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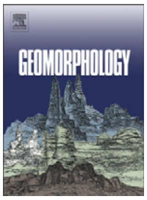

A suburban inter-dike river reach of a large river: Modern morphological and sedimentary changes (the Bratislava reach of the Danube River, Slovakia)

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ABSTRACT

The paper outlines contemporary geomorphic and sedimentary changes (1949–2007) in the suburban inter-dike reach of the Danube River in Bratislava underpinning requirements of its management. The studied river reach represents the right bank inter-dike area of a tectonically determined bend of the Danube River which is about 5 km long with a radius of 1.5 km. The landform and floodplain roughness classification schemes show variations in hydraulic and depositional conditions during flooding. Investigation of landform and floodplain roughness changes and the bank retreat rate is based on the multitemporal interpretation of aerial photographs. Sedimentological analysis of 10 borings and 20 pit exposures helped to delimit the morphostratigraphic units. The process and the rate of the vertical accretion of the modern floodplain were investigated by sedimentological and dendrochronological methods. The behaviour of the study reach is dependent on upstream dams in Austria. Dams produce changes in the suspended load regime and a steady riverbed erosion of 2 to 3.5 cm occurs upstream of the study river reach near the Slovak–Austrian border. The Čunovo dam downstream expediates upstream channel filling in spite of the ongoing channel gravel mining in the Danube channel. This has resulted in channel bed aggradation of about 1 m since 1992. The bank retreat of about 100 m during 1949–2007 was caused by the natural bank erosion processes as well as by channel straightening as a flood control measure for Bratislava. The bank shift resulted in the development of the new levee. The current overbank deposits differ from the older gravels, consisting of a fine-grained alluvium varying in thickness from 0.5 m to 1 m. The lithofacies of three flood deposits (March 2002, August 2002, and September 2007) were examined. Overbank sediments differentiate with distance from the bank and vertically. Suburban settings of the study reach and the flood control measures along with the external forcing (dams) induced changes in channel morphology as well as in floodplain roughness variability. This has resulted in changes in the present floodplain sedimentary conditions, channel forms and biodiversity. The landscape evolved through three distinct evolutionary phases.

1. Introduction

During the past tens or hundreds of years, in many fluvial systems, river dynamics has been significantly affected by human interventions such as land-use changes, urbanization, canalization, dams, diversions, gravel and sand mining (Surian and Rinaldi, 2003). Urbanization is a complex process creating new and highly heterogeneous riverine landscapes. Urban and suburban areas however present some of the most challenging environments for stream management and restoration projects (Gregory and Chin, 2002). The geomorphic analysis of a large river in urban and suburban areas requires a systematic and organized approach because of the spatial scale and system complexity involved (Thorne, 2002). While geomorphological processes create dynamic and diverse habitats, in-stream, riparian and floodplain ecotones (Sear and Newson, 2003), river restoration and individual rehabilitation works are often small scale and ad hoc in nature, and fail to take into account the upstream/downstream linkages and impacts within the geomorphic system. The geomorphic framework provides the template for restoration and rehabilitation (Fryirs and Brierley, 2000). Spatial patterns of channel adjustments are important for managing urban river channels. This encourages adoption of a holistic catchment perspective resulting in better engineering practices based on sound geomorphic principles (Gregory and Chin, 2002; Chin and Gregory, 2005). Nearly every major city around the world has been built along major river corridors because they are important natural networks as well as cultural and recreational resources. Major rivers are among the most important and most dynamic factors in the landscape. Hence, they are certainly phenomena that require special attention of both researchers and managers. 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

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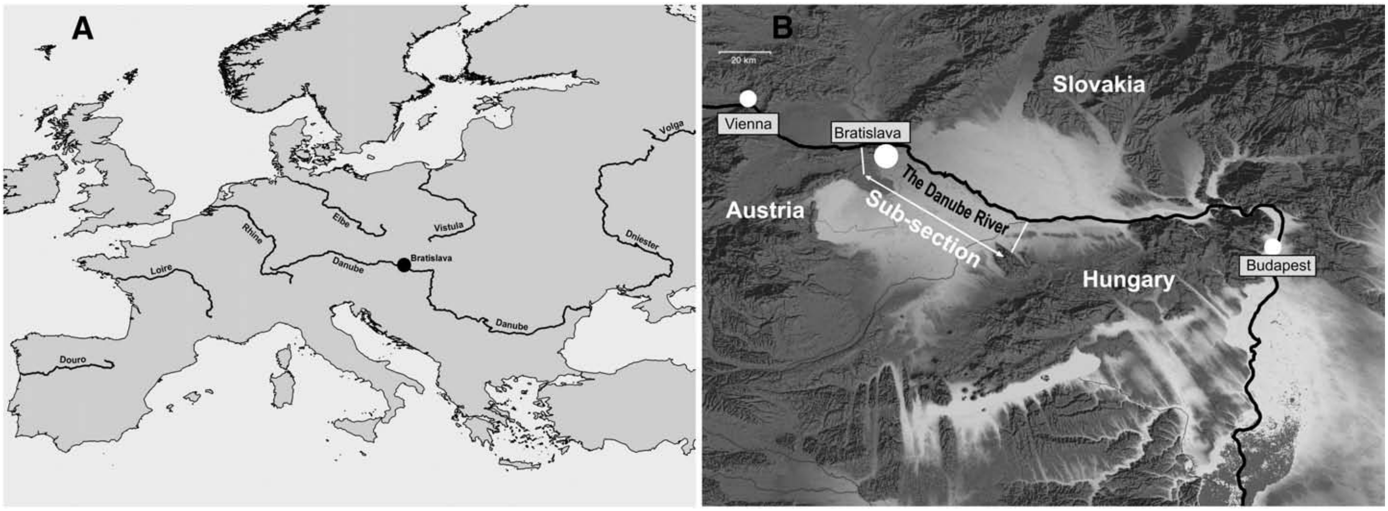

Fig. 1. A) Location of Bratislava in Europe (data source: (c) ESRI Data). B) Catchment setting of the study river reach as a part of the Danube river basin sub-section; DTM of the Danube River Inland Delta with surroundings (data source: Shuttle Radar Topography Mission version 2 (c) 2000–2006 SRTM Mission team and (c) 2004 CGIAR (www.anedra.com.ar), reprocessed and vizualised by authors).

Rhône, Rhine and Danube Rivers during the 18th and 19th centuries. The history of their channels and floodplains is one of progressive change from bedload-rivers to suspended load dominated, wandering channels. 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 (1949–2007) in the suburban large river reach of the Danube River between dikes in Bratislava. The changes were put in order to improve riverine management. It begins with a brief outline of the characteristics of the studied reach from the point of view of its uniqueness and regional setting. The landform and floodplain roughness classification schemes as variation in hydraulic and depositional conditions during flooding were determined. Investigation of changes in landforms and floodplain roughness and rate of retreat of banks is based on the multitemporal interpretation of aerial photographs. The rate of vertical accretion of the modern floodplain was investigated using sedimentological and dendrochronological techniques and by inspection of an artefact (a military bunker) on the floodplain.

2. The study reach

The study reach is classified after Robert et al. (2003) as a subsection represented by the inland delta (Fig. 1) of the section type four “Lower Alpine foothills Danube” of the Danube River classification. It is characterized by the beginning of the lowland reaches with meandering, anabranching and braided channels except for two short

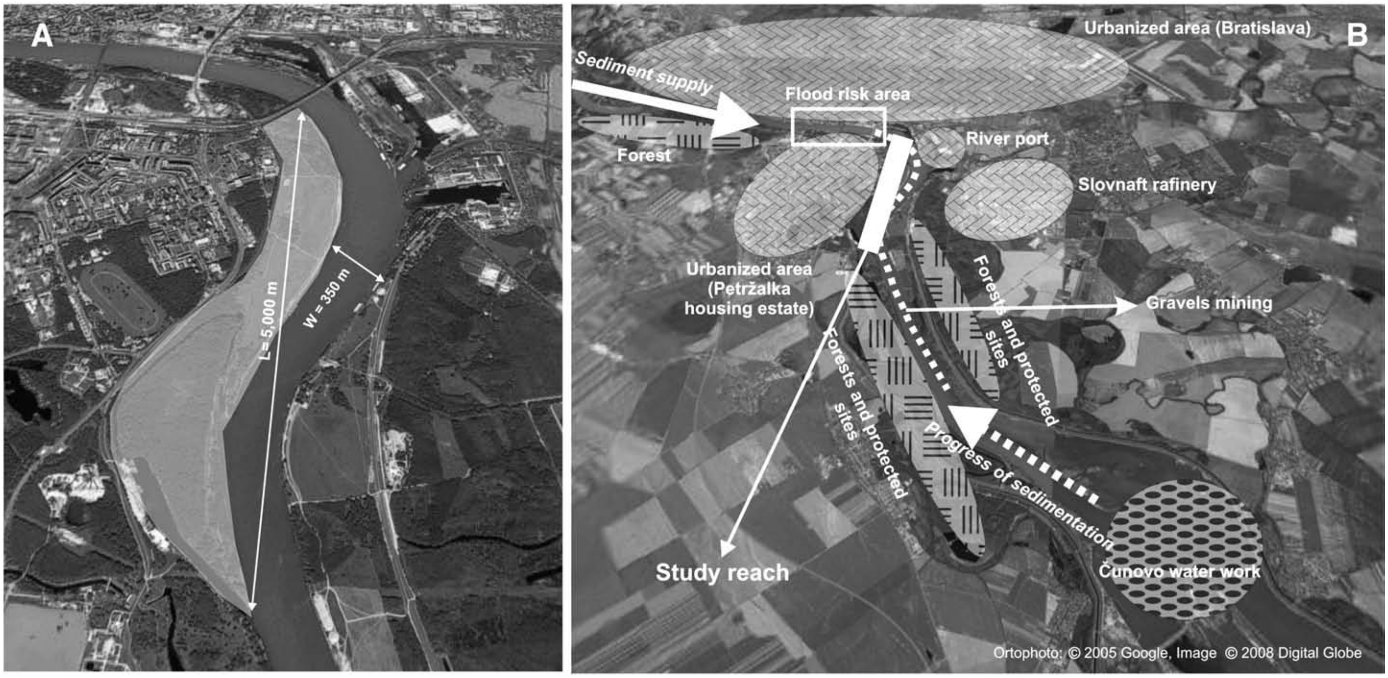

Fig. 2. A) An oblique aerial photograph indicating the location of the Bratislava suburban area. The residential area of Petržalka is on the left (data source: (c) 2005 Google. Image (c) 2008 Digital Globe). B) The oblique aerial photograph indicates the detailed location of the river reach and the main spatial structures and processes influencing its operation (data source: (c) 2005 Google. Image (c) 2008 Digital Globe).

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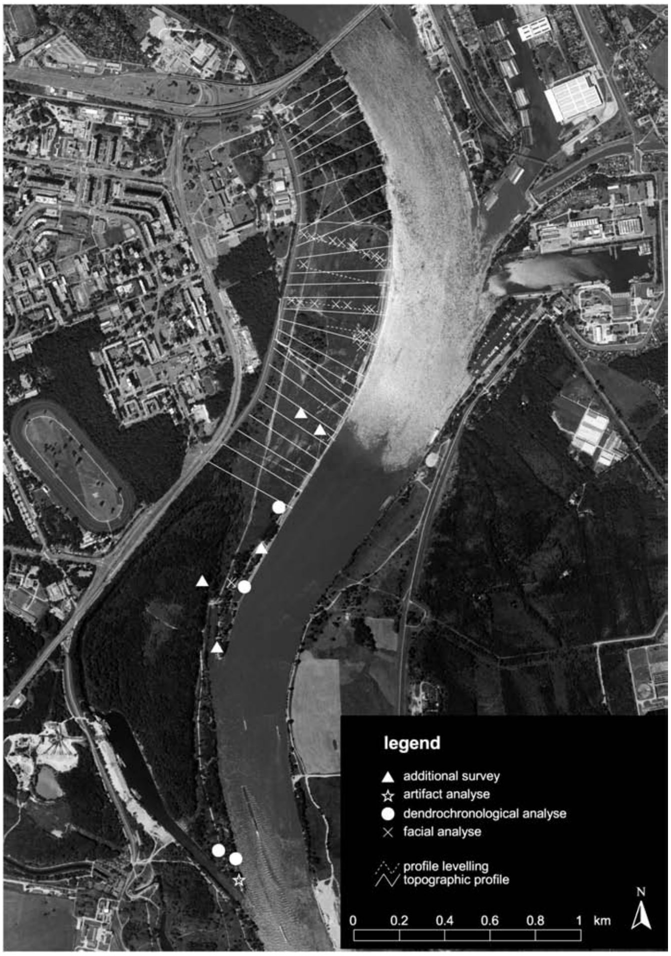

Fig. 3. The geographic location of sampling points and cross-sections. Symbols of sample points in the map indicate applied methods (data source: Eurosense, Ltd. and Geodis, Ltd.).

gorge-like valleys at the Vienna Gate and the Devín Gate. The dominant main channel substrates consist of large cobbles and pebbles in the gorge sections, and medium to coarse gravel overlain by sand and loam in the accumulation zone of the Danube Lowland.

The study reach represents the toe of an extensive alluvial fan (inland delta) of the Danube River. From the 17th to 20th centuries, the Danube River near Bratislava was reduced to one main channel with its floodplain constrained between dikes to protect the city against floods. The decrease in fluvial activity, resulting from climatic changes after the Little Ice Age, also contributed to a simplification of channel planform (Pišút, 2002). Before that time the study river reach could have been classified as an anabranching, laterally active meandering river type (Nanson and Knighton, 1996). In the past, the Danube in this reach represented a multichannel system of type 3e of Brice (1975). It was a complex of channels with over 65% anastomosed. Such a river planform is classified as a gravel-bed, anastomosing stream type 4 Da (Rosgen, 1994). Type 4 Da streams exhibit gravel-bed material, narrow and deep well-vegetated multichannels, very gentle floodplain relief with a surface covered by fine-grained alluvium.

Regular hydrological gauging began on the Danube in Bratislava in 1876 and discharges have been registered since 1901 as in the gauging data records of Slovak Hydrometeorological Institute. The mean annual discharge is 2045 $m^3 s^{-1}$ and the computed 100-year discharge $Q_{100} = 11{,}000$ $m^3 s^{-1}$ (Svoboda et al., 2000).

The study river reach (Fig. 2) 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‰ and 0.53‰ and the width of the floodplain between 300 and 600 m. Development of the bend is controlled by 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 (sand, clay, loam earth, gyttja, and fens) (Hulman et al., 1974). The study area belongs to the suburban zone (in the sense of Antrop and Van Eetvelde, 2000) of the Bratislava city and includes urban areas as well as agricultural fields and forests. Its land cover is a combination of grassland, shrubs and forests. This area has been designated as the "flood way" and stores floodwaters under the flood protection measures of Bratislava. In addition, the study area serves as a suburban riverside recreation zone, as the Danube Biocorridor of the European scope and as a protected wetland area (Dunajské luhy — Danube alluvial forests). 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.

3. 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 (Figs. 3 and 4).

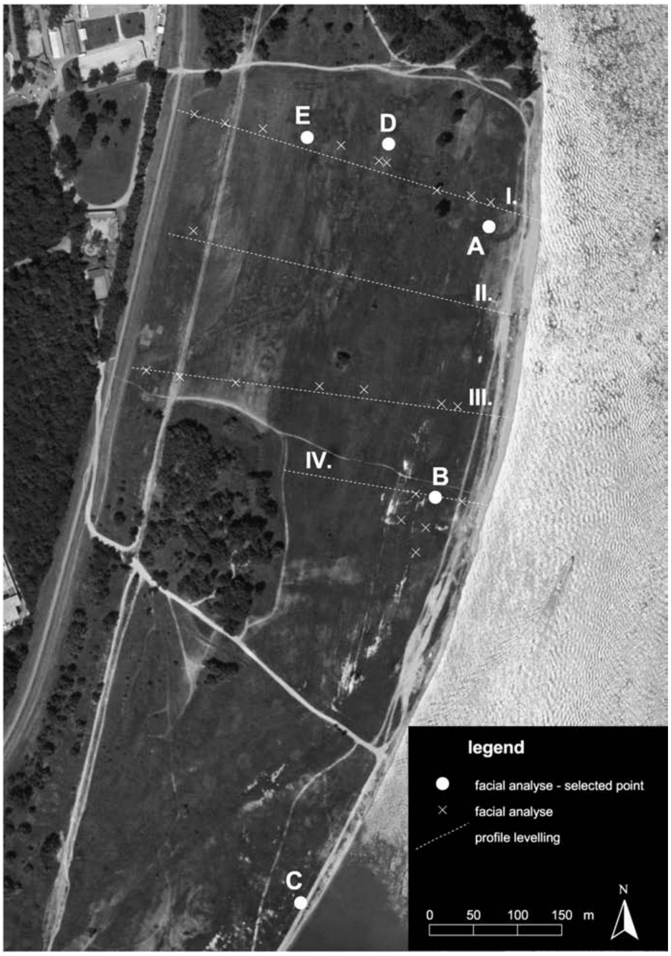

Fig. 4. The detailed map of geodetically levelled cross-sections including the sites of sampling points. The lithofacial analysis was performed at these sample points. A–E sites of sampling points are described in the text (data source: Eurosense, Ltd. and Geodis, Ltd.).

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Morphostratigraphic units in the study area were delimited by field mapping, analysis of 10 borings and 20 pit exposures, 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. 4 and 5) and by recording the position of individual points using the GPS (at present horizontal precision is from 1 to 5 m). Sediments were classified using established methods (Brierley, 1991, Zwoliński, 1992, Marston et al., 1995). Both natural and anthropogenic landforms were identified in the field and from aerial photographs and finally transferred to orthophotomaps.

Borings and pits served as sample points for determining the process and rates of the vertical accretion using an allostratigraphic approach classified on the basis of fluvial style (Miall, 1996). Dendrochronology (Alestalo, 1971) and dating of the military bunker as an artefact (Trimble, 1998) were also used. 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 orthophotomaps for the above-mentioned time horizon.

Roughness is an important geomorphic characteristic of floodplains because it affects the velocity and direction of the flood water flow, sediment transport and deposition, and plant growth and succession. Floodplain roughness is a function of topography, soil and substrate properties and density of vegetation or land cover. Owing to the magnitude of floods and the width of the Danube we could not directly measure the discharge of the Danube River but estimated it across the floodplain surface, using direct measurements of flow velocity across floodplain land cover structures following Wyżga (1999). Thus the method of Arcement and Schneider (1989) was used as the basis for characterizing floodplain roughness based on Manning coefficient (n) values. Their method was modified and ordinal values assigned for land cover properties (Fig. 6) for the floodplain roughness as follows:

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;

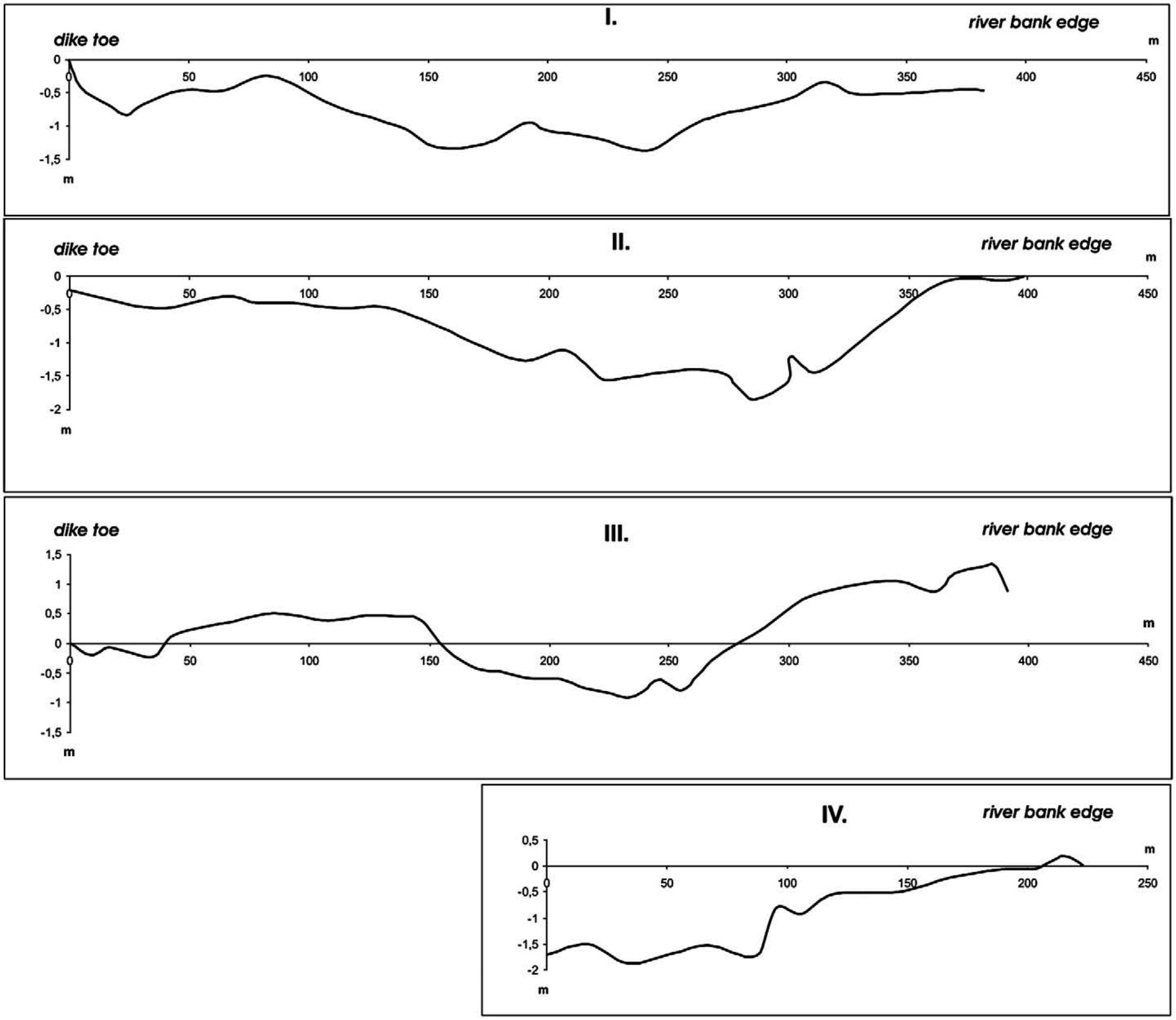

Fig. 5. The cross-sections (I–IV) where geodetic levelling was carried out. The central part indicates the palaeochannels that were later filled in with sediments. The elevations on cross-sectional profile on the right side near the riverbank edge indicate the levees (Fig. 4 shows the location of cross-sections I–IV).

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Fig. 6. Examples of floodplain roughness categories: 1. water bodies, 2. very low, 3. low, 4. medium, 5. high, 6. very high (photos by authors).

6. mature forest with low and high shrub floors — very high roughness.

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.

4. Results and discussion

Landform distribution (Fig. 7) 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 (Fig. 8, Table 1).

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 (1956, 1959, 1964, and 1969) 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. As late as the 1960s, some 600,000 m^3 of gravel and about 7 million t of suspended solids passed through the Bratislava cross-section of the river. Measurements carried out from 1970–1987 showed that the mean annual bedload discharge of gravel and the mean annual discharge of suspended solids dropped to about 280,000 m^3 and to 2.87 million t respectively (Mucha, 1999). 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^3 s^{-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

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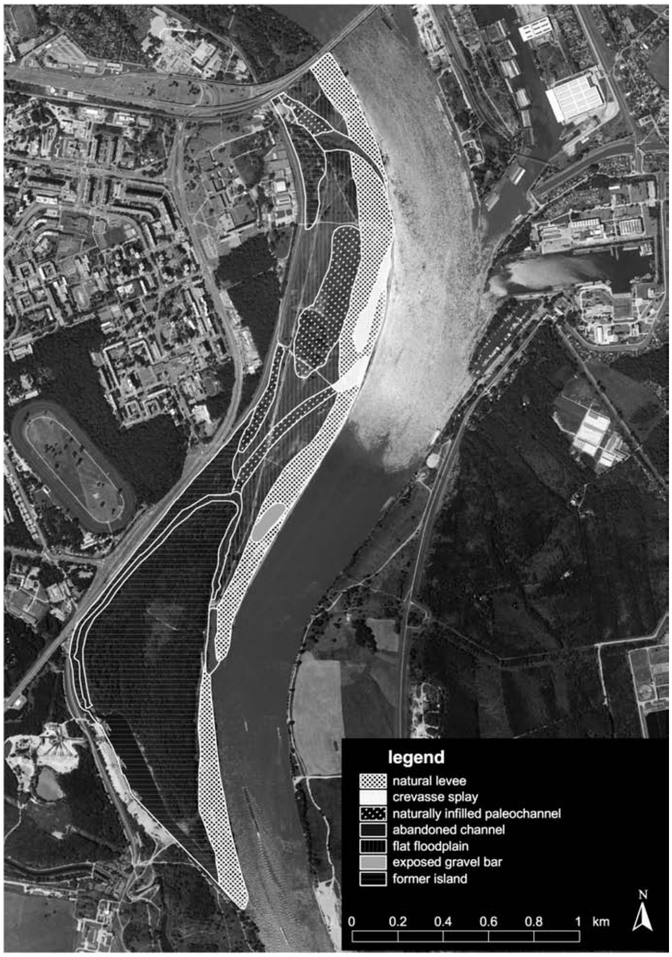

Fig. 7. The 2007 map of morphostratigraphic unit types (data source: Eurosense, Ltd. and Geodis, Ltd.).

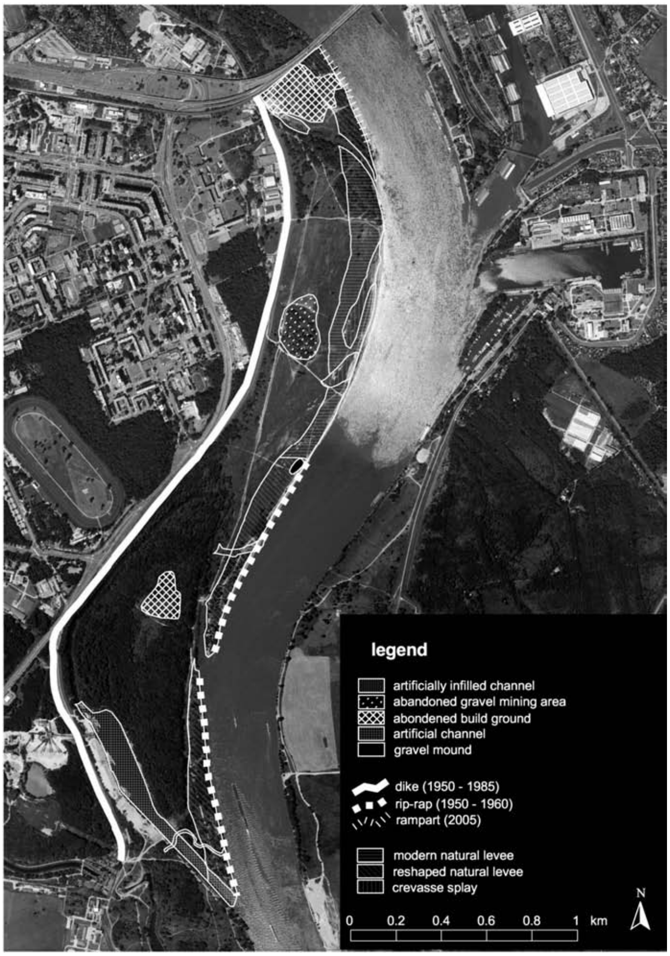

Fig. 8. Map depicting modern landform changes; both natural as well as artificial landforms. The dates of dikes, rip-rap revetment and rampart construction are included on the map (data source: Eurosense, Ltd. and Geodis, Ltd.).

still evident (Fig. 9). The original very high and medium roughness floodplain categories decreased significantly in terms of areal extent with time during this phase (Fig. 10, Table 2).

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. Another effect that emerged was that of activities connected with the construction of the Waterworks Gabčíkovo–Nagymaros.

The old dike was heightened and rebuilt and rock block fills (rip-rap) stabilized parts of the riverbanks. Construction of five dams (1974, 1978, 1980, 1983, and 1985) 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/

Table 1
Areas of the main morphological features in the study area (1947–2007): (+) indicates an increase of area, (−) indicates a diminishing/disappearance of the area, (+, −) indicates an increase of the area and a diminishing/disappearing of the area at different times.

Morphological features	Area (ha)
Artificially infilled channels	(+) 1.8
Abandoned gravel mining area	(+, −) 3.9
Abandoned build ground	(+, −) 7.8
Artificial channel with rip-rap revetment	(+) 8.1
Gravel mound	(+) 0.2
Modern natural levee	(+) 13.5
Older sand-wave reshaped natural levee	(+) 21.9
Crevasse splay	(+) 3.1
	Length (m)
Dike	(+) 3768
Rip-rap	(+) 1913
Rampart	(+) 498

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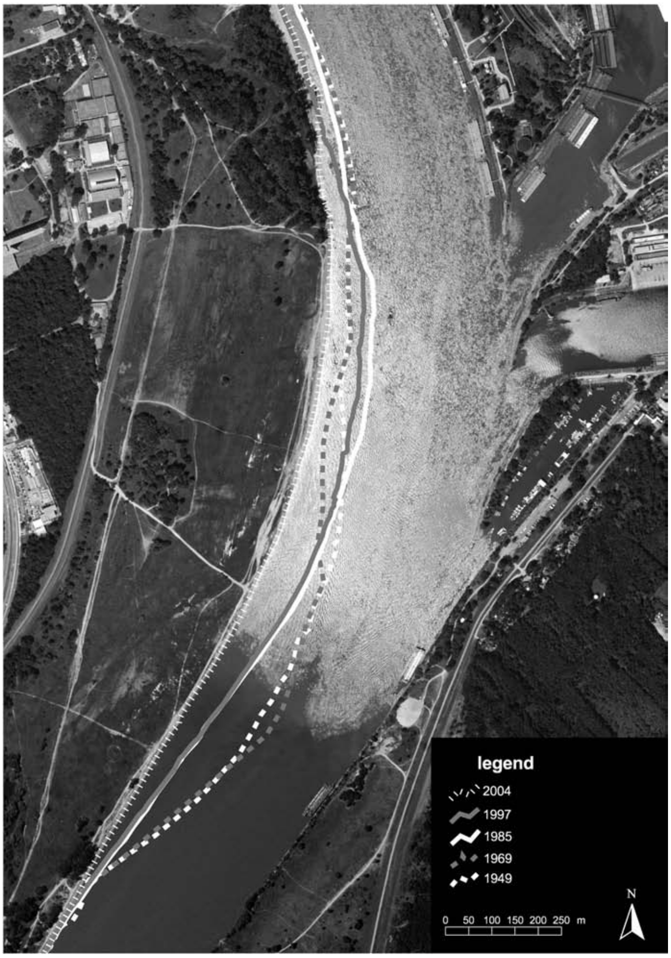

Fig. 9. Map showing the bank retreat along time horizons (data source: Eurosense, Ltd. and Geodis, Ltd.).

Table 2
The areas of floodplain roughness categories expressed in ha over time.

Year	Area of floodplain roughness categories (ha)					
	Water bodies	Very low	Low	Medium	High	Very high
1949	11.2	4.2	9.2	35.5	6.3	119.7
1969	10.8	20.4	60.2	17.0	1.2	70.6
1985	15.9	9.7	57.2	37.8	1.5	58.0
1997	15.4	2.0	21.9	47.0	26.7	63.4
2007	14.7	1.8	28.4	24.0	26.1	67.1

mixed to a suspended load regime during this phase. Despite gravel extraction and bank shifting the depth of the channel increased nearly a meter in the ten years after the Gabčikovo Waterworks came online (Blaškovičová et al., 2006). Two extreme flood events in March ($8560\ m^3\ s^{-1}$, Q_{50}) and August ($10{,}390\ m^3\ s^{-1}$, Q_{100}) of 2002 affected the development of the floodplain surface in terms of morphology and sedimentology. Field surveys, facies analyses (see below) and comparison of the two 2002 flood events showed that the geomorphic response to the August flood was greater. The August flood eroded strongly and aggravated the sedimentation processes initiated in March. A considerable amount of sediment was transported and re-deposited. 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 (Figs. 7 and 8). 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.

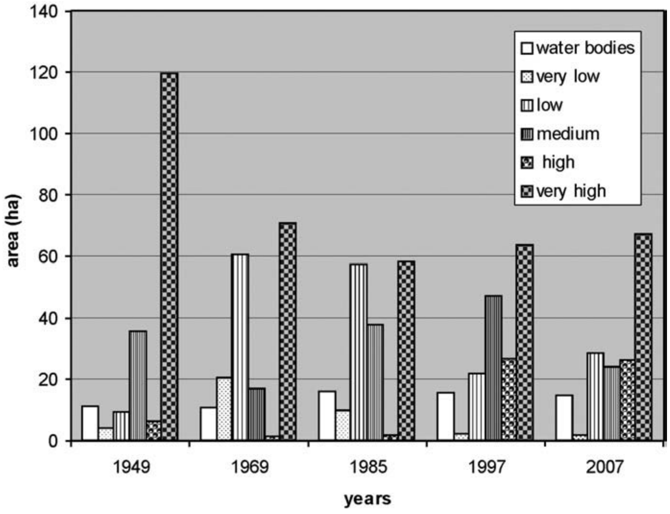

Fig. 10. Floodplain roughness categories compared over time. In 1949 the areas of very high roughness category dominated floodplain and areas of low and medium categories were prominent from 1969 to 1985; increase of high category areas, varieties of channel form, and biodiversity has been evident since 1997.

4.1. Cross-floodplain sedimentological variability of modern overbank deposits

Floodplains comprise of overbank and lateral accretion deposits and are intricately linked to river channels (Allen, 1965). 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. However, the geomorphological and sedimentological attributes of fluvial levees demonstrate remarkable spatial variability and no consistent pattern in the location of levees in relation to the channel exists (Brierley et al., 1997). This suggests that channel and floodplain conditions act as local controls on dispersal of flood sediment and ultimately formation of the floodplain topography (Hudson and Heitmuller, 2003). 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 1 m suggesting the height of levee deposition.

Lithofacies differentiation of the flood alluvium is based on five samples taken from the modern overbank deposits. The structure and texture of these sediments in the lithofacies reflect deposits of an

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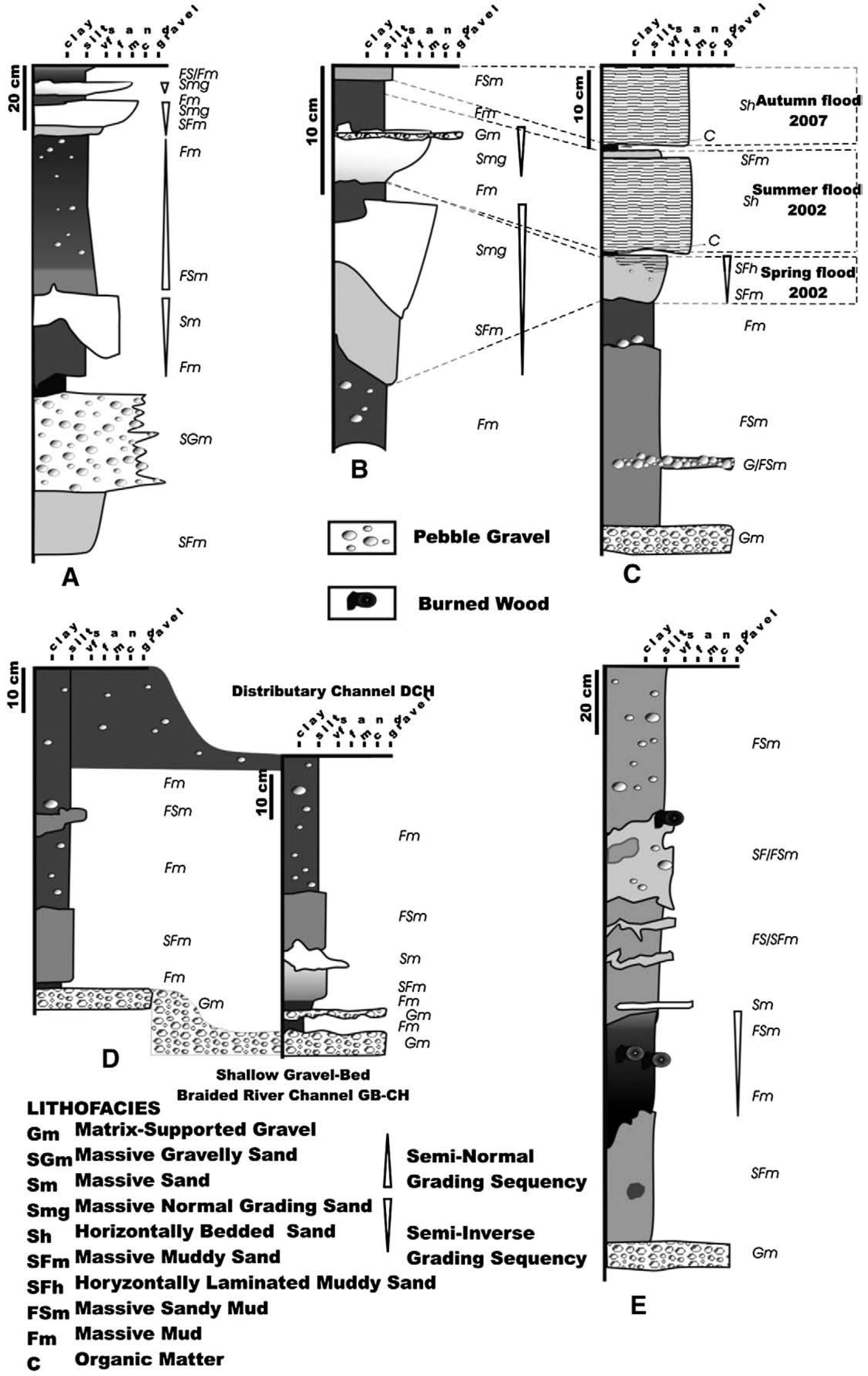

Fig. 11. The application of lithofacial analysis after Miall (1996) and variability of overbank sediments (Fig. 4 shows the sample point location).

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anastomosing river and floodplains formed by regular flow events (Nanson and Crooke, 1992; Miall, 1996).

The lithofacies profile near the present Danube River bankline, in the levee (Fig. 11A) exhibits sedimentological characteristics consistent with distal portion of levees. Two sets of beds showed a semi-normal graded sequence: massive silt and massive sand lithofacies (Fm–Sm), massive silty sand and normal graded sand (SFm–Smg). Above these deposits lies a normal graded sand lithofacies (Smg). All sequences record the rising phase of single flood events. The 20 cm layer of a massive gravel/sand lithofacies (GSm) is overlain by a thin massive mud lithofacies Fm also worthy of attention. The alluvium shows clear lithologic evidence of low- to high-velocity overflows during a single major flood event (Mansfield, 1938; McKee et al., 1967; Antczak, 1985; Szmańda, 2006). Moreover, we observed one layer with a lower semi-inverse graded sequence: massive silty sand–massive silt lithofacies (FSm–Fm). This layer may record the decreasing flood flow velocities associated with the floodplain gradient. Correlation of overbank flow conditions with their deposits is only possible in cases of two sets representing semi-symmetrical (normal to inverse) graded sequences (Mansfield, 1938). Sediments deposited during two flood events in 2002 are evident in the upper part of the profile (Fig. 11A and B). The first event occurred in the spring (8474 m^3 s^{-1} 24.03.2002 in Devín) and the second occurred in summer (discharge 10,370 m^3 s^{-1}, 16.08.2002 in Devín). At that time, the levee was covered by 20–50 cm thick deposits. Fig. 11B shows a representative lithofacies record for floods.

Analysis of the lithofacies profile (Fig. 11B) reveals three phases for each of the floods. Klimek (1974) described them as a single cyclothem corresponding with three hydrological phases: ascent, culmination and descent of flood flow. The ascent phase of a flood wave is deposited as a massive silty sand lithofacies (SFm: the spring flood event), and graded sand lithofacies (Smg: the summer flood event). Both lithofacies constitute a record of two flood phases out of the five described by Zwoliński (1986, 1992): (1) the rising of the water stage and bank modification; and (2) floodplain inundation and initial deposition. The culmination phase and ascent flood phases (Klimek, 1974) are marked by widespread sediment transport and deposition (3). The descent phase is represented by the normal graded sand lithofacies (Smg) and the matrix-supported gravel lithofacies (Gm) (Zwoliński, 1986, 1992). Massive mud lithofacies (Fm) in the upper sediments of both cyclothems record the last phase of the flood descent (Klimek, 1974). The two phases listed by Zwoliński (1992), (4) the falling water stage with massive deposition and (5) the cessation phase of overbank flow and final deposition also occur at this level. A 2 cm sand layer accumulated in one autumn flood in 2007 overlies the upper portion of the profile. 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 (Fig. 12).

Fig. 12. A) Branch of a tree buried under a 55 cm thick sand layer during the 2002 flood. B) New, three-year old branches growing vertically from the previous branch after the flood event (photos by authors).

Alluvium deposited by the three floods (spring and summer floods of 2002) and autumn flood of 2007) was also found in the channel bank profile (Fig. 11C). The spring flood deposits from 2002 are represented by massive silty sand (SFm) and a horizontally laminated silty sand (SFh) lithofacies. These two beds may correspond to an ascent phase (SFm) and the culmination of the flood (SFh). The summer flood of 2002 is recorded as a pair of stratum — horizontally bedded sand (Sh) and massive sandy silt (SFm). It corresponds to a flood rhythm (Mansfield, 1938; Antczak, 1985; Farrell, 2001; Szmańda, 2006). The above-mentioned sediments represent two flood stages: (1) ascent and culmination (Sh) and (2) descent (SFm). The autumn flood of 2007 deposited only one 10 cm surface layer, a horizontally laminated sand lithofacies (Sh). The modern levee development is strongly related to the distance from the Danube River channel. Deposits of horizontally bedded sand (Sh) and massive sand (Sm) lithofacies, sandy silt, massive silty sand (SFm) and horizontally laminated silty sand (SFh) lithofacies (Fig. 11B and C) were deposited close to the proximal part of the floodplain. Evidence of muddy deposits, massive mud (Fm) and massive sandy mud (FSm) lithofacies accumulated in the distal part of the floodplain surface (Fig. 11D and E) indicates the fining of deposits with increasing distance from the channel (Allen, 1965, 1970).

Overbank deposition on the current floodplain is comparable. Horizontally bedded (Sh) and massive sand (Sm) lithofacies, as well as sandy silts, massive silty sands (SFm) and horizontally laminated silty sands (SFh) (Fig. 11B and C) occur near the proximal part of the floodplain surface. Muddy deposits, massive muds (Fm) and massive sandy muds (FSm) accumulate in the distal part of the floodplain (Fig. 11A, D and E). Sediment grain size decreases with the distance from the channel (Allen, 1965, 1970).

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 (Fig. 13). At present, a 103 cm thick sedimentary deposit covers the

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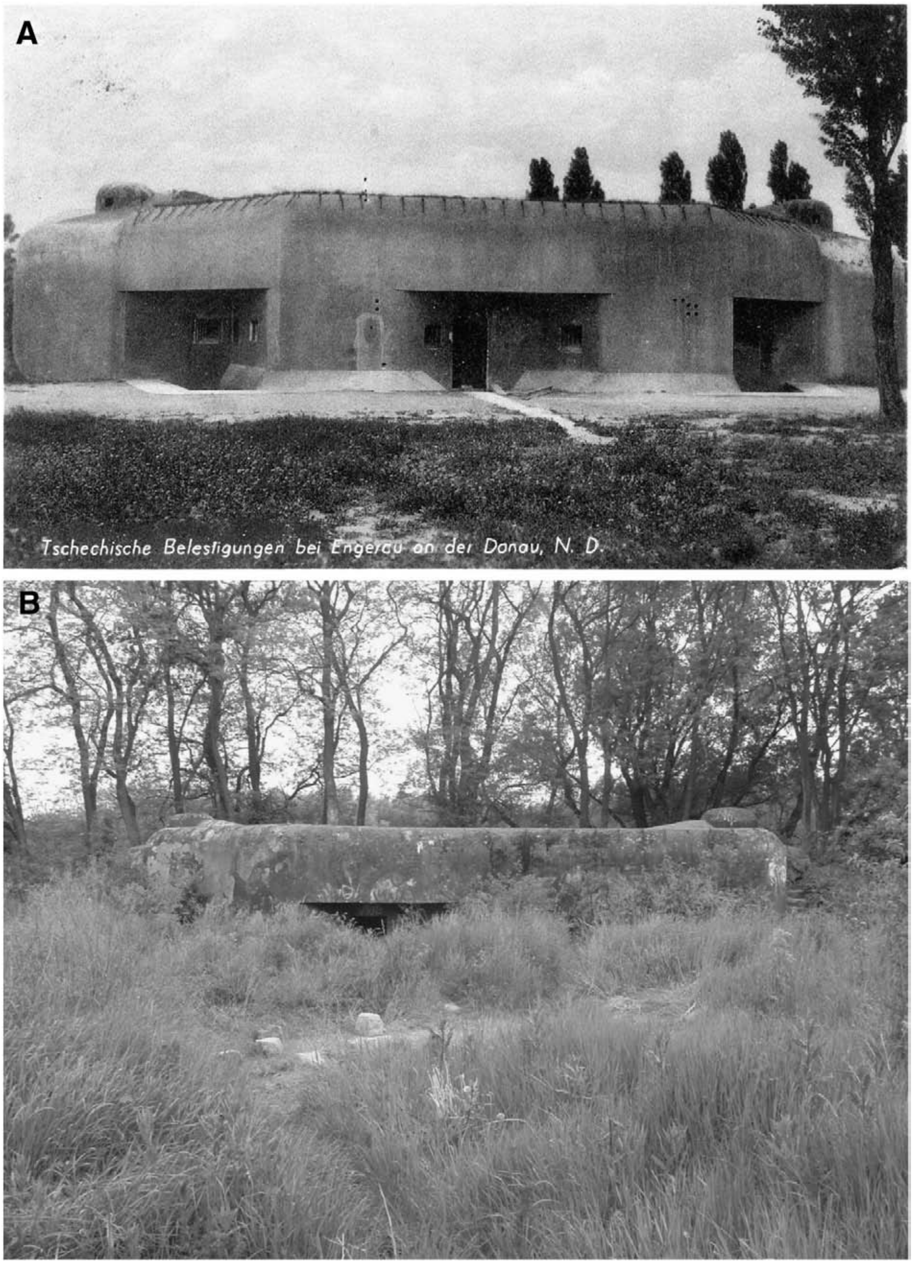

Fig. 13. The military bunker (see Fig. 3 for location). A) The same type of bunker after construction in 1937 (data source: postcards archive of J. Hanušin). B) Partly buried bunker under 103 cm thick overbank sediment in 2006. The rate of vertical accretion equals 1.4 cm per year (photo by authors).

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.

5. Conclusions

Conflicts between urban development and flood regime of the Danube occur along the study reach. The evolutionary and qualitative "top–down" approach (Murray et al., 2009) 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 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

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in the recent development of the river reach and nine factors related to the current 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

In sum, the suburban river reach near Bratislava conforms to Phillips's construct of perfect landscapes (Phillips, 2007; Marston, 2008) and with the multiple environmental controls and forcings represents a non-linear, dynamically unstable landscape system (Phillips, 2006).

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