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Review Article: Structural flood-protection measures referring to several European case studies

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Abstract. The paper presents a review of structural measures that were taken to cope with floods in some cities along the Danube River, such as Vienna, Bratislava, and Belgrade. These cities were also considered as case studies within the KULTURisk project. The structural measures are reviewed and compared to each other according to the type, duration of application, the return period of the design flood event, how the project measures are integrated into spatial planning and the problems that occur in the flood defences today. Based on this review, some suggestions are given on how to improve the flood risk management in flood-prone areas.

1 Introduction

Flooding is the most common of all environmental hazards (Smith, 2001). Catastrophic floods endanger lives and cause human tragedy as well as heavy economic losses. Between 1998 and 2009, Europe suffered over 213 major damaging floods, including the catastrophic floods along the Danube and Elbe rivers in August 2002 (Gräfe, 2004). Severe floods in 2005 caused by the tributaries of the Rhine in Switzerland (Bezzola and Hegg, 2007) and Austria, and by several tributaries of the Danube in Germany, Austria and Hungary, as well as in Serbia and Romania, further reinforced the need for concerted action. Between 1998 and 2009, floods in Europe caused 1126 human fatalities, the migration of about half a million people and at least EUR 52 billion in insured economic losses (EEA, 2010). In addition to the economic and social damage, floods can have severe environmental consequences as well. Based on this and because in the coming decades we are likely to see a higher flood risk in Europe and greater economic damage (see http://ec.europa.eu/environment/water/flood_risk), a new EU flood directive, Directive 2007/60/EC, has been proposed by the European Commission. Its aim is to prevent and reduce the damage caused by floods (e.g. environmental damage, damage to the cultural heritage and economic activity), and to emphasize that despite the fact that floods are a natural phenomenon, their likelihood and impacts can be significantly reduced if adequate and coordinated measures are taken. In view of this, a project called "Knowledge-based approach to develop a culture of risk prevention" (KULTURisk) was launched in 2010. It is currently ongoing and focuses specifically on water-related hazards. It aims at developing a culture of risk prevention by evaluating the advantages of different state-of-the-art risk prevention measures such as early warning systems, non-structural options (e.g. mapping and planning), risk transfer strategies (e.g. insurance policy), and structural measures. For further details about the project an interested reader is referred to http://www.kulturisk.eu. The focus of the present paper is to present the structural measures that have been developed over the years to protect agglomerations against flooding in selected KULTURisk case studies. The structural measures of each case study will be reviewed. Finally, some conclusions and further suggestions will be given.

2 Case studies

In this section the KULTURisk case studies focusing mainly on structural flood protection measures are presented and reviewed. The emphasis of this contribution is on these well-documented case studies located in the Danube River basin

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Table 1. Danube case studies – general information.

City	distance from source [km]	catchment size [km^2]	mean annual discharge [$m^3 s^{-1}$]	Q_{100} [$m^3 s^{-1}$]
Vienna (Nussdorf)	916	101 731	1900	10 400
Bratislava (Devin)	981	131 338	2048	11 000
Belgrade (Pančevo)	1697	525 009	4000	18 671

(Fig. 1): for information on other KULTURisk case studies see e.g. http://www.kulturisk.eu/case-studies. The main emphasis of the next subsection will be on the structural measures for flood protection in the three cities along the Danube River, i.e. Vienna, Bratislava and Belgrade.

2.1 Danube

The Danube River basin is shared by 19 countries, and is the most shared basin in the world. Europe's second largest river basin with a total area of about 800 000 km^2 is also home to 83 million people of different cultures, languages, and historical backgrounds (Brilly, 2010). Besides, the Danube River is the largest Central European river. It rises in the Black Forest mountains of western Germany and flows for approximately 2850 km to its mouth on the Black Sea. During its course, it flows through four Central European capitals and passes through, or flows along, the borders of ten countries, see Fig. 2. A review of hydrological processes and related aspects in the Danube River basin is presented in Pekárová et al. (2008).

The Danube case study of the KULTURisk project focuses specifically on the socio-economic effects of large-scale inundations in a transnational river by applying the risk-based methodologies developed in this project. Besides, a critical and comprehensive review of the flood mitigation measures taken to cope with flooding along the Danube (specifically in Vienna, Bratislava, and Belgrade, see Table 1) will be carried out within this case study.

2.1.1 Vienna

Description

The city of Vienna, the capital of Austria, has been exposed to severe flooding of the Danube since its foundation, i.e. since 500 BC. Only the oldest part of the city, where the Roman fort was once established, is not prone to floods. The Danube flowed through a wide belt of marshy meadows, severely hampering the trade routes towards Bohemia and Moravia and limiting the expansion of the city in the 19th century. The establishment of a secure port close to the city and the construction of permanent crossings were considered important issues. In 1869, the decision was made to regulate the course of the Danube in the vicinity of Vienna with structural measures (Starosolszky, 1994). This first regulation project entailed a cut-off through the meandering arms, thereby unifying and straightening the river bed. The controlled Danube bed was 280 m wide and was adjoined by a 450 m floodplain on the left bank and a dike to protect the flat, low-lying surrounding areas. Work on the cut-off lasted from 1870 to 1875. However, shortly after the first Danube regulation had been finished, the catastrophic floods in 1897 and 1899 gave rise to doubts concerning the estimates used to design the height of the embankments, especially concerning the right bank of the Danube at Handelskai ("Trade pier"). Furthermore, the largest flood on the Danube in the last century, in July 1954, clearly illustrated that the protection provided by the embankments was not sufficient. Extensive scientific studies were performed to determine the design flood upon which Vienna's flood protection system should be based. The flood of 1501 can be considered the highest flood ever observed in the upper Danube reach (and also in Bratislava) according to reliable historical records of the Austrian Hydrographic Service. The peak discharge at Vienna was estimated up to 14 000 $m^3 s^{-1}$. There is also some evidence of floods in the 16th–17th centuries (1594, 1598, 1670, and 1682). Thus, the result was a generally accepted figure of 14 000 $m^3 s^{-1}$. A number of flood protection studies focused on increasing the conveyance (i.e. the capacity to convey a higher river discharge). The different proposals called for raising and reinforcing the existing dikes, removing parts of the floodplain, widening the river bed and constructing bypass canals within and in addition to the existing protection facilities. In 1969 the city council supported, against strong political opposition, a project proposing the construction of a new flood bypass canal (the "New Danube") and the use of the excavated material to build a flood-free island (the "Danube Island", see Fig. 3). Hence, the excess water would be directed through the New Danube during high-water periods; while, for most of the year, the water in the New Danube is kept constant by two weirs, resulting in a calm, lake-like surface. This project was supported by a political decision which was also confirmed by a referendum. Works for this project started in March 1972. It took 17 yr to complete the New Danube and the Danube Island. The overall project was completed in 1998 with the commissioning of the Freudenau power plant. It is estimated that the Vienna flood protection system can manage flows with a return period of around 10 000 yr, which is one of the highest safety levels in Europe.

Fig. 1. Map of the case studies.

Fig. 2. Map of the Danube River Basin (http://en.wikipedia.org/wiki/File:Danubemap.jpg).

Fig. 3. The Danube Island (http://www.viennaresidence.com/files/800px-Wiener_Donaubruecken.JPG).

Structural measures

Digging the bed for the New Danube involved excavation of 28.2 million m^3 of earth, most of which was used to create the 390 ha-large Danube Island. The New Danube is about 21 km long and has an average width of 210 m. The discharge in the flood relief canal is regulated by means of weirs; three sets of sluice gates control the water level of the New Danube. The inlet structure at the upstream end is used to regulate the flow into the New Danube and, further downstream, two weirs are used to maintain the water level during non-flood periods. When the Danube carries high water, the three gates are opened according to strictly defined operating procedures, and the excess water flows into the bypass canal. The discharge capacity of the New Danube amounts to about 5200 $m^3\,s^{-1}$.

An overview of the main technical information about the Vienna flood protection project is shown in Table 2. As the works proceeded, sections of the island were opened to the public, and comments made then were integrated into the plans for the final design and landscaping of the Danube Island. As a result, while the original layout had foreseen a strictly trapeze-shaped cross section for the New Danube, the design was modified to create banks with a more natural

Table 2. Technical data about flood protection system in the city of Vienna.

Hydraulic/hydromechanics data	Construction data
– Design flood: 14 000 $m^3 s^{-1}$	– Amount of material excavated for the New Danube canal: 28.2 million m^3
– Danube discharge rate: 8800 $m^3 s^{-1}$	– Portion used to create the Danube Island: 23.8 million m^3
– New Danube discharge rate: 5200 $m^3 s^{-1}$	– Humus: 1.5 million m^3
– Length of New Danube/Danube Island: 21 km	– Rocks used as bottom protection structure: 1.3 million m^3
– Width of New Danube: approx. 200 m	– Rocks for bank protection (riprap): 0.5 million m^3
– Bed slope of the Danube/New Danube: 0.046 %	– Length of cycling/walking paths on Danube Island: approx. 135 km
– Water depth in the New Danube at design high water: 11.5 m	– Concrete edging stones: 390 000 m^3
– Width of Danube Island: 70–210 m	– Bulkheads: 36 000 m^3
– Flood-free surface of Danube Island: 390 hectares	– Quay walls: 7.3 km
– Intake structure: 5 sluice gate sections, each 24 m wide	
– Sluice gate 1: 5 sluice gate sections, each 24 m wide	
– Sluice gate 2: 5 sluice gate sections, each 30.6 m wide	

shape. Also, the City of Vienna eventually decided that the Danube Island would be kept free from civil constructions and would be developed as a recreational area that would also bring ecological benefits. Nowadays, the Danube Island is used mostly as a leisure park.

2.1.2 Vienna – experience

Experience

The flood protection project was implemented by the City of Vienna's Water Resources Department with the financial aid of the Federal Ministry of Transport, Innovation and Technology. No other bilateral or multilateral assistance was included. The budget was planned on a long-term basis together with the Ministry in accordance with annual construction rates. The planning and permitting process took approximately 4 yr, while the construction of the main elements (New Danube and Danube Island) took about 15 yr. New components to the original project became necessary since in the 1990s, a hydropower plant was built on the Danube within the project area. The flood protection project ended up being not just a successful solution in terms of economic advantages, but it also facilitated the development of large green areas within the city, and led to ecological improvement. The impact of the project was even more positive than envisioned during the decision-making and design period. The project allowed for the transformation of parts of stagnant wetlands into functioning ecosystems by strongly enhancing its once river-controlled dynamics. Groundwater has also shown benefits from the implementation of the project. Overdraft of groundwater has occurred over many years and due to the construction of the New Danube, infiltration in the aquifer has improved strongly. On the island, new wells were built for the Vienna water works to supply drinking water. At the same time as the construction of the flood protection system, the sewage collection system was also improved.

After the completion of the project, the urban development on the left banks of the Danube took place more rapidly. Of course, other factors, such as the introduction of a new subway line, also increased the attractiveness of the area, but proper flood protection made sure that investments in property were more secure. The once neglected districts on the left side of the Danube became the major development areas for services and industry as well as for new housing projects. Since the implementation of the project, the population in these two districts approximately doubled. Due to proper planning and involvement of people affected by flooding, the project finally received a high level of acceptance. Although recreational aspects were already included during the design period, it was not foreseen that the 21 km-long island would become such a major attraction for all Viennese.

2.1.3 Bratislava

Description

Bratislava is the capital city of Slovakia. It is situated in Central Europe, approximately 62 km east of Vienna. The Danube river distance from Bratislava to Vienna is only 65 km, see Table 1. That is why the flood regimes for both cities are very similar. As a result, some parts of Bratislava, particularly Devín and Devínska Nová Ves, are vulnerable to the Danube floods. These regions have been prone to flooding for many years due to storm rainfall events, especially during the snowmelt period. Historically, the Danube floods at Bratislava (and also at Vienna) most often occur in May and June. The first flood records in the Slovak portion of the Danube date back to 1526 and are documented in the municipal archives of the City of Bratislava. However, the morphology of the watercourse was different at that time. In the Middle Ages, there were either none or only very low flood-preventing dikes alongside the river. The stream channel had a low capacity and the water often flooded the lower parts of the city (including a part of the city's downtown – Main Square). The entire 130 yr data set of mean daily discharge of

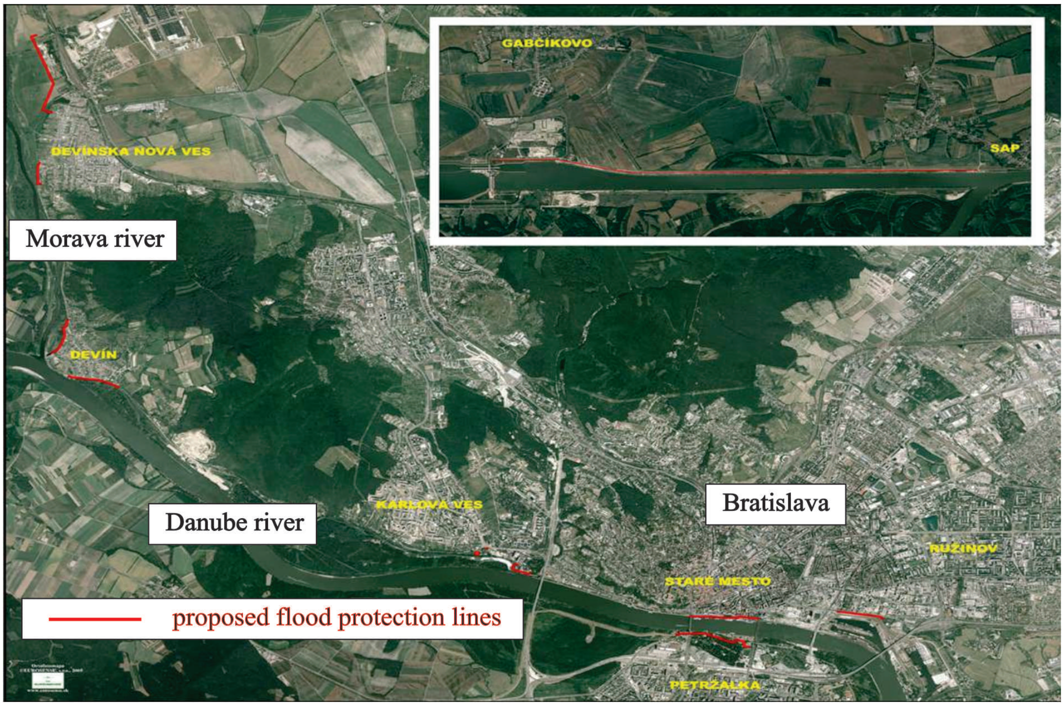

Fig. 4. Proposed flood protection lines in the city of Bratislava and its surroundings (e.g. Gabčikovo). The figure in the upper right corner shows an improvement to the safety of dikes on the left-hand side channel of Gabčikovo, which is located about 50 km downstream from Bratislava.

the Danube at Bratislava (1876–2005) reveals a total of four flood events with peak discharge exceeding 10 000 $m^3 s^{-1}$. Since 1920, there have been two such floods, i.e. in July 1954 and in August 2002.

Structural measures

The main protection measures taken between 2007 and 2010 to cope with floods are located in the southwestern part of Slovakia on the border with Austria and Hungary and include the city area of Bratislava with its surroundings, see Fig. 4. These measures were established to address gaps in the existing Danube flood protection system and to cope with under-protected areas in the Slovak territory in general and the Bratislava area specifically. High flow of the Danube during extreme floods can have disastrous consequences, such as the flooding of an urban area of 383 km^2 and 2000 km^2 of agricultural land, which would directly affect some 490 000 people. The above-mentioned structural flood mitigation measures include the reconstruction of existing and construction of new flood control structures on both sides of the Danube. These structures include dams, levees, reinforced concrete protective walls, mobile elements, etc. (Fig. 5). For a technical review of the type and amount of the measures built see Table 3. All these structures are designed for a peak flow value of the Danube in Bratislava of 13 500 $m^3 s^{-1}$ which has an estimated return period of around 1000 yr. The requested security freeboard along the Danube is 0.5 m above the design flood water level.

Finally, we should emphasize that the structural measures constructed within the "Bratislava – Flood protection" project were implemented by the Government of Slovakia and co-financed by the Cohesion Fund (up to 85 %). The planning and permitting process started in 2004, while the construction started in 2007 and was completed in December 2010. The objectives of the "Bratislava-Flood protection" project are listed below; they were all completely achieved:

- construction of new flood protection lines in urban and suburban areas of Bratislava,
- complete restoration (replacement and increase) of the initial flood protection line in Bratislava Old Town,
- increase in the flood protection line in the Petržalka Bratislava municipality,
- increase in the safety of levees on the left side of the flue channel in the Gabčikovo municipality,
- prevention of economic damages in the project area, including the capital city Bratislava and its neighbouring municipalities,
- prevention of environmental damages in the project area, including prevention of contamination of drinking water sources.

Fig. 5. Various structural flood protection measures in the city of Bratislava, see Table 3; **(a)** concrete wall, **(b)** underground sealing wall, **(c)** reinforced concrete wall, **(d)** mobile flood wall.

Table 3. Technical data of the flood protection measures taken in the city of Bratislava (Fig. 5).

Structural measure	Quantity
Construction underground wall	860 m
Groundwater sealing wall (injection)	14 460 m
The sealing film (foil)	125 000 m^2
Protective levee, dam	2760 m
Flood parapet	5640 m
Mobile elements	3600 m

2.1.4 Belgrade

Description and structural measures

Belgrade, capital of the Republic of Serbia, is situated on the confluence of the Danube and the Sava rivers (Fig. 2). The city of Belgrade is situated approximately 450 km southeast of Bratislava. The Danube river distance from Belgrade to Bratislava is 716 km (Table 1).

The old part of the town developed along a hilly area on the right side of the Sava River. The area on the left side of the river bank used to be unpopulated wetlands. The first construction in this area was a fortification, which was built in 1720 by the Austrian monarchy on the border between the Ottoman Empire and Austria. First discussions on the potential development of the wetland area started much later, after the First World War.

After the Second World War the development of the area on the left side of the Sava River was strongly supported by the government of the Federal People Republic of Yugoslavia. Hence, New Belgrade and some new parts of the city started to be developed on elevated left areas of the Sava River. The layer of excavated sand from the Danube main channel is about 3.5 m thick, on average. The water level elevation corresponding to the 100 yr return period flood is estimated to be about 76 m, one metre below the surface elevation. The highest water level recorded since 1921 is around 76 m, observed in 2006. Besides, the water level of 76 m is also introduced here because the Iron Gate I Hydroelectric Power Station impacts the water levels upstream the corresponding dam, namely, the installed water level of this hydropower station is 76 m. Whereas no damage was caused by surface water during the 2006 flood event, the groundwater was affected (Stanić et al., 2008). Therefore, a study was carried out to investigate the impact of flood duration on groundwater rise (Babić et al., 2003).

In the 1950s, large wetlands containing a few metres of sediment dredged from the rivers covered an urban area more than 10 km^2 at the confluence of the Sava River and the Danube. The amount of the dredged material was approximately 6.7 billion m^3(Hranisavljević , 1963). In the 1960s, a new part of the town was constructed there. During the Danube flood in 1965, and later floods, there was no damage or disturbance in the aforementioned heavily urbanized raised area. The built-up area is arranged with a friendlier landscape and is safer; less land is dissipated than with levees (Brilly, 2001).

In the territory of the Belgrade city, most of the urban flood protection was made in the period from 1972 to 1989. At that time, about 8.3 km of bank fortifications and nearly 234 km of embankments were built or reconstructed, more than 97 km of basins were regulated and also three small reservoirs were built. After 1989 the investment in the flood protection system was significantly reduced. Thus, between 1989 and 1995, only 3.5 km of levees were built and approximately 1.6 km of Sava River banks were regulated (Babić et al., 2003; Milanović et al., 2010).

Nowadays, flood control along the Danube and Sava rivers in Belgrade city is mainly provided by the concrete flood-protection walls (within the inner city circle), and levees (outside the inner city circle).

All these protective structures are built up between 1.5 to 1.7 m above the water level associated with a flood with a 100 yr recurrence interval at the confluence of the Sava and the Danube, 76 m a.s.l. (Babić et al., 2003).

Experience

A multi-year reduction of investments in regular maintenance of protective structures has led to a significant decrease in the facilities' safety, and hence to the reduction of the degree of protection in relation to the earlier situation. Due to inadequate maintenance and use of river beds, the banks of the Danube tributaries characterized by flash flood regimes are particularly threatened in the Belgrade area. Hence, the current flood-protection system is not fully sufficient. Much of the Belgrade city area is still threatened by floods. Even where structural measures have been implemented, a potential risk of flooding still persists, because the protection facilities are often not appropriate and the flood-protection system is usually built only locally where no closed areas of defense are provided. Thus, we can conclude that the most densely populated city area is not adequately protected from flooding of the Danube and the Sava rivers. From this perspective, a new implementation of the flood-protection system of the city of Belgrade has to be proposed as soon as possible. The level of flood protection should be increased to provide security against floods with a 200 yr return period. Eventually, the goal should be to assure protection against 1000 yr floods. The latter can be achieved with the combination of fixed facilities with prefabricated or mobile elements (Kreibich and Thieken, 2009).

3 Conclusions

The paper presents a review of structural measures that were taken to cope with floods in the three cities along the Danube, i.e. Vienna, Bratislava, and Belgrade. These cities were also selected as case studies within the KULTURisk project. Based on the review of the structural measures in each particular case study, the following general conclusions can be drawn:

1. Flood management measures can occupy large areas and have a strong impact on urban space development. The most efficient solution would be if structural measures were taken before urban development takes place in the cities of Bratislava and Belgrade.

2. As flood defences can be very costly to design, construct, and maintain, the flood control projects are in general very expensive and take years to complete. In the cities of Vienna and Belgrade the construction of flood-protection systems started in the 1970s, but still have not been finalized. Because local communities usually cannot afford the costs resulting from large mitigation projects, significant investments by governments are required. Moreover, political decisions supported by a referendum could help in successful project development for a long period of time, sometimes even for many election periods.

3. The level of protection in the City of Vienna against floods is assured with a recurrence interval of 10 000 yr. On the other hand, in the cities of Bratislava and Belgrade, the level of protection is assured against a 1000 yr flood.

4. Analysing the structural flood defense system measures in these case studies, it can be concluded that even with significant investment, flood risk can be reduced but not completely eliminated. There will always be the presence of the remaining (residual) risk which has to be accepted by the society. Hence, informing the affected population of the potential risks, including remaining risks that could occur, is indispensable. Besides, correct risk communication and preparedness of the populations is necessary.

5. For sufficient, appropriate, and successful flood protection along international rivers, good transboundary cooperation is indispensable. This depends above all on understanding and recognition of the problems and needs of transboundary partners as well as the causes of these problems with respect to natural and social processes. For progress to occur, common goals and

agreed strategies are needed, as well as, in some cases, compensation mechanisms to balance advantages and burdens. These can only be reached if the partners meet and work together frequently and share access to all relevant information, thus creating the necessary level of trust.

6. In the future, the concept of flood defence systems will have to be based on contemporary world trends (e.g. living with floods), which are to be introduced by respecting the current best practices throughout the world. Often, this concept is limited by the economic possibilities of the society which lives in the flood-prone areas.

7. As flood safety in most vulnerable areas cannot be achieved with the help of structural means only, further flood risk reduction via non-structural measures is usually indispensable (Kundzewicz, 2002a, b), and a site-specific mix of structural and non-structural measures seems to be a proper solution.

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