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The application of geomorphological analysis of the Vistula River, Poland in the evaluation of the safety of regulation structures

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ABSTRACT:

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Investigations within the channel zone of the Middle Vistula River have shown the presence of protrusions of the alluvial basement composed of deposits resistant to erosion. On their surface, and in the basal part of the present-day channel facies, occur residual lags composed of gravels and pebbles. These lags indicate exposure of the surface of the alluvial basement in the channel bottom during high-water stages. Protrusions of the resistant alluvial basement often show a complex morphology which influences the course of the thalweg, particularly during floods. The constant trend to concentrate the high-water stream may be the reason for the damage to regulation and flood control system structures. The concentration of the high-water flow causes the formation of specific erosional and depositional forms on the terrace surface. Such forms can thus serve as indicators of the zones of alluvial basement protrusions. The paper presents examples of three reaches of the Middle Vistula River Valley (The Mid-Polish Lowlands).

Key words: River valley, Alluvial basement, Hydrotechnical structures.

INTRODUCTION

The main focus of river channel regulation is ensuring the stability of erosional and accumulation processes as well as sufficient channel dimensions for the transit of water and sediment. (e.g. PRZEDWOJSKI & *al*. 1995). However, many hydrotechnical regulation structures undergo systematic destruction during high-water stages. This may indicate the occurrence in the river environment of a natural trend to concentrate the flow in particular zones. In lowland river valleys (with post-glacial morphology, as in the Polish Lowlands), such concentrations of the natural flow may be due to protrusions of the alluvial basement, composed of erosion-resistant deposits (FALKOWSKI 2006). Such protrusions are often exposed in a channel during high-water stages, thereby influencing the course of the main stream (thalweg).

The occurrence of a trend to concentrate the high-water stream is also visible in the morphology of the terrace surfaces and in the lithology of the high-water (bankfull and overbank discharges) deposits. The location of basement protrusions within a river channel may thus be of crucial importance in the determination of engineering geological conditions within the river valley, and particularly in forecasting the possible course of fluvial processes.

The present-day Middle Vistula River represents a braided river, overcharged with sediments (FALKOWSKI 1982, SKIBIŃSKI 1994), mainly as a result of human activity in the catchment areas (FALKOWSKI 1982, 1990; STARKEL 1983, 1995). It must be added that most of the rivers of the Polish Lowlands show an increasing difference between the high-water and low-water stages (OZGA-ZIELIŃSKA 1997, DUBICKI 1997, STACHY & BOGDANOWICZ 1997), mostly because of increasing human impact on the natural environment of the drainage area, and climatic changes (FALKOWSKI 1982; KOZARSKI 1983; STARKEL 1994; VANDERBERGHE 1995, 2002). This trend will result in further increase in high-water flows and concomitantly in increased erosion of alluvial deposits during high water. This must cause an increase in the influence of erosion-resistant alluvial basement protrusions on channel processes. The consequent influence of the protrusions on stream concentration will cause an increasing hazard to hydrotechnical structures.

Investigations carried out within the Middle Vistula River channel zone (FALKOWSKI 2006) show the influence of protrusions of the resistant alluvial basement both on the concentration of the river flow and on the features of the terrace surface. Identification of these features could be used to establish the precise location of the protrusion zones.

The present paper provides the results of investigations carried out in the Middle Vistula River channel, between the Radomka River and the town of Góra Kalwaria (Text-fig. 1), with the aim of deter-

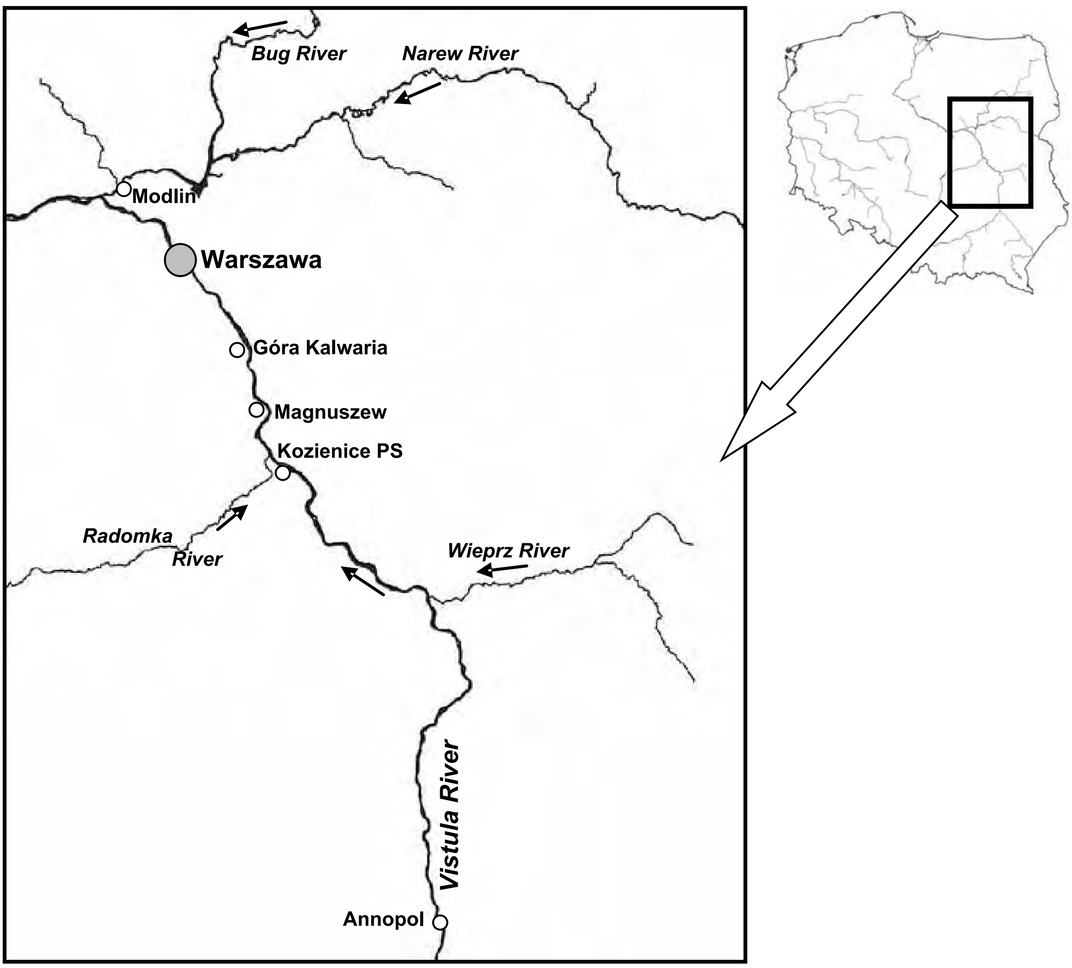

Fig. 1. Middle Vistula River (from Annopol to Modlin) with location of the reach analysed

mining the inter-relationship between the presence of erosion-resistant alluvial basement protrusions and the durability of the regulation structures. Such a relationship would confirm the usefulness of geomorphological analysis in reliable engineering geological forecasts concerning the functioning of regulation structures in river channels of lowland areas. The significance of geological and morphological analyses in river engineering has already been pointed out (e.g. FALKOWSKI 1990, GILVEAR 1999, THORNE 2002 and ŻELAZO & POPEK 2002).

METHODOLOGY

Initial investigations were carried out in the Middle Vistula Valley on a reach ca. 250 km long between Annopol and Modlin (Text-fig. 1) (FALKOWSKI 2006), with the aim of detecting zones of protrusions of the alluvial basement. The assumption was made that the existence of these zones induces permanent concentration of the flood waters, even on the floodplain surface. Protrusion zones can be recognized by the existence of scour trough systems. Erosion chutes (bypasses) can also be created during winter floods connected with the formation of ice-jams.

The protrusion zones are predisposed for the formation of grounded (GRZEŚ 1985, WILLIAMS & MACKAY 1973) ice-jams (FALKOWSKI 2006). In addition, analysis was carried out of archival data from the hydrological survey (Regional Water Management Board (RWMB)) in Warsaw concerning ice-jam occurrence and damage to regulation structures. The results of echo-sounding investigations in the channels have also been analysed, with the aim of finding channel zones with a stable long-term bottom level. The first phase of the investigation comprised geomorphological analysis of the floodplain surface and was focused on recognition of intense high-water (overbank flow) erosion and deposition.

The evaluation of the influence of protrusions on the durability of the regulation structures is based herein on observations made in the Vistula River channel, between the outlet of the Radomka River and the town of Góra Kalwaria (Text-fig. 1).

Subsequently, borings and soundings were made within selected reaches of the channel zone. Most of these were carried out on the water. These actions were focused on determining the morphology of the surfaces of the protrusions, the lithology of the deposits comprising the protrusions, as well as the lithology of contemporary channel alluvial deposits.

Echo-sounding of the channel was made at different river stages. The method applied included bathymetric measurements using GPS technology. The measuring device comprised an echo-sounder with a GPS receiver. The minimum depth at which a precise measurement could be made was 0.35 m. The device registered the depths at particular points with a frequency of one measurement per second together with the coordinates of the measured points.

Evaluation of the regulation structures was then carried out. The archival data relevant to the form of the regulation structures was also analysed.

The analysis of the data was carried using GIS - Geographic Information System (ArcGIS 8.X).

RESULTS

Throughout the reach of the Middle Vistula River studied (from Annopol to Modlin, Text-fig 1) the top of the deposits building the protrusions of the alluvial basement has been recorded as, on average, 5-7 m below the mean water level. Beyond the protrusions the top of the basement occurs, on average, at about 15 m below the mean water level (FALKOWSKI 2006).

In the vicinity of Magnuszew (km 438) (Text-fig. 1), in the southern part of this reach, the alluvial basement forms a SW–NE orientated ridge (Text-fig. 2). The altitude of the surface of this ridge is about 95 m a.s.l. on the left bank (km 438) and 96 m a.s.l. on the right bank of the present-day river channel. In the channel axis its surface falls to 92 m a.s.l. Farther to the north, between km 441 and 442, there is a small flattening of the alluvial basement surface with the top level at 93 m a.s.l. Between km 443 and 446 there is a longitudinal ridge with the top at over 93 m a.s.l. The base of a narrow trough on the right-hand side of this ridge has an altitude of about 90 m a.s.l. Downstream from km 446 the surface of the contemporary alluvial basement falls below 88 m a.s.l.

The basement of the Holocene valley in the southern part of the protrusion under discussion (shown with the isohypses in Text-fig 2) is composed of preglacial (Eopleistocene) sands, gravels (a_{Pr}) and silts with clays (f_{Pr}) (Text-figs. 3 I, 3 II), belonging to the so-called Magnuszew series (SARNACKA & KRYSOWSKA-IWASZKIEWICZ 1974). In the Eopleistocene these sediments built up vast alluvial fans of rivers running N and NE towards extensive tectonic depression in the area of Central Poland. These sands with a concentration of large grains forming a lag deposit, have been observed in the topmost part of these sediments. Boreholes

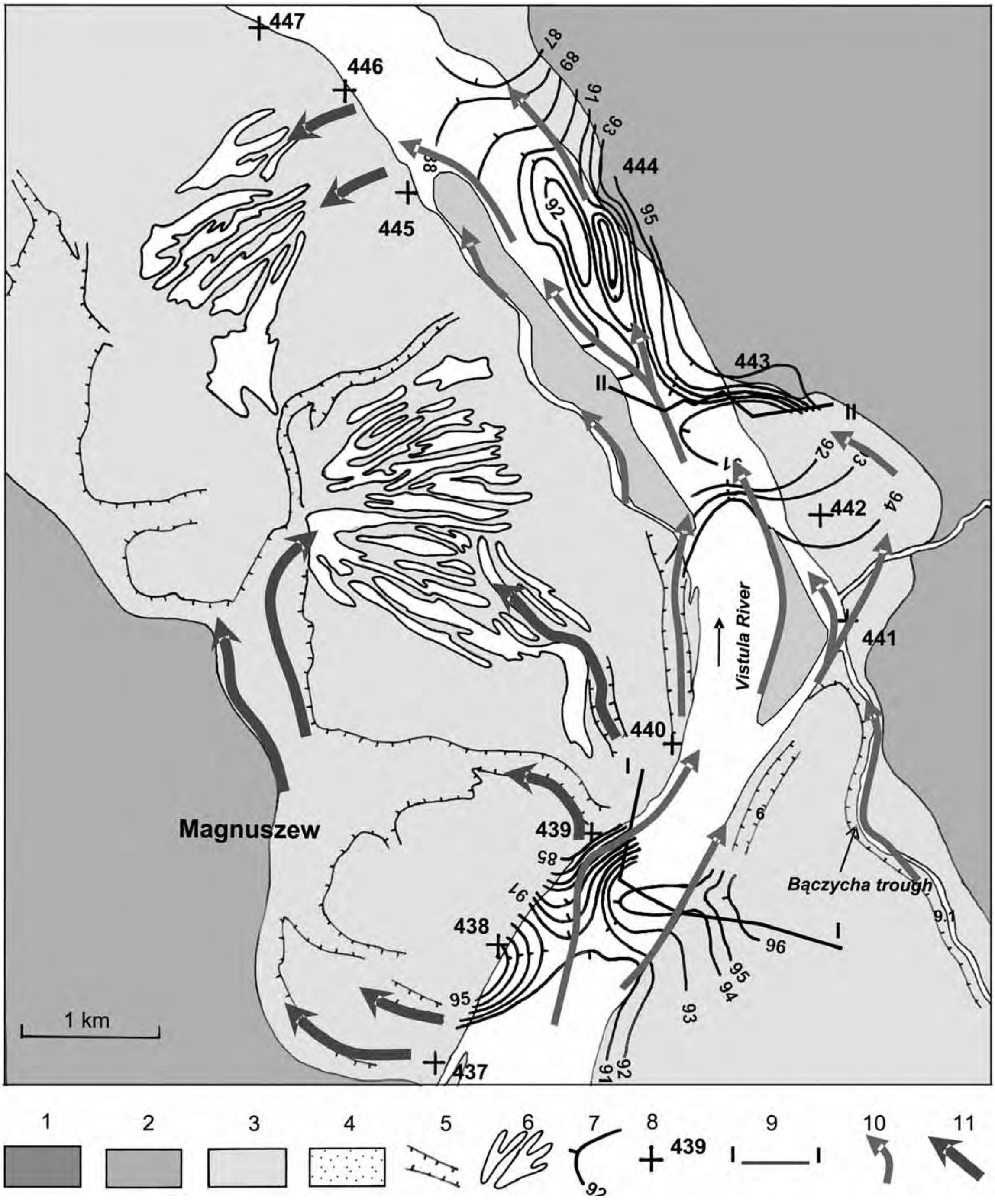

Fig. 2. Morphology of the top of the alluvial basement near Magnuszew in relation to the morphology of the floodplain (after FALKOWSKI 2006, modified). 1 – morainic plateau (only Fig. 7); 2 – Pleistocene terrace; 3 – floodplain; 4 – dunes on the Pleistocene terrace near Góra Kalwaria (only Fig. 7); 5 – erosion troughs and transformed oxbow lakes; 6 – alluvial fans; 7 – isohypse of alluvial basement surface; 8 – kilometre of river course (after RWMB); 9 – geological cross-section lines; 10 – channel main stream direction; 11 – direction of flood flows on the floodplain derived from its morphology and lithology

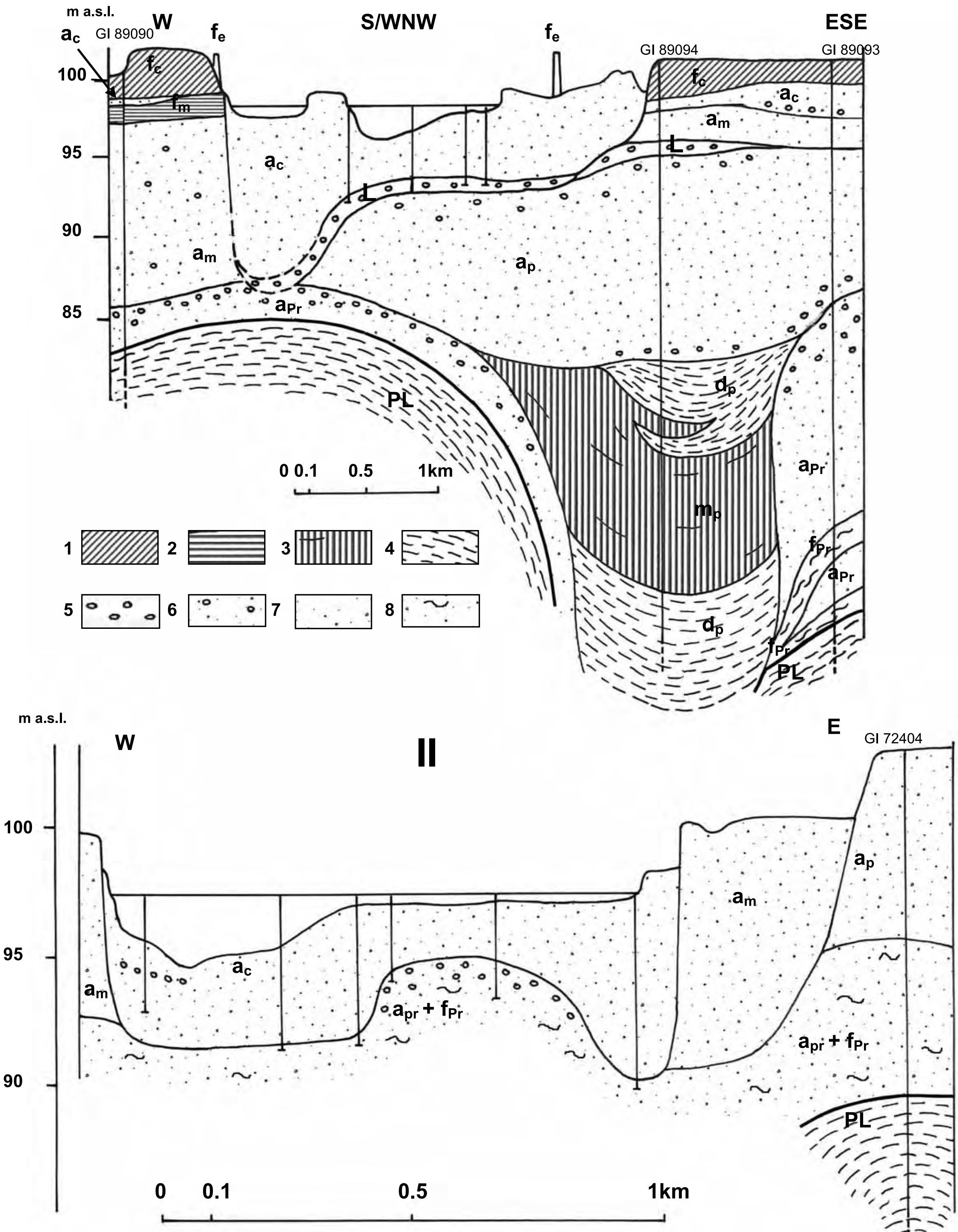

Fig. 3. Cross-sections through the Vistula River channel zone in the vicinity of Magnuszew (for location see Fig. 2). f_c – flood facies deposits of the present-day braided river; a_c – channel facies deposits of the present-day braided river; f_m – flood facies deposits of the meandering Vistula River (Holocene); a_m – channel facies deposits of the meandering Vistula River (Holocene); L – residual lags; a_p – channel alluvial deposits (Pleistocene); m_p – morainic deposits (Pleistocene); d_p – glacilacustrine deposits (Pleistocene); a_{Pr} – channel alluvial deposits (Eopleistocene); f_{Pr} – flood deposits (Eopleistocene); PL – Pliocene; fe – flood protection embankment; 1 – clayey silts, silts and sands, 2 – clayey silts, 3 – glacial tills, 4 – clays and silts, 5 – gravels, 6 – sands and gravels, 7 – sands, 8 – sands with silts (after FALKOWSKI 2006, modified); GI 89094 – archival borehole (Geological Institute)

89090 and 89093 (Text-fig 3 I) proved the top of Pliocene plastic deposits – so-called 'motley clays' (PL) – beneath the Eopleistocene deposits. Data from borehole 89094 (Text-fig. 3 I), in which the base of the Quaternary deposits was not reached at the final depth of 61 m, suggest the presence of a depression, most probably of glaciotectonic origin. This presumed depression is filled with disturbed Pleistocene glaciolacustrine deposits [silts and clays (d_p), glacial tills (m_p)], as well as occasional

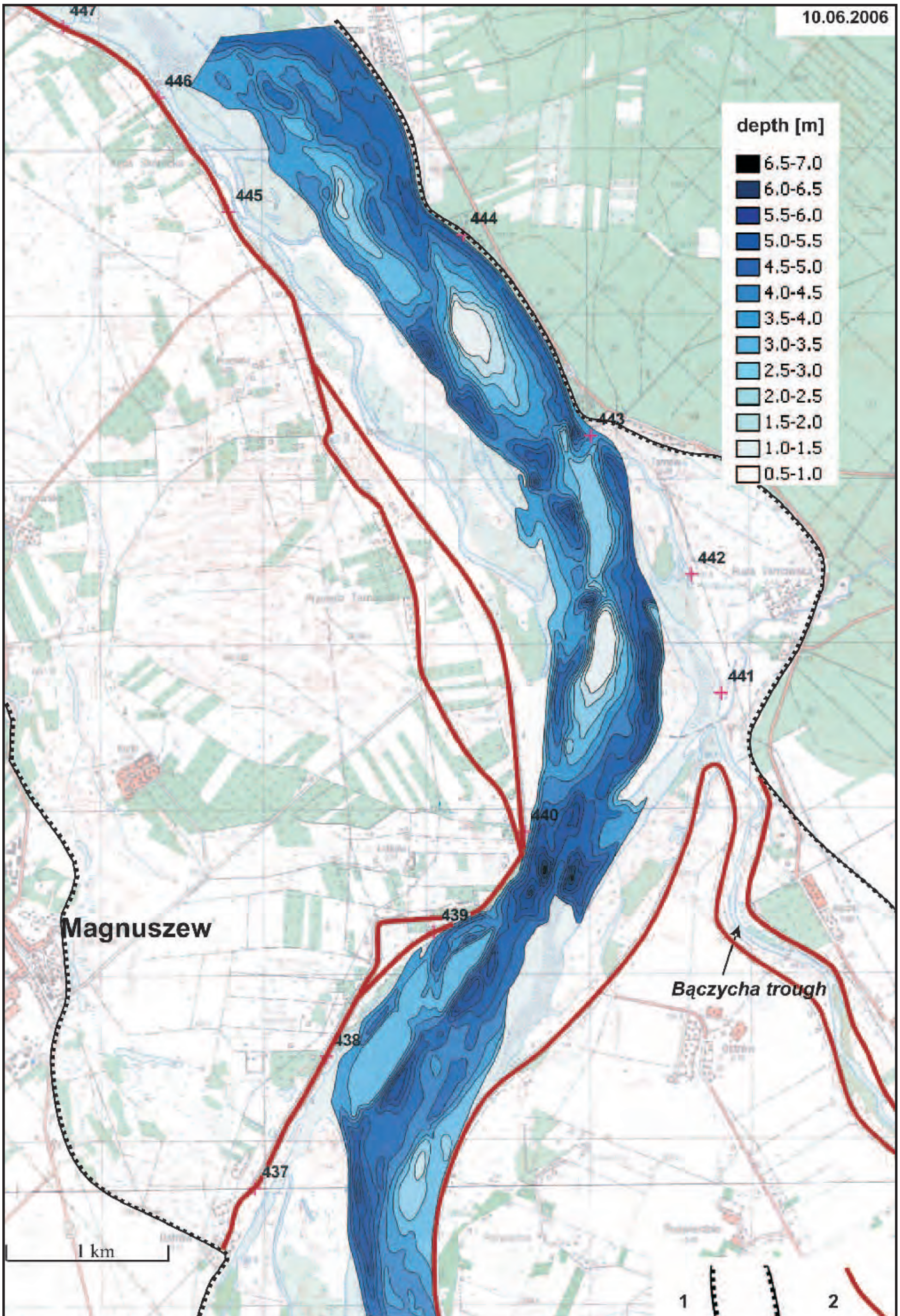

Fig. 4. Bathymetry of the Vistula River channel in the vicinity of Magnuszew on 10.06.2006 (during high-water stage – overbank discharge), with borders of the floodplain (1) and flood protection embankments (2) (after FALKOWSKI 2006, supplemented)

sands and gravels. These deposits are overlain by a series of Pleistocene channel alluvial deposits (a_p) covered by an erosion-resistant lag (L) of residual gravel pebbles (Text-fig. 3 I).

In the northern part of this reach the basement of the Holocene alluvial deposits and the present-day channel facies is composed of Eopleistocene preglacial alluvial deposits – strongly compacted sands and gravels (a_{pr}) with intercalations of clays and muds (f_{pr}). In the central part of the channel

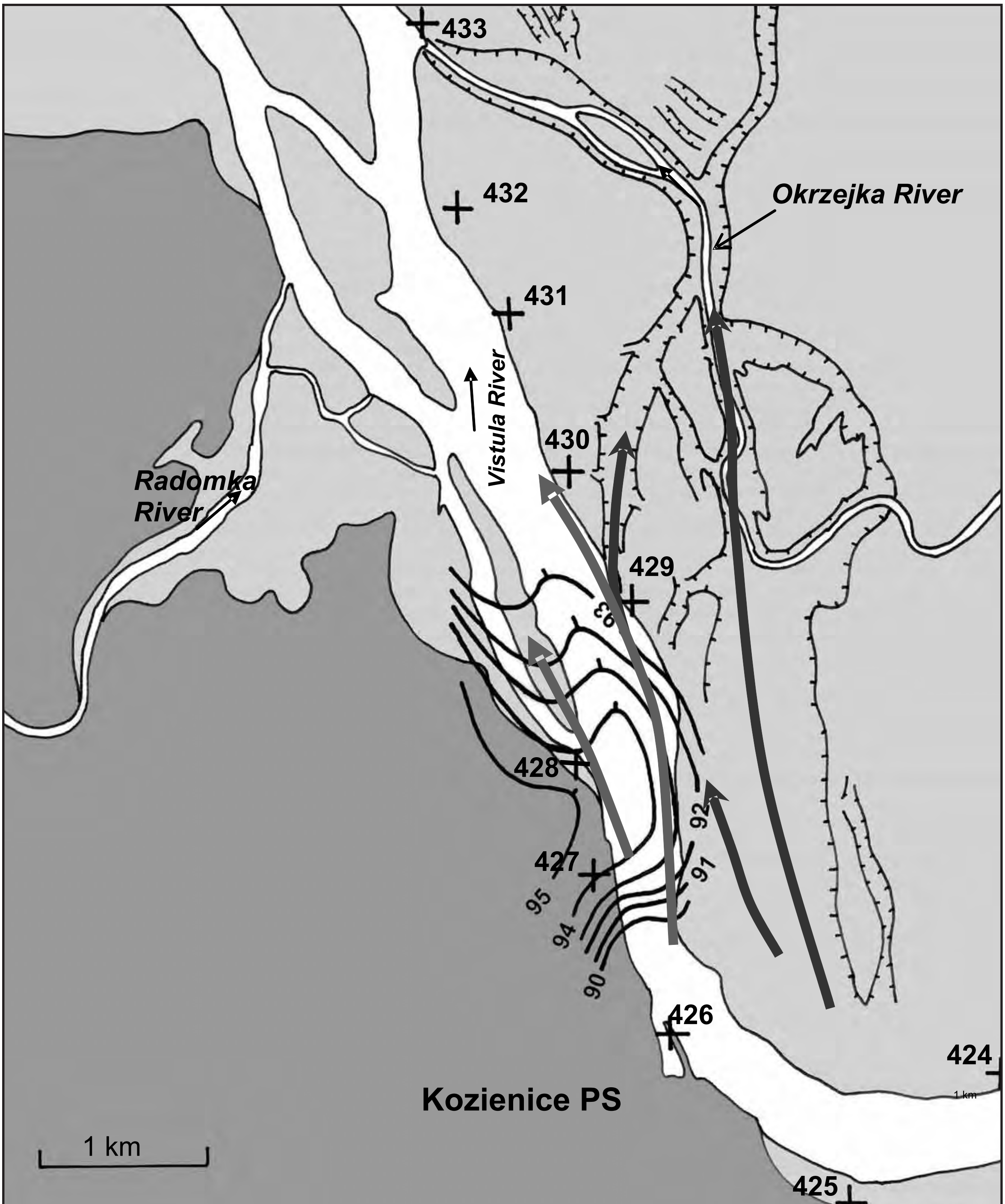

Fig. 5. Morphology of the alluvial basement in the vicinity of the outlet of the Radomka River to the Vistula River in relation to the morphology of the floodplain (after FALKOWSKI 2006, modified) (for location see Fig. 1); explanations Fig. 2; PS – Power Station

zone the upper part of these deposits bears a residual lag of gravels and pebbles (Text-fig. 3 II). In archival borehole 72404, the Pleistocene 'motley clays' were again proved beneath the Eopleistocene deposits.

Echo-sounding investigations enabled registration of the morphology of the channel bottom during the high-water stage (overbank discharge). The complex system of troughs, pot-holes and shallows in the river bed morphology indicates the presence within the channel of several zones over 10 metres deep in which the flow is concentrated (Text-figs 2, 4). The flow pattern depends on the morphology of the surface of the alluvial basement, as well as on the geometry of the high-water channel restricted by hydrotechnical constructions. The directions of stream concentration interpreted on the basis of bathymetric data are concordant with the pattern of depositional and erosional forms on the surface of the flood-terrace (Text-fig. 2, 4). These forms

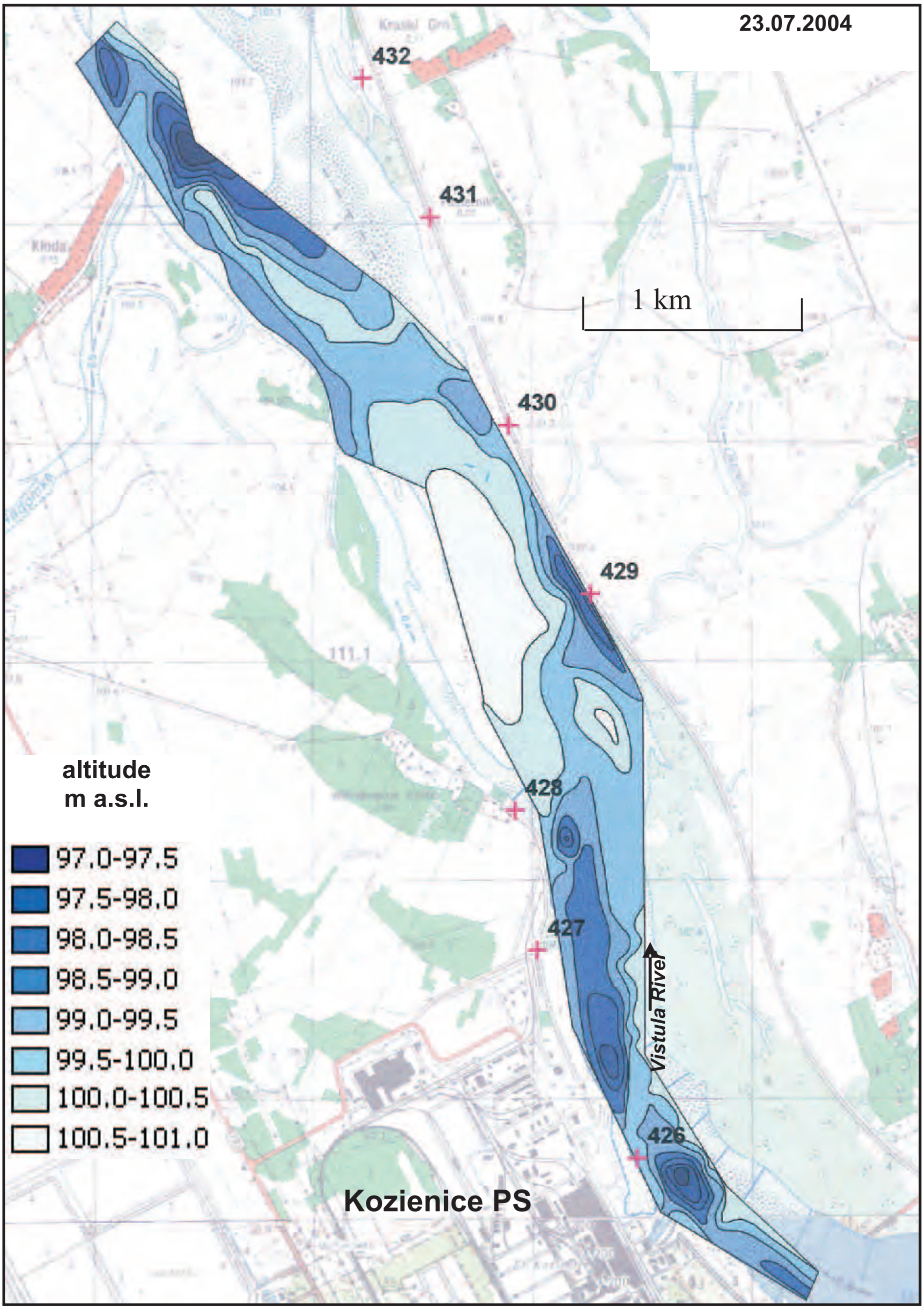

Fig. 6. Morphology of the Vistula River channel in the vicinity of the Radomka outlet during the mean water stage (after FALKOWSKI 2006)

originated both before the construction of flood embankments (in the Middle Vistula valley from after the flood in 1813 to the 1970s) and after breakage of the embankments.

On the flood terrace, high waters flow along newly eroded troughs or along abandoned longitudinal channels. In the outlets of high-water flows vast depositional zones commonly occur. These are alluvial fan-like sheets formed mainly due to deposition from suspended load material. They are related to depositional forms outside the channel, as described by ZIELIŃSKI (2000) in the Nysa Kłodzka

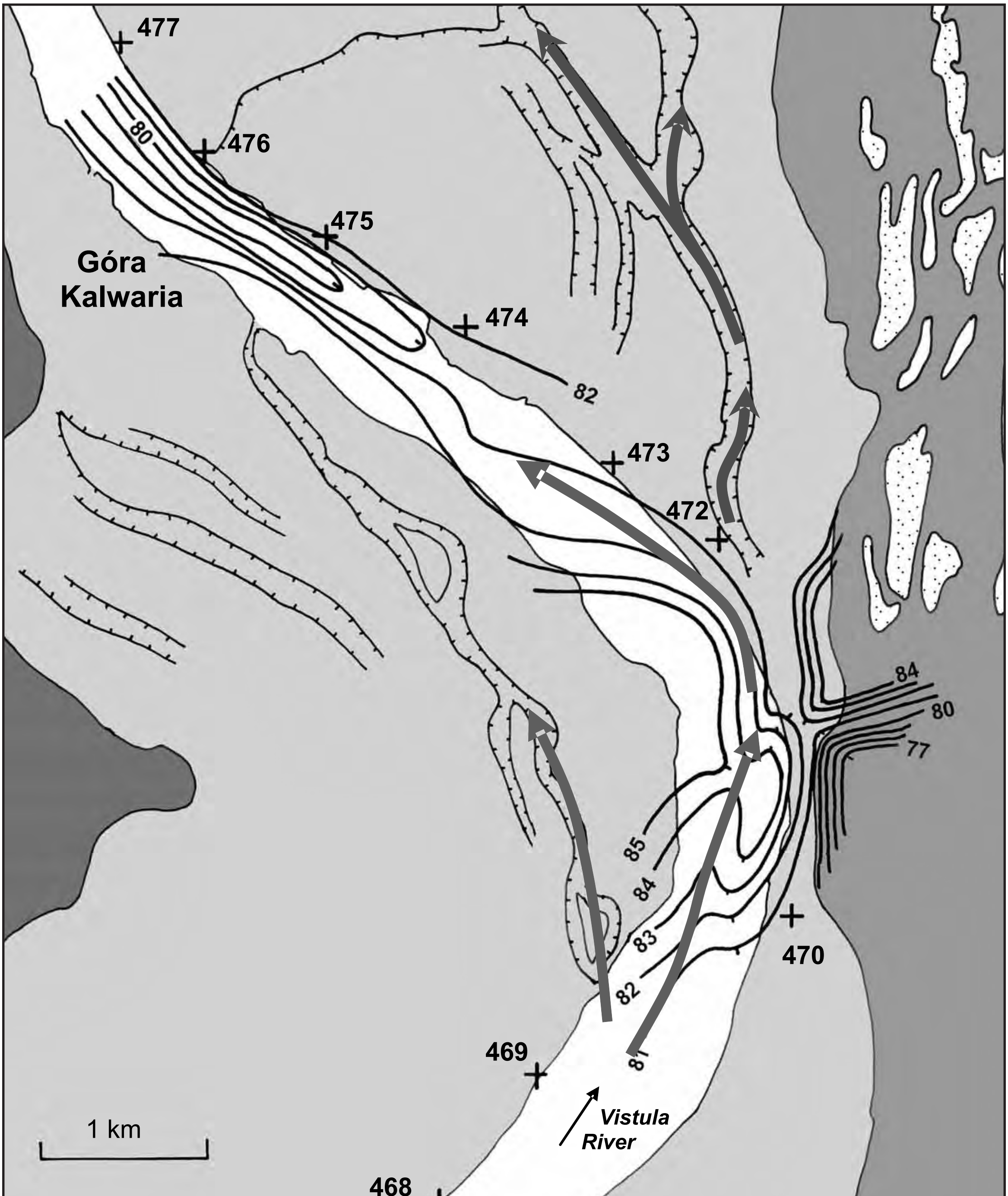

Fig. 7. Morphology of the alluvial basement in the vicinity of Góra Kalwaria in relation to the morphology of the floodplain (after FALKOWSKI 2006, modified) (for location see Fig. 1); explanations Fig. 2

valley (SW Poland) and by GĘBICA & SOKOŁOWSKI (2001) in the Upper Vistula valley. Depositional forms of this type from the Middle Vistula valley were linked by KARABON (1980) with the flows of the floods caused by ice jams. Such a form occurs north-east of Magnuszew (Text-fig. 2). It comprises radial sandy and sandy and silty bars, between which occur organic muds. In the south-east part, it shows traces of remodelling by waters which broke through the left-hand flood protection embankment at the sector between km 439 and 440, prior to its being reinforced by an additional construction (Text-fig. 4).

The second alluvial fan observed in this area, between km 445 and 447 (Text-fig. 2), is less distinct. Its formation can be linked with the SW flow after breaking of the embankment at km 446. Such damage has been noted previously in the history of this reach.

Investigations focused on the influence of the alluvial basement on changes of channel morphology in medium- and low-water stages have been carried out, among other places, near the outlet of the Radomka River to the Vistula River (Text-fig. 5). The protrusion of the alluvial basement occurs here in the form of a ridge composed of coarse-grained, compacted fluvial deposits of Pleistocene age, covered by a residual lag. Its surface reaches 94-95 m a.s.l. (on average 7.5 m below mean-water level). The Vistula channel in this reach runs below the escarpment of the Pleistocene terrace. Its surface is covered with aeolian sands forming vast sets of dunes.

Echo-sounding investigations were carried out during the mean-water stages. Downstream from km 426, a longitudinal trough was observed in the central part of the channel at about 97.5 m a.s.l. (Text-fig. 6). The course of this trough corresponds to traces of high-water erosion within the flood-terrace beyond the flood embankment (north of the channel) (Text-fig. 5). Deepening of the channel bottom surface also occurs near the left bank, at the outlet of the Radomka River.

Measurements made in a low-water stage showed a similar trend of concentration of the main flow as during mean water (FALKOWSKI 2006).

Comparison of the echo-sounding results with the morphology of the surface of the alluvial basement and the pattern of the channel zone shows that the presence of a resistant threshold caused, prior to the construction of flood embankments, eastward shifting of the high-water thalweg. The erosional trough of this flow is adopted by the Okrzejka River for its outlet section. The trend to form the flow in this direction is currently observed also in the channel bottom morphology. Troughs of high-water flows on the floodplain have the same directions (Text-figs 5, 6).

The stability of the channel morphology is also linked to the permanent position of depositional macro-forms in the channel. Examples of this phenomenon have been observed in the vicinity of Góra Kalwaria. The substratum of the present-day channel facies deposits (medium-grained sands with gravel) is developed in residual lags, formed due to washing out of coarse-grained fluvioglacial deposits and glacial tills. The surface of this basement forms a protrusion, reaching above 83 m a.s.l. in the south-east part of this valley reach. Along with the channel course the top of the alluvial basement lowers, forming a narrow trough near Góra Kalwaria, with its base at about 79 m a.s.l. (Text-fig. 7).

A distinct erosional niche occurs at km 470-471 in the right bank of the channel below the flood embankment. It lies in the axis of the high-water erosional trough, running northwards beyond the flood embankment. Its presence evidences the stable trend to concentrate the Vistula River thalweg during high water northwards from this zone. Furthermore, the pattern of the high-water channel confirming this trend has been indicated by echo-soundings. Such a trend to concentrate the high-water flow most probably also occurred during the late Pleistocene. This is evidenced by the orientation of elongated sandy bars (most likely remodelled aeolian dunes) on the surface of a Pleistocene terrace northwards from the channel (Text-fig. 7).

Aerial photographs taken in 1991 and 1999 (Text-fig. 8) showed the presence of stable elements of channel morphology in the form of large sand bars in the upper part of the reach under discussion. These sand bars occur in the area with the basement protrusions and do not undergo any significant transformation during high-water stages. Their formation cannot be attributed to the influence of regulation structures.

The lower part of the reach (km 475-478) is characterised by a rather stable morphology, which is the result of the reaction of the alluvial basement with regulation constructions.

DISCUSSION

As shown by the results of boreholes and soundings carried out in the Middle Vistula channel, the protrusions of the present-day alluvial basement, composed of resistant deposits, are exposed in the channel during high-water stages. This is evidenced by, for example, residual lags covering the protrusion surface, as well as by the lack of compaction of the present-day channel alluvial deposits. The present channel sands are loose or only slightly compacted. Exposure of the surfaces of the protrusions is also evidenced by echo-sounding measurements carried out in the Middle Vistula channel during high-water stages (i.e. the above-presented investigations near Magnuszew – Text-fig. 4). The exposed surface of the alluvial basement directly influences the pattern of the main stream in the high-water channel (FALKOWSKI 2006). As evidenced by echo-sounding, the course of the high-water stream is generally concordant with the course of the thalweg at medium- and even low-water stages. This is shown by the example from near the outlet of the Radomka River (FALKOWSKI 2006). The same phenomenon has also been observed in reaches devoid of regulation structures. In such reaches the course of the thalweg should change according to the water stages in the channel (e.g. FRIEDKIN 1945, DURY 1969). However, in zones with protrusions of the alluvial basement in the Vistula River, the course of the thalweg also depends on the specific 'channel memory' (FALKOWSKI 2006). The zone of high-water current concentration determined by the morphology of the alluvial basement is also the zone of systematic and deep alluvial reworking. During fall of high-water flows, loose sediments are deposited in the channel. Loose sediments are then more readily washed out during flows lower than the maximum (FALKOWSKI 2006).

The occurrence of a stable trend to concentrate the flow depending on the morphology of the basement surface culminations poses a hazard to the

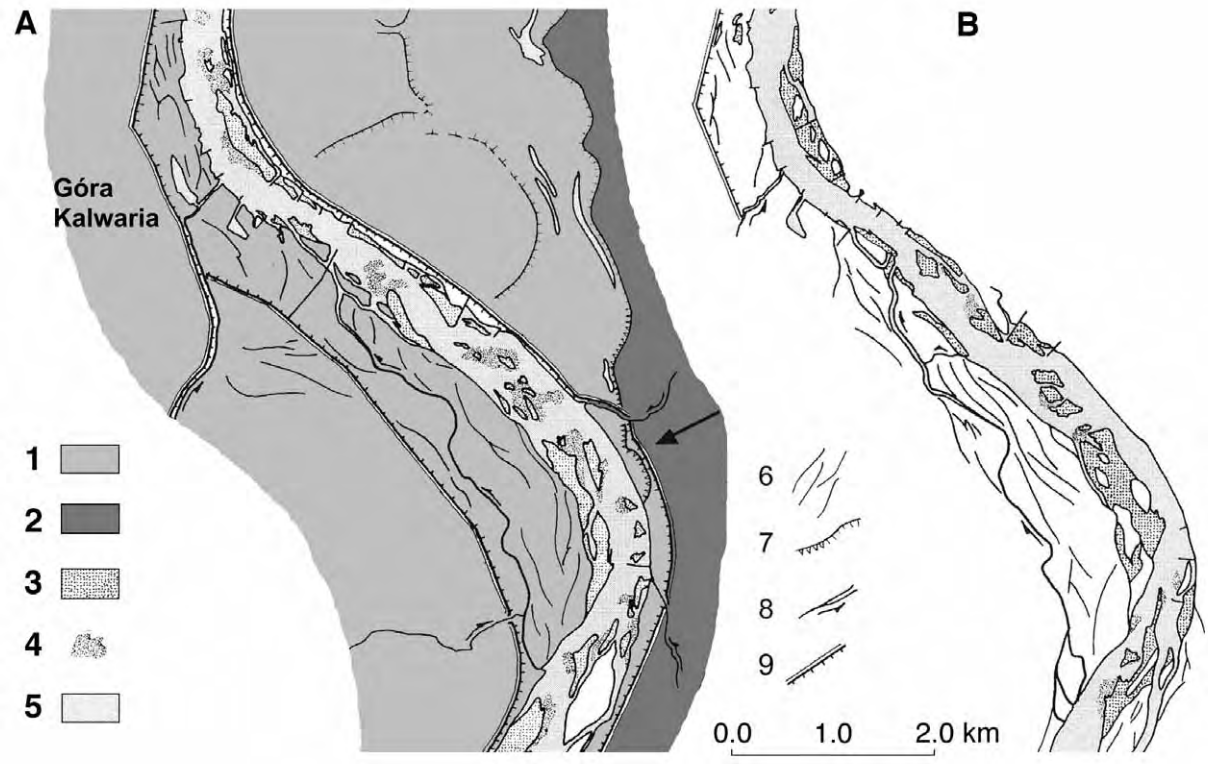

Fig. 8. Changes in the morphology of the Vistula River channel in the vicinity of Góra Kalwaria based on aerial photographs from 1991(A) and 1999(B) (FALKOWSKI & ZŁOTOSZEWSKA-NIEDZIAŁEK 2003). 1 – surface of the present-day terrace (braided river) and bars stabilised by vegetation, 2 – surface of Pleistocene terrace, 3 – young sandy bars without vegetation, 4 – larger bars below water level (shoals), 5 – water, 6 – traces of braided channels on the surface of the present-day terrace, 7 – escarpments formed due to erosion of high-water, 8 – direction of water flow in erosional flows and troughs on the surface of the present-day channel, 9 – flood embankments; arrow points to erosional escarpment formed by high-water (bankfull discharge)

existing regulation structures and the flood control system. This is exemplified by the flood embankment near the the Radomka River outlet (Text- figs 5, 6), which is eroded at both medium-and low-water stages, as well as by the region of Góra Kalwaria (Text-figs 7, 8).

A startling example of such a hazard is the reach of the Vistula channel near Magnuszew between km 438 and 440 (Text-figs 2, 4). The concentration of high-water currents controlled by the basement morphology is the cause of continuous damage of the bank constructions, particularly at km 439. The presence of the groynes and transverse dams built there in 1992 resulted in the deposition of sands in the cut-off part of the channel. As shown by echo-sounding data, this is the place where the high-water stream concentrates. It erodes the artificial island formed by the action of regulation structures (groynes and transverse dams). The constructions themselves (built of a rubble bed on a fascine mattress) undergo continuous degradation. From the reconstruction in 2005 until the present (May 2006), the height of their top has decreased on average by 0.5 m. The concentration of the high-water flow caused by the protrusions of the alluvial basement is the reason for the damage caused to the flood embankment on the left bank of the Vistula River at km 445.

The concentration of the high-water stream also causes erosion of the bank of the Pleistocene terrace between km 443 and 444, which is a hazard for a busy traffic route. A similar case was recorded downstream at Góra Kalwaria (Text-figs 7, 8).

CONCLUSIONS

1. The concentration of the high-water flow caused by the presence of erosion-resistant protrusions of the alluvial basement is the reason for spatial differentiation of erosion intensity and for the character of the high-water sedimentary environments. This phenomenon can be the cause of continuous damage to regulation structures.
2. The geomorphological features of the terrace surface can be used as an indicator of the occurrence of erosion-resistant protrusion zones in the alluvial basement. The influence of the alluvial basement on the stream concentration should be considered in engineering geological forecasts concerning the durability of hydrotechnical structures.
3. Consideration of protrusions of the resistant alluvial basement in determining the river action, and in influencing the stability of hydrotechnical constructions, should be included in the river regulation system. This requirement is concordant with the present-day practice in river engineering related to the rule of natural regulation (e.g. KERN 1992, LARSEN 1994, ŻELAZO & POPEK 2002).

Acknowledgements

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