Contemporary geomorphological-sedimentary consequences of flooding - the Bratislava reach of the Danube River

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1 Introduction

Increasing focus on the importance of the channel and floodplain physical habitats created by geomorphological processes, and concerns raised by recent flooding have served to highlight the importance of geomorphological processes in creating and sustaining biodiversity and flood conveyance. Monitoring change in the geomorphology of the river environment is, therefore and belatedly, becoming an important measure both of river management practice and system resilience to external environmental change. This paper outlines the recent geomorphic changes (1949-2008) in the suburban large river reach of the Danube River between dikes in Bratislava. The investigation of changes in landforms and floodplain roughness and rate of retreat of banks is based on the multi-temporal interpretation of aerial photographs. The sedimentological response of three flood events (24 March 2002 - Q_{50}, 16 August 2002 - Q_{100} and 8 September 2007 - Q_{10}) were investigated. The study reach represents a part of the tip of an extensive alluvial fan (inland delta) of the Danube River. The mean annual discharge is 2,045 m^3s^{-1} and the computed 100-year discharge Q_{100} = 11,000 m^3s^{-1} (Svoboda et al., 2000). The study river reach (Fig. 1) represents the right bank floodplain (inter-dike inundation area) of a unique tectonics-controlled bend of the Danube. It is approximately 5 km long with a radius of 1.5 km. The channel width is 350 m, the slope between 0.43 $^0/_{00}$ and 0.53 $^0/_{00}$ and the width of the floodplain between 300 – 600 m. Substrate deposits consist primarily of Pleistocene and Holocene gravels overlaid by sand to clay-sand sediments filling abandoned channels of the Danube (Hulman et al., 1974). The study area belongs to the suburban zone of Bratislava city. This area has been designated as the “flood way” and retains floodwaters under the flood protection measures of Bratislava. Upstream of the study reach in the urban area of Bratislava the Danube River today is a straight and canalized river. Downstream, the study reach ends in the impoundment area of the Čunovo dam. As far as fluvial processes are concerned, this reach represents the most active and also the most problematic (in terms of management) of the Slovak reaches of the Danube River.

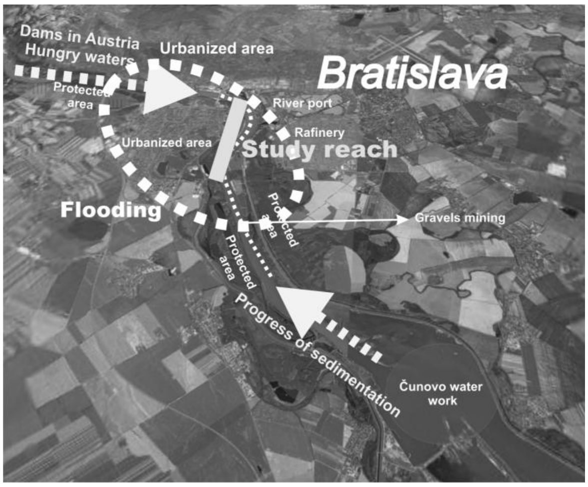

Figure 1. *Study river reach location*

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2 Methods

The basic data sources for this research were 1949, 1969, 1985 aerial photographs and ortho-photomaps for 1997 and 2004, and field work. Overbank deposits were identified by 10 borings, using handy soil driller and 20 pit exposures. Borings and pits served as sampling points to determine the processes and rates of the vertical accretion using an allostratigraphic approach classified on the basis of the fluvial style (Miall, 1996). Sediments were classified using established methods (Brierley 1991, Zwoliński, 1992). All data were processed using GIS ArcView 3.2. Bank retreat was documented by identifying the bank line from aerial photographs, and transferred to the respective ortho-photomaps for the above-mentioned time horizon. The method of Arcement & Schneider (1989) was used as the basis for characterizing floodplain roughness based on Manning coefficient (n) values.

3 Results

Overbank vertical accretion and levee formation processes during flood events dominate floodplain evolution of the study reach. According to Allen (1965), levees are best developed on the concave side of bends. Our study suggests that the development of levees proceeds, albeit unusually, in the convex part of the Danube's bend. Levee development can be explained by limited lateral migration due to the embankment of the concave left bank which strongly influenced flow direction during floods. Although the convex bankline was shifted (naturally and artificially) by 70 m into the floodplain after the 1997 flood (Q_{10}), an approximately 50 m wide strip of overbank sediments was deposited (new levee) in the vicinity of the new bankline after the flood of 2002. This is demonstrated by the profile of the new bankline which is 3 m above the average annual water level. The basal portion of the bankline consists of gravel horizons overlaid by fine sand fractions i.e. this is the new levee. The transition between the channel (gravel) and the floodplain (finer) facies is sharp. The thickness of sand sediments in the upper portion of the bank profile is about one metre, indicating the height of levee deposition. It is possible to observe the sedimentary records of the flood events of 2002 and 2007 in the overbank alluvia mainly in the neighbourhood of the riverbank. The structure of alluvia deposited on the levee by the 2007 flood as a lithofacial profile is shown in Fig. 2A. We recognised two three-unit sequences making up the record of three flood phases on this profile. They are deposited above a massive silt with isolated pebbles. The similar flood cyclothem of overbank deposits was found on the bank profile (Fig. 2B). It is possible to identify three units of different lithofacial features in each of these layersets:

(i) The lower unit represents an initial, rising phase of flood wave (Allen, 1965) that is "rising of water stage and bank modification" .The lithofacies representing this unit:

- the Massive Sandy Silt lithofacie (SFm) 5 cm thick (Fig. 2A),
- the roof part (2-3 cm thickness) of the Massive Sandy Silt lithofacie and the higher lying lithofacie of Massive Inversely Graded Fine Sands – Smi fragment 2-3 cm thick (Fig. 2A),
- the organic matter layer (C) with the Massive Silt admixture (C/Fm) of a few millimetres of thickness (Fig. 2B);

(ii) The middle unit is recording the phase of rising and distribution of flood water or "floodplain inundation and initial deposition" (the 2nd phase) The middle unit is represented by:

- the layer of 3-8 cm thickness of the Inversely Graded Massive Fine- and Coarse Sand lithofacie (Smi) and a layer of 4 cm thickness of the Inversely Graded Massive Coarse Sand lithofacie (Smi) associated in roof with the Matrix-Supported Gravel lithofacie (Gm) on the levee lithofacial profile (Fig. 2A),
- the layer of 15 cm thickness of the Semi-Horizontally and Low-Angle Cross Laminated Medium Sand lithofacie (Sh/Sl), in the bank lithofacial profile (Fig. 2B);

(iii) The top unit of flood cyclothem is recording the fall of flood wave and clearing of flood basins "falling of water stages and height intensity of deposition" and "cessation of overbank flow and final deposition". The top unit is represented by:

- a few centimetres thick layers of the Massive Mud lithofacies (Fm) occurred in two cyclothem on the natural levee profile (Fig. 2A),
- a few centimetres thick layers of the Massive Mud (Fm) lithofacies founded in the bank profile (Fig. 2B).

Taking into account the lithofacial features of the analysed layer sets and their position in profiles, the following correlation between them and flood events is assumed:

(i) The 2002 spring flood corresponds to the sequence of the three-unit flood cyclothem SFm - Smi - Fm affirmed in the levee profile (Fig. 2A) as well as the two-unit inversely graded sequence SFm - SFh in the bank profile (Fig. 2B).

(ii) During the 2002 summer flood, the three-unit flood cyclothem Fm – Smi (Gm) - Fm situated in the levee profile (Fig. 2A) as well as the three-unit layerset C/Fm - Sh/Sl - SFm in the bank profile (Fig. 2B) were deposited. It should be underlined that this sequence is the closest to the three-unit flood cyclothem described by Klimek (1974).

(iii) The Massive Mud (Fm) with organic matter (grass) was accumulated in the rising phase of the 2007 summer flood. Furthermore the Horizontally Laminated Sand and Low-Angle Laminated Sand (Sh/Sl) were deposited in the culmination phase of this flood in the bank profile (Fig. 2B). Moreover, during this flood a Massive Silty Sand (FSm) layer of a low thickness was accumulated on the natural levee (Fig. 2A).

The 2002 spring flood had less effect at the riverbank (up to 10 cm of mainly silt) and a bigger effect on the natural levee (up to 30 cm of silt and sand). The 2002 summer flood had a more balanced effect (up to 20 cm of sediments on both sides), on the bank mainly horizontally laminated sand, on the levee complete flood cyclothem (silt – sand – silt). On the bank the structure of sandy sediments is mainly semi-horizontally laminated and on the levee there is a complete 'flood cyclothem' (three-unit layerset, characterizing pensymmetrically graded sequence: silt – sand – silt). The last flood event (in 2007) induced sedimentation mostly in the close vicinity of the bank (up to 10 cm of sandy material), and only thin layers of finer sediment far away from the bank-line could be found.

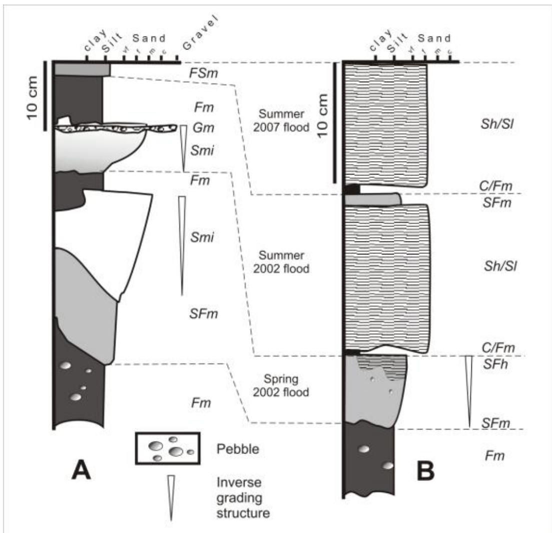

Figure 2. *Overbank alluvia lithofacial profile: A – natural levee lithofacial profile, B – channel bank lithofacial profile. Further explanations are given in the text.*

The flood of 2002 was also identified by dendrochronological analyses. Tree trunks silted by grey sand were found in four localities situated near the bank line. Beds of the same thickness were identified using estimates of the age of individual trees (read from growth rings) and the depth of their main root collar.

The military bunker at the southern tip of the Danube floodplain in the study area provides a long-term rate of vertical accretion of the floodplain. The bunker was erected by the Czechoslovak Army in 1937. At present, a 103 cm thick sedimentary deposit covers the entrance to the bunker. As the bunker was built in 1937, the rate of vertical accretion averages 1.4 cm per year. The estimated vertical accretion rate includes the alluvium deposited from approximately ten flood events in which floodwaters reached the bunker (Lehotský et al. 2010). Floodplain roughness was visually determined using aerial photographs and ortho-photomaps (1949, 1969, 1985, 1997 and 2004 respectively) for each land cover category (1. water bodies as special category; 2. grassland - very low roughness; 3. scarce shrubs - low roughness; 4. scarps covered by reed cover - medium roughness; 5. young forest with low shrub floor - high roughness; 6. mature forest with low and high shrub floors - very high roughness). Changes in floodplain roughness were classified for each time horizon by either the presence or absence of a given category (Fig. 3).

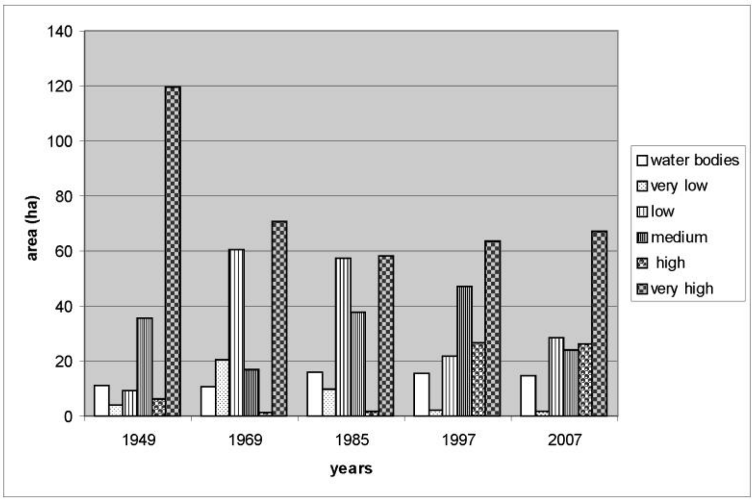

Figure 3. *Changes in floodplain roughness categories*

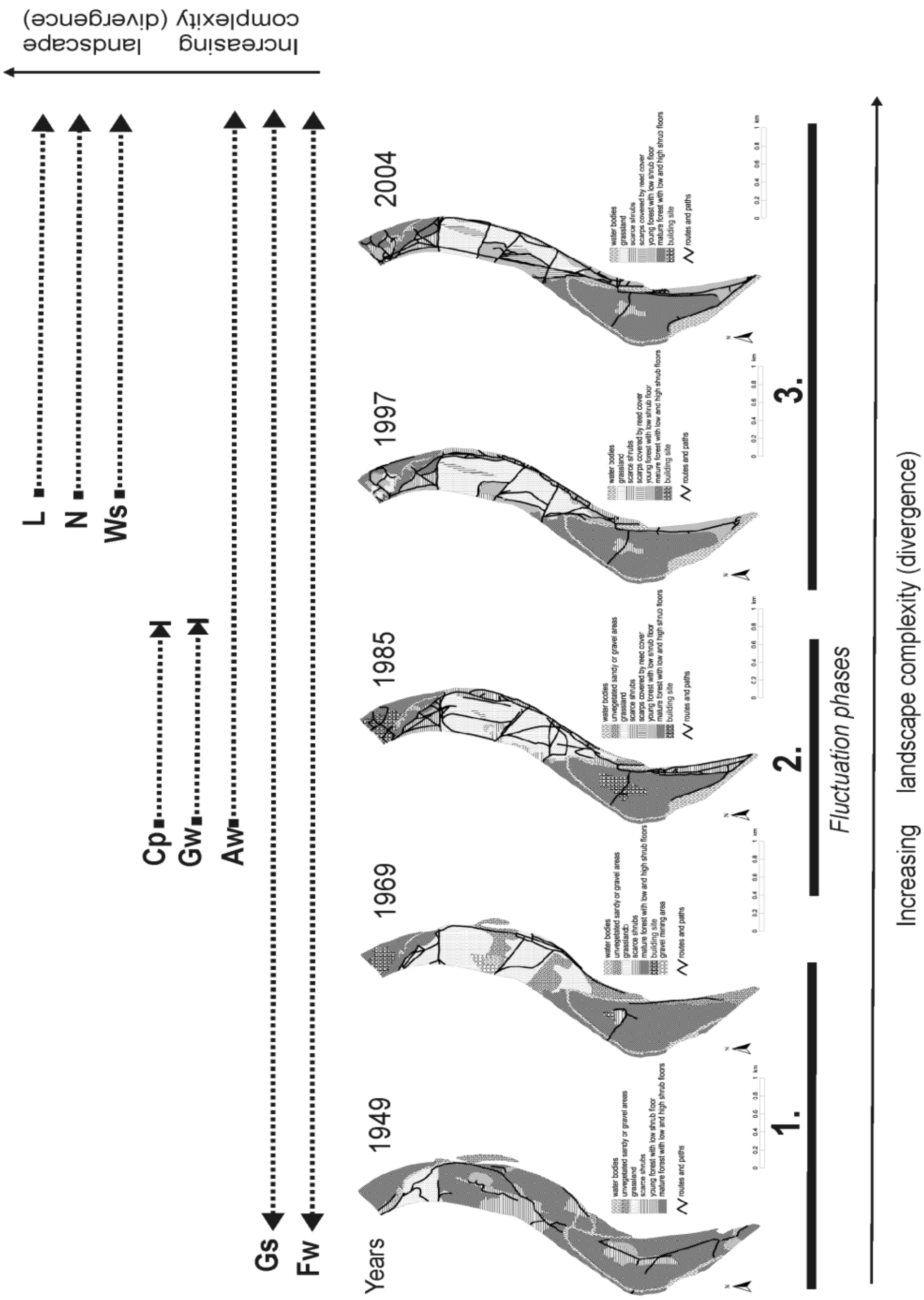

Fig.ure 4. *Phases of contemporary evolution of the study area (Lehotský et. al 2008)*

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4 Conclusions

Conflicts between urban development and flood regime of the Danube occur along the study reach. The evolutionary and qualitative “top-down” approach applied here to the problem of the current evolution of the study reach is based on the identification of a non-linear trajectory designated by changes in landform floodplain roughness categories and sedimentological response to flooding. The reach as a floodway represents a riverine environment in which a large river and its flood events conflict with the increasing urban development. The present geomorphic behaviour of the fluvial system reflects upstream measures such as dams in Austria, which have changed the suspended load regime leading to annual riverbed erosion of 2 to 3.5 cm near the Slovak-Austrian boundary (upstream of the study reach) and progressive aggradation of river bed along the study reach in Bratislava. The downstream Čunovo dam reinforces the upstream progression of sedimentation in the channel. Despite continuous gravel mining in the channel, its bottom has aggraded about 1 m. Bank retreat averaged nearly 100 m during 1949-2007 resulting in the formation of a new levee. The current deposits on the proximal part of the floodplain and of the natural levee differ in texture from the older ones. The old deposits are gravelly whereas the current sediment consists of fine-grained sands and sandy silts ranging in thickness between 0.5 m and 1 m. Thin overbank deposits of silt, silty sand and clay up to 0.2 m thick occur in flat floodplains and on the distal part of the levee. Gravel mining and flood control measures influenced changes in channel forms and biodiversity and sedimentation conditions. Three specific developmental phases have been identified in the recent geomorphological as well as land cover development of the river reach and eight factors related to the current changes. These are (Lehotský et al., 2008, Fig. 4):

1. flood control measures in the proximity of Bratislava - **FW**
2. gravel mining **- Gs**
3. construction of the Petržalka housing estate - **Cp**
4. construction and operation of the Čunovo dam - **Gw**
5. operation of upstream waterworks in Austria - **Aw**
6. woodland succession on the floodplain – **Ws**
7. leisure activities - **L**
8. operating of nature protection policies - **N**

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