values are observed in early spring (February, March, and April). In winter time, there is an increase in the development of surface runoff. Out of the monthly figures of the decrease in water input caused by runoff, the following decreases were significant: at the end of winter in February, then from the end of spring in May, June, and July. The phenomenon experienced in this latter period is doubly dangerous; first, the statistically justified failure in lake water input occurred in summer, in the hottest period with the highest evaporation level; second, the amount of water coming from the catchments and feeding the lake fell back in several subsequent months.

The release of excess water through the Sió sluices is the only water budget member that is a result of controlled human intervention. The aim is to control the lake water level that is regulated by actual law whose borders are not constant in time. The desired level of Lake Balaton is between 0.7 and 1.1 m regulated in 1997 for the last time.

Because of precipitation deficit and surface runoff depression, the quantity of release dropped drastically in the past decade (*Fig. 5*). During the drought of 2000–2003, the Sió sluices were closed, but in 2006 and 2007 they were opened again. Note, that there is an other important affecting factor, the evaporation, but since this is not directly influenced by the precipitation, it is excluded from this study.

Cumulative precipitation and surface runoff shortage were the causes of the change of sign in natural water storage from positive into negative from 2000 to 2003 (*Fig. 6*). During this unique dry period, the water input was not enough to cover the water necessity of lake evaporation. This negative phenomenon left a mark on *ΔS* as well. The most variable indicator of Lake Balaton is change in natural water storage, whose average is 592.8 ± 400 mm. Its highest value reached 2031 mm in 1965, and the lowest one was only –180 mm in 2003. The cumulative water deficit of the lake broke the record between 2000 and 2004.

Analysis of the annual variation in *ΔS* statistically proves a decreasing tendency at less than 0.05 significance level (389.9 mm/100 years). Similarly to the other factors at the input side of the lake water budget, the values of the past two decades falling behind average are worrisome.

Decline in natural change in water storage is more pronounced during summer. In most cases the *ΔS* increased in winter.

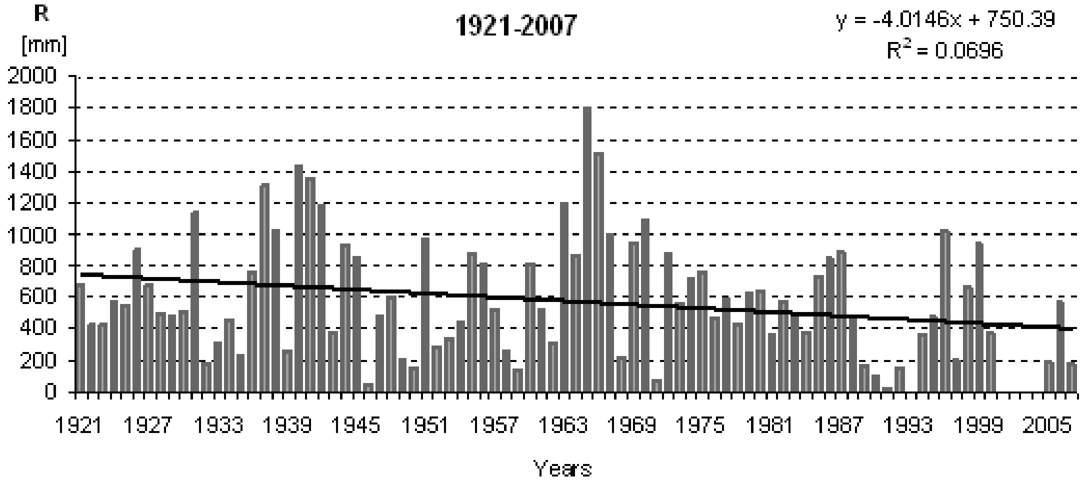


Fig. 5. Annual variation in release (*R* mm) through the Sió sluices from 1921 until present (based on data provided by the VITUKI).

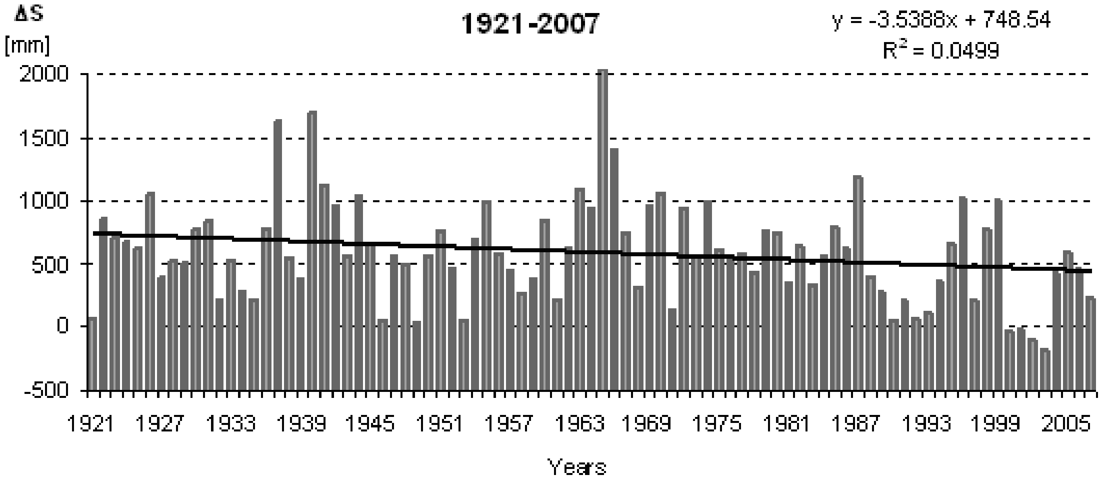


Fig. 6. Natural change in water storage (*ΔS* mm) from the beginning of the investigation period ((based on data provided by the VITUKI)). The change is significant at less than 0.05 significance level.

4. Conclusions

In the period between 1921 and 2007, the annual precipitation showed a decreasing tendency in the catchments of Lake Balaton, though this change could only be significantly justified in the western part of the basin of Zala River and at several stations close to the lakeshore. At the same time the western side of Zala River is the wettest part of the whole catchments regarding the annual amounts of rainfall. The statistically justifiable decrease in precipitation of the lakeshore stations of the other sub-catchments renders lesser danger, since these contribute to the surface runoff to a smaller extent, and the occurrence of less, and less "disturbing" precipitation is unanimously positive for the bathing holiday-makers.

Distribution of precipitation has not significantly changed at the 25 stations of the lake's catchments. Examining a longer time period, the two maximum points can still be followed. It is a positive phenomenon that a 5–10% rise in the precipitation of August can be experienced. This event is beneficial, since this is the period when the intensified evaporation owing to the higher summer temperature can seriously decrease the water level.

An unfavorable sign considering the water level of the lake is that the runoff has significantly decreased, mainly in the past two decades. In the decades before 1990, the runoff seemed to be a more stable element based on yearly means. The reduction of the lake's water inflow was compensated by the reduction of release in the period after the 1990s. Release through the Sió sluices is the only controlled factor to regulate the water level of Lake Balaton. Similarly to the reduction of inflow, release has also decreased over the past several decades. This human intervention should be implemented with special care, mainly with the knowledge of the reduced amount of inflow during the summer months.

A good example of the local variability caused by global climate change is the annual rainfall sum recorded at various meteorological stations in the watershed of Lake Balaton. The most sensitive region of the watershed is the western part containing the river Zala, where, although the mean drop in annual rainfall quantity since 1921 was only 1.5 mm, the annual decrease in runoff, which is also influenced by rainfall, was more than twice as great. Earlier observations suggest that this is especially dangerous, because when wet years follow dry periods, the infiltration and replenishment of groundwater resources causes a further delay in the runoff (*Varga et al.*, 2007). One positive observation is that, despite the decline in mean annual rainfall over the last 30 years, a 10–15% increase in monthly precipitation has been noted in August at most stations. This could compensate the water supplies of the lake to some extent for the increased evaporation experienced during the summer months.

Greater changes in the rainfall sums recorded at the various stations were observed at stations situated in the immediate vicinity of the lake (Keszthely, Siófok, Fonyód). This is important, because these are the most frequented regions of the watershed, and thus, they are the most exposed to environmental load. This should be emphasized when compiling long-term land-use plans.

Acknowledgement—We express our gratitude to colleagues of the Central-Transdanubian Environmental and Water Authority (VITUKI), especially *György Varga*, for providing data used in this analysis.

References

A*mbrózy, P., Koflanovits, E.* and *Kövér, B.*, 1990: Shift in temporal distribution of precipitation amounts in Hungary (in Hungarian). *Időjárás 94*, 156-167.

Antal, E., 1974: Characterisation of the members of heat and water balances in Balaton region. In *The Climate of Balaton* (eds.: *B. Béll* and *L. Takács*) (in Hungarian). Országos Meteorológiai Intézet, Budapest, 188-204.

Antal, E., 1963: Evaporation of Lake Balaton (in Hungarian). *Időjárás 67*, 290-297.

Bartholy, J., Pongrácz, R., Gelybó, Gy. and *Szabó, P.*, 2009: Analysis of expected climate change in the Carpathian Basin using the PRUDENCE results. *Időjárás 112*, 249-265.

Bartholy, J., Pongrácz, R. and *Gelybó, Gy.*, 2007a: Regional climate change expected in Hungary 2071–2100. *Applied Ecol and Environ Res 5*, 1-17.

Bartholy, J. and *Pongrácz, R.*, 2007b: Regional analysis of extreme temperature and precipitation indices for the Carpathian Basin from 1946 to 2001. *Global Planet Change 57*, 83-95.

Bartholy, J., Matyasovszky, I. and *Weidinger, T.*, 2001: Regional climate change in Hungary: a survey and stohastic downscaling method. *Időjárás 105*, 1-17.

Bartholy, J., Bogárdi, I. and *Matyasovszky, I.*, 1995: Effects of climate change on regional precipitation in Lake Balaton watershed. *Theor Appl Climatol 51*, 237-250.

Climate Atlas of Hungary (in Hungarian), 2002, Országos Meteorológiai Szolgálat, Budapest.

Gianniou, S.K. and *Antonopoulos, V.Z.*, 2007: Evaporation and energy budget in Lake Vegoritis, Greece. *J Hydrol 345*, 212-223.

Greenland, D. and *Kittel, T.G.F.*, 2002: Temporal variability of climate at US Long-Term Ecological Research (LTER) sites. *Climat Res 19*, 213-231.

Kertész, A. and *Mika, J.*, 1999: Climate Change in South-Eastern Europe. *Phys Chem Earth (A) 24*, 913-920.

Koflanovits-Adámy, E. and *Szentimrey, T.*, 1986: The variations of precipitation amounts in the Carpathian Basin during the present century (in Hungarian). *Időjárás 90*, 206-216.

Lenters, J.D., Kratz, T.K. and *Bowser, C.J.*, 2005: Effects of climate variability on lake evaporation: Result from a long term energy budget study of Sparkling Lake, northern Wisconsin (USA). *J Hydrol 308*, 168-195.

Mercier, F., Cazenave, A. and *Maheu, C.*, 2002: Interannual lake level fluctuations (1993–1999) in Africa from Topex/Poseidon connections with ocean-atmosphere interactions over the Indian Ocean. *Global Planet Change 32*, 141-163.

Nováky, B., 1991: Climate effects on runoff conditions in Hungary. *Earth Surface and Landforms 16*, 593-601.

Schindler, D.W., 2001: The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millenium. *Can J Fish Aquat Sci 58*, 18-29.

Somlyódi, L. and *Honti, M.*, 2005: The water substitution of Lake Balaton (in Hungarian). *Magyar Tudomány 5*, 570-581.

STATA 5.0, 1996: Stata Corporation LP Texas, USA, www.stata.com

Varga, Gy., 1986: Developing calculation of water budget of Lake Balaton (in Hungarian). *Report on Research carried out on Lake Balaton by VITUKI*, Budapest.

Varga, Gy., Papp, U.J. and *Bálint, G.*, 2007: Recent extremes in the water budget of Lake Balaton. *Georgikon for Agric 10*, 25-40.

Varga, B., *Boldizsár, A.* and *Gimesi, L.*, 2006: Some remarks on water balance components of Lake Balaton. *Georgikon for Agric 10*, 69-82.

Varga, Gy., Papp, U.J., Mika, J., Pálfy, L. and *Bálint, G.*, 2004: The 2000–2003 extremes in the water budget of Lake Balaton. *Geophys Res Abstract Vol. 6 07795*, SRef-ID: 1607-7962/gra/EGU04-A-07795.

Winter, T.C., Buso, D.C., Rosenberry, D.O., Likens, G.E., Sturrock, A.M. and *Mau, D.P.*, 2003: Evaporation determined by the energy budget method for Mirror Lake, New Hampshire. *Limnol Oceanogr 48*, 995-1009.