HYDROLOGICAL ANALYSIS OF THE JUNE 2013 FLOOD ON THE DANUBE ALONG THE HUNGARIAN REACH

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ABSTRACT. – Hydrological analysis of the June 2013 flood on the Danube along the Hungarian reach. In the last decades extreme water situations increasingly occurred on the Danube catchment area. In June, 2013 the highest flood wave of any time run off on the German, Austrian, Slovakian and Hungarian sections. During the floods in 2002 and 2006 on the upper Danube section new records were registered only until Budapest. In June, 2013, the Danube overstepped the maximum flood levels ever registered on almost the entire length in Hungary. From 2002 this was the fourth time the Danube overstepped the 800 cm level, in the 20th century this level was overstepped only two times by iceless floods. The water quantity could be maintained inside the high water bed and between the dams, it did not flood any settlements or any large areas.

Key words: maximum discharge, high flow periods, hydrological statistical analysis, water uses, discharge values probabilities.

1. Introduction

The Danube catchment area is 801 463 km^2, its length is 2780 km, from which the length of the Hungarian bed is 417 km. The river regulation started in a bigger manner from the eighteenth-twentieth century, for today the flood control has been built up on the main part of the main branch and the tributaries, the length of the protection dikes is around 15 000 km (Paşoi, 2004). The longest connected protection lines are on the Hungarian and Romanian territories. The first hydroelectric power station on the Danube was opened in 1927 (Kachlet-Passau), the newest has been operating from 1996 (Freudenau). Above the Hungarian section there are 32 water barrages (Stancikova Alzbeta, 2001), which cause

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damming up on a length of nearly 290 km. The Gabčíkovo barrage operating in Slovakia from 1992 affects The Hungarian section of Danube as well, its storage capacity is nearly 196 million m^3. In spite of the technical interventions, the water discharge is still mainly determined by the quantity of the precipitation and the amount of the runoff. The mountainous basins total 36 % of the entire basin, but contribute with 75 % to the Danube estuarine discharge (Újvári, 1964).

The first major Danube tributary is the regulated Isar (173 m^3/s) with a catchment area of 8964 km^2. The Inn catchment area of 26 130 km^2 is less than half of the Danube's, though the discharge at its mouth in Passau (727 m^3/s), is higher than that of the main branch (ICPDR, 2004). The main tributaries of the Danube section in Austria are the Traun (150 m^3/s) and the Enns (200 m^3/s). The Morava collects its waters from the Czeh, Slovakian and Austrian territories and from its catchment area with a dimension similar to that of the Inn river (26,578 km^2), but the medium discharge is much lower (110 m^3/s). The tributaries in Austria are the Vág (152 m^3/s) and the Garam (54.0 m^3/s). The main tributaries in Hungary are the Rába (80.0 m^3/s), the Ipoly (22.0 m^3/s) and the Sió (30.0 m^3/s).

2. Former major danube floods

According to the chronicles, in the IInd millennium, 75 significant floods run off on the Hungarian section of the river. The oldest historical record referring to the Danube flood dates from 1012. High floods have been recorded in 1092, 1126, 1193, 1235, 1248, 1267, 1268 as well. There were mentioned 14 devastating floods in the 14th-17th centuries (including the flood in 1501 when 3108 houses collapsed and 438 people drowned), 23 significant floods in the 18th century (Szlávik, 2006). The top levels of the floods from March, 1744 (812 cm), February, 1775 (864 cm) and March, 1799 (830 cm) are marked by the memorial signs placed on many buildings in Budapest (around 80 places).

The most destructive Danube floods of the 19th century occurred in March, 1838, in February-March, 1876 and in August, 1879. During the flood in March, 1838 caused by the snow melting, the ice floes congested in the bed curves, dammed the river back and thus there occurred the historical maximum water level observed till that time (1038 cm). The centre of Pest, situated on the left bank of the Danube, was covered by 2m deep water, 153 people died. (http://www.ng.hu/Fold/2013/06)

The high Danube floods of the 20th century occurred in 1954, 1959, 1963, 1965, 1975, 1991.

On the Hungarian Upper Danube section breaches in dikes occurred in 1954, July 15th and 16th even in three places. On the flooded areas around 1500 houses collapsed, 2000 buildings got damaged.

Table 1. The highest ice-free top levels on the Slovakian and Hungarian sections of Danube

Gauging station	08,1897	09,1899	09,1920 .	02,1923	06,1926	03,1940	04,1944	07,1954	06,1965	08,1991	08,2002	03,2006	06,2013
Bratislava	940	970	867	886	795	747	782	984	914	864	***991***	829	***1032***
Komárom	680	687	684	721	662	672	682	751	782	745	***801***	782	***845***
Nagymaros	622	600	574	610	560	610	575	641	682	634	707	***714***	***751***
Budapest	780	770	744	784	737	787	754	805	845	783	848	***860***	***891***
Dunaföldvár	673	647	620	643	618	640	612	651	***703***	633	685	690	***721***
Baja	905	888	833	842	876	878	869	912	***976***	875	942	951	***989***
Mohács	900	878	851	820	887	889	877	924	***984***	864	926	931	964

At the beginning of the 21st century two main floods have already run off. In 2002, in a few days on the effect of the quantity of water more than the average of more months, the flood in Austria caused catastrophic flooding. In Nagybajcs it peaked on the 17th of August with a maximum level of 878 cm, the maximum discharge was 9250 m^3/s. In Komárom the maximum level was 20cm higher, in Esztergom it was 31 cm higher than the maximum ever observed until 1965.

On the Austrian section of the river the maximum level of the flood developed from snow melting and precipitations in 2006 was lower than the top levels observed till that time. On the effect of a significant water transport of the rivers Morva, Váh, Hron, Ipoly, a new historical maximum water level occurred between Nagymaros (714 cm) and Budapest (860 cm). The flood wave ran off on the Danube and the Tisza with a very small difference in time, thus at the mouth in Titel the Danube dammed up the Tisza river and raised its level.

3.Flood triggering weather and fluctuation conditions

According to the Information released by The National Water Service of the National Water Directorate (OVF-OVSZ) in March, 2013, between 1st of November, 2013 and 28th of February, 2013 the precipitation level (272 mm) on the Danube basin in Nagymaros exceeded the many years' average (230 mm) with 118 %.

The amount of the water stored in the snow stock was 16.5 km^3 on the 25th of February, this exceeded the many years' maximum. On the 1st of March its value was 15.8 km^3 which represented 155% of the many years' average (10.15 km^3) (OVF-OVSz, 2013, http://www.hydroinfo.hu/Html/ho/hografikonok.html).

In May, 2013 on the Upper Danube Basin the monthly medium temperature was 1.6-1.8°C lower than the many years' average, but the monthly precipitation total reached 155-235% of the many years' average. (www.wetteronline.de). In the mountains over 2000 m the snow did not melt and in the lower levels the soil humidity was high due to the melting snow in April.

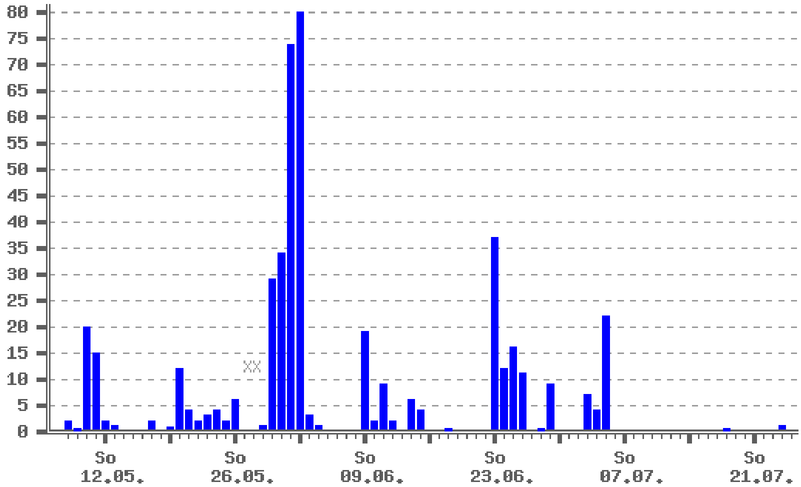

Figure 1. The daily precipitation amounts (mm) at the Austrian Salzburg station (altitude: 450 m above the sea level), between 13,04,2013-30,06,2013 (www.wetteronline.de)

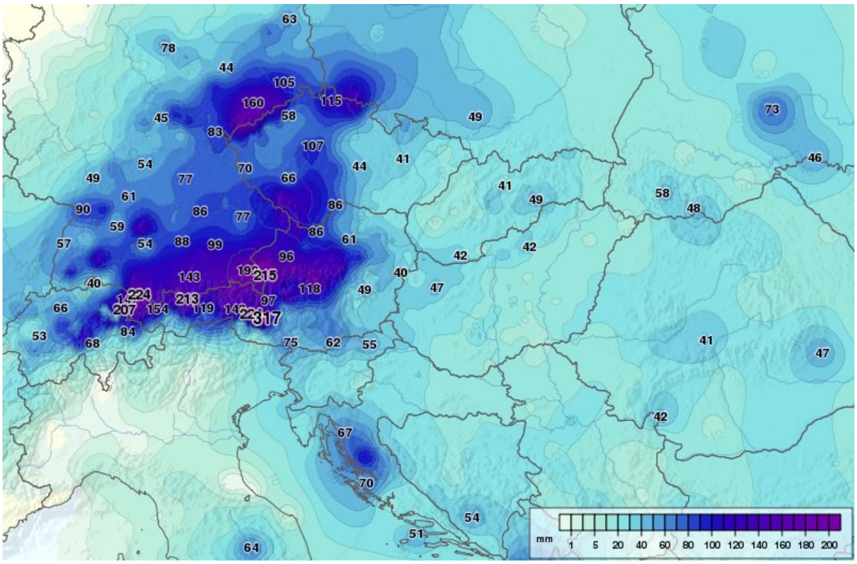

Figure 2. The amount of the precipitation off between 30,05,2013. 6 UTC and 03,06,2013. 6 UTC (OMSZ, Homokiné Újvári, 2013) http://www.met.hu/ismerettar/erdekessegek_tanulmanyok/index.php?id=747&hir)

In Hungary, between June and May, 2013 the regional precipitation average was 364 mm, that means 168 mm (186%) higher than the periodical average.

At the end of May the humidity of the soil layer between 50-100 cm was close to 100% of the characteristic saturation value. The lowland groundwater level was 15-20 cm higher than the many years monthly average in May (OFV, 2013)

Between the 26th of May and the 5th of June, 2013 the weather was formed by the cold whirlwind whirling and filling up for 4-5 days above our area. On the 30th of May the warm and wet conveyor folded back from North-East towards the Alps. In the next days the shallow cyclone centre slowly passed further towards North and the folding back of the wet air from North got more intensive on the 1st of June and concentrated in a relatively small area. On the North side of the Alps the special occlusal process of cyclones rear rainfall activity created a favourable condition to the mountain effect (OMSZ, Horváth et. al, 2013 and Homokiné Újvári, 2013). A significant quantity of precipitation off from that cyclone on the Danube catchment area in Germany and Austria, in some places the rain intensity was over 100 mm several times per day.

On the 30th of May, in the evening hours an average of 15-20 mm fall on a big area mainly between Győr and Linz. The rainfall continued during the night, but the average of 20-25 mm rain fall was concentrated on the upper section of Danube. On the 31st of May during the day, between Wien and the source area the average of rainfall was around 20 mm. In the next 24 hours a more significant quantity of precipitation rather fell only on the upper section. In some places values exceeding 100 mm/24 h were measured as well. From 1st to 2nd of June there was an intense precipitation again, mainly between Passau and Linz. Around 70 mm in

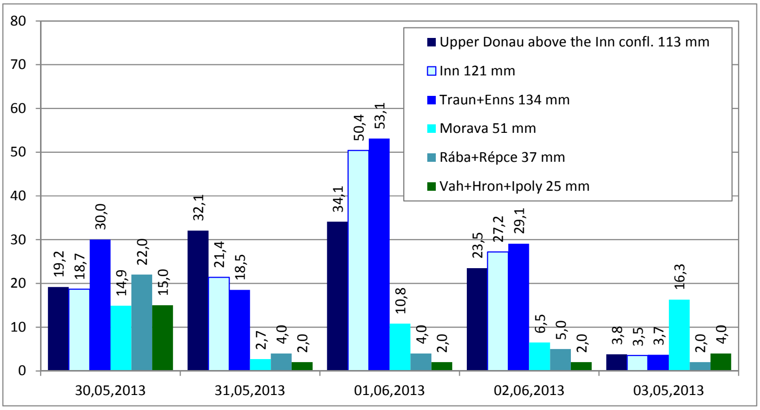

Figure 3. The regional averages of daily precipitation amounts for the certain catchment areas (based on data OVF-OVSZ, 2013)

regional average fell on a wide area then on the 2nd of June the rainfall continued with an average of 40 mm on the catchment area of the rivers Inn, Isar and Traun mainly in the first part of the day. The intense rainy period ended on the 2nd of June, in the evening. In the higher areas the remained snow did not melt due to the high temperature, thus the flood was not fed by snowmelt (Horváth et al., 2013).

From the 30th of May, 2013, 6a.m. to the 3rd of June, 2013, 6a.m. on the Upper Danube catcment area the highest rain runoff values were measured in Asshau-Stein 405 mm, Kreuth-Glashuette 373 mm, Obere Firstalm/Schlierseer Berge 323 mm, Jachenau Tannern 321 mm (Germany), Laterns-Gapfohl 276 mm, Bad Ischl 265 mm, Salzburg/Freisaal 259 mm, Koessen 238 mm (Ausztria) (http://www. wettergefahren-fruehwarnung.de/Ereignis/20130531_e.html). The intensity of the precipitation was particularly high between the 1st of June in the evening and the 2nd of June in the morning.

According to the information of the OVF-OVSZ from the 3rd of June, 2013, above the Inn mouth, in 6 days, 121 mm rain was perceived on the Inn catchment area, 134 mm on the Traun and Enns catchment area and 113 mm on the Upper Dannube (Fig. 2, Fig. 3).

4. Main hydrological characteristics of flood waves

The floodwave was generated by the significant regional average precipitation between 30th of June and the 4th of June. On the Upper Danube at the hydrographic stations (Magfall–Rosenheim, Kitzbüheler Ache–St. Johann, Tiroler Ache-Staudach, Saalach-Weißbach, Lammer-Obergäu, Traun-Enns) placed on small watercourses with a catchment area of 300-3000 km^2, following the 160-228 mm regional average precipitation, the runoff coeficient was very high, between 0.44-0.58 (Blöschl et al., 2013).

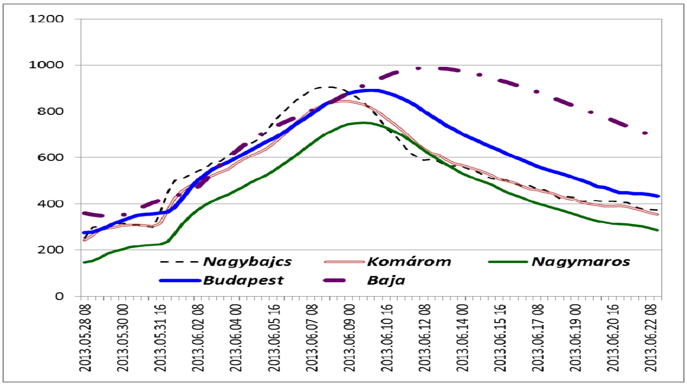

Figure 4. The development of water levels on the Danube Hungarian section between 28.05.2013 and 22.06.2013.

On the upper section, the water level started to increase at Inglostadt on the 29th of May, in the evening, near the German-Austrian border at Passau it started on the 30th of May, in the evening. At Passau it rose 7,3 m in 4 days, the peak level was 1298 cm, which exceeded the historical maximum water level of 1220 cm noticed in 1501. In Austria the peak level of 1078 cm with the discharge of 11 100 m^3/s was at Kienstock. In Kroneuburg near Wien the maximum water level was 793 cm and the maximum discharge was 10 600 m^3/s. On the Hungarian upper section in Nagybajcs the water level reached the 1st grade flood control alert level on the 1st of June at dawn and on the 15th of June, in the evening it decreased under the 1st grade alert level. On the lower section, at Mohács on the 5th of June in the afternoon it exceeded the 1st grade alert and on the 23rd of June at noon it decreased under the alert level.

The flood wave top arrived from Passau to the Hungarian border section (378 km) in 3,5 days, to Budapest (580 km) 6 days, to Mohács (780 km) 10 days.

On the entire length of the Danube in Hungary the maximum water levels exceeded the 3rd grade of alert, even all the gauges indicated values exceeding the historical maxima, excepting the lower sections. The previous historical maxima were perceived in 2002 (at Nagybajcs, Komárom), in 2006 (Nagymaros, Budapest), and in 1965 (Dunaföldvár, Paks, Baja, Mohács).

Table 2. Danube alert levels in Hungary, maximum water level yet ($H_{maxhist}$), the maximum water levels of the flood wave in June, 2013

Gauging station	Distance from the mouth (river/chainage km)	Catch-ment area (km^2)	Gauge "0" above Balti sea level	Grade of alert			$H_{maxhist}$	H_{max} 2013
				I	II	III		
Nagybajcs	1801.0	131 614	107.40	470	540	610	875/2002	907
Komárom	1768.3	150 820	103.88	500	620	680	801/2002	845
Nagymaros	1694.6	183 534	99.43	520	620	670	714/2006	751
Budapest	1646.5	184 893	94.97	620	700	800	860/2006	891
Dunaföldvár	1560.6	188 700	88.86	600	750	850	703/1965	721
Paks	1531.3	189.092	85.38	650	800	900	872/1965	891
Baja	1478.7	208 282	80.99	700	800	900	976/1965	989
Mohács	1446.9	209 064	79.20	700	850	950	984/1965	964

On the section above Budapest, the maximum level was 25-40 cm higher than the maximums perceived before. The highest level was at Komárom (43 cm higher), between Budapest and Baja it was 13-27 cm higher. The frequent flattering of the flood wave occurred only under Baja (at Mohács the level was 20 cm lower the maximum levels measured till now) which can be explained by the extracting effect of the low level of the Drava river (Fig. 5).

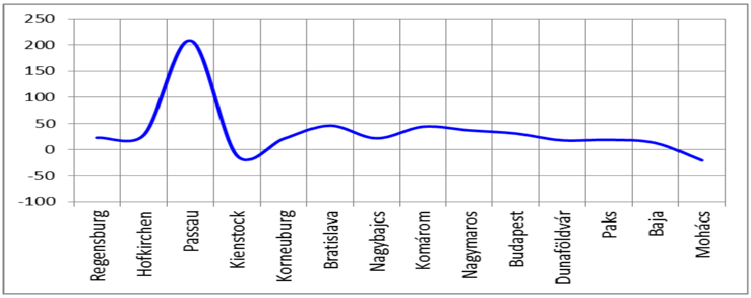

Figure 5. Differences between the maximum water levels (cm) in June and the historical maximums yet.

The highest value measured at the Danube Budapest hydrographical station occurred on the 15th of March, 1838 and it was 1030 cm, which can be explained by the damming effect of the ice packs. In the period between 1870 and 2013 among the 20 highest ice-free maxima, the three highest values are those in 2002, 2006, 2013, so they occurred in the last 11 years (Fig. 7).

The durability of the flood wave from the 1st of June, 2013 exceeding the flood control alert increases from the upper section of the Danube in Hungary towards the south border, 157 hours (Nagybajcs) 428 hours (Pécs), a 2.7-fold.

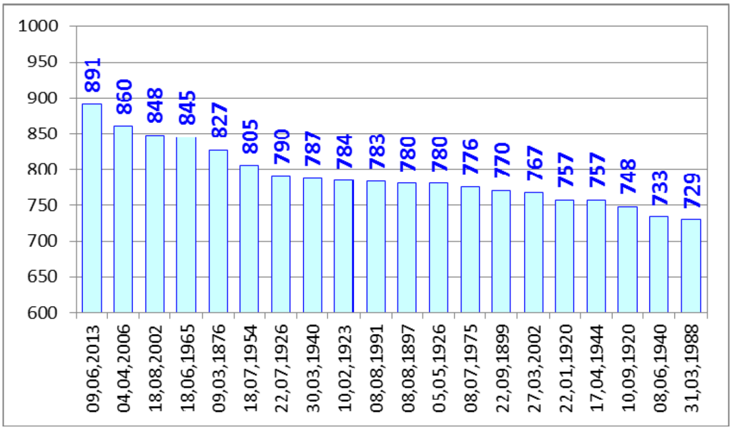

Figure 6. The Danube highest ice-free water level maximums in Budapest (1870-2013).

The load of protective works and the risk level shows that the durability of the historical maximum water level was 44-47 hours (Table 3).

Tabel 3. The durability (hour) of the Danube flood wave in June, 2013

Gauging station	**Distance from the mouth river /chainage km)**	**I-II**	**II-III**	**III-$H_{maxhist}$**	**$H_{maxhist}$ - $H_{max2013}$**	**$\sum$ I.-$H_{max2013}$**
Nagybajcs	1801,00	88	100	145	44	157
Komárom	1768,30	141	42	71	70	324
Nagymaros	1694,60	80	34	36	67	217
Budapest	1646,50	82	78	51	65	276
Dunaföldvár	1560,60	104	0	0	52	156
Paks	1531,30	66	85	0	56	207
Baja	1478,70	115	117	120	58	410
Mohács	1446,90	196	162	70	0	428

Photo 1. Dike rising with sandbags and water jet catching on the Upper Danube in Hungary in Győrújfalu area on the 7th of June, 2013 (Photo: Nagy)

During the flood wave runoff on the Danube Hungarian section (Nagybajcs, Komárom, Esztergom, Nagymaros, Budapest, Dunaföldvár, Baja, etc.), more hundreds of measurement were made on the flooding, dwindling branch and close to the flood peak, 1-3 measurings per day were made. The measurings were made using a Doppler technology based ADCP (Acoustic Doppler Current Profiler) instrument already tested during the floods in 2002 and 2006. The geometric measuring was made by computer control, from a measuring boat along the running path. Over a discharge of 6000 m^3/s, 13 measurings were made in Nagymaros and 13 in Budapest. On the 8th of June, at 5pm, the maximum discharge of 9505 m^3/s was measured in Nagymaros, when the water level was 736 cm, the bed width was 595 m, 5698 m^2 section area and 1,67 m/s average water speed.

The water level-discharge relations edited by the measurings are loop curve shaped, thus there is a significant discharge difference between the increasing and the decreasing branch, which shows the surface fall changes of similar water levels and partial impediment of the runoff in the bed (Figure 7).

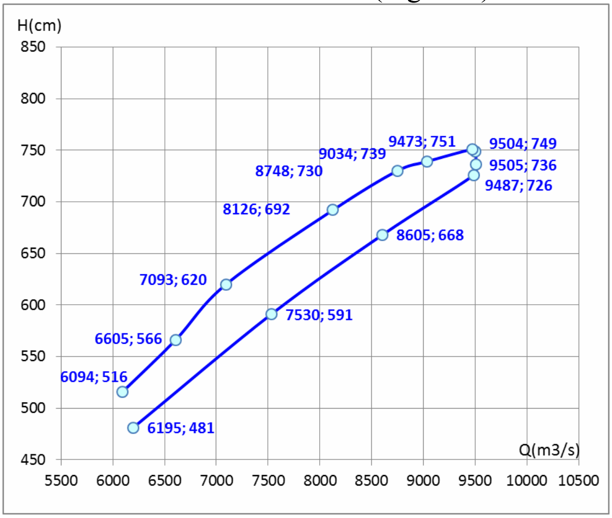

Figure 7. Danube Nagymaros water level – discharge interrelation (according to KDVVIZIG data)

The maximum discharge of 10 116 m^3/s ever measured during the Hungarian Danube floods, was measured during the present flood on the upper section, near Nagybajcs. As the Danube was running towards Mohács, the maximum discharge gradually decreased to around 20 % (Fig. 8).

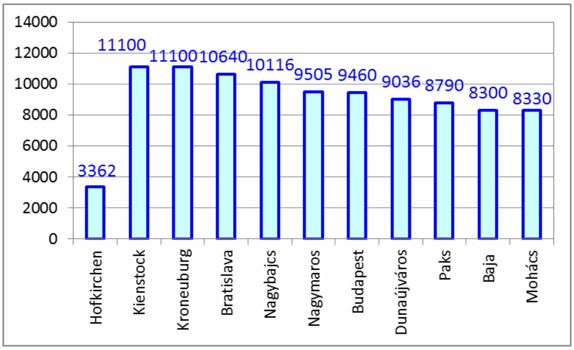

Figure 8. The maximum discharges on the Danube between Hofkirchen and Mohács recorded during the flood wave in June 2013.

Based on the hydrological statistical analysis of the yearly maximum discharge database (Fig.9) of the period 1883-2013 we revealed that in Nagymaros the statistical probability of the 9470 m^3/s maximum discharge in June, 2013 was around 1,5 %.

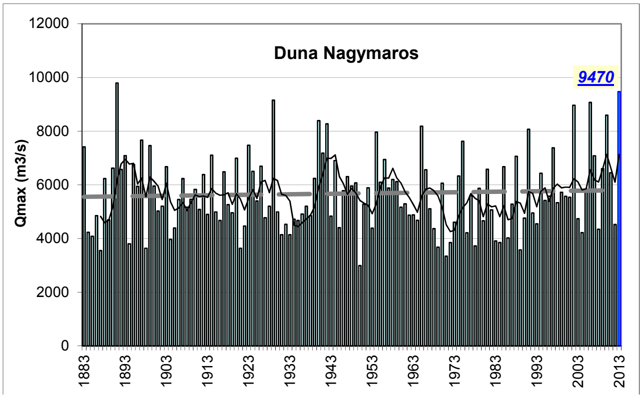

Figure 9. Time series of yearly maximum discharge at the Danube Nagymaros gauging station between 1883-2013.

The probability of the maximum discharges recorded on the Hungarian Danube section above Nagymaros was between 0.9-1.0 % (Katona et al., 2013).

The volume of the flood wave running off between 31st of May and 17th of June at Korneuburg on the Danube, including the base flow, all together it was 9.5 billion m^3 volt (Blöschl et al., 2013) and between 1st and 18th of June, at Nagymaros it was 10.5 billion m^3.

5. The flood forecasts

The precipitation forecasts issued by the Hungarian National Meteorological Service (OMSZ) are mostly based on the model of the Medium-range Weather Forecasts European Centre (ECMWF). The deterministic run and the Ensemble Prediction System (EPS) probabilistic predictions were used. The torch diagram (Figure 10) illustrates the rainfall temporal distribution in 12 hours, in addition to the deterministic run the 50 EPS member precipitation value also figures. 5 days before the rainfall activity the expected precipitation period figured in the forecasts.The curves made for the Upper Danube River Basin from the 12 UTC forecast in 2013, May 25th showed that between 30th of May and the 3rd of June many EPS members figure 10 mm, some above 20 mm for 1st of June 12-hour rainfall amount. In the forecast made for the Inn catchment area the expected rainfall amounts are a bit higher and in reality more fell on this area. For the 1st of

June, the model figured a 12-hour quantity exceeding 25 mm. The following forecasts were more exact as they got closer to the event. On the Traun and Enns Basins – where the rainfall was also significant - the 12 UTC running from the 28th of May forecasted the process with double maximum, the 12 UTC running from the 30th of May has 30 mm/12 hours running as well (Homokiné Újvári, 2013).

For the Danube Basin, by the ECMWF model, quantity rainfall forecasts were made two times per day, in 6 and 12 hour resolution.

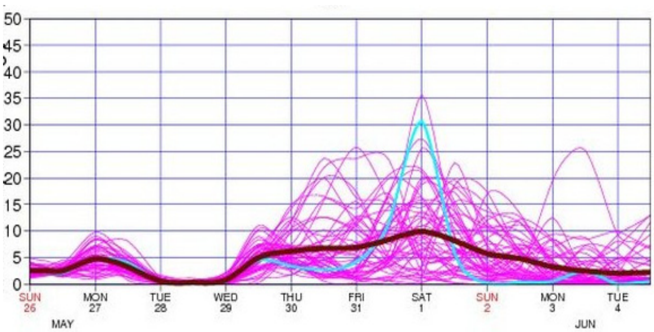

Figure 10. The torch diagram on the Inn basin, based on the 12 UTC running from the 25th of May, 2013 (according to NMS, Homokiné Újvári, 2013).

Table 4. The OVF-OVSZ forecasts during 10 days before the top level (OVF-VSZ, 2013)

Gauging station	VI.3	VI.4	VI.5	VI.6	VI.7	VI.8	VI.9	H_{max}	Date
Nagybajcs	865±20	890±20	890±20	900±10	910±10			907	VI.7-8.
Komárom	810±25	820±25	820±25	830±10	840±10	845±5		845	VI.8.
Esztergom	775±25	785±25	785±25	795±15	805±10	810±10		813	VI.9.
Nagymaros	715±30	730±30	730±30	740±15	740±15	740±15	752	751	VI.9.
Budapest	860±30	875±30	875±30	885±20	885±20	885±15	885-895	891	VI.9-10.
Dunaújváros			740±30	750±25	750±25	750±20	750±10	755	VI.11.
Dunaföldvár				710±25	710±25	710±20	710±10	721	VI.11.
Paks				880±30	880±25	880±20	890±25	891	VI.11.
Baja					970±30	970±25	990±20	989	VI.12.
Mohács						950±25	965±20	964	VI.13.

On the 29th of May the OVF-OVSZ firstly forecasted two weeks before the peak in Budapest the possibility of an extraordinary flood wave. The hydrology information from the 2nd of June forecasted for the entire Danube Hungarian section already the alert above the 3rd grade, peak water levels close to the $H_{maxhist}$. On the 3rd of June, in the forecast 6 days before the flood peak, levels around the LNV figured, thus for example for Budapest 860±30 cm. As the flood wave approached, in terms of both the level as the date of occurrence, the forecasts gradually became more exact, so on the 6th of June there figured levels over $H_{maxhist}$, for Budapest 885±20 cm top level (Table 4) and that time forecasts were made on the sections below Budapest as well (Dunaújváros, Dunaföldvár, Paks). The forecasts in 6 days advance were properly accurate, so the temporary defences were built up by the indicated value.

6. Flood consequences, control, damages

Responsible organizations for the Danube flood control in Hungary were mainly the water service and municipal governments, and the affected water utilities as well. The defence in Budapest was directed by the Budapest Sewage Works Ltd. The control activity meant the increasing of existing defensive works, restraint them, the development of new defences, water jet catchments, bridges pressing, the specific protection of high-value facilities. The total length of operational interventions reached 170 km. During the flood control a 95.2 km long defensive line was built (Szlávik, 2013).

Photo 2. Flood control in Budapest central part 11,06,2013. (Photo: Konecsny)

In Szentendre town, mobile flood protection walls were used for the first time in Hungary, and the structure provides proper protection for the City. The gum dam used in the protection of the Margaret Island on a length of 1400 m, demonstrates the effective applicability of these tools.

The intense flood lasted for 6 days and along 807 kilometre-long defence section, a total of 13 253 people (a daily average of 1600 people were water workers) participated. 10 million sandbags and 242 500 m^2 sand were used to strengthen the embankments. In addition, 254 machine, 1092 trucks and 338 pumps, 9 helicopters and 573 all terrain vehicles have been used (www. katasztrofavedelem.hu/index2.php?pageid=szervezet_hirek&hirid=1966). The most critical locations were in Győrújfalu, Dunaszentpál, Neszmély, Sződliget, Mecsér, Pilismarót, Tát, Dunabogdány, Kisoroszi, Nagymaros, Szigetmonostor, Tahitótfalu, Kisapostag, Báta, Baja and Dunaszekcső settlements.

According to the evaluation made by the water organization (OVF - Göncz, 2013), it was the experience of the flood control activity that the defence lines increasing could be made by staff outside the water directorate, but, in the protection against flood events, for solving geotechnical problems of water management specialists were needed. The sandbag filling stations helped a lot the defence activity. There were difficulties on the sections missing flood defence works, in the protection of high banks, sometimes the lack of municipal water damage prevention plans. An important task is the reviewing of hydrological statistical probability calculation methods, their analysis or any possible changes. The Danube flooding aerial survey in Hungary was completed, which affected an area of 1250 km^2 on a 2800 km long flight line (http://www.vizugy.hu /index.php?module=content&programelemid=1&id=805).

In June 2013 in Hungary the Danube flooded a total of 47,285 ha area of 36 575 ha of forest and 10 710 ha of agricultural area. The flood directly risked 206000 people, from which 1570 people were evacuated, but casualties did not occurred. On 48 national road, totally 102 sections, on a length of 222 kilometres traffic restrictions were in force, on 69 locations complete closure, while on 33 locations half lane closure were introduced, for shorter or longer time. The buildings built on unprotected flood plain areas were inundated by the flood, their protection did not happen. Though the Danube has achieved record levels, the damages were smaller than those occurred during large floods in the earlier years. The biggest damages were reported in the Danube-curve and Budapest. The municipalities, the farmers, the government organs and the cost of restoration amounted to 100 million Euro. The relatively lower expenses is thanks to the fact that there was no dike breach, so there was no need for reconstruction needed (http://fn.hir24.hu/itthon/2013/07/ 12/itt-vannak-az-arvizi-szamok/). The number of residential buildings that suffered damages did not reach 100 (Szlávik, 2013).

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