Alluvial bottom geology inferred as a factor controlling channel flow along the Middle Vistula River, Poland

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Within the channel zone of the Middle Vistula River, elevations of the Holocene alluvial basement occur, composed of deposits resistant to erosion. In this paper two kinds of such forms are discussed. Within the Małopolska gorge (an upstream part of the Middle Vistula, near Kępa Gostecka and Zakrzów), the elevations are composed mainly of Upper Cretaceous and Paleogene rocks covered with clayey debris and residual lags. Below this, the elevations are built of Paleogene and Neogene soils as well as of various Pleistocene glacial deposits, and are often covered by residual lags. This type of valley stretch occurs in the vicinity of Dęblin. The surface of the erosion-resistant Holocene alluvial basement averages at 5–7 m below the mean water level. It is exposed on the channel bottom during high-water stages, as seen from a residual layer and from the low density of the contemporary channel deposits above them. The morphology of these elevations influences the pattern of the main stream also during mean-water stages. The trend to flood flow concentrations is also seen in the relief of the floodplain.

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INTRODUCTION

The influence of channel zone geology on the dynamics of river flow has been linked with the occurrence of deposits resistant to erosion in the river bottom or at the channel margins (Schumm, 1971; Knighton, 1984). The presence of such rocks (deposits resistant to erosion, Falkowski, 1971) is reflected in the longitudinal river and channel bottom profile by changes of the river gradient, and often influences the geometry of the river network (Gerber, 1959; Leopold and Wolman, 1957; Spitz and Schumm, 1997; Twindale, 2004). The shallow occurrence of deposits resistant to erosion in the valley basement may also be explain a decrease in the sensitivity of the fluvial environment to changes in the flow regime within the river (Hey, 1991, 1997). Moreover, deposits resistant to erosion, which can be exposed during high-water stages, may influence the stabilisation of the channel and valley bottom morphology. Such phenomena, however, are linked mainly with young river valleys, running through areas of young surface morphology, mountains and uplands. The erosional base of such forms has not yet developed its final form.

In valleys of rivers flowing in lowland areas, often referred to as mature rivers, the deep erosional base is filled with thick alluvial deposits of the channel facies. This geological structure allows the river free adaptation of the flow dynamics to the hydrological regime of the drainage basin. The changes centre on achieving equilibrium between sediment transport and the flow energy in the channel according to the general formula of Lane (1955):

$$Q_S \times d_{50} \sim Q_w \times S$$

where: Q_w [m^3/s] — the flow rate, Q_S [T/s] — transport rate, d [m] — size of the transported grains, S — river gradient.

Such evolution of the river system is caused by climatic changes, base level changes and human activity (Falkowski, 1971; Kozarski, 1974; Mycielska-Dowgiałło, 1978; Blum and Tornqvist, 2000; Vanderberghe, 2002; Mount *et al.*, 2005). These factors are reflected in the type of river channel development.

In the floodplain of the Middle Vistula River valley, two kinds of alluvial plain have been distinguished: meandering river terraces and a wild-braided river contemporary terrace. The former

were built under the natural climatic conditions of the Pleistocene/Holocene transition and of the Holocene. Deposit succession of a few meander generations (reflecting climatic changes) may be distinguished (Falkowski, 1971, 1982; Mycielska-Dowgiałło, 1978; Laskowski, 1986). Channel deposits are covered by loamy flood facies mud of the meandering Vistula.

The latter, a braided river alluvial plain, was formed under conditions of increasing human impact on the environment of catchment area (Falkowski, 1971, 1982; Mycielska-Dowgiałło, 1978).

The silty and sandy muds of the contemporary braided river partly cover the meandering river floodplain. The contemporary channel deposits occur mainly along the channel zone. They also form sandy outwash: separated splays and bars of flood flows on the floodplain surface (of the meandering as well as of the braided Vistula).

The existence of the cohesive Vistula River flood deposits confines the lateral relocation of the present-day braided channel. The average thickness of these deposits (moderately resistant to erosion) in many cases reaches 4.5 metres (Kraużlis *et al.*, 2003). Their base is found in the border zone between the meandering river floodplain and the contemporary braided river floodplain to a depth of 3 metres below the medium-water level. Cohesive deposits forming the channel bank are generally considered to be resistant to erosion (Knighton, 1984; Schumm and Spitz, 1996; Eaton and Millar, 2004).

Studies carried out within the channel zone of the Middle Vistula River documented the presence of elevations built of deposits resistant to erosion in the basement of the Holocene alluvia. They are present both within the Vistula gorge through the mid-Polish uplands (2 and 3, Fig 1), as well as in the valley stretch within the lowland area (5 and 6, Fig. 1). These forms act as local erosional bases stabilising the longitudinal profile of the river channel and valley. Due to their presence the river cannot develop a deep erosional base along its whole length.

The presence of residual lags on the surface of these elevations in the basement of Holocene alluvia indicates their exposure on the channel bottom during high-water stages. Thus, the morphology of the elevations should influence the position of the main stream during high-water stages, and may also influence the variability of alluvial sedimentary environments as well as the distribution of erosional processes.

Analysis the Middle Vistula River valley, described here, shows the influence of the basement of Holocene alluvia on the morphology of the channel during high-water stages and on flow directions on the floodplain surface (before embankment construction). Understanding how natural processes may impact on the presently observed channel processes can have a crucial effect on the engineering geological analysis of the fluvial environment constructed for water-engineering (regulation and flood control structures, communication structures) as well as for regional planning and management and environment protection. Utilisation of natural elements stabilising channel stretches in projects that manage the river valley bottom may favour the practical realisation of "sustainable development" requirements in management of the natural environment.

METHODOLOGY

The studies have been carried out in the Middle Vistula River valley along stretches selected by means of on geomorphological and geological analyses (Fig. 1). The distribution and stability of hydrotechnical structures as well as other hydrological archival data have also been taken into consideration. This preliminary study was focused on selecting stretches of the channel zone with a dense network of erosional troughs from the high-water stages. These should form in places where elevations of the alluvial basement occur, built of deposits resistant to erosion which, by restricting the possibility of enlarging the channel cross-section during high-water stages, act to dam the water flow.

Synoptic echo-sounding measurements of the channel located places with a stable bottom level. Ice-jam locations were also analysed, assuming that the formation of ice-jams (heavy ice-jam after Grześ, 1985, or grounded ice-jam after Wiliams and MacKay, 1973) is favoured by the presence of elevations of erosion-resistant deposits within the alluvial basement. A stable basement prevents the passage of dammed water under the ice, that in turn would have led to relaxation of the ice-jam and its removal (Falkowski and Popek, 2000).

The first stage of field-studies comprised geological probing of selected stretches of the channel zone. Additional borehole were drilled in places where elevations were encountered in the alluvial basement. In effect, the variable morphology of
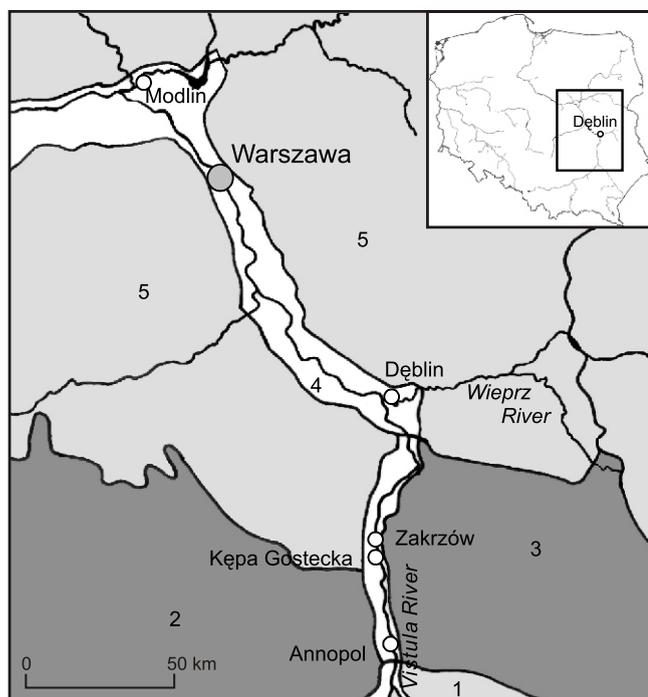
Fig. 1. Location of the channel zone reaches studied (Kępa Gostecka, Zakrzów and Dęblin) on the Middle Vistula River valley from Annopol to Modlin

Geographic region: 1 — Sandomierz Basin, 2 — Małopolska Upland, 3 — Lublin Upland, 4 — Vistula River valley, 5 — Middle Polish Lowland (after Kondracki, 2001)

the alluvial basement surface was recorded, as well as the lithology of the deposits building the elevations.

In order to determine the influence of the elevations on flow concentration, echo-sounding of the channel was repeated at different water stages. The method applied included bathymetric measurements using GPS technology. The measuring device comprised a portable echo-sounder with a Differential Global Positioning System (DGPS) receiver. The echo-sounder fitted with active digital converters generated impulses at the frequencies of 190–210 KHz. The velocity of the sound wave emitted was 1500 m/s, and the width of the beam varied between 5 to 10°. The minimal depth from which a precise measurement could be made was 0.35 m. The echo-sounder made point measurements of the water area every second. The data obtained were saved in the internal memory of the device.

The DGPS device connected to the echo-sounder was used to determine the geographic coordinates of the measurement points. Due to DGPS correction with geostationary satellites of the European Space Agency in the European Geostationary Navigation Overlay Service (EGNOS), the position of the measured points could be determined with an accuracy below 1 m. The data obtained were exported to the echo-sounder and also saved in the internal memory of the device.

In effect, a series of measurement points with three Cartesian coordinates: X, Y and Z, corresponding to the longitude and latitude as well as the river depth, was obtained.

After field analysis, the measurement series (*ca.* 10 000 measurement points per river stretch analysed averaging 5 km long) were exported from the internal memory of the device to a PC computer for further analysis. Based on the data obtained , bathymetric maps for each stretch analysed were prepared with the help of *Surfer* software.

Because the measurement series were made at various water stages, a comparative analysis of the morphological changes were required to run additional comparisons of the depth measurements. All measured values were calculated as metres above sea level, based on longitudinal profiles at the scale 1:100/1:100000 and on water stages from river gauge stations; therefore the final result comprised hypsometric maps of the channel bottom (Ostrowski, 2004).

Final analysis was carried out in the Geographic Information System (GIS) environment using ArcGis 8.X software. The studies included also analysis of archival data from the Regional Water Management Board (RWMB) in Warsaw. The location of studied Vistula channel stretches is given below in kilometres of the river course (after RWMB data).

RESULTS

In the channel stretches of the Middle Vistula River valley, selected on the basis of geomorphological analysis of the terrace surface, the presence of elevations in the Holocene alluvial basement has been determined. Within the Małopolska Vistula gorge (between the Małopolska Upland and the Lublin Upland; Fig. 1) these forms are mainly composed of Upper Cretaceous and Paleogene rocks, covered with clayey debris and residual lag deposits, exemplified by parts of the Vistula channel zone in the vicinity of Kępa Gostecka.

GEOLOGY OF SELECTED STRETCHES OF THE VISTULA RIVER CHANNEL ZONE

VICINITY OF KĘPA GOSTECKA (331–334 KM)

The alluvial basement in this area is composed of glauconite marls, limestones and opokas representing the Lower Maastrichtian (Pożaryski *et al.*, 1994). Boreholes drilling in the channel during this study showed the presence of clayey debris (z_c) overlying these, containing fragments of opokas, marls and well-rounded quartz grains (Fig. 2). Sporadically, grains of crystalline rocks of Scandinavian origin have also been recorded. The basement surface here forms a trough with its axis parallel to the orientation to the present channel.

A zone of elevations occurs along the channel near Kępa Gostecka (Fig. 3). Interpretation of the drilling results shows that the basement at the left channel margin (below a steep plateau embankment cut by narrow and deep troughs) reaches a height of *ca.* 123 m above sea level. In the central part of the channel this surface occurs at 114 m above sea level, and in the vicinity of the right margin it is at 116–117 m above sea level. Most probably, the surface of the alluvial basement rises eastwards from the Vistula channel forming a dome-like elevation. Its presence may cause the eastwards forcing of the high-water stream, as seen in the presence of a wide belt of high-water flows termed Wisełka (Fig. 3). The course of the deep erosional trough of the proto-Vistula from the Mazovian Interglacial is located within this zone (Pożaryski *et al.*, 1994). The presence of numerous erosional troughs of high-water flows and parallel sand bars encountered at different levels of the Holocene terrace suggest that, before the construction of flood embankments, this was an area of frequent overback flow.

The relief of the erosional channels was caused by the damming of high-water by ice-jams formation. Such phenomena were observed here for example in 1964 and 1980.

Above the top of the alluvial basement in the studied zone there occur unconsolidated medium-grained, slightly gravelly sands (a_c). This is the deposit of the contemporary braided river (Fig. 2).

In the vicinity of Kępa Gostecka near Zakrzów (338–340 km) within the zone with closely-spaced erosional high-water forms there also occurs an elevation built of Upper Cretaceous deposits. It forms a threshold running oblique to the present channel, and bounded to the south by a trough where flow concentrated during high-water.

Below the Małopolska Vistula gorge, on the Polish Lowlands (Fig. 1) soils representing the Paleogene and Neogene, as well as various Pleistocene deposits occur in the alluvial floor. The Pleistocene deposits include glacial tills, ice-dammed clays and silts, as well as coarse-grained glacial deposits. This can be exemplified by a section of the valley near Dęblin.

VICINITY OF DĘBLIN (391–394 KM)

In this stretch the elevation of the Holocene alluvial basement is composed of cohesive Paleogene deposits (Oligocene) (Pa, Fig. 4) and Quaternary residual lags gravels (L, Fig. 4). The surface of the alluvial basement in the channel zone forms a trough running along the right bank of the present Vistula
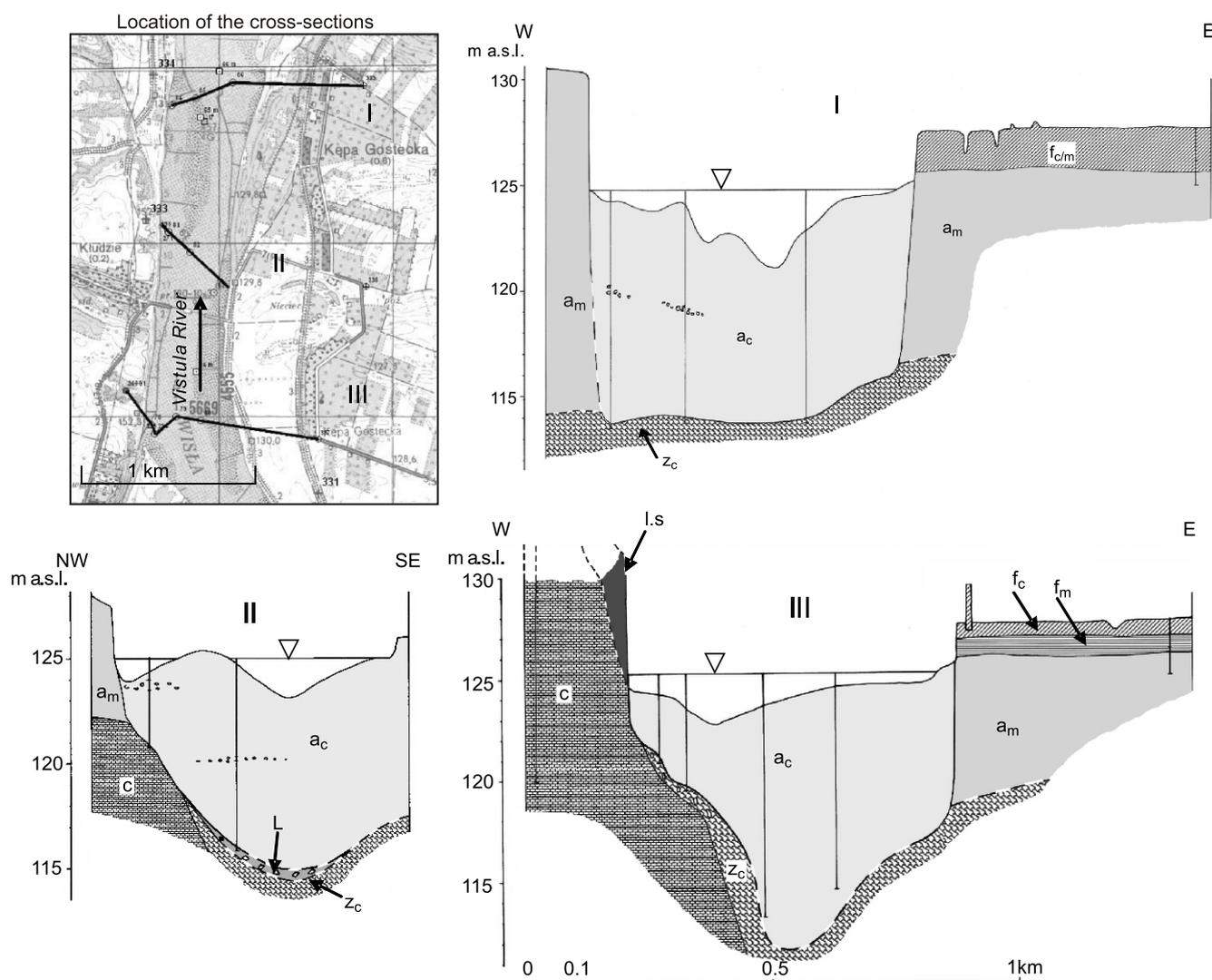
Fig. 2. Geological cross-sections through the channel zone of the Middle Vistula River in the vicinity of Kępa Gostecka (Fig. 1) and their location

f_c — clayey silts, silts and sands, flood facies deposits of the contemporary braided river (1 and 2 in the Figs. 3 and 5); a_c — sands and sands with gravel representing the channel facies of the contemporary braided river; f_m — clayey silts of the flood facies of the meandering Vistula River (Holocene); a_m — sands and gravels of the channel facies of the meandering Vistula River (Holocene); L — residual lags; l.s — loesses and slope deposits; z_c — clayey debris of Cretaceous rocks; C — limestones, opokas and marls (Upper Cretaceous)

River. At the level of the Wieprz River outlet, stabilised by hydrotechnical constructions, a hump-shaped elevation occurs in the central part of the channel. The top of this hump is over 106 m above sea level. It plays the role of a bar, blocking the flow of high-water in the present-day channel (Fig. 5).

The Holocene alluvial basement in this stretch is composed of greenish silty clays with organic matter, determined as the Early Oligocene–Rupelian (Ziembińska-Tworzydło, unpubl.). The stratigraphic position of these deposits based on palaeobotanical criteria is consistent with the interpretation shown on the Dęblin sheet of the Detailed Geological Map of Poland at 1:50 000 scale (Żarski, 1991, 1993).

Apart from the gravel lag in the Holocene alluvial basement, the presence of sands and gravels probably of Pleistocene age has also been noted (a_p), with a coarse-grained residual surface layer (Fig. 4). Larger pebbles, such as in the lag layer on the Oligocene deposits, have not been found.

CHANGES IN CHANNEL MORPHOLOGY

In the vicinity of Kępa Gostecka during medium low-water stage on 27.06.2004, the course of the main stream was approximately as normal (Figs. 3 and 6). The location of deep-waters reached 120 m above sea level, thus the alluvial surface was locally exposed in the region above the ferry. The impact of the hydrotechnical constructions and the scarps in the alluvial basement resulted in evorsion creating isolated pot-holes. A tributary of the main stream running upward in the direction of the base of the embankment of the ferry crossing was observed below the ferry under the right bank. This zone is located beyond the axis of the regulation route. This seems to be the place eroded by water which overflows the embankment of the crossing during high-water stage. The location of the embankment of the ferry crossing is inferred also to divide the zone, where earlier high-water (one of its streams) was concentrated.

During high-water stage (bankfull discharge) on 31.07.2004, the course of the main stream was approximately along the direction registered during lower medium-water conditions. Characteristic for this measuring period was the larger number of pot-holes (of evorsion origin), within which the minimal depth of the bottom reached about 120 m above sea level. Locally, numerous whirlpools up to 50 m in diameter were observed on the water surface during the measurements. At the 333+300 km section, a subordinate stream, separated from the main stream ran below the left bank of the channel, along the steep plateau margin. Simultaneously another stream directed obliquely to the course of the regulation route was also observed below the right bank upwards from km 331 and below the left bank, at the Krępianka outlet. The concentration of both streams in this place is inferred to have caused the destruction of the regulation constructions.

The terrace surface to the right of the channel is built of clayey flood facies sediments deposited by a Holocene meandering river, and later covered by silty muds of the contemporary braided river (Fig. 3). It is noteworthy that the surface of the terrace between km 330 and 334 (E of the channel) is rather indistinctly reworked by high-water from the Vistula River, whereas high-water from the Wiselka had formed numerous erosional troughs on its surface. This is evidence for a stable trend of high-water flowing along the Wiselka trough. As mentioned above, this is the zone of the Pleistocene valley axis, functioning here before the Odranian Glaciation (Pożaryski et al., 1994).

The morphology of the channel bottom has been recorded near Dęblin on 20.07.2004 and on 17.09.2004 at low-water stage conditions.

On 20.07.2004 at km 390, a connection of two streams was observed the eastern one linked with an erosional high-water trough running along the flood embankment, and a second one linked with the axis of the regulation route (Fig. 7). Slightly above the outlet of Wieprz River, the main stream turns NE, passing above a gravel layer lying on an elevation of the alluvial basement composed of cohesive Oligocene deposits. The surveys showed that to the railway bridge (bridge 1; Figs. 5 and
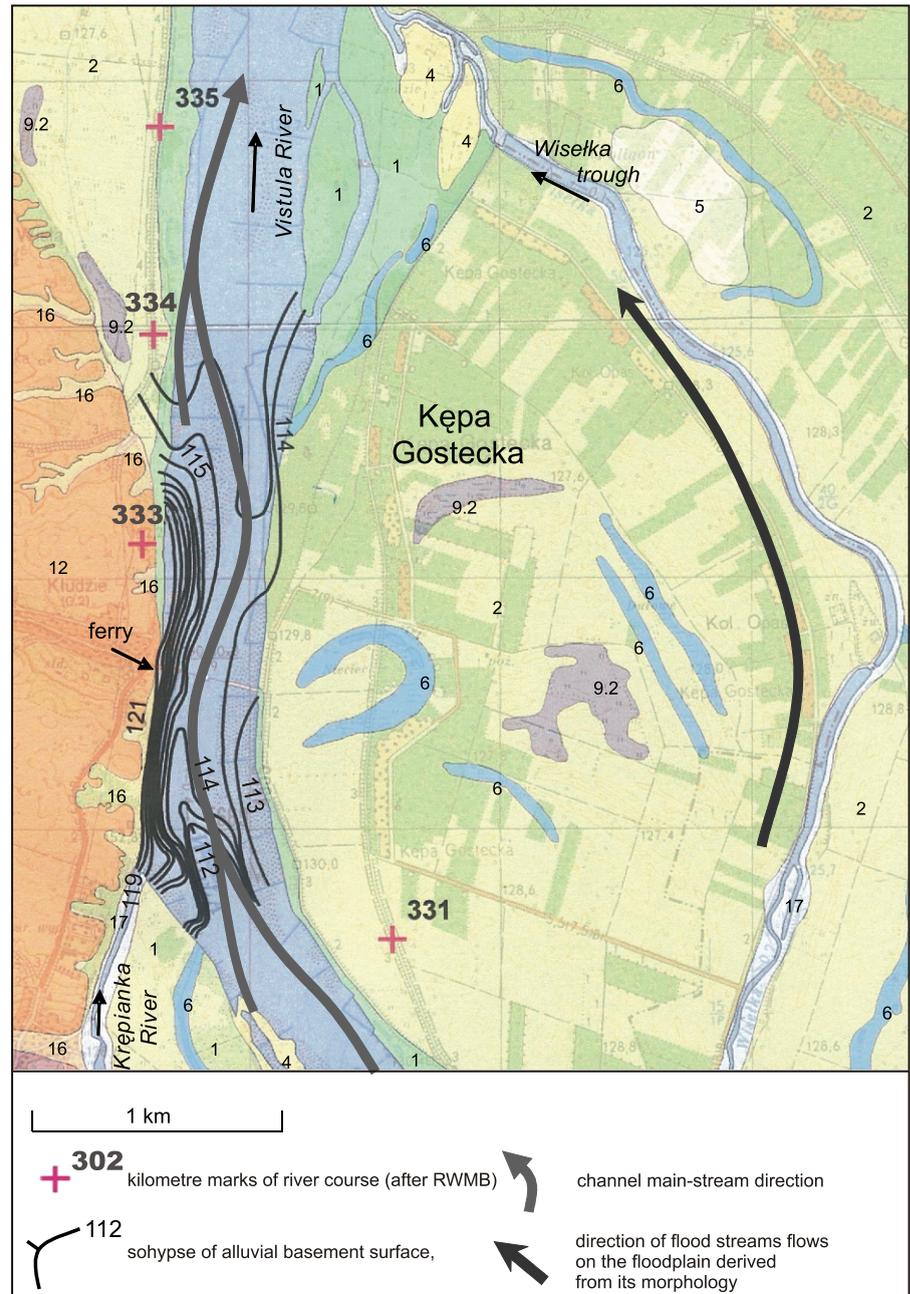
Fig. 3. High-water flow directions and their link with the lithology and morphology of the valley surface and of the alluvial basement in the vicinity of Kępa Gostecka (fragment of GIS database of Middle Vistula Valley from Annopol to Modlin; geological setting after Falkowski *et al.*, 1978, supplemented)

1 — silty-sandy mud of the flood facies of the contemporary Vistula River (braided river); 2 — silty-sandy muds (contemporary braided river) over clayey muds of the meandering river (Holocene); 3 — sands with gravel clasts of the channel facies, contemporary outwash; 4 — sands with gravel clasts of the channel facies, contemporary outwash on the floodplain surface; 5 — sands with organic matter, sandy silts, silts, loams and peats of ox-bow lakes (contemporary and Holocene); 6 — peats (Holocene); 7 — loesses; 8 — alluvial fans; 9 — tributary valleys

7) the main stream forms a concentrated flow zone. Below, in the channel bottom there occurred pot-holes of evorsion origin, resulting probably from the impact of the bridge pillars (this is a zone of visible whirlpools). Deep water (a pool) in this stretch is located below the right bank of the channel. From 393+500 km a
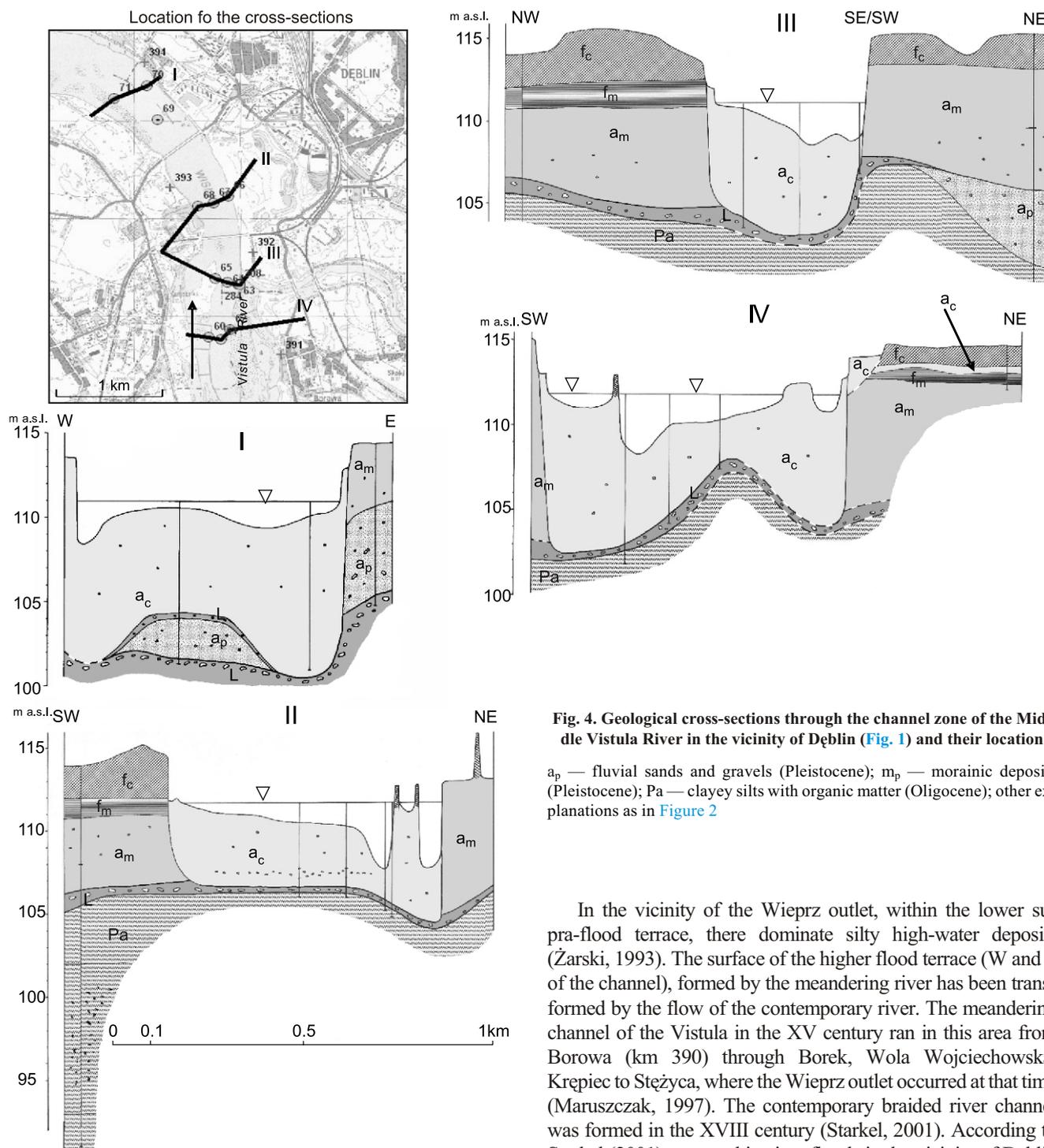
Fig. 4. Geological cross-sections through the channel zone of the Middle Vistula River in the vicinity of Dęblin (Fig. 1) and their location

a$_p$ — fluvial sands and gravels (Pleistocene); m$_p$ — morainic deposits (Pleistocene); Pa — clayey silts with organic matter (Oligocene); other explanations as in Figure 2

deeper trough in the channel appears also below the left bank. The deepest pool has been noted in the vicinity of the road bridge (bridge 2; Figs. 5 and 7) below the right bank and slightly below, where the position of the bottom reached about 106.5 m above sea level. This pot-hole was probably associated with the concentration of stream flow caused by the bridge pillars.

During measurements made on 17.09.2004 the morphology of the channel bottom was very similar. Its minimal positions were about 0.5 m higher in comparison with those measured in July.

In the vicinity of the Wieprz outlet, within the lower supra-flood terrace, there dominate silty high-water deposits (Żarski, 1993). The surface of the higher flood terrace (W and S of the channel), formed by the meandering river has been transformed by the flow of the contemporary river. The meandering channel of the Vistula in the XV century ran in this area from Borowa (km 390) through Borek, Wola Wojciechowska, Krępiec to Stężyca, where the Wieprz outlet occurred at that time (Maruszczak, 1997). The contemporary braided river channel was formed in the XVIII century (Starkel, 2001). According to Starkel (2001), repeated ice-jam floods in the vicinity of Dęblin had the most crucial significance for the course of the present channel. Such phenomena have been registered e.g. in 1845, 1852 and 1854. According to data of the RWMB in Warsaw, ice-jams have originated in this zone 10 times since 1924.

High-waters flowing on the surface of the higher flood terrace used also a series of ox-bow lakes of the meandering river, simultaneously transforming them. Sediments comprising intercalating clays, clayey silts, silts and silty clays 2.0 to 2.5 m thick were deposited on the surface of this terrace. They are overlain by longitudinal sandy bars (4; Fig. 5).
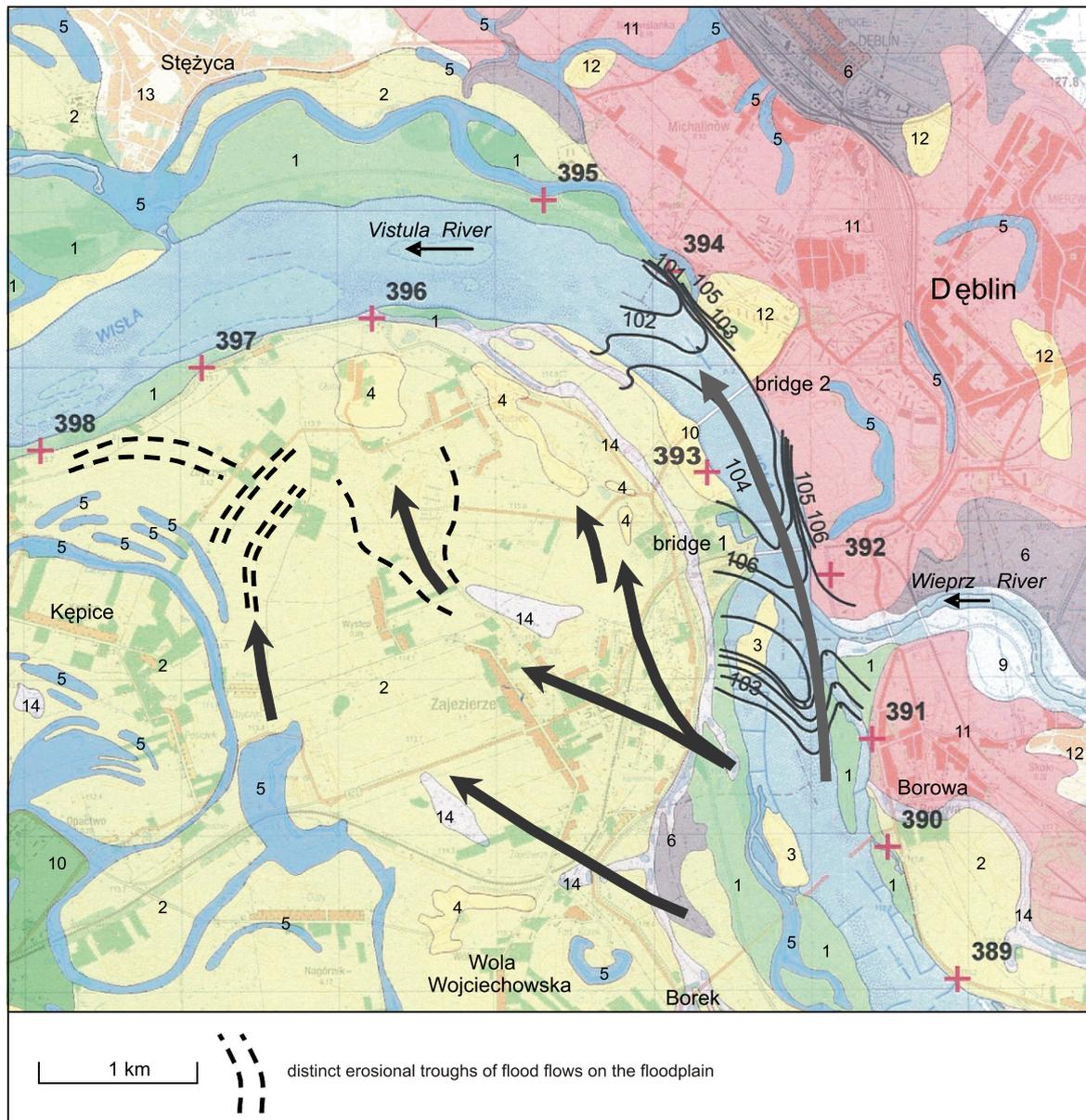
Fig. 5. Flow directions at high-water and their link with the lithology and morphology of the valley surface and of the alluvial basement in the vicinity of Dęblin (fragment of GIS database; geological setting after Falkowski *et al.*, 1978, supplemented)

10 — clayey mud of the meandering river (Holocene); 11 — brown muds (silty-sandy flood deposits of the Pleistocene braided river); 12 — sandy outwash on the surface of the Pleistocene terrace (11); 13 — aeolian sands on the surface of Pleistocene terrace (11); 14 — humic soils, loams (Holocene); other explanations as in Figure 3

DISCUSSION

The top of the Holocene alluvial basement in elevation zones occurs on averagely at 5–7 m below the mean water level, although there are places where it is exposed directly in the channel. For example in the Warsaw stretch of the Vistula River, the residual lag composed of gravels resulting from winnowing of glacial tills, in the Żoliborz threshold location, is visible in the channel during low-water stages.

Between the elevations, the top of the alluvial basement was noted at depths of 10–11 m below mean water level. The maximum depths at which this surface is located in the Middle Vistula River are about 20 m (Falkowski, 1990).

Above the elevations, loose channel deposits of the Vistula River, mainly fine and medium sands occur. These contemporary deposits locally contain intercalations of gravels, this being evidence of the depth of alluvial reworking during high-water stages. In some cases the sediments also contain material from the destruction of the stone and concrete elements of hydrotechnical constructions in the channel. They also stabilise the channel bottom.

Results of the studies show a link between the morphology of the alluvial basement with the location of the stream concen-
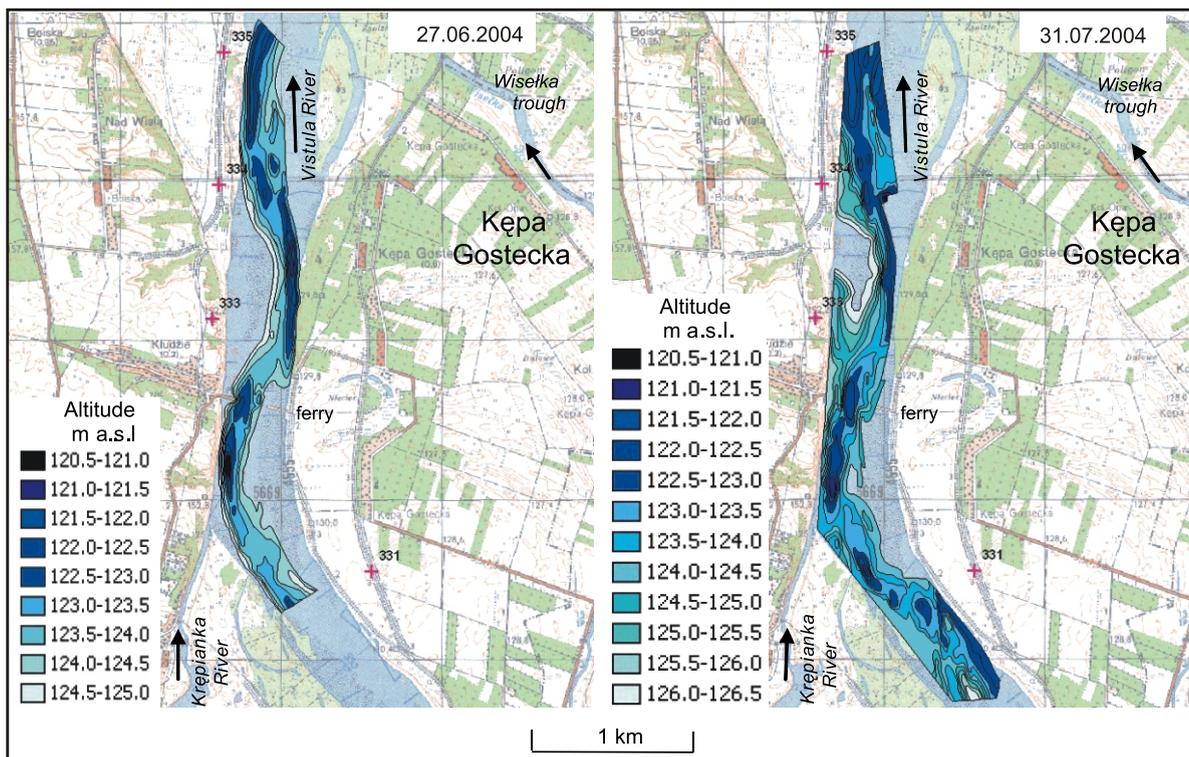
Fig. 6. Changes of the Vistula channel bottom morphology in the vicinity of Kępa Gostecka (fragment of GIS database)
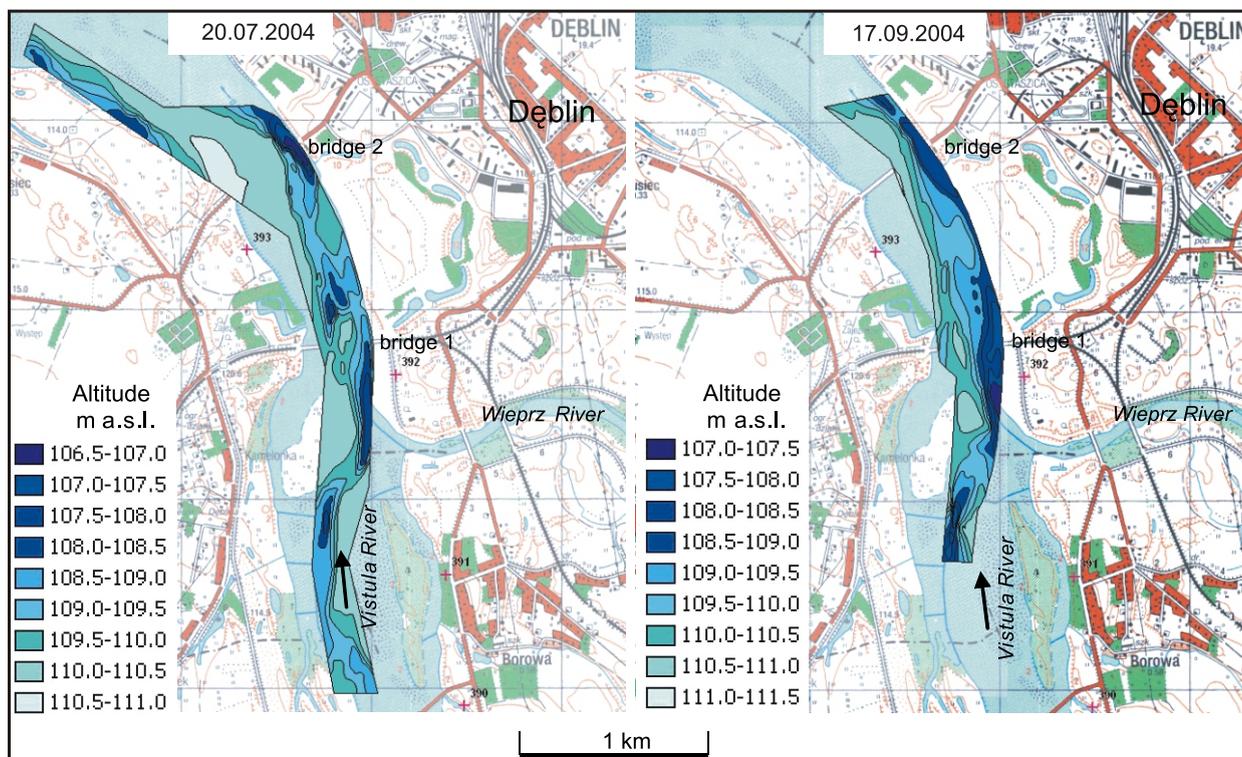
Fig. 7. Changes of the Vistula channel bottom morphology in the vicinity of Dęblin (fragment of GIS database)
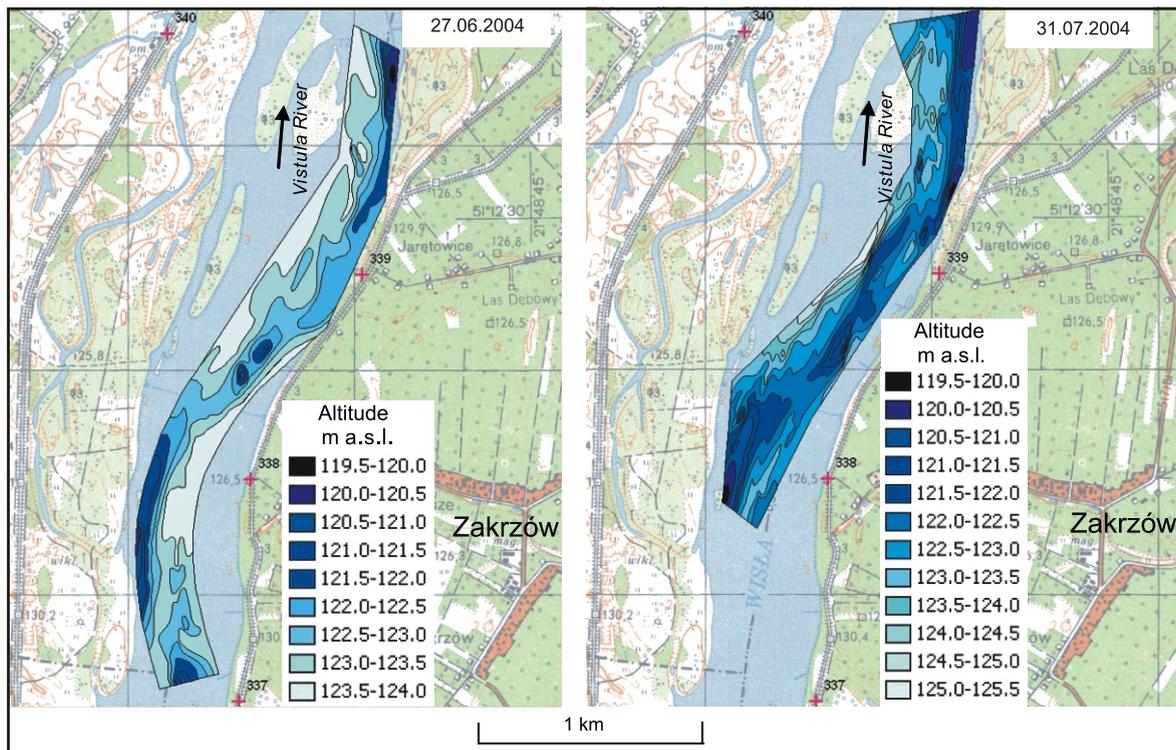
Fig. 8. Changes of the Vistula channel bottom morphology in the vicinity of Zakrzów (fragment of GIS database)

tration, both during high- and low-water stages. This relation is seen by the presence of traces of high-water erosion (erosional troughs, relief channels) on the surface of the flood terrace (also older, before the construction of flood embankments) and in the morphology of the channel bottom (not only during high-water). Repeatability of the channel morphology during high-, medium- and low medium-water results from the low density of the contemporary alluvial deposits. During the high-water stage the top of the alluvial basement can occasionally be exposed, as shown by residual lags. The morphology of the basement in such cases greatly influences the course of the main stream. During the fall of high-water, loose channel sands are deposited in the channel, which also at medium-water stages are more easily reworked by the water. Thus the specific channel "memory" is established.

The constant tendency to concentrate the main stream in particular zones of the river channel is probably the result of mutual action, influence of the erosion-resistant deposits (in the alluvial basement and in the channel bank) as well as the influence of hydrotechnical structures. Flood protection embankments confine the zone of channel relocation. However, the existence of flood water erosional troughs in the area beyond the embankment shows that geological structures seem to be the dominant factors here. This is confirmed by permanent failures of the hydrotechnical structures.

As shown by hydrological investigations (Bogdanowicz and Fal, 1997; Stachy and Bogdanowicz, 1997; Fal *et al.*, 2002), discharges of the Middle Vistula River in the last few decades (e.g. floods in 1997, 2001) have not reached their ab-

solute maximum. This shows that the predisposition to the main stream concentration had been established earlier, probably simultaneously with the creation of the contemporary braided Vistula floodplain.

Partial exhumation of the high-water channel during each high-water stage may lead to the formation of a lag zone within the deposits of the contemporary (*sensu* Falkowski, 1971, 1990) braided river. Based on the studies presented, several such zones have been observed, pointing to a gradual decrease of reworking depth. The gravel layer becomes a deposit resistant to washing out even at water stages higher than those at which it formed. Below this gravel layer occur loose, contemporary channel deposits.

The phenomenon of "temporary" channel stabilisation has been observed in the vicinity of Kępa Gostecka and Dęblin. An interesting example of the impact of a lag layer on channel morphology during high-water (bankfull discharge) stages has been observed below Kępa Gostecka in the vicinity of Zakrzów (338–340 km). As noted, an elevation of the alluvial basement also occurs in this zone.

In the vicinity of Zakrzów the course of the main stream is concordant with the course of the regulation route (Fig. 8). The morphology of the channel zone indicates the presence of a trend of the flow of high-water on the surface of the flood terrace westwards from the channel. This is seen it numerous sand bars and traces of high-water erosion. Eastwards from the channel the floodplain surface does not bear traces of distinct activity of concentrated high-water flows. On the contrary, traces of meandering are preserved on it. During low me-

dium-water stage on 27.06.2004, reworking of the alluvia reached locally the level of 119.5 m above sea level. During high-water stage (bankfull discharge on 31.07.2004) the zones of maximum depths of the channel are present across a much larger area. However, the bottom hypsometry does not show the presence of a distinct sand bar, the isohypses are "rugged". Gravel intercalations, noted in the boreholes at about 119 m above sea level, formed elevations of the high-water channel bottom, stabilising its morphology. The presence of "temporary" stabilisation of the channel in regulated stretches can be the cause of stepwise changes in its morphology. In the cases of high-water washing out of the "temporary" lag, a large part of loose alluvia below the lag can also be removed. Accretion of the flow in this case seems not to be proportional to the increase of the alluvial reworking depth.

The presence of elevations in the alluvial basement built of deposits resistant to erosion in the Middle Vistula River valley points its immaturity. Restricting deep erosion, these forms presently stabilise the longitudinal profile of the channel, and thus the valley bottom. Elevations of the basement form local erosion bases. They are often marked by changes in the channel gradient. In parts of the channel upstream of them, erosion/reworking of deposits during high-water stages reaches, however, in some cases occurs below the level of the resistant surface. This phenomenon is linked with pot-hole formation (evorsion).

CONCLUSIONS

1. The presence of elevations in the alluvial basement indicates the immaturity of the valley stretch. Such forms are encountered both in the area of the Małopolska gorge, charac-terised by young relief, as well as within the mature stretch in the Polish Lowlands.

2. The presence and morphology of Holocene alluvial basement elevations as well as other factors restricting the width of the channel zone (e.g. embankments and other hydrotechnical structures, presence of cohesive deposits in the channel bank) impacts on the direction of water flow on the surface of the floodplain.

3. Those factors have influence not only on the pattern of the main stream during high-water stages, but also on the concentration of the main stream during medium-water stages. This phenomenon is referred to as the channel "memory".

4. Gravel intercalations marking the depths of the present alluvial reworking form lag layers in the channel bottom during high-water stages, "temporarily" stabilising the channel morphology. Currently, when individual water stages of the Vistula River show increased differences between extreme values, particularly at increases of high-water stages, breaking of such "barriers" can cause stepwise changes in the channel morphology.

5. The trend towards concentration of the main high-water stream according to the morphology of the alluvial basement top may influence the stability and durability of hydrotechnical constructions in the channel.

6. The confirmation of a relationship between geological structures and concentrations of the river flows necessitates further investigation into channel morphology changes conducted in different hydrologic conditions.

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