Alluvial basement influence on channel processes in urban reaches of the middle Vistula River, Poland

TOMASZ FALKOWSKI[1]

[1] *Dept. of Geotechnical Engineering Waw Agr. Univ. (e-mail: tomasz_falkowski@sggw.pl)*

Abstract: During a geological survey of the valley of the Vistula River, sub-alluvial 'basement highs' were detected in certain sections of the river channel. These sections proved to be outcrops of Mesozoic rocks - marls and limestones, Tertiary sediments such as clays and sands; Quaternary sediments such as boulder clays, ice-dam deposits and occasionally dense, coarse-grained, fluvioglacial sediments were found. Overlying these structures the presence of residual lags was observed. The relatively shallow depth of these features implies they are more resistant to erosion than other parts of the sub-alluvial channel. The presence of such resistant sections has a crucial influence on the natural stability of the long profile of a river and is also suspected to be a factor increasing the probability of the initiation of ice jams and resulting ice jam flooding - characteristics which are the most important considerations for planning urban development along such known river stretches.

This paper also highlights some of the geological sub-alluvial 'basement' characteristics of the Middle Vistula River for the cities Pulawy, Deblin and Warsaw.

Résumé: Les études géologiques du lit de la Vistule centrale ont démontré l'existence dans ses limites d'une culmination de la couche d'alluvions. Parmi les roches qui composent ces formes, les études confirment l'existence de roches solides du mésozoïque : gaizes, marnes, calcaires, gaizes du tertiaire, mais aussi des sables et des argiles et des dépôts datant du pléistocène : argiles glaciaires, argiles, dépôts de limons et matériaux de fonds à gros grain localement densifiés.

A la surface de ces formations, on constate couramment la présence de pavés résiduels. La localisation peu profonde de ce type de structures confirme leur résistance aux processus d'érosion. Dans le profil longitudinal du lit de la doline, les zones de leur apparition sont caractérisées par une croissance visible de l'inclinaison de sa surface. Les seuils difficilement affouillables observés dans la couche des alluvions sont très importants pour la stabilisation du lit de la rivière dans le profil longitudinal ; ils peuvent également retenir l'onde de crue.

Ils contribuent également à un plus grand risque de manifestation d'embâcles et des crues qui s'ensuivent. Ces phénomènes sont à la base de la morphologie caractéristique de la surface en terrasse dans les zones d'apparition des seuils. Nous y trouvons des couloirs d'érosion des écoulements des crues ainsi que des formes de dépôt caractéristiques.

L'ouvrage présente une courte caractéristique de certaines sections urbaines du lit de la Vistule centrale où l'on observe différentes culminations de la couche d'alluvions du point de la lithologie des roches qui le composent (Puławy, Dęblin et Varsovie). L'ouvrage présente également certaines des structures caractéristiques des matériaux de fond et des matériaux de crue présents dans ces zones.

Keywords: alluvium, erosion, floods, geomorphology, rivers and streams.

INTRODUCTION

The presence of sub-alluvial 'basement highs' has been noted within river valleys in the Polish Lowlands. These 'highs' comprise deposits more resistant to erosion than the usual lithologies comprising alluvium. Moreover, they may act as erosion bases for upstream reaches, which have a tendency to stabilize the longitudinal profile of the river channel.

Consequently, during high water, the river channel cannot increase its cross-sectional area by erosional deepening as in the case of mature rivers. Therefore, in such high water events erosion (as well as depositional processes) is intensified beyond the zone of the main river channel.

As noted, the morphology of these sub-alluvial 'basement highs' constrains the channel course. In such places the water depth is typically shallower, because during the flooding conditions, alluvial sediments (building macro- and meso- sedimentary forms) tend to be deposited on these 'highs'. Comparative analysis of air-photos and historical map data confirms the stable position of such sedimentary forms. They undergo little transformation, and are permanent elements of the channel morphology. In the past they often provided natural opportunities for river crossings (fords), around which settlements grew in many instances becoming established towns.

Culmination zones of the alluvial substratum playing a crucial role in stabilizing the natural environment of valleys are subject to strong anthropopression in their urban reaches.

AIM OF INVESTIGATIONS

The investigations were focused on determining the influence of sub-alluvial 'basement highs' on the dynamics of erosion and deposition processes, both within and beyond the river channel. Forecasting the scale of such events is particularly important for urbanized areas, where the potential damage caused by high water can be of economic significance. The density of hydrotechnical structures of the channel in such reaches is an additional element constraining the river and influencing the course of high water (they cause flood water damming). Most probably in the future, this influence will increase due to the rising trend of extreme rainfall events, currently observed in the Polish Lowlands (Ozga-Zielinska 1997), and, what follows, the increase of the discharges volume and extreme states in the rivers. This phenomenon can be exemplified by the flood, which took place in Poland in July 1997 (Stachy & Bogdanowicz 1997). The zones of these 'basement highs' are also predisposed to the formation of ice jams (Falkowski & Popek 2000).

The investigations also included:

- determination of morphological features of the terrace surface and the structural and textural features of the fluvial deposits in the said zones
- what parameters aided forecasting the position of these sub-alluvial 'basement highs'? Knowing where they occur enables a prediction of the fluvial and substrate environments (e.g. Florsheim & Mount 2003), necessary for planning engineered structures.
- seeking indicators of sub-alluvial 'basement highs' within mature rivers beyond the study area

The occurrence of natural elements stabilising the channel in the valley bed (Falkowski 1990, Eaton et al. 2004) should be taken into account in river valleys management projects, projects of rivers regulation and renaturisation (e.g. Gilvear 1999), location of river water intakes, riverbank groundwater intakes or other objects located in the river valley beds.

METHODOLOGY

The investigations were carried out within a 250 km reach of the Middle Vistula from Annopol to Modlin (Figure 1), characterized by a variable surface morphology and lithology of the rocks building the valley substratum. The upper part of the investigated reach, from Annopol to Puławy is a narrow zone of the so-called Vistula Gorge through the Middle-Polish uplands (Pozaryski 1953, 1955, Pozaryski et al. 1994, 1999). The sub alluvial stratum here comprises Upper Cretaceous rocks – opokas, marls and chalk. Below the gorge the valley widens. Down to Puławy the alluvial substratum comprises Palaeogene rocks – opokas and gaizes. Further downstream, deposits representing the Oligocene (sands, muds and clays), Miocene (sands and muds), Pliocene (clays) and Pleistocene (various lithologies) occur.

The investigations included the geomorphological analysis of the terrace surface. Its main aim was to find traces of high-water erosion – relief channels, or arrays of oxbow lakes transformed by high water on the Holocene terrace surface (the geological setting of E. Falkowski was utilised). High-water flows (with high erosive capability) normally result in rapid deposition downstream. Thus, alluvial fans should occur at the mouths of relief channels below the 'basement highs'.

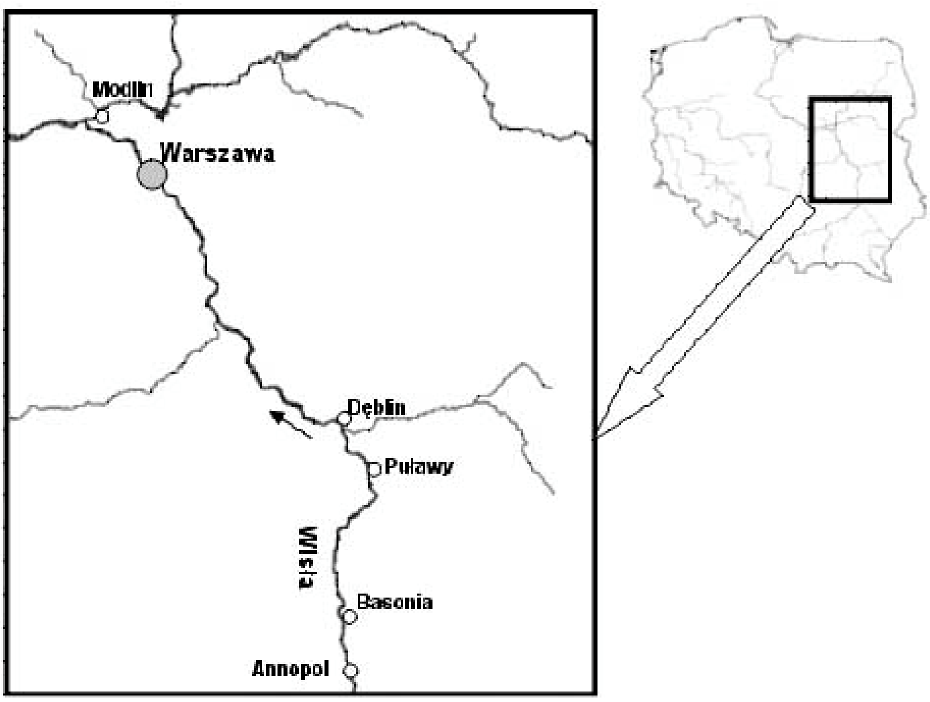

Figure 1. The study area: the middle section of the Vistula (Wisła) River and in particular the urban centres of Pulawy, Deblin and Warszawa (Warsaw)

The formation of such features may be linked with water head on ridges (sub-alluvial 'basement highs'), as well as ice-dam floods generated in such zones (Falkowski & Popek 2000). Analysis of historical data, referring to the presence of ice-damming phenomena in the studied reach was also carried out.

Results of repeated echo sounding investigations of the channel have also been analysed. Further investigations were carried out in these localities with a stable position of the channel level in longitudinal cross-sections. Comparative analysis of the channel morphology, focused on zones with permanent depositional forms was also undertaken.

Drilling was carried out in 18 channel zones selected during the preliminary analyses; each zone was between 5-7 km long. Samples of the alluvial sequence and strata below the alluvium were collected for laboratory tests; the physical-chemical parameters of the sub alluvial strata were determined and the stratigraphic position of the beds was established.

Sedimentary structures observed in the present-day deposits and at channel margins were described and analysed. These sediments were deposited during high water, often before the construction of flood embankments.

The selected 18 channel zones were also subject to echo sounding of the channel at different water states. An integrated measuring device comprising an echo sounder + GPS receiver (DGPS), allowing measuring and registering the coordinates of the measuring point along with the channel depth at a selected time interval (the measurements were made every 3 seconds) was used.

Historical hydrogeological data together with records of past man made structural failures and the known presence of scour zones have been reviewed and analysed. These results form part of the GIS database.

RESULTS

The research distinguished different types of sub-alluvial 'basement highs', the morphology of which influenced the concentration of the main high water current, and thus caused permanent variability of the sedimentary environments in the channel before the regulation and after constraining the river by man made engineered structures. Sedimentary structures observed after the fall of high water may provide invaluable indicators in assessing the geological-engineering environment within the channel zones, and enabling the construction of better conceptual geological models. Examples of morphology and lithology of escarpments in urban reaches and their influence on river processes are presented below:

Puławy (Figure 2)

Detailed investigations were carried out in the channel zone between Parchatka and the bridge at Puławy (365-371 km) (Figure 2). This is a fragment of a narrow valley formed as an epigenetic river gap after the retreat of the Odranian Glaciation ice-sheet. The pre-Odranian valley, observed in borehole sections, occurs from the vicinities of Parchatka towards the NE, omitting Puławy (Pożaryski et al. 1994). The higher, Pleistocene terrace, in the analysed reach occurs in form of a narrow shelf between Parchatka and Puławy.

Borehole investigations commenced in the channel indicated the presence of a several kilometres-long zone of sub-alluvial 'basement highs', built of Upper Cretaceous opokas and limestones, covered by clayey carbonate residuum. This surface is commonly covered by a residual lag comprising boulders of the substratum rocks as well as Scandinavian material. Here the sub alluvial stratum forms a ridge running parallel to the channel. The ridge surface lies maximally at 112 m a.s.l. between marker points 365 and 367 km. The surface of the higher flood terrace in this reach (Pożaryski et al. 1994, Żarski 1998) lies at ca. 120 m a.s.l. This surface rises at 2-3 meters above the average water level. Echo sounding investigations of the channel allow the supposition that the presence of the ridge causes separation of the high water into two streams parallel to the present-day channel. Before the construction of flood embankments, high water flowed on the surface of the flood channel, causing it to change shape and direction, pre-existing ox-bow lakes, provided preferred flow routes whilst earlier deposits of clay-rich muds were subsequently covered by silt-rich muds (Falkowski 1982, Myślińska 1984);

The presence of sub-alluvial 'basement highs' over a 5-km reach of the River Vistula above Puławy is considered the main reason of why so many ice-dams have been recorded here (e.g. in 1924, 1963, 1964 and 1967).

Dęblin (Figures 3 and 4)

The sub alluvial stratum in the channel zone adjacent to the town of Dęblin is composed of sands, silts and clays (locally with organic matter) of Palaeogene (Oligocene) age. Investigations indicate a longitudinal ridge covered by a residual lag, adjacent to the right bank – the highest point lying at 107 m a.s.l. (Figures 3 and 4).

The River Vistula near Dęblin is subject to frequent ice-jams (recorded here in 1924, 1935, 1940, 1963, 1964, 1965, 1966, 1974, 1977, and 1979). Before the construction of flood embankments, flood water damming the mouth of River Wieprz (including ice-jam initiated floods) flooded NW on the area of the higher flood terrace (mud terrace), incising longitudinal depressions within it. At their downstream ends, elongated sandy bars were often deposited. One such bar has been utilised for protection against flooding and forms several hundred metres of the flood embankment in Głusiec (Figure 3).

W and NW of the zone of concentrated high water flows, the surface of the mud terrace is only slightly altered. It shows signs of displacement of the meandering Vistula channel and ox-bow lakes whilst clayey muds dominate on the terrace surface.

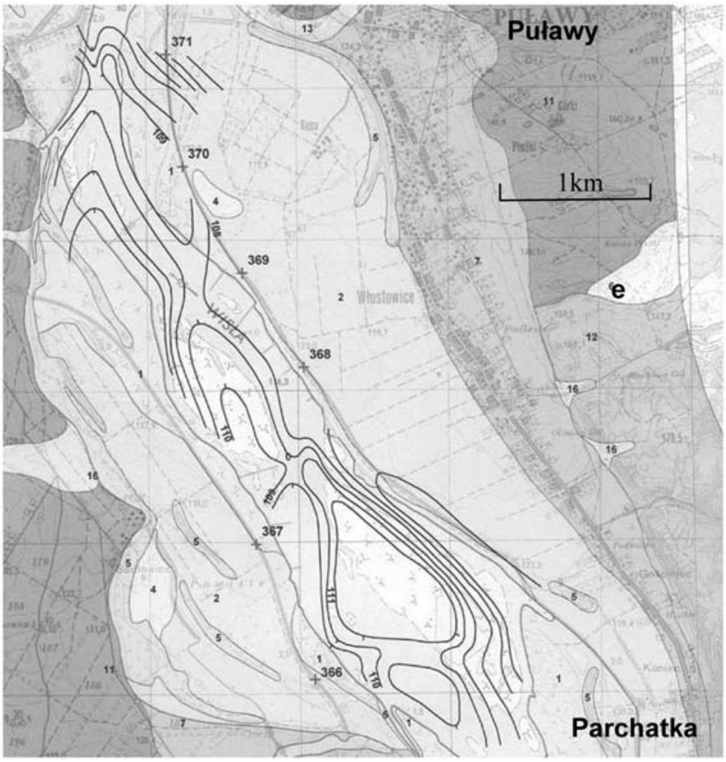

Figure 2. Geological map of the Vistula River Valley near Puławy with isohypses of erosion resistant deposits surface (part of the GIS project); 1 – silty-sandy mud of contemporary Vistula, 2 -– silty-sandy muds on clayey muds of the meandering river, 3 – clayey mud of the meandering river, 4 – sands of the channel facies of the contemporary river, 5 – humus sands, alluvia and peats of the ox-bow facies, 6 – sands forming water bars on the flood terrace (flood fans), 7 – 'brown' silty-sandy muds of the braided Pleistocene river, 8 – other humus soils, 10 – slope deposits, 11 – glacial deposits, 12 – loesses, 14 – Upper Cretaceous opokas, gaizes and marls, 16 – alluvial fans, 17 – tributary valleys bottom, e – aeolian sands.

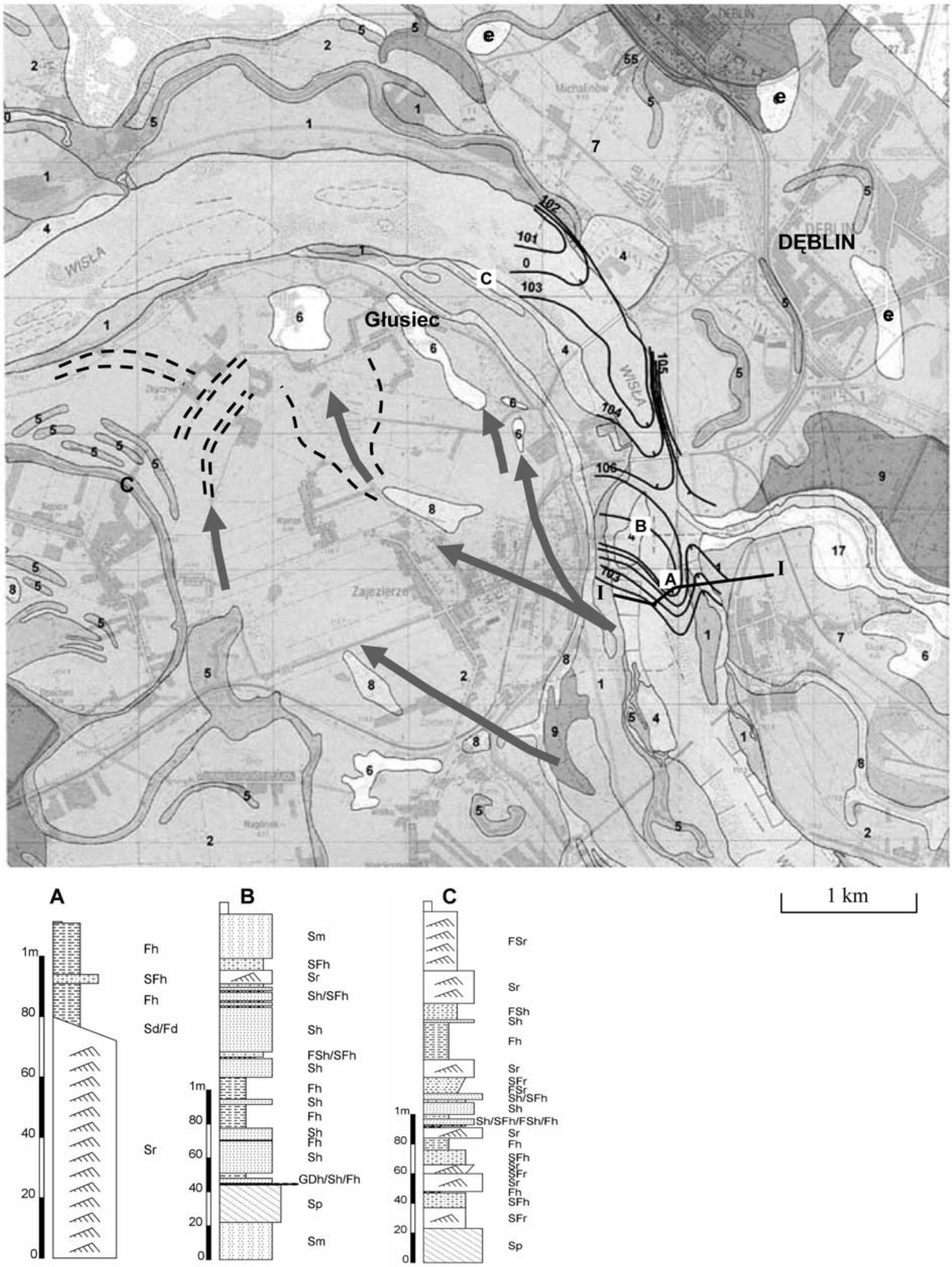

Figure 3. Lithology of Vistula Valley surface near Dęblin with isohypses drawn on the Holocene alluvial basement and structures of contemporary alluvial deposits (lithofacies code after M.D. Miall 1996); arrows shows main stream direction of flood waters, dashed line – examples of erosion scarps of flood waters, e – aeolian sands, A, B, C – litofacial analysis of contemporary alluvia, crops out in the channel zone, I-I cross-section line (Figure 4); further explanations on Figure 2.

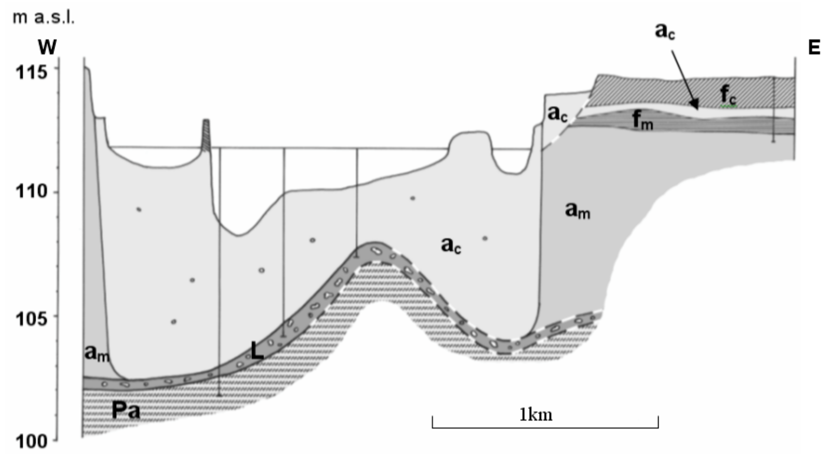

Figure 4. Geological cross-section of Vistula River channel zone in D blin (see Figure 3 for the locality); Pa – Paleogne clays, L – residual lag (gravels, pebbles), a_m – channel sands of meandering Vistula, f_m – flood deposits of meandering Vistula (clays), a_c – channel sands of contemporary Vistula, f_c – flood deposits of contemporary Vistula (silts, clayey silts).

Since the construction of flood embankments, floodwater now tends to flow towards the NW resulting in the formation of erosion troughs on the lower flood terrace, at the base of the flood embankment.

During flood events, alluvial sediments typical of the flood plain environment [lithofacies Sr, SFr, Sh, Fh and SFh according to Miall (1996)] are deposited over the sub-alluvial 'basement highs' (see graphic logs illustrated in Figure 3).

Warsaw (Figures 5,6 and 7)

In the vicinity of Warsaw, the sub-alluvial 'basement highs' occur between marker points 503 and 527 km (Figure 5). The surface of the resistant alluvial substratum comprises Pliocene clays, morainic tills, ice-dammed clays and silts as well as fluvial gravels and sands (glacial and interglacial) (Falkowski 1990, Falkowski 1999, Sarnacka 1992) (Figure 6).

The surface morphology and properties of lithologies forming the resistant ridges indicate their low susceptibility to erosion. The Pleistocene channel facies sands, as well as ice-dam deposits such as fine-grained sands, silty sands and silts, which built up the ridges tend to be very dense, the deposits forming the resistant ridges are often strongly compressed. Samples of Pliocene and Pleistocene clays, and in some cases of the glacial tills, collected from beneath the riverbed proved high levels of induration suggesting glaciotectonic compression. In some cases the topmost part of these ridge deposits exhibited a soft-plastic state (ca. 0.5 m), whereas below this they became more indurated (hard plastic or semi-cohesive). Similarly as in the case of the fluvioglacial deposits, the presence of residual moraine lags, comprising gravels and pebbles, is a common feature of the cohesive deposits (Pliocene clays, glacial tills and ice-dammed deposits). Locally, concentrations of boulders are also observed. The thickness of the residual zone typically does not exceed one metre.

Several zones can be distinguished in the morphology of the alluvial substratum in Warsaw:

- ridge zones where the thickness of alluvial deposits is the smallest (substratum deposits are practically exposed in the channel),
- depressions of alluvial substratum zones (pot-holes of high waters), where the thickness of alluvial deposits reaches up to 20 m, zones in which the substratum forms an almost horizontal surface, and
- zones of longitudinal depressions in form of troughs running often obliquely to the present-day channel (Figure 6). The diverse character of the culminations morphology resulted from glaciotectonic and glacioisostatic deformations, erosion and presently also with human activity (e.g. channel dredging).

Channel reaches upstream of the stabilising ridges are built of sediments with low susceptibility to washing-out and are thus zones of intense sedimentation whilst reaches below the ridges tend to be zones of intense high water erosion leading to pot-hole formation. After the fall of high water, channel sediments are subsequently deposited here. These sediments are characterised by variable grain size (from fine sands to gravels), typical of braided river sediments, and very low density. The reworking level after each high water is recorded in this loose sediment as a bed enriched with coarser grains. The width of the Holocene terrace distinctly narrows in reaches underlain by the 'basement highs'.

As noted previously, the occurrence of sub-alluvial 'basement highs' stabilises the mean course of the channel bed at a current flow regime. Man induced modification (or destruction) of the residual lag typically covering these ridges, or changes of flow regime in the channel may result in the lowering of the mean bed level. According to Kornacki (1960) and Zielińska (1960), the Vistula channel in the Warsaw urban reach has undergone gradual lowering since the late 1940-ties. To complicate the issue at Warsaw, this riverbed lowering may be the result of known intense gravel extraction from the channel for building purposes, which inevitably locally increased water velocity and stream erosive energy. Most probably, another cause of the lowering of the riverbed bed in the Warsaw reach was the exploitation of boulders from the topmost residual part of the resistant ridge (cofirmed by RZGW survey observations

- Figure 7). Lowering of the riverbed level has hazardous implications for the Warsaw surface water and groundwater intakes, as well as the safety of the hydrotechnical channel structures.

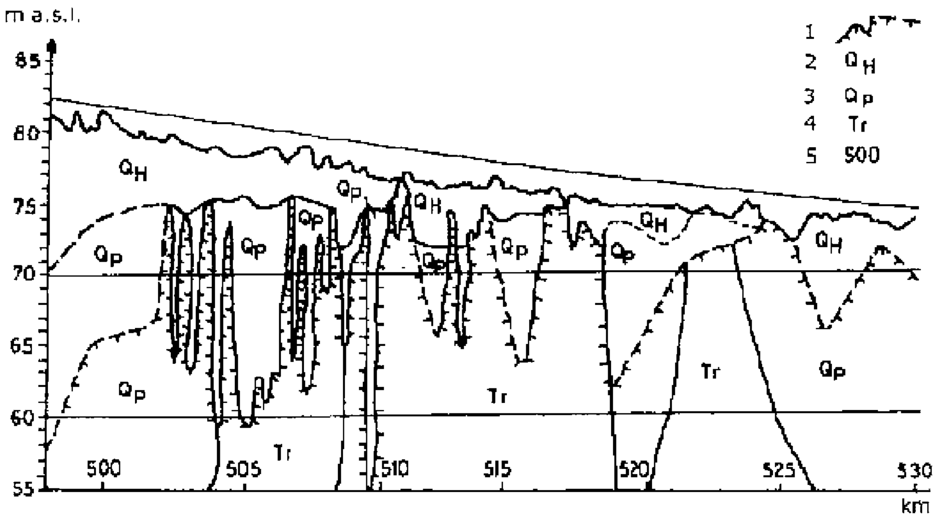

Figure 5. Longitudinal schematic cross-section of Vistula River channel zone in Warsaw (Falkowski 1990); 1 – surface of erosion resistant deposits surface, 2 – Holocene channel deposits, 3 – Pleistocene deposits, 4 – Tertiary Pliocene clays, 5 – kilometres of river course

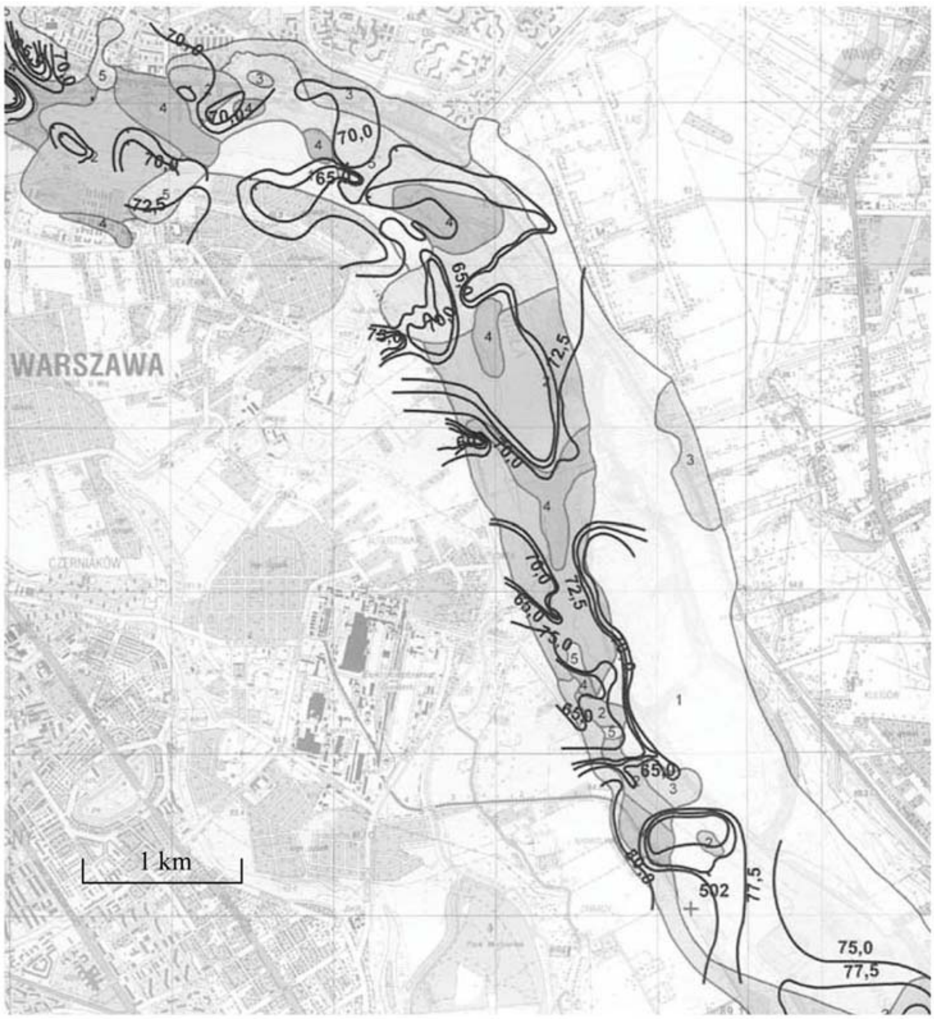

Figure 6. Map of Holocene alluvia basement lithology and morphology (isohypses) of channel zone - example from south and central part of Warsaw Vistula reach; 1 – channel sands, 2 – ice-dam silts, silty sands and clays, 3 – gravels, 4 - boulder clays, 5 – clays; 1,2,3,4 – Pleistocene, 5 – Pliocene,

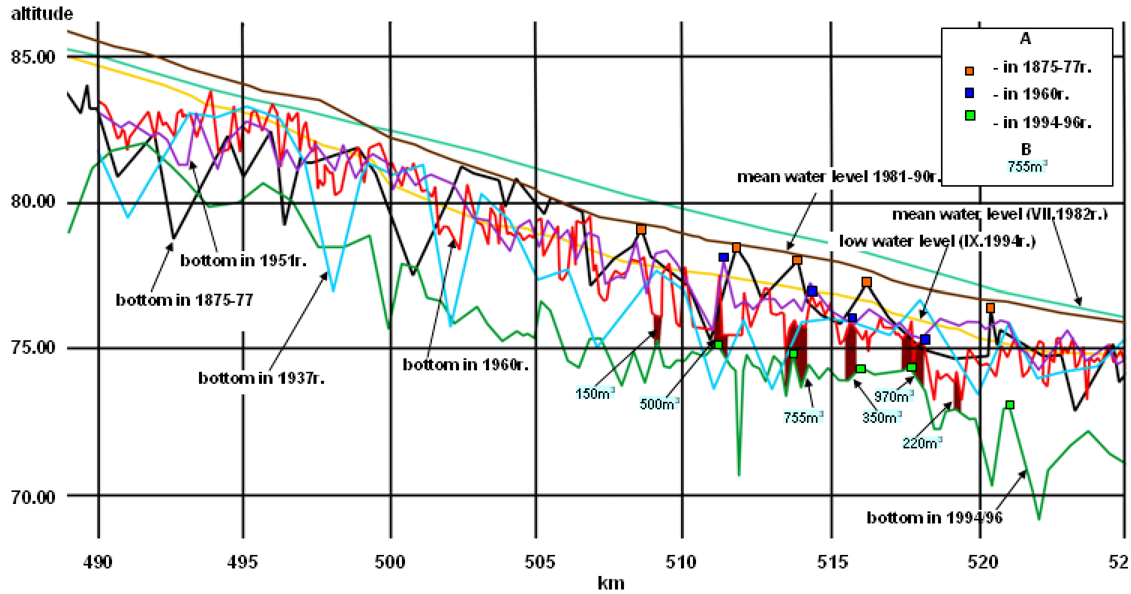

Figure 7. Changes of Vistula channel bottom level in Warsaw (after RZGW).

CONCLUSIONS

The investigations have shown that:

- in many reaches of rivers in the Polish Lowlands, sub-alluvial 'basement highs' are a common feature – importantly, they are present in a number of major urban developments
- sub-alluvial 'basement highs are characterised by localised riverbed erosion, therefore particularly in the urban areas where they may subject to intense modification by man s activities, they should be carefully monitored and protected.
- the influence of sub-alluvial 'basement highs' on the concentration of fluvial erosion processes is clearly visible in the pattern of geomorphological structures on adjacent terrace surfaces. This feature should be recognised and taken into account in investigations related to planning future hydrotechnical constructions.
- The tendency of these areas to give rise to high water flows should be a crucial element of the geological-engineering forecasts referring to the safety of objects located or built within the present-day channel zone.

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Corresponding author: Dr Tomasz Falkowski, Dept of Geotechnical Engineering Waw Agr. Univ, Nowoursynowska 166, Warsaw, 02-787, Poland. Tel: +48 22 5935235. Email: tomasz_falkowski@sggw.pl.

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