Review of Historic Floods in Hungary and the Extent of Flooded Areas in Case of Levee Failures

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ABSTRACT
The Carpathian Basin covers an area of 330,000 km^2 in Central Europe, surrounded by geographic boundaries of the Carpathian Mountains, the Alps, the Dinarides and the Balkan Mountains. It is divided approximately in two halves by the rivers Danube and Tisza. Both rivers have two regular floods each year the early spring "icy flood" and the early summer "green flood". Forty percent of the Danube's catchment area is located within the Carpathian Basin and little more than 12% of the Basin's territory represents the Danube's floodplain, approximately 40,000 km^2. This large floodplain is presently bordered by approximately 11,000 km of levee network, built across six countries. This paper presents the results of statistical analysis of historic flood data, collected and reviewed in connection with large number of floodplain reach inundations along the two rivers within the Carpathian Basin generally, and in Hungary particularly.

RÉSUMÉ
Le Bassin des Carpates couvre une superficie de 330,000 km^2 en Europe centrale. Il est bordé par les Carpates, les Alpes, les Dinarides et les montagnes des Balkans. Il est divisé en deux par le fleuve Duna (Danube) d'un côté et par la rivière Tisza (Theisse) de l'autre. Ces deux cours d'eau sont en crue deux fois l'an. Une crue au début du printemps "icy flood" et l'autre en début d'été "green flood". Quarante pour cent du bassin de drainage du Danube est situé dans le bassin des Carpates et un peu plus de douze pour cent du territoire du bassin représente la plaine d'inondation du Danube, soit environ 40,000 km^2. Cette grande plaine est présentement bordée par un réseau de digues d'environ 11,000 km de long, construit dans six pays. Cet article présente les résultats de l'analyse statistique des données historiques, recueillies et examinées dans le cadre du grand nombre de débordements de portée le long des deux rivières dans le bassin des Carpates en général, et dans la République de Hongrie notamment.

1 FLOODPLAINS IN THE CARPATHIAN BASIN

1.1 Topographic details

The Carpathian Basin's 330,000 km^2 area is an unrivaled geographical and hydrological unit, located in the 1,000 km long central section of the Danube River, as shown on Figure 1.

Figure 1: Topography of the Carpathian Basin

Little over 12% of the Basin's territory, approximately 40,000 km^2 (4 million ha), is considered as floodplain. Hungary is situated in the central lowland part of the Basin and the majority of rivers are draining surface run-offs from the surrounding mountains to this country. The Carpathian Basin's large-scale flood protection program began in 1846. Prior to that date the length of flood protection barriers (levees) was about 1,200 km, while their present length is nearly 11,000 km.

The area of present day Hungary within the Carpathian Basin is 93,000 km^2, but only 1% of this land is located higher than 500 m above sea level (masl). Most of the country's territory has an elevation of lower than 200 masl. The highest point is Mount Kékes at 1,008 masl in the Mátra Mountain, northeast of Budapest. The lowest spot is at 77.6 masl, located in the Hortobágy, next to the Tisza River. The total floodplain area within the country is 21,200 km^2 (23%). Currently, 97% of the country's floodplain is bordered by approximately 4,200 km long levee network.

Floodplains are part of a river valley that may be inundated by high flood waters or being inundated by floods in case when the river is confined between levees. In the latter configuration (except in case of dam failures or overtopping) the river may only inundates the area between the levees, while the protected floodplain zones (floodplain reaches) will not be flooded. Since the flood level is higher when rivers are confined between levees, there are two distinguished floodplain areas. A larger "ancient" floodplain, which occurred in an unregulated state of the river valley without levees or dams, and a smaller floodplain, which is inundated by flood waters between the levees.

According to a 1996 survey, 40% of Hungary's GDP is produced on the floodplains and floodplain reaches. 2.5 million People live in more than 700 settlements there and 32% of the country's rail lines and 15% of roads are also located in these low topographic areas. Within the floodplain areas of Hungary there are 151 specific floodplain cells or reaches. 55 located in the valley of the Danube and 96 in the valley of Tisza and its tributaries. The floodplain reaches are very diverse and the variation in their area is in the order of magnitude of five, while the variation in the protected value is in the order of magnitude of seven. The largest number of residents living within a specific floodplain reach is 230,000.

1.2 The extent of floodplains

When analyzing the extent of floodplains the first task is to clarify the size of the floodplain that can potentially be flooded during high water periods. There are various data available in connection to the full extent of the floodplains in the Carpathian Basin generally, and within the area of present-day Hungary specifically. One of the most well-known figures is based on floodplain data compiled by Kvassay in 1900. According to him the size of the gross floodplain area was 36,225 km^2 (3.62 million hectares); however, he included areas that were accessible only for those companies that were responsible for flood prevention and protection at that time. The extent of floodplains has changed over time based on survey accuracy in one hand, and on applied definition of the floodplains in the other. The extent of floodplains has also changed over time with different authors and according to official government statements. The main reason in the differences was the fact that the rivers' floodwater level was continuously rising. In Szeged, for example, the fourth largest city in Hungary, situated at the Tisza River, the highest flood level rose by more than 400 cm in the last 150 years.

Figure 2 presents the river gauge readings at another town along the Tisza River, at the town of Tiszabecs during the March-April floods in 1999, 2000 and 2001. It may be noted that in 1999 and 2000 it took several days to reach the maximum flood level; however, in 2001 the river level rose by 550 cm in one day. Figure 3 shows the inundated town of Gulács during the 2001 flood, also located next to the Tisza River near the Ukrainian border.

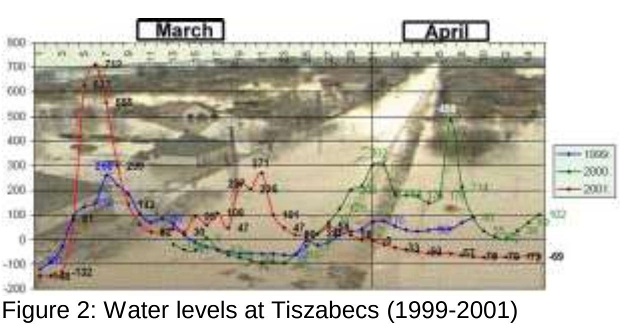

Figure 2: Water levels at Tiszabecs (1999-2001)

The extent of floodplains initially included the so called "ancient" floodplain or "low" floodplain areas. At the end of the 19th century, however, in almost all floodplain cells the extent of "high flood level" areas had been determined with the consideration of the ever increasing flood levels. The implementation of the floodplain development lasted more than twenty years at that time, despite to the repeated and urgent requests from the responsible Ministry. There was also great resistance from landowners, claiming that their land had never been inundated. They were still required to provide funding (flood protection tax) for the country's Local Water Authorities (LWA) that were responsible for developing and implementing comprehensive schemes for floodwater management and protection in the individual floodplain reaches.


Figure 3: The inundated town of Gulács in 2001

Landowners with larger lands within a floodplain reach had to pay more tax, but also had more say in the affairs of the LWA-s. Some of the landowners with lands on higher grounds were not happy when larger portion of their land became incorporated in the floodplains, and as a result they had to pay more taxes. This was in contrast to the interest of the farmers operating within the topographically "low" floodplains, who wanted the number of landowners paying flood protection taxes to be increased. As a compromise, the rate of "floodplain tax" became largely dependent on the value and location of the farmlands within the individual floodplain reaches.

Due to the increasing flood levels, more and more lands were incorporated in the floodplains, increasing the income and power of the Local Water Authorities. It should be pointed out that the floodplain tax was collected by the State, and the treasury transferred the money to the Water Authorities that were under strict technical and financial control by the respective Ministry. The landowners also exercised a certain level of control over the Authorities through general assembly meetings. In many instances the Ministry had requested new floodplain management initiatives; however the General Assembly of the landowners refused to implement the recommended tasks.

In a State survey, reported by Kvassay in 1916, they only included data of those floodplain cells which were protected by levees, controlled by the Local Water Authorities and hence, the Government has exercised technical control over them. Thus, information and details about floodplain cells protected by municipal, private and Church-owned levees had not been included in the State survey. In a number of individual surveys special consideration was given to the incorporation of the so-called "floodplain islands", areas that were surrounded by flood water within the area of the floodplain reaches. The inclusion or exclusion of the topographically high ground islands may have increased or decreased the size of the floodplain cells. The calculated area of the floodplains was influenced by the known high water levels. There were various methods used in the determination of the high water level within the floodplain cells:

- Projection of observed maximum water level to the surrounding surface topography.
- Projection of previous high water levels to the surrounding surface topography. This latter survey was completed for many floodplain reaches and one of them was for the city of Szeged, completed by the Szeged Flood Management and Drainage Control Directorate. Survey data for the 1830, 1879 and 1895 high water levels are shown in Table 1.
- Calculated maximum water level, based on 100 year return period, by the Environmental and Water Management Research Institute (VITUKI) 1976/77.

Table 1: Floodplain mapping at the city of Szeged (Tisza)

Date	Area of the floodplain (km^2)
1830 flood "ancient floodplain"	101.5
1879 flood	56.4 increments
1895 flood	39.6 increments
+7 m anticipated flood level (river gauge)*	14.4 increment
TOTAL	211.9

* In Szeged they anticipated that the flood level will reach the +7 m river gauge elevation and the flood protection was planned for that level. Nobody assumed that the floodwater will reach +10.1 m level during the 2006 flood.

The changes in the area of the floodplains became more interesting when the results were reviewed for individual Water Authorities. These groups were initially formed to manage important water infrastructure and to attend administrational duties in individual floodplain cells; however the rising flood level resulted in changing floodplain areas and subsequent merger or reorganization of some of the neighbouring Water Authorities. The extent of the protected areas was usually increased with the length of the line of defense, particularly where levees joined high ground areas.

Table 2 shows areas of representative floodplain cells for the last 120 years. The areas increased consistently, except for some floodplain cells that had been changed during and after the two World Wars, when some borders had been realigned and more and more levees were built, followed by changes in territories of some LWA-s. The 1977 detailed floodplain mapping is now declared the most reliable source of floodplain data in Hungary. Although the 1977 data were based on the highest water levels ever recorded to that date, some of the historic data indicated larger floodplains for certain LWA-s.

Table 2: Historic floodplain data

Water	Area of floodplain cells (km^2)				
Authority	1892	1900	1916	1941	1977
Upper-Szabolcs/ Tisza	431.6	473.5	584.5	587.1	468.1
Hosszúfok	250.3	447.7	448.8	416.0	-
Szekszárd-Báta	232.7	233.5	233.5	-	-
Bodrogköz	839.2	897.3	897.3	545.8	525.4

2 HISTORIC LEVEE BREACHES

The collection of information about historic dam breaches at the floodplains had focused on the following:

- Year and date
- River at the breach
- Failure mechanism
- Location (bank, stationing)
- Origin of the flood causing the failure
- Length of breach
- Overtopping without failure
- Size of the inundated area
- Losses according to detailed assessments
- Number of casualties
- Exact time of failure
- Existence of a scour pit
- The affected floodplain section
- Other circumstances

Based on historic data, details of 2,858 dam failures were collected to date, out of which 1,433 (50.1%) have been recorded within the present day territory of Hungary. The distribution of failures within the countries sharing the Carpathian Basin is shown in Table 3. Distribution of levee failures for fifty-year time periods during more than 300 years is shown on Figure 4.

Table 3: Country-based distribution of levee breaches

Country	Number of levee breaches	%
Croatia	10	0.3
Hungary	1433	50.1
Romania	546	19.1
Serbia	156	5.5
Slovakia	630	22.0
Ukraine	68	2.4
Not well defined	15	0.6
Total	2858	100

During the evaluation process of the failure mechanisms of the failed levees, historical terminologies were kept in files that were initially used in the 19th and 20th centuries. In 1,193 of the 2,858 cases, the failure mechanism had been well defined. The predominant cause of failure was overtopping (77.5%), which was related to the insufficient height of the dams at the time of high water periods. Engineering reasons represented 17% of the failures. The distribution of levee failure mechanisms from the 16th century to date are detailed in Table 4.

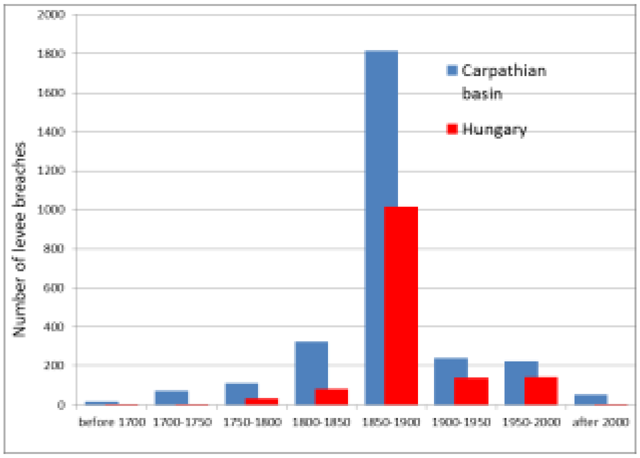

Figure 4: Distribution of levee failures for 50-year periods

Table 4: Distribution of failure mechanisms (1564 – 2010)

Type of failures	%
Overtopping	77.5
Deliberate cut	5.5
Embankment (slope) failure	4.8
Subsoil (base) failure	4.3
Wave erosion	2.4
Failure of a structure within the dam	2.6
Other	2.9

3 INUNDATION OF FLOODPLAIN REACHES

3.1 The extent of inundated areas during historic flooding

The extent of flooded areas after levee failures depends on many factors, among which the most important are:

- Topographic features of the floodplain reach (size, topography, etc.)
- Characteristics of the flood wave (height, time, etc.)
- Characteristics of the river (stream flow, drop, etc.)
- Characteristics of the levee (height, material, subsoil stratification and conditions, etc.)
- The extent of the failure
- The location of the failure
- Time (date) of the failure in relation to the occurrence of the maximum flood level, etc.

The area of the floodplain cells vary widely in the Carpathian Basin. The smallest cells are less than 0.5 km2 in area, while the largest ones are greater than 1,000 km^2. Representative data on the largest and smallest floodplain cells are shown in Table 5.

Table 5: List of the largest and smallest floodplain cells in the Carpathian Basin (km^2)

Largest cells	Area	Smallest cells	Area
Budapest – Baja	2287	Szentendre	0.3
Felső - Torontál	2270	Titel II.	0.4
Körös-Tisza-Maros	1681	Sajónémeti	0.4
Hortobágy	1578	Zsadány	0.5

The extent of inundated areas within the floodplain cells is known for 925 of the 2,858 cases, when flooding occurred as a result of levee breaches (32.4 %). Within the territory of present-day Hungary, there are data for 192 inundations related to 487 dam failures. It should be noted that in many cases dams had failed at multiple locations within one floodplain cell. The first known dam failure in the Carpathian Basin occurred in 1672; however the first inundation data were obtained from 1775. Reliable data for flooded areas are available from the early years of the 19th century. Historic inundation data for ten-year periods in the Carpathian Basin, starting from 1670, are shown in Figure 5. It may be noted that there were three decades when the inundated areas exceeded 10,000 km^2, (1,000,000 ha). The maximum flooded area (23,054 km^2) was recorded between 1870 and 1879.

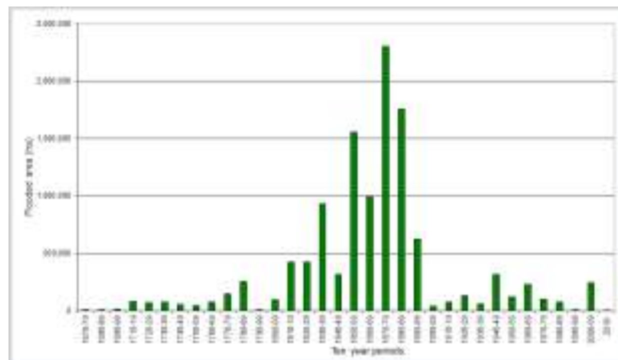
Figure 5: Historic inundation data for ten-year periods in the Carpathian Basin

Figure 6 presents the historic inundation data for fifty-year periods. Special attention should be given to the years between 1850 and 1900, when the total inundated area was twice as large as the sum of inundated areas ever before and after that period. In Hungary, they call that fifty-year period the „golden age of dam failures".

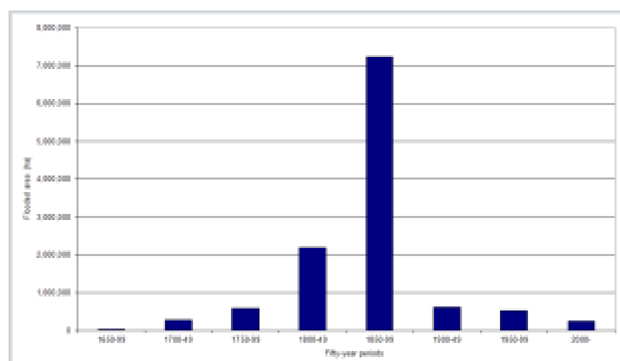
Figure 6: Historic inundation data for fifty-year periods in the Carpathian Basin

3.2 The extent of inundated areas after individual dam failures

The knowledge of the extent of flooded areas for floodplain reaches is also important in the planning process of flood defense systems. Based on available historic data, average flooded areas may be calculated for individual levee breaches. The historical data indicated that the flooded areas for individual dam failures varied within almost five orders of magnitude. Calculating average flooded areas would, however eliminate extreme approximations. In the Carpathian Basin the representative flooded area after a dam failure was 67.2 km^2, while within the territory of present-day Hungary the same value is 70 km^2, the difference is only 4%, not significant.

From the 925 levee failures in the Carpathian Basin 338 occurred in the valley of the Danube and 587 in the valley of the Tisza. According to historic data, the gross extent of inundated areas in the Tisza valley was approximately twice as large as in the valley of the Danube. The 62,170 km^2 total flooded area (assuming that the missing flood data are distributed evenly) was split as 20,240 km^2 and 41,930 km^2 between the two valleys. Hence, the average flooded area for one levee breach was 59.9 km^2 along the Danube, and 71.5 km^2 in the Tisza valley. The difference is almost 20%, which may be a direct result of the differences in characteristics of the two rivers and individual floodplain reaches.

3.3 The extent of annually inundated areas, based on information from various authors

It is evident that literary references to the flooded areas vary significantly. Examples in Table 6 show the extent of calculated flooded areas, presented by various authors for the 1876, 1879, 1881 and 1888 year floods. There are quite significant differences in the calculated values. Unfortunately, the authors of published papers (prior to the 1977 floodplain mapping) did not disclose the source of their data. The difference is well presented in the 1876 annual flood data, where the recent detailed review of actual archived information resulted in almost 9,000 km^2 inundated areas (Nagy 2007). Since the archived data did not include all levee breaches, it is likely that the actual extent of flooded areas in 1876 may have been closer to 10,000 km^2.

Table 6: The extent of inundated areas during historic (1876 – 1888) floods by various authors (km^2)

Author/Date	1876	1879	1881	1888
Zawadowski (1892)	3243.3	1250.3	1656.6	4472.0
Kvassay (1916)	3669.1	1129.3	1402.3	2875.2
Babos–Mayer (1937)	4100.0	1400.0	1400.0	3280.0
Zrínyi–László (1961)	1725.0	3664.7	897.0	972.9
Nagy (2007)	8792.6	-	-	-

3.4 Frequency of floods in floodplain reaches

Currently in Hungary there are 55 floodplain reaches along the valley of the Danube, registered as 1:01 to 1:55 in Table 7, and 96 in the valley of the Tisza, registered as 2:01 to 2:96 in Table 8. In the archives, there are data from the early years of the 19th century for levee breaches and 884 inundation cases. From the 884 cases, 398 were recorded along the Danube and 486 along the Tisza. For the 398 floodplain reach inundations, the recorded number of levee breaches was 754 along the Danube, as detailed in Table 7.

Inundation of one floodplain reach may have been caused by multiple levee breaches within one reach. At reach #1.53 for example, they recorded only 5 inundation cases, but 19 levee failures. It is evident from Table 7 that the distribution of inundations is not uniform. Flood water never entered into 19 of the 55 floodplain reaches in the valley of the Danube, while in the valley of the Tisza 51 of the 96 reaches remained "dry". It appears that these 70 reaches are the safest and people living there are the main beneficiaries of the flood-protection and levee construction program in Hungary. However, there are still a number of disadvantaged floodplain areas with frequent levee failures and flooding. Future flood protection programs will have to concentrate on the disadvantaged floodplain zones, like the # 1.01, 1.05, 1.25, 1.26, 1.49, 1.51, 2.54, 2.57, 2.58, and 2.90 reaches.

In the valley of the Danube, flood water entered 104 times into the Budapest-Baja floodplain reach (#1.49), as a result of 202 known dam failures. Since this reach is the largest one, its area has never been submerged for more than 80%. However, residents living at the downstream end of the reach suffered the greatest damage, even though the conditions of the levees along their section of the river are relatively good.

Table 7: Number of regular floods and dam failures in the 55 floodplain reaches of the Danube in Hungary

	1.0x		1.1x		1.2x		1.3x		1.4x		1.5 x	
	RF	LF	RF	LF	RF	LF	RF	LF	RF	LF	RF	LF
1.x1	34	35	7	17	0	0	13	15	0	0	36	39
1.x2	5	5	4	10	5	6	9	11	0	0	2	2
1.x3	0	0	1	10	4	4	0	0	0	0	5	19
1.x4	1	1	1	1	1	1	0	0	0	0	16	16
1.x5	25	37	0	0	37	46*	2	4	0	0	3	3
1.x6	7	10	0	0	27	27	0	0	0	0	-	-
1.x7	1	1	8	8	2	2	2	2	3	3	-	-
1.x8	0	0	0	0	16	16	0	0	5	5	-	-
1.x9	0	0	0	0	2	4	1	1	104	202	-	-
1.10	6	7	0	0	2	2	1	1	1	1	-	-

Total: Regular flood (RF): 398 Levee failure (LF): 754

* The number of floods in floodplain reach #1.25 was 37, as a result of 46 dam failures.

Table 7 does not include data for trans-boundary floodplain reaches, where the inundation was caused by floodwater flowing in from a neighbouring country, and for multiple inundations of the same reach, when the failed dams had not been repaired quickly and a second flood-wave reached the "open" floodplain zone. One floodplain reach may have been flooded during one flood from multiple directions. For example, during the 1956 icy flood, reach # 1.51 had been flooded from three different directions through 20 dam failures. It happened in reaches located at the junction of two rivers and water had broken into the reach from both rivers. In these cases only one inundation should be considered in statistics.

Table 8 summarizes the number of inundations in the 96 floodplain reaches along the Tisza River, within the territory of present-day Hungary. The Tisza River originates from the North-Eastern part of the Carpathian

Mountains in the territory of Romania, at elevation of around 1,600 masl; however, it enters Hungary at the approximate elevation of 120 masl, and leaves the country at around 75 masl.

The numbers in Table 8 highlight the fact that 47% of the inundations occurred in the eight most vulnerable floodplain reaches, # 2.02, 2.54, 2.57, 2.58, 2.70, 2.90, 2.91 and 2.95.

Table 8: Number of inundations in floodplain reaches of the Tisza, within the territory of present-day Hungary

	2.0x	2.1x	2.2x	2.3x	2.4x	2.5 x	2.6x	2.7x	2.8x	2.9x
2.x1	5	1	0	0	3	1	0	3	3	10
2.x2	10	0	0	0	1	0	0	2	8	9
2.x3	0	0	0	0	0	4	1	0	0	4
2.x4	0	0	0	0	0	13	0	0	0	8
2.x5	0	0	0	0	2	8	0	0	2	12
2.x6	0	0	0	1	2	1	0	0	4	6
2.x7	3	0	1	7	1	21	0	0	2	-
2.x8	0	0	0	0	0	13	0	3	6	-
2.x9	0	3	0	1	2	1	0	4	0	-
2.x10	0	0	0	3	3	0	12	0	15	-

4 CONCLUSIONS

Information presented in this paper are based on statistical analysis of historic flood data, collected and reviewed in connection with the number of floodplain reach inundations within the Carpathian Basin generally, and in the Republic of Hungary particularly. Many reaches had never been under water since the construction of the extensive levee network along the two major rivers in the area, the Danube and the Tisza. Floodplain reaches that were submerged only once had provided only limited information in connection with levee breaches and characteristics of subsequent flooding. Reaches that had been under water at least twice may provide more opportunities for comparison of important data. Hence, comprehensive studies may be completed for floodplain reaches that were inundated by floodwater almost annually. In such cases it would also be necessary to analyze the impact of rising flood levels, the width of dam failures, and the topography of surrounding areas on the extent of floodplain reach inundations; however, such review was beyond the scope of the present study.

The extent of the inundated area of a floodplain reach depends on several factors, such as: location and extent of the failed zone at the adjacent dam, the size and topographical conditions of the reach, the river's flow rate, the height and longevity of the flood wave, etc. These factors together determine the amount of water entering the reaches during flooding and the filling and subsequent drainage conditions of the reach. There is no doubt that the above described factors and conditions at the reaches are not identical and should be analyzed for each floodplain reach individually.

Based on historic flood data for 925 levee breaches it can be concluded that the extent of inundated areas in the Carpathian Basin was 62,170 km^2. Considering that the gross area of the Basin's floodplain was estimated at 40,000 km^2 in the 19th century, the total flooded area represented around 150% of the Basin's floodplain land. Without the construction of the existing extensive levee network the area of the inundated floodplain reaches would have been 180,000 km^2.

Within the territory of present-day Hungary 487 levee breaches resulted in the flooding of 34,100 km^2 floodplain areas. This gross land is equal with nearly 40% of the country's territory and 150% of the current floodplain area. It appears, therefore that the impacts of floods in Hungary and in the Carpathian Basin were similar.

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