FLOODING AND GEOMORPHIC EVOLUTION OF MODERN FLOODPLAIN – CASE STUDY OF THE DANUBE RIVER DOWNSTREAM OF THE DEVÍNSKA GATE[1]

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Les crues et l'évolution géomorphologique de la plaine alluviale moderne – Étude de cas le Danube aval de Devínska Brána (la Porte de Devín). L'article présente l'évolution géomorphologique contemporaine et la réponse sédimentologique des crues dans l'espace endigué du Danube à Bratislava. La construction des barrages en partie autrichienne du Danube, l'incision du lit, l'extraction du gravier de la plaine alluviale et l'utilisation de la plaine comme espace suburbain pour la récréation ont provoqué des changements morphologiques de la plaine alluviale et du lit aussi que le changement granulométrique des sédiments alluviaux à la suite des crues. Sur la base d'étude des photographies aériennes à partir de 1949 jusqu'en 2004 on a analysé les changements des formes de relief, le changement de la rugosité de la plaine et la régression de la ligne de berge. La réponse sédimentologique est analysée sur l'exemple des événements de crue de 2002 et de 2007.

INTRODUCTION

One of processes, creating new and highly heterogeneous riverine landscapes, is urbanization. There are many works dealing with various aspects of urban and suburban fluvial systems, especially in terms of their management, restoration or rehabilitation (e.g. Fryirs and Brierley 2000; Gregory and Chin 2002; Thorne 2002; SEAR and Newson 2003; Chin and Gregory 2005); Gupta *et al.* (2002) noted that much of the knowledge about fluvial morphology comes from studies of small streams leaving gaps in our knowledge concerning the dynamics of major fluvial systems. Construction of embankments and canalization altered many large rivers across Europe, including the Rhône, Rhine and Danube Rivers during the 18th and 19th centuries. Their floodplains are characterized by islands and their channels are now incised and narrowed due to major human interferences. Channels are now single-thread ones with simple forms and almost devoid of islands (Gurnell and Petts 2002).

This paper outlines the modern geomorphic changes (1949–2008) in the suburban large river reach of the Danube River between dikes in Bratislava. 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 – Q_{50}, 16 August 2002 – Q_{100} and 08 September 2007 – Q_{10}) were investigated by analysis of 10 borings and 20 pit exposures.

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THE STUDY REACH

The study reach represents a part of the toe 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 gradient between 0.43 $^0/_{00}$ and 0.53 $^0/_{00}$ and the width of the floodplain between 300 – 600 m. Development of the bend is controlled by a W–E (upstream in the Devín Gate and the urban Bratislava) and NE–SW oriented faults (Maglay, 1999). Substrate deposits consist primarily of Pleistocene and Holocene gravels overlain 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 the Bratislava city. This area has been designated as the "flood way" and stores floodwaters under the flood protection measures of Bratislava. Upstream 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.

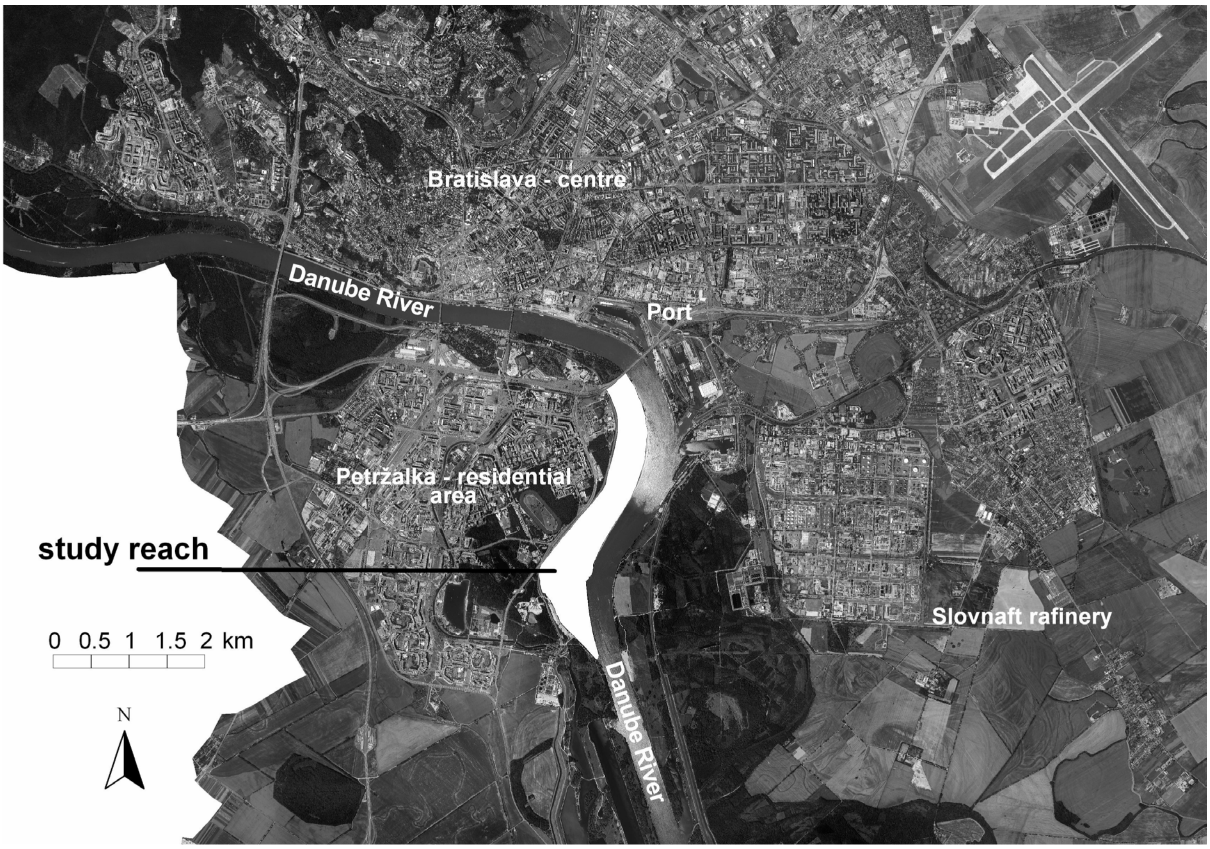

Fig. 1 – Study reach location (Data source: (c) 2005 Google. Image (c) 2008 Digital Globe).

DATA AND METHODS

The basic data sources for this research were 1949, 1969, 1985 aerial photographs and orthophotomaps for 1997 and 2004 and field works.

Morphostratigraphic units in the study area were delimited by field mapping and analysis of cross-floodplain topography using 25 transects on a topographic map of scale 1:10 000. Topographic analysis of the central part of the study reach was supplemented by levelling four profiles. (Figs. 2 and 3) and by recording the position of individual points using the GPS (at present horizontal precision is from 1 to 5 metres). Both natural and anthropogenic landforms were identified in the field and from aerial photographs and finally transferred to orthophotomaps. 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; Marston *et al*. 1995). All data were processed using GIS ArcView 3.2.

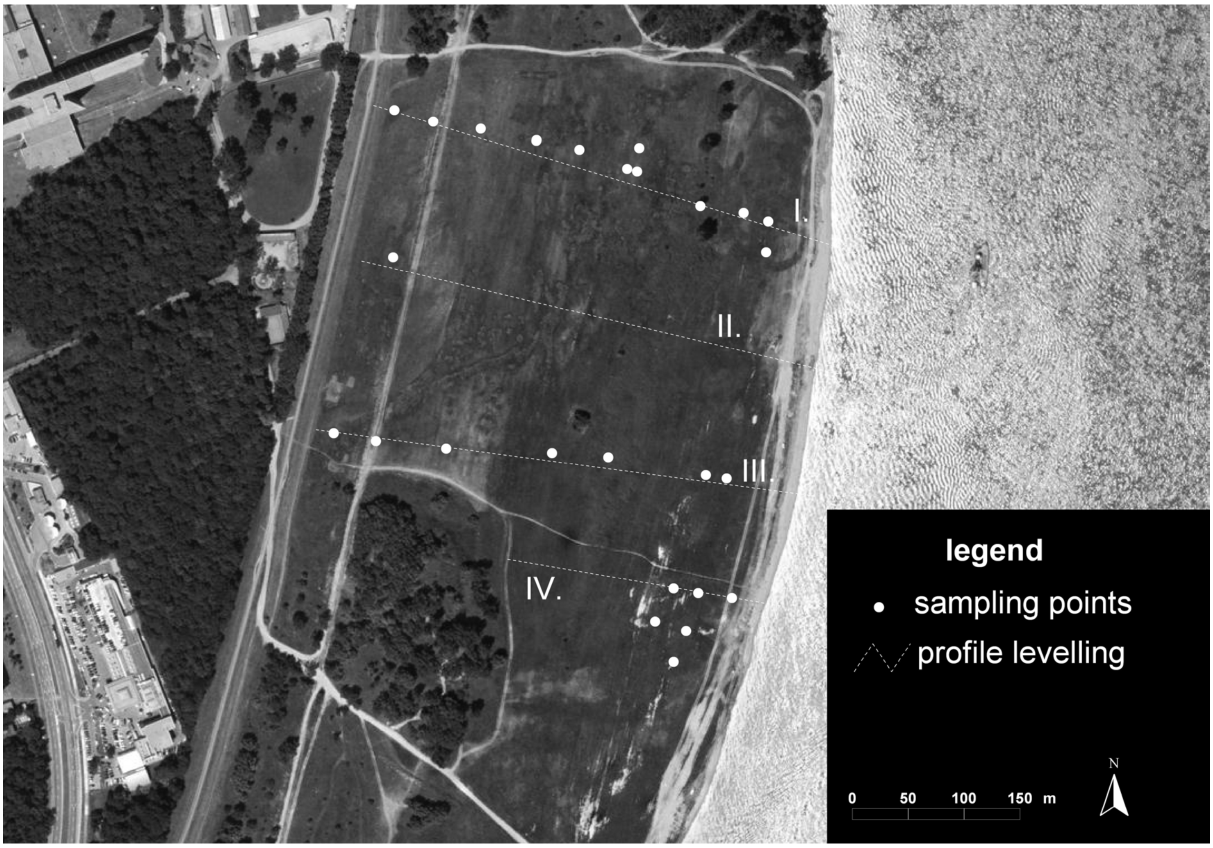

Fig. 2 – The detailed map of geodetically levelled cross-sections including the sites of lithofacial analysis sampling points. (Data source: Eurosense, Ltd. and Geodis, Ltd.).

Bank retreat was documented by identifying the bank line from aerial photographs, and transferred to the respective orthophotomaps for the above-mentioned time horizon. The method of Arcement and Schneider (1989) was used as the basis for characterizing floodplain roughness based on Manning coefficient (n) values. Floodplain roughness was visually determined using aerial photographs and orthophotomaps (1949, 1969, 1985, 1997 and 2004 respectively) for each land cover category. Changes in landforms and floodplain roughness were classified by either the presence or absence of a given category.

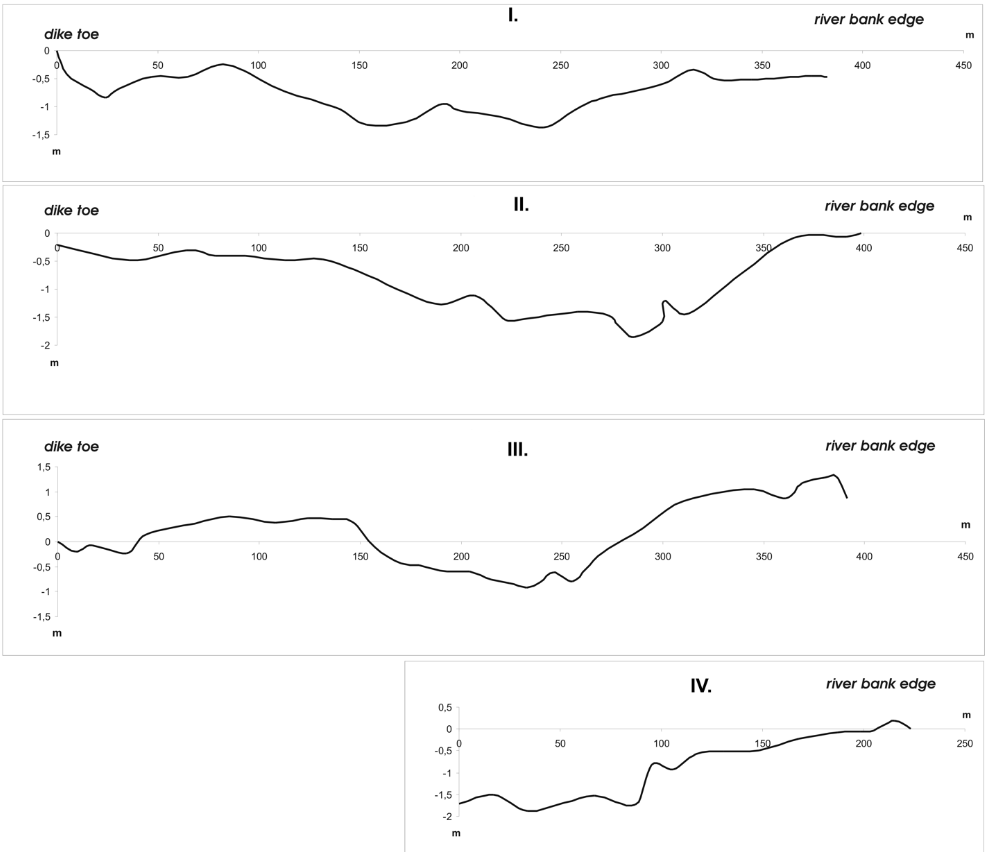

Fig. 3 – The cross-sections (I–IV) where geodetic leveling was performed. The central part indicates the palaeochannels that were filled in with sediments. The elevations on cross-sectional profile on the right side near the riverbank edge indicate the levees (Fig. 2 exhibits the he cross-sections (I–IV) location).

EVOLUTION OF MODERN FLOODPLAIN

Landform distribution (Fig. 4) along the study river reach reflects several factors including dike control, remnants of the old river system (abandoned anabranches, islands, naturally infilled palaeochannels), modern natural landforms (natural levees, crevasse splays, modern floodplain) and anthropogenic features (artificial channel, abandoned built ground, gravel mound, bank revetment structures). The geomorphic, local and regional landscape histories reveal three distinct phases of the evolution of the study reach.

The first phase, approximately between 1949 and 1970, was characterized by completion of the continuous dike system on both sides of river confining the river and reducing its original active floodplain and altering the valley bottom topography. Four dams on the Austrian reach of the Danube were constructed in this phase. The resulting reduction in suspended load and bed load initiated significant channel degradation. Mean annual bedload discharge of gravel dropped from 600,000 m^3 to 280,000 m^3 and the mean annual discharge of suspended solids from 7 million t to 2.87 million t (Mucha 1999).

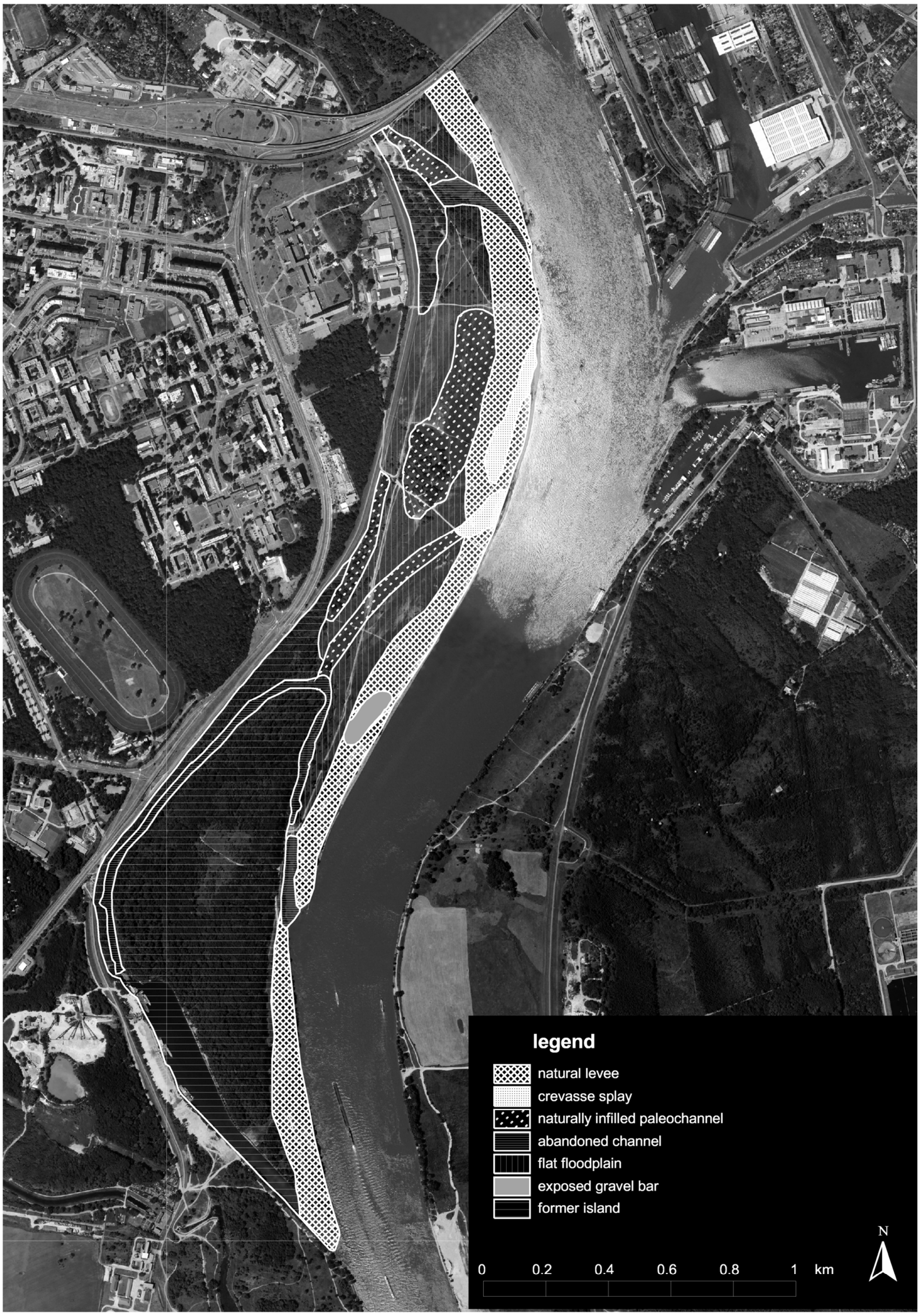

Fig. 4 – The 2007 map of morphostratigraphic unit types (Data source: Eurosense, Ltd. and Geodis, Ltd.).

Extraction of gravel was also intended to improve navigation in the Danube and resulted in the progressive increase in bank height. The bank line was relatively stable during the first phase despite a relatively large flood event (1954) in which the discharge reached 10,400 m^3s^{-1} (comparable to Q_{100}). Bank retreat in the bend progressed locally up to a maximum of 30 m and point bar development and gravel overbank sedimentation was still evident. The original very high and medium roughness floodplain categories decreased significantly in terms of areal extent with time during this phase (Fig. 5).

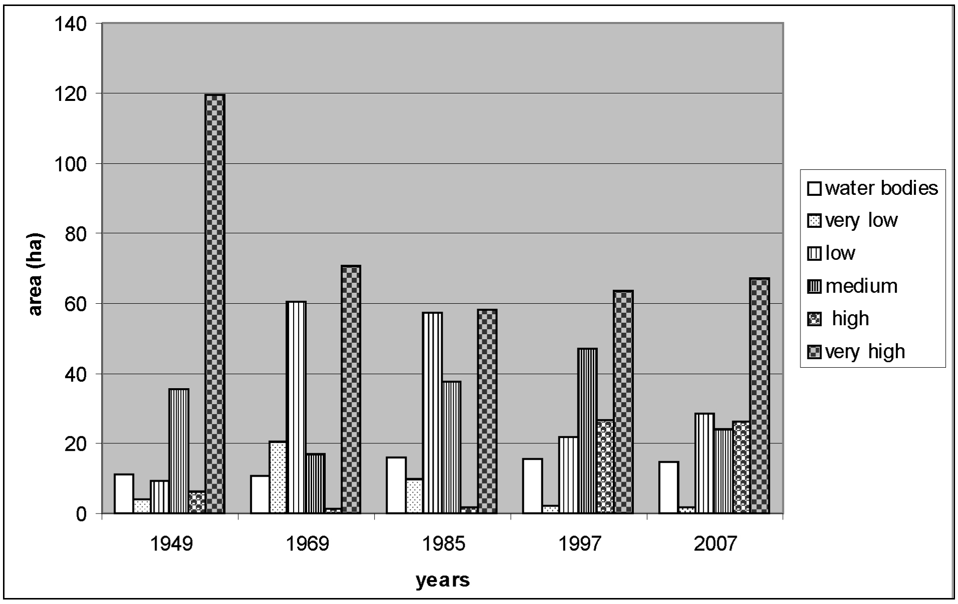

Fig. 5 – Floodplain roughness categories by time horizons. In 1949 the areas of very high roughness category dominated floodplain and areas of small and very small categories dominated from 1969 to 1985; increase of high category areas and the increase of bio- and geodiversity has been evident since 1997.

The second phase of development spanned the years 1970–1992. In the 1970s and 1980s, most of the study area was stripped of vegetation cover and locally scraped to the level of the gravel horizon. Hence, lower floodplain roughness categories characterize this phase. Deepening of the riverbed and limited development of point bars were caused by extraction of gravel in the Danube River channel for construction of the large prefabricated housing of Petržalka for 150,000 inhabitants. In other localities on the floodplain, gravel was extracted for a new gravel mill outside the study area. A new artificial channel was constructed in order to improve navigation regarding such gravel. The old dike was heightened and rebuilt and rock block fills (rip-rap) stabilized parts of the riverbanks, too. Construction of five dams in Austria led to further reductions of the suspended load. During the second phase, right bank retreated by 15–30 m. Decreases in water surface area occurred in response to natural infilling of the abandoned channels as well as from placement of artificial fill.

The third phase started in 1992 by putting in operation the upper step of Waterworks Gabčíkovo, the Čunovo dam. Its barrage is about 13 km downstream of the study reach causing upstream impoundment of the Danube with effects observable even at the gauging station in Bratislava. In 1996, the waterpower station Vienna–Freudenau began operation about 70 km upstream of the study reach. Vienna–Freudenau operation triggered erosion of the riverbed upstream of the study reach (in Austria) at an average rate of 2.3 cm a year (Fischer-Antze and Gutknecht 2004). Both facilities affected channel morphology and sedimentation processes in the study reach resulting in progressive channel aggradation. The bank line was artificially shifted by several tens of meters following the 1997 flood (Q_{10}). Simultaneous extraction of gravel also continued during the third phase. The flood regime definitely changed from the gravel/mixed to a suspended load regime during this phase. Despite gravel extraction and bank shifting the depth of the channel increased nearly a metre in the ten years after the Gabčikovo Waterworks came online (Blaškovičová *et al*. 2006). Two extreme flood events in March (8,560 m^3s^{-1}, Q_{50}) and August (10,390 m^3s^{-1}, Q_{100}) of 2002 affected the development of the floodplain surface in terms of morphology and sedimentology. Phase three is also characterized by the gradual succession of poplar and maple forest and enlarged areas of reeds. Both contributed to the roughness of the floodplain surface, which in turn affected sedimentation processes. After an artificial bankshift in the 1998 and the two floods in 2002, two crevasse splays in the new levee (about 50 m width) covered the older relatively flat floodplain surface (Fig. 4). In 2005, a rampart was built up in the northern part of the study reach to divert floodwater. During 2006 and 2007, a new large mound (20 m high, 20 m perimeter) of gravel dredged from the channel bottom was deposited on river bank. Forests on the alluvium of the study reach were recognized as protected wetland areas and the reach also started to operate as a suburban riverside recreation zone. The consequences are manifested in a slow increase of very high floodplain roughness category area replacing the previous medium roughness category.

GEOMORPHIC EFFECT OF THE RECENT FLOODS

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 its 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 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 overlain 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 suggesting the height of levee deposition.

It is possible to observe the sedimentary records of the flood events from 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. 6A. 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. 6B). 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 1970; Klimek 1974) that is “rising of water stage and bank modification” (Zwoliński 1992; The 1st phase). The lithofacies representing this unit:
  – the Massive Sandy Silt lithofacie (SFm) of thickness 5 cm (Fig. 6A),
  – 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. 6A),
  – the organic matter layer with the Massive Silt admixture (C/Fm) of a few millimetres of thickness (Fig. 6B);

(ii) The middle unit is recording the phase of rising and distribution of flood water (Allen 1970; Klimek 1974) or "floodplain inundation and initial deposition" (the 2nd phase) and "flood peak and widespread transport and deposition" (the 3rd phase) after Zwoliński (1992) that corresponds with the lithofacies of middle unit of cyclothem. 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 c.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. 6A),
- 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. 6B);

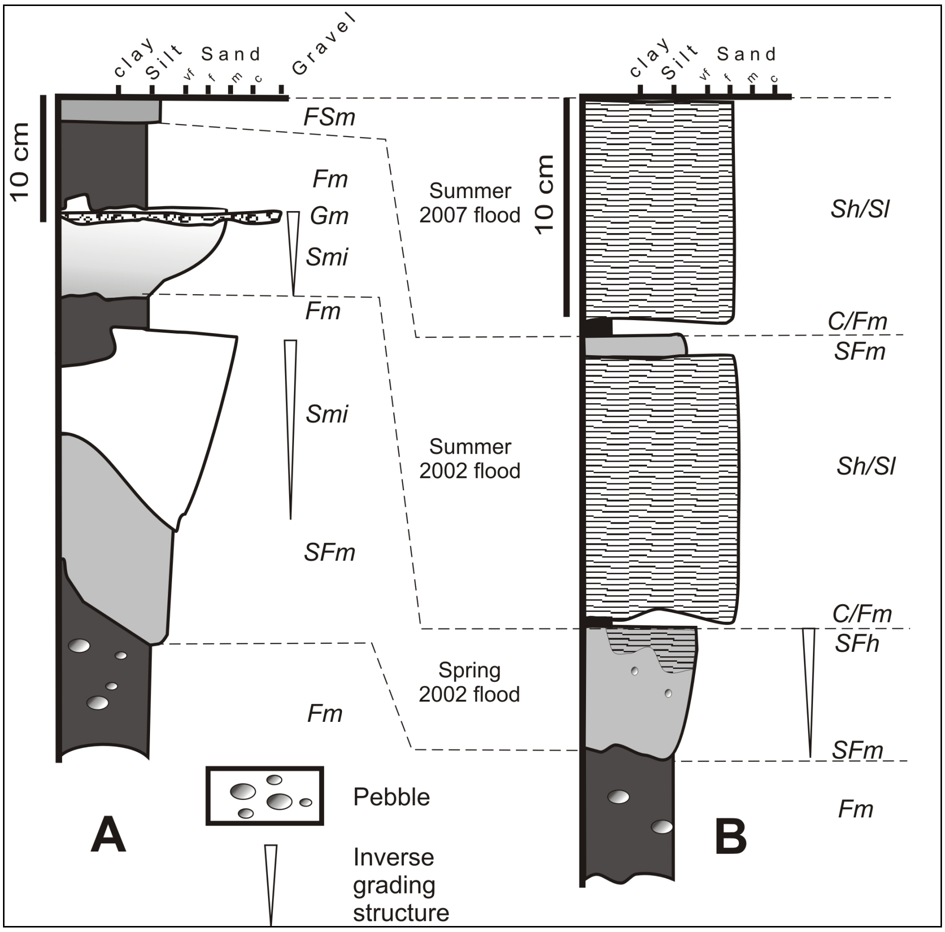

Fig. 6 – Overbank alluvia lithofacial profile: A – natural levee lithofacial profile, B – channel bank lithofacial profile.

(iii) The top unit of flood cyclothem is recording the fall of flood wave and clearing of flood basins (Allen 1970; Klimek 1974) or two final phases recognised by Zwoliński (1992): "falling of water stages and height intensity of deposition" (the 4th phase) and "cessation of overbank flow and final deposition" (the 5th phase). 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. 6A),
- a few centimetres thick layers of the Massive Mud (Fm) lithofacies founded in the bank profile (Fig. 6B).

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

(i) The 2002 spring flood corresponds to the sequence the three -unit flood cyclothem SFm – Smi – Fm affirmed in the levee profile (Fig. 6A) as well as the two -unit inversely graded sequence SFm – SFh in the bank profile (Fig. 6B).

(ii) During the 2002 summer flood, the three-unit flood cyclothem Fm – Smi (Gm) – Fm situated in the levee profile (Fig. 6A) as well as the three-unit layerset C/Fm – Sh/Sl – SFm in the bank profile (Fig. 6B) 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 culminated phase of this flood in the bank profile (Fig. 6B). Moreover, during this flood a Massive Silty Sand (SFm) layer of a low thickness was accumulated on the natural levee (Fig. 6A).

The 2002 spring flood has less effect at the riverbank (up to 10 cm of mainly silt) a bigger on natural levee (up to 30 cm of silt and sand). The 2002 summer flood has more balanced effect (up to 20 cm of sediments on the bank as well as on natural levee), on the bank mainly horizontally laminated sand, on 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) afflicted sedimentation mostly in the close vicinity of the bank (up to 10 cm of sandy material), only slight shadows of finer sediment far away from the bank-line could be found.

Results show a relatively high variability of sedimentation processes during floods. The total amount of new sediments, their texture characteristics and spatial distribution do not depend only on flood discharge, but also on the sources of floodwater and sediments in the river basin.

CONCLUSIONS

Conflicts between urban development and flood regime of the Danube occur along the study reach. 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 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 floodplain roughness and consequently changes in channel forms and biodiversity and sedimentation conditions. Three specific developmental phases have been identified in the recent development of the river reach and nine factors related to the current landscape changes. These are (Lehotský *et al*. 2008):

- flood control measures in the proximity of Bratislava
- gravel mining
- construction of the Petržalka housing estate

- construction and operation of the Čunovo dam
- operation of upstream waterworks in Austria
- woodland succession on the floodplain
- leisure activities
- mobility of people
- operating nature protection policies

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REFERENCES

Allen, J.R.L. (1965), *A review of the origin and character of recent alluvial sediments*, *Sedimentology*, 5, 89–91.

Allen, J.R.L. (1970), *Physical processes of sedimentation*, G. Allen & Unwin University Books, London.

Arcement, G. J., Schneider, V. R. (1989), *Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains*, U.S. Geological Survey Water Supply Paper 2339.

Blaškovičová, L., Martinka, M., Poórová, J. (2006), *Changes of river cross-sections on Slovak part of Danube in the period 1986–2005*, in Proceedings 23nd Conference of the Danube countries on the hydrological forecasting and hydrological bases of water management, Beograd, CD-ROM.

Brierley, G. J. (1991), *Floodplain sedimentology of the Squamish River, British Columbia: relevance of the element analysis*, Sedimentology, 38, 735 – 750.

Chin, A., Gregory, K.J. (2005), *Managing urban river channel adjustments*, Geomorphology, 69, 28– 45.

Fischer-Antze, T., Gutknecht, D. (2004), *Morphological changes of the Danube River east of Vienna over the last nine years*, in Proceedings of the XXIInd Conference of the Danubian countries on the hydrological forecasting and hydrological bases of water management, ČHMU, Brno, CD-ROM.

Fryirs, K., Brierley, G.J. (2000), *A geomorphic approach for identification of river recovery potential*, Physical Geography, 21(3), 244–277.

Gregory, K.J ., Chin, A. (2002), Urban stream channel hazards, *Area*, 34, 3, 312–321.

Gupta, A., Lim, H., Huang, X., Chen, P. (2002), *Evaluation of part of the Mekong River using satellite imagery*, Geomorphology, 44, 221–239.

Gurnell, A.M., Petts, G.E. (2002), *Island-dominated landscapes of large floodplain rivers, a European perspective*, Freshwater Biology, 47 (4), 581–600.

Hulman, R., Šajgalík, J., Vámoš, F. (1974), *Geotechnické pomery výstavby Petržalky*, Mineralia Slovaca, 6, 1, 41–53.

Klimek, K. (1974), *The structure and mode of sedimentation of the flood-plane deposits in the Wisłoka valley (South Poland)*, Studia Geomorphologica Carpatho-Balcanica, 8, 136–151.

Lehotský, M., Novotný, J., Grešková, A. (2008), *Complexity and landscape*, Geografický časopis, 60, 95–112.

Maglay, J., Ed. (1999), *Neotektonická mapa Slovenska (1:500 000)*, GSSR, Bratislava.

Marston, R. A., Girel, J., Pautou, G., Piegay, H., Bravard, J. P., Arneson, C. (1995), *Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France*, Geomorphology, 13, 121–131.

Miall, A.D. (1996), *The Geology of Fluvial Deposits*, Springer-Verlag, Berlin – Heidelberg – New York, 1–582.

Mucha, I. (1999), *Pre dam development of the Danubian Lowland*, http://www.gwc.sk/svd/doc/brown/chapters/ch2.htm.

Sear, D.A., Newson, M.D. (2003), *Environmental change in river channels: a neglected element. Towards geomorphological typologies, standard and monitoring*, The Science of the Total Environment, 310, 17–23.

Svoboda, A., Pekárová, P., Miklánek, P. (2000), *Flood hydrology of Danube between Devín and Nagymaros*, Institute of Hydrology SAS, Bratislava, 96 p.

Thorne, C.R. (2002), *Geomorphic analysis of large alluvial rivers*, Geomorphology, 44, 203–219.

Zwoliński, Z. (1992), *Sedimentology and geomorphology of overbank flows on meandering river floodplains*, Geomorphology, 4, 367–379.

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