Dike failures in the Carpathian Basin

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Abstract

The history of dike failures in the Carpathian Basin goes back some four and a half centuries. It can be used to monitor changes in water policy and the method of technical approach. The large number of dike failures provides an opportunity for statistical evaluation and offers input data for the application of a risk-based approach, as there are some technical-economic data that cannot be obtained either by modelling or by conceptualisation. Although not all data on all dike failures are available, data such as the distribution of dike failures per year, within a year, per river or per river valley, provide much scientific information. In this communication, only national and Carpathian Basin level data are presented, but the slicing can be continued for river valley data and individual rivers.

Keywords: dike failure, historical data, failure mechanism, Carpathian basin, dike safety

Gátszakadások a Kárpát-medencében

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Összefoglalás

A Kárpát-medencei gátszakadások története mintegy négy és fél évszázadra nyúlik vissza. Az építőmérnöki gyakorlatban ritka lehetőség, hogy egy létesítményfajta tönkremenetelével kapcsolatban nagyszámú adat álljon rendelkezésre. A Kárpát-medence területére összegyűjtött csaknem háromezer gátszakadás lehetőséget nyújt nemcsak a gátszakadások különböző adatainak statisztikai értékelésére, de egyfajta tönkremeneteli valószínűség becslésére is. A történelmi adatok gyűjtése így hasznos többletinformációt nyújt a gátszakadások és következményeik feltárásához, akkor is, ha nem minden gátszakadáshoz áll rendelkezésre minden adat.

A gátszakadások nagy száma lehetőséget nyújt kockázatalapú megközelítés alkalmazásához, ugyanis vannak olyan műszaki-gazdasági adatok, melyekhez sem modellezéssel, sem gondolati úton nem lehet hozzájutni. Bár nem minden gátszakadás minden adata áll rendelkezésre, mégis olyan adatok, mint például a gátszakadás évenkénti megoszlása, éves megoszlása, napon belüli megoszlása sok tudományos eredményt szolgáltat és bemenő adatot nyújt a kockázatszámításhoz. Jelen közleményben csak országos és Kárpát-medence szintű adatok vannak feltüntetve, de a szeletelés tovább folytatható a folyóvölgyi adatokra és az egyes folyókra.

Magyarország legnagyobb természeti veszélyforrása az árvíz. A legfontosabb konklúziók, amelyek leszűrhetők a történelmi adatokból a következők:

- Az év bármelyik részében kialakulhat olyan árvíz, amelyik gátszakadáshoz vezethet.
- A gátszakadások számának csökkenése a XX. századra azt jelenti, hogy Magyarországon az árvízvédelem meglehetősen magas szintet ért el, bár a veszélyt még nem sikerült felszámolni.
- Csökkenő tendenciát mutat a meghágás okozta gátszakadások aránya, és inkább a kis vízhozamú folyókra korlátozódik.
- Az altalajhoz kapcsolódó meghibásodások (buzgárok és hidraulikus talajtörések) aránya a vízszintemelkedéssel, a gátakra ható terhelés növekedésével valószínűleg nőni fog a jövőben.
- Viszonylag kevés információ áll rendelkezésre a Maros, a Dráva és a Száva árvizeiről, továbbá a jelenlegi határokon túli, 1921 utáni árvizekről. További együttműködésre, további információcserére van szükség a szomszédos országokkal.
- Nem rendelkezünk olyan adatokkal a Kárpát-medencéről és a Duna felső szakaszáról, hogy az árvízgeneráló tényezők hogyan változtak, változnak meg a globális felmelegedés hatására. A történelmi adatok feldolgozásából azonban egyértelműen látszik, hogy:

  - A jeges árvizek szerepe csökken. A XIX. század második felében az évek 2/3-ában volt jeges árvíz a Duna völgyében. Ugyanakkor a XX. században az utolsó jeges árvíz 1956-ban volt, amelyik gátszakadást okozott, vagyis 65 éve.
  - A nyári és kora őszi esőzések szerepe nőtt az előző fél évszázadban a Duna völgyében, a vízállásban egymás után alakultak ki csúcsdöntő magasságú árvizek.
- A Tisza középső és alsó szakaszán csaknem másfél méterrel nőtt az ezredfordulón a legmagasabb árvíz szintje.
- A kis folyókon, melyeknek betöltésezett alsó szakasza van, a vízjárás szélsőségesebb ingadozása mutatkozott.

Kulcsszavak: gátszakadás, történelmi adatok, tönkremeneteli mechanizmus, Kárpát-medence, gátbiztonság

1. Introduction

Hungary is situated in the part of Europe drained by the Danube, in the deepest part of the hydrographic unit known as the Carpathian Basin. Her territory covers 93,000 km² and represents 11.4 % of the 817,000 km² large Danube catchment. The Carpathian Basin is bounded to the west by the 2,000–3,000 m high ranges of the Alps, to the north and east by the Carpathian Range the peaks of which rise to over 1,500–2,300 m. In contrast thereto, 70% of the territory comprises of plains below 200 m, while hardly 1% consists of hills higher than 500 m. Owing to this topography, an area of around 21,200 km², that is 23% of the territory of Hungary is below the flood level of the rivers. This fact alone presents flood defence problems which are unique in Europe.

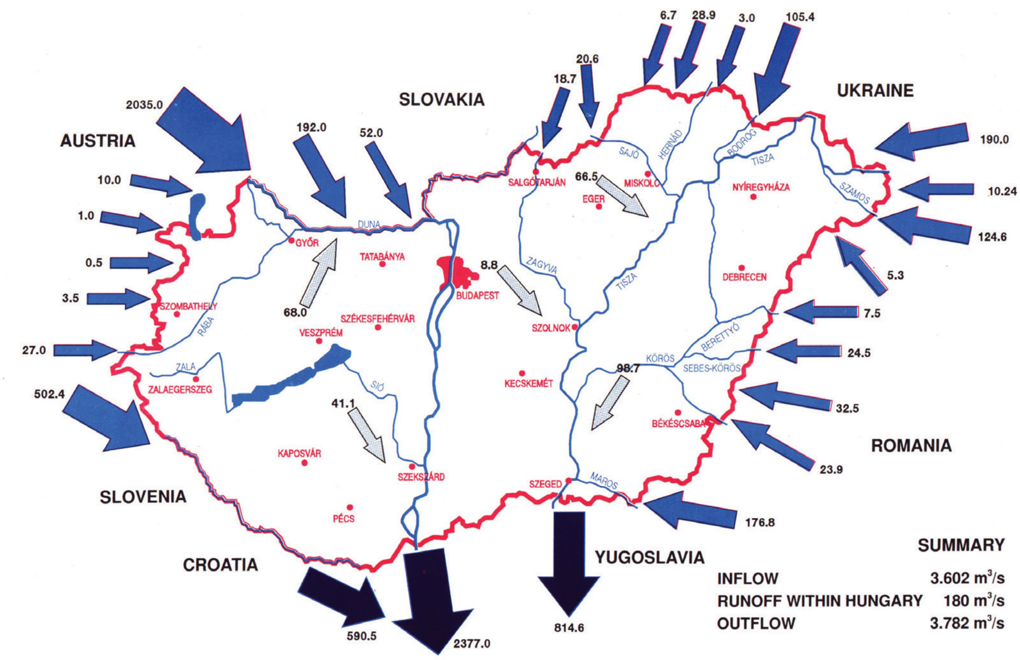
The Danube is the only river in the Carpathian basin that does not originate in the basin. Before the regulations, the Danube crossed 997 km of the Carpathian basin. Two other large rivers are the Sava and the Tisza. The Carpathian Basin is drained by the Danube.

2. The history of the flood control in the Carpathian Basin

Until the Treaty of Trianon, the water catchment area of the Carpathian Basin was managed as a single basin, currently divided between six countries. Hungary is located at the bottom of the basin, and, due to the Treaty of Trianon, has a very limited impact in the areas where flooding is generated.

The first evidences of local flood embankment construction date back to medieval times. Construction work on local flood embankments was started again along the Danube, the River Tisza and their tributaries towards the end of the 18th and early in the middle of the 19th centuries. In 1840, the total length of flood embankments in Hungary was 792 km, of which 464 km were in the Danube Valley and 328 in the Tisza Valley.

Rivers flowing from the mountains into the lowlands continue their journey between embankments. The growing market for cereals in Western Europe, the recurring inundations and especially the 1845 flood on the



Normal mean flow in the major Hungarian rivers (m^3/s)

Figure 1 After 1921, the single management of the water catchment area of the Carpathian Basin ceased, Hungary has become a typical sub-water country

Source: National Water Authority

River Tisza prompted the landowners to join their forces in flood defence associations. Large-scale river regulation and also flood embankment projects extending to entire flood plain sections were thus launched in 1846. The first 11 km long embankment section was built on the initiative of Count István Széchenyi according to the designs of the engineer Pál Vásárhelyi along the short cut of the meander at Tiszadob.

There are several approaches to estimate the failure probability of flood dikes. The results differ in their accuracy and the methods can be classified according to reliability. One of the possible approaches is collecting historical data. Identification by processing historical data, the causes, location, size, etc. of earlier failures must be examined. This approach will be dealt with more in detail later. The large-scale dike construction works basically finished for the beginning of 20th century.

After 1921, as a result of the annexation of the upper water catchment areas, Hungary became a sub-water country, which is not in small measure exposed to the flooding strategy of the upstream countries. Water flows into Hungary in 24 places and only three places are drained by rivers *(Fig. 1)*. In the past 100 years, Hungary has been inundated by floodwaters several times after the dike failure in the upstream country.

Care should be taken to ensure that the investigations form a system and that the results are compatible. In analysing failures (or dike breaches), the compatibility of the failure categories is extremely important. The results should be examined for any trends, and regularities.

Currently, more than 11,000 km of flood dikes along rivers are distributed between countries according to *Fig. 2*. A very significant proportion of these – both in length and volume – were built before 1921. Remember, dike failures can only occur where there was a dike.

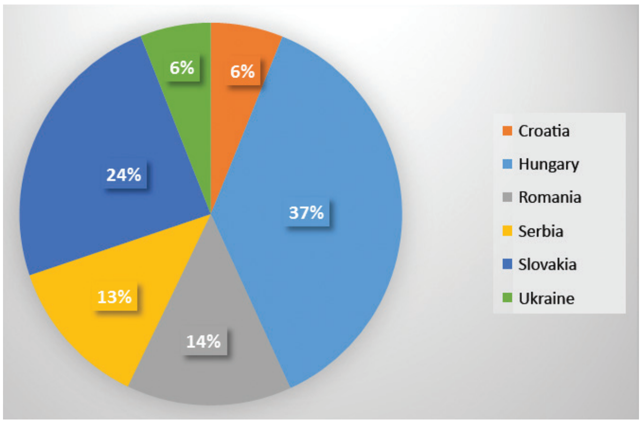


Figure 2 Length of flood protection dikes in the countries of the Carpathian Basin

Source: author.

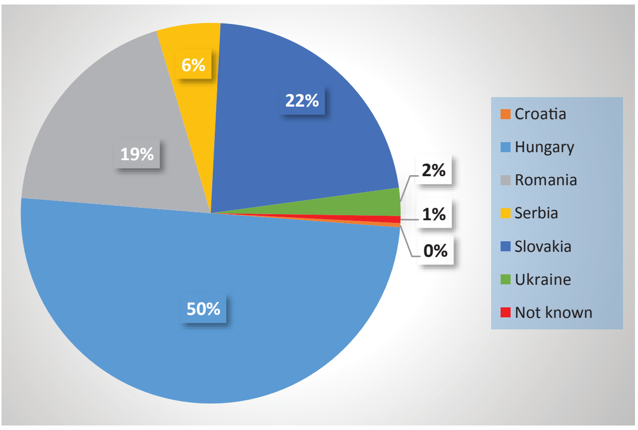


Figure 3 Distribution of dike failures by country in the Carpathian Basin

Source: author.

Rivers running at high speed from the mountains slowed down and spread across the lowlands. After the great water control, torrential waters reached the lowlands, creating high floods in the diked riverbed, which caused high flooding when the dike failed. After the rivers were filled, many dike failures occurred due to the fact that in the 19th century it was not yet possible to determine the expected maximum water levels. The present communication deals with 2,858 dike failures in the Carpathian Basin, of which 1,436 occurred on the territory of present-day Hungary. Dike failures are treated in a uniform way, regardless of the country in which the dike is currently located *(Fig. 3)* in the compact water catchment area of the Carpathian basin.

3. The philosophy of data collection

I started collecting data on the failure of flood protection dikes in 1992, and the books on them were published in 2018 and 2019 *(Nagy 2018, 2019)*. The historical data sources were reviewed with the aim of finding the following data on dike failures *(Nagy 2006b):*

1. Year
2. River
3. Failure mechanism
4. Location (bank, stationing)
5. Origin of the flood causing failure
6. Length of the breach
7. Cases of overtopping without failure
8. Size of area inundated
9. Losses according to contemporary assessment
10. Number of casualties
11. Exact time of failure
12. Existence and size of a scour pit
13. The competent District Water Authority
14. The floodplain section affected
15. Other circumstances and notes

Figure 4 Dike breach in 1980 in the Körös valley

Source: ABKSZ

4. Distribution of failure mechanism

I have used historical names to describe the failure mechanisms. The failure mechanism is an engineering process that shows what happens during a dike failure (for example: subsoil failure, structure failure, wave scour, etc. in *Table 1*). The failure mechanism should not be confused with the cause of dike failure, which can be attributed to existing conditions (such as uncompacted earthworks, low embankment, poor quality earthworks material, etc.) and the factors directly causing dike failure (such as earthquakes, faulty flood defences, human negligence, etc.).

Table 1 Distribution of failure mechanism

Failure mechanism	Failure	
	Numbers	%
Overtopping	925	32.4
Subsoil failure	51	1.8
Deliberate cut	64	2.3
Wave scour	29	1.0
Loss of dike stability	58	2.0
Structure failure	31	1.1
Other known	35	1.2
Unidentified	1,658	58.1
Total	2,858	100

Source: Nagy, 2018

The failure mechanism is known in 1,200 cases, that is, 42% of the total. The distribution is shown in *Table 1.*

Undoubtedly, most dike failure mechanisms (77% of all dike failures with known mechanisms) were due to erosion after the failure (see e.g. the cases in *Fig. 4, 6*). This failure mechanism means the occurrence of a water level higher than the design water level or the construction level of the dike *(Table 1)*.

The "deliberate cuts" do not include officially approved diversions to emergency reservoirs to lower peak stages. Obviously, post-flood drains when the dike was opened to allow the spilled water to return to the river do not fall into this category, either. The majority of these dike cuts were due to fears of flooding, which led to the illegal opening of the dike on the opposite bank *(Nagy 2011b)*. Fears of illegal dike cuts went so far, for example, that during the Danube flood of 1862 the chief magistrate of Kalocsa ordered that "the disturbers of the embankments in the locality may be beaten to death".

We know of only one dike cut by military action in the Carpathian Basin, although carpet bombing damaged dikes in the Second World War.

Wave scour was considered one of the most dangerous flood phenomena in the 19th century. Nevertheless, the prevalence rate of 1% is low. Winds were considered particularly dangerous in the spring, when the Tisza was often flooded during the equinox.

The category of "structure" contains the failures related to deteriorated culverts, etc. and leakage in their surroundings *(Nagy 2011a)*. Several of the sluices that were destroyed were old wooden sluices that simply collapsed under the force of the flood. There are currently around 2,500 crossing structures in Hungary alone, which are potential threats to the 4,200 km long dike system. Maintaining them safely is a huge task *(Nagy 2018)*.

The term "subsoil", or "hydraulic soil failure" was coined in the 20th century in connection with flood dikes, so that its application to earlier incidents is a retrospective interpretation *(Nagy 2018)*. Despite the fact that this concept has only existed since the beginning of the 20th century, the 1.8% share is significant, but it should also be remembered that the most accurate data on dike failures come from this period.

The list on "deliberate (illegal) cuts", "wave scouring" and "culvert failures" are probably correct, in that, as special cases, these were mentioned repeatedly in the contemporary and more recent press and in the professional literature *(Nagy, 2018)*.

For an international comparison of failure mechanisms, see the following authors: *Middlebrooks (1953), Gruner (1967), Takase (1967), Babb–Mermel (1968), ICOLD (1974), Sametz (1981), Krol (1983), ICOLD (1984), Fukunari (2008), van Baars–van Kempen (2009)*. In many cases, however, these works contain not only failures but also damages. Several works confuse the notion of failure mechanism with the cause of failure, several of them not only refer to flood protection dikes, but also include data on large dikes and channel embankments, and do not use the same conceptual framework for, for example, failures due to seepage.

5. Dike failures

The list compiled is probably an incomplete one. Some of the conclusions are as follows:

- The first record of a dike failure dates back to 1564, when a dike on the Hernád River in the town of Košice failed, causing streams and rivers to flood due to late autumn showers and downpours. The water broke through the dikes and flooded large areas.
- A unique attempt has been launched at reviewing the history of flood dike failures in a hydrographic unit shared by several countries.
- The number of failures surpasses all former expectations.
- The collection of this type of historical data is a time-consuming and laborious task.
- Considerable difficulties have been encountered in identifying ancient, no more used names of communities, sections, etc. mentioned by two authors under different names. This problem may have resulted in some overlaps in the data collection.
- The data trend to become more ambiguous as moving back in passing time, though, unfortunately, the records on failures during the last three dates are also far from perfect.
- The number of failures per five-year periods demonstrates clearly that the large-scale flood control project launched in 1845 was not fully successful up to the turn of the century *(Fig. 5)*.
- Over 100 failures per year occurred annually during a few disastrous years in the second half of the 19th century. The majority of these was caused by the large floods on the River Tisza in 1876, 1881 and 1888.
- The greatest flood was probably the Danube flood of 1501, the height of which is known only from the upper Danube in Austria, but no mention of it in Hungary has been found so far. The water is likely to have spread over the so called Little Plain, the flat area surrounding Győr. However, according to the Novi Sad records, it was also the highest flood in that area in living memory.
- The largest number of failures, over 190, was recorded in 1888 in Tisza River basin.
- The biggest flooding in the Carpathian basin was caused by the simultaneous flooding of the Danube and the Tisza in 1876. At that time, the Danube flooded twice in the spring, first due to ice, second due to rain, one immediately after the other. These two tidal waves met the Tisza tidal wave at its mouth, causing significant backwater on the Tisza all the way to Szeged. The records are contradictory about the number of dike failures, for example, the Emperor received a report on the damage before the Danube flood had even left the Carpathian Basin. But the number of dike failures identified with certainty was more than 340.
- In the second half of the 19th century only three years were found thus far in which no dike failure was registered (1852, 1863, 1898).

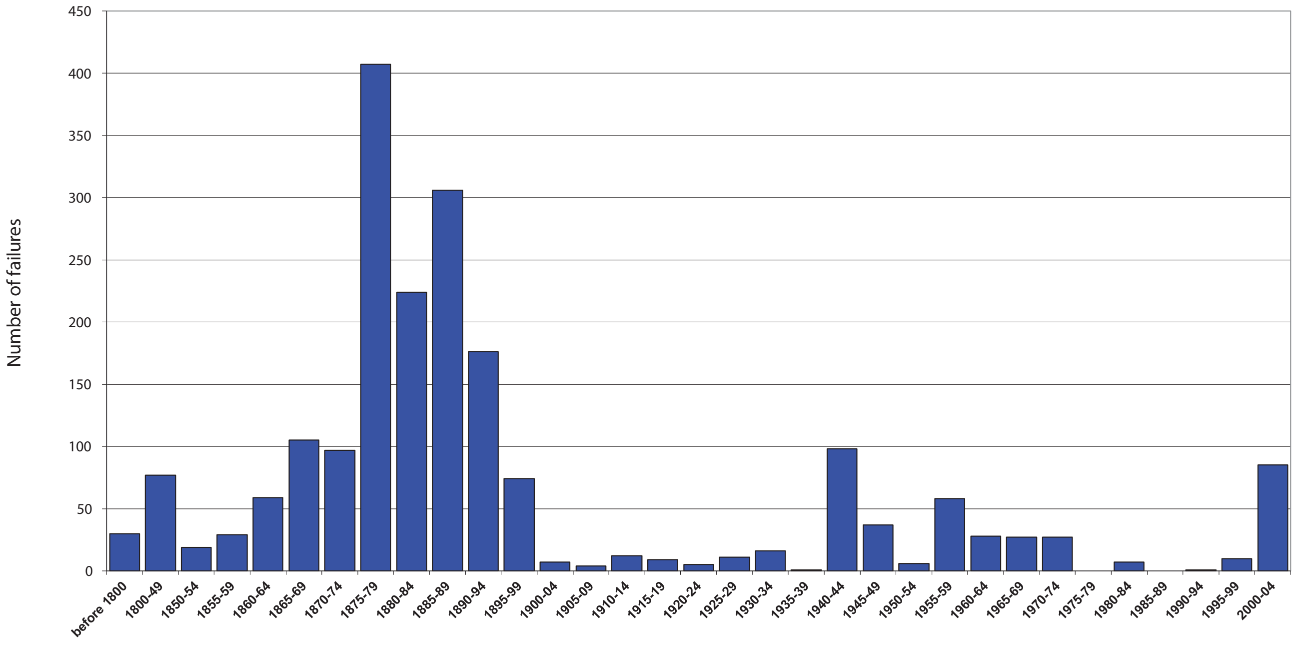


Figure 5 Number of dike failures in the Carpathian Basin until 2004

Source: Nagy, 2018

- Most of the failures (375) occurred in the Körös Valley, where a total of 82 were recorded in 1879.
- From a life protection point of view, special mention should be made of days when many dike failures occurred on the same day along a river. Undoubtedly, escaping to the dike seems like a good solution, but the water on the dike can cut off the refugees from the world, food and drink for days. When a river or the floodplain of a valley is flooded one day, it is difficult to decide which way to escape. Such days were the following: Danube 12 March 1891 with 77 dike failures, Szamos 09 March 1881 with 48 dike failures and Fekete-Körös 15 November 1869 with 36 dike failures.
- The last known dike failures in the Carpathian Basin so far were in 2013, with the right bank of the Sava River flooding in Bosnia and the left embankments of the Sava River bursting in Croatia.

The distribution of dike failures over time is a good indicator of the reliability of the dike system. Prior to the 1800s, when there were relatively few flood control dikes, albeit steadily growing, historical accounts record few dike failures *(Fig. 5)*. The flood of 1838 caused great devastation in Pest and was the worst flood involving dike failure in the Carpathian Basin in terms of human life. The length of the dikes increased significantly only after the start of the great works for the regulation of the Tisza (27 August 1846). The series of rising water levels and the subsequent high number of dike failures is reflected in the data for the period 1850–1900. Processing the data series, it seems that by 1900 the dike-building boom had caught up with the rising water levels, and a calmer time for flood protection in the Carpathian Basin came, interrupted only by a few major floods, such as the Danube Valley floods of 1940, the 1956 Danube ice flood, the 2001 Tisza floods *(Fig. 5)*.

Failures were especially numerous and frequent along the Tisza tributaries at their emergence from the mountain reaching onto the plains.

- Along the Fekete-Körös 132 failures occurred between 1868 and 1887, 36 in 1869, 35 in 1879 and 11 in 1881.
- The right-hand dike along the River Szamos failed on 205 occasions during the 32 years between 1864 and 1896, e.g. at 49 places in 1881 and at 31 in 1888.
- The left-hand dike along the River Szamos failed on 75 occasions between 1864 and 1896, e.g. at 18 places in 1881 and at 9 places in 1888.
- In the Tisza Valley 74 failures were registered up to 1850. From 1851 to 1900 the Tisza dikes failed on 150 occasions. High banks (considered safe) were overtopped 35 times.
- Along the Körös and Berettyó Rivers 85 failures occurred in 1879.

Figure 6 The beginning of the dike failure in 2001 at Tarpa

Source: ABKSZ

The last dike failures on the Tisza were in 2001. In Hungary, the dike failed in three places, two of which came together. The location of one of the dike failures as an emblematic image of the flood is shown in *Fig. 6*. At the same time, 42 dikes failed on the Ukrainian side.

6. The flood generation and the dike breaches

According to international literature, the origin of floods can be traced back to six factors. In the history of flooding in the Carpathian Basin, only three of these floods have occurred: floods from snowmelt, rainfall and ice-jam. Although the meteorological events that trigger them are different, their distribution reflects the weather diversity of the Carpathian Basin. Two points need to be made. On the one hand, weather events have changed over the centuries, and on the other hand, the weather behaviour of large rivers and river valleys varies. Almost all of the ice-jam floods have occurred along the Danube. In the Danube's upper headwaters, the warming had already triggered the flooding of the Danube, which was expected by the ice still standing in the Carpathian Basin. The river was unable to absorb the extra water and ice jams formed. In the Tisza Valley, where the warming from the west first broke up the ice in the Tisza riverbed and only then did the tide start to rise, practically no ice jam has developed *(Nagy 2018)*.

In the Tisza Valley, floods from snowmelt were the most dangerous flood, especially when the snowmelt was supported by warm rain *(Fig. 7)*. In the upper Danube water catchment area, on the other hand, the snow melted gradually due to the high mountains, so only in a few cases did the snowmelt cause a significant flood.

In both the Danube and the Tisza Valleys, heavy rainfall on smaller rivers caused significant flooding and dike failure in some small water catchment areas. In any case,

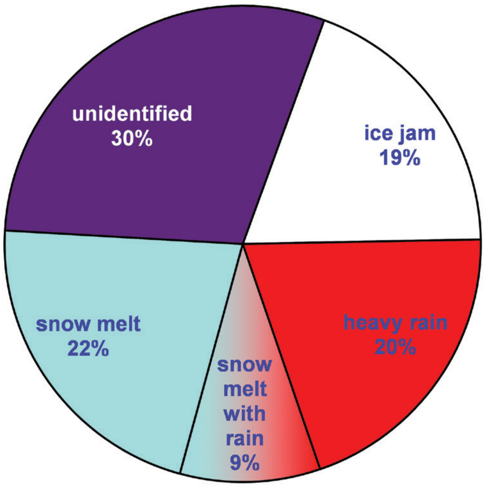


Figure 7 The origin of the flood caused dike failure in the Carpathian Basin

Source: Nagy, 2018

floods from rainfall are less significant on the Danube (probably due to its large water catchment area) than on the Tisza and its tributaries. So-called summer dikes were built along the Tisza to protect the cultivated area, as the flood waters from the summer rains usually receded at a lower height than the snowmelt. The distribution of these causes of flood generation are seen in *Fig. 7 (Nagy, 2018)*.

7. Dike breaches monthly distribution

The exact date of 1,688 of the 2,858 dike failures (59.1 %) in the Carpathian Basin is known by the day, and further 449 (15.7 %) is known by the month, in all 2,137 data (74.8 %). The distribution of these data by month are shown in *Fig. 8,* where the most important statements are:

- A flood, that can cause dike failure can occur in any month of the year.
- Most of the dike failures occur in the month of March both in the valley of Danube and Tisza.
- 80 % of the dike failures in the Danube Valley occurred in the first three months, mostly caused by icy flood.
- The most dike failures in the Tisza Valley occurred between February and May, mostly because of snow melting and rainfalls related to it.
- The fewest dike failures are observed on the hydraulic new years eve, when the water renews, in October.

8. Conclusions

It is a rare opportunity in civil engineering practice to have a large amount of data on the failure of one type of facility. The almost three thousand dike failures collected in the Carpathian basin provide an opportunity not only to statistically evaluate the various data on dike failures, but also to estimate a probability of failure. The collec-

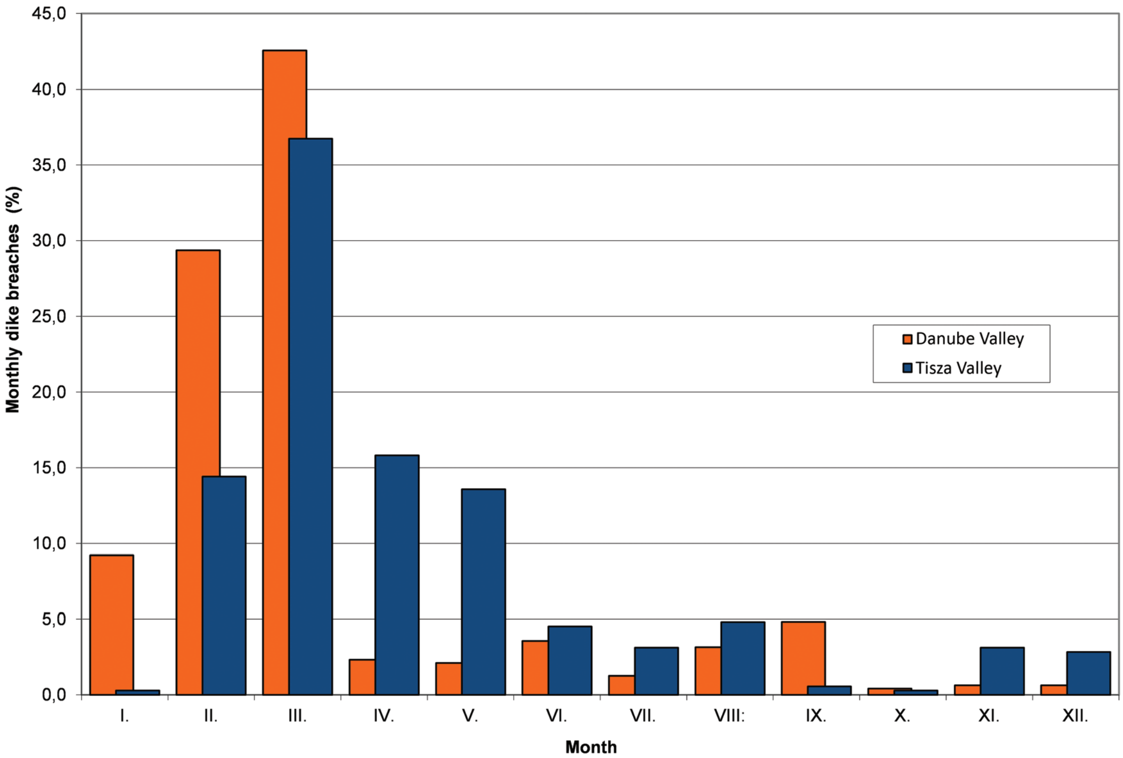


Figure 8 Monthly distribution of dike failures in the Carpathian Basin

Source: Nagy, 2018

tion of historical data thus provides useful additional information to explore dike failures and their consequences, even if not all data are available for all dike failures. Historical data on past dike failures cannot be determined by any other method, and the lessons learned from them are of unique value.

Owing to the continuous efforts at raising and strengthening the flood dikes in Hungary, the failure thereof has become rare in recent times. A review of the historical records may offer welcome help in the analysis of such rare events. The data thereon must be examined critically in the light of the contemporary conditions. It should be noted that the historical data are often inaccurate, but the role of such inaccuracies is likely to diminish, as the database becomes wider.

The study of dike failures also contributed to the conclusion that flooding is Hungary's greatest natural hazard. The main conclusions drawn from the statistics of the historical dike failures:

- At any time of the year, flooding can occur that could lead to a dike failure *(Fig. 9)*.
- The diminishing number of failures implies that flood control in Hungary has attained a fairly high level, though not all hazards have been eliminated yet;
- The proportion of failures caused by overtopping has decreased and reveals a diminishing trend;
- The likelihood of failures caused by overtopping, however small, is confined presently to streams carrying a small flow;

Figure 9 Dike breach at Surány (Danube right bank) 09 August 1991
Source: ABKSZ

- According the investigation the potential danger areas for hydraulic failure and piping along the dikes are well identified determined;
- The probability of failures associated with the subsoil (boils and hydraulic soil failure) is liable to grow;
- Relatively little information is available on the flood on the Maros, Drava and Sava Rivers, further on the floods after 1921 beyond the present boundaries. For more information on these cooperation with the neighbouring countries is necessary.

We do not have data on how the factors generating flooding in the Carpathian Basin and the upper Danube have changed and are changing in response to global warming. However, it is clear from the historical data that:

- The role of ice jam floods is declining. In the second half of the 19th century, the Danube Valley was flooded by ice in 2/3 of the years. At the same time, the last ice flood in the 20th century was in 1956, which caused a dike failure, 65 years ago.
- The role of summer and early autumn rains has increased over the past half century in the Danube Valley, with successive peak floods in the water table following large rainfalls in Austria.
- In the middle and lower reaches of the Tisza, the highest flood level at the turn of the millennium rose by almost one meter and a half.
- The small rivers, which have embankments on the lower reaches, have experienced more extreme fluctuations in flow.

There is no doubt that flood protection in Hungary has come a long way in the last 170 years or so. It is also true that the number of dike failures has fallen to a tolerable level, but the system is vulnerable, the level of deployment is below the desired level and there is a significant residual probability of a dike breach occurring. Further efforts (e.g. investments) are needed to increase the reliability of the dike system.

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