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Morphodynamics of lowland river valley bottoms in the identification of zones convenient for their crossing by heavy military vehicles in the Polish Lowlands

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An essential factor ensuring freedom of manoeuvre of land forces in lowland areas is the ability to cross water obstacles, especially river channels. For heavy military vehicles to cross river beds, places need to be indentified where both the channel's depth and the alluvial deposits' resistance to dynamic loads enable safe passage. In the case of many Polish rivers characterized by a predominance of low water levels, the use of Motorized Floating Bridges to ferry armoured vehicles is possible only in brief periods of high water level. Convenient places for crossing channels during low and medium states are zones where sub-alluvial bedrock protrudes. These forms are made of load- and erosion-resistant lithologies. Since the presence of bedrock protrusions determines the morphodynamics of the floodplain, the specific relief, and the outcrop pattern of the valley bottom, may indicate their location. In this study, we indicate specific features of the morphodynamics of river floodplains in the Polish Lowlands, visible in the topographic relief of these forms, that may help identify sections of the riverbed suitable for crossing by heavy military vehicles. Such recognition limits the amount of geological research needed, increases the safety of river crossings, and allows for the optimal use of limited resources of specialist military technology (floating pontoon bridges). We describe research results from river valleys of different sizes in the Polish Lowlands. Geological and geomorphological mapping was carried out using remote sensing, drilling along channels, and bathymetric measurements.

Key words: river channel crossing, armoured vehicles, ford, river valley, river channel, geological structure.

INTRODUCTION

Experience from the current armed conflict in Ukraine proves that the manoeuvering capabilities of land forces are still key to achieving success at operational and tactical levels. One of the basic problems in ensuring this is the ability to cross water (Szelka, 2017; Mądrzycki et al., 2019; Komornicki, 2021), bodies of which usually act as natural defence lines. On the European Plain, they are, next to dense forests and swamps, the basic natural factor limiting the movement of heavy military vehicles. Water obstacles also make it difficult to supply the amounts of fuel and weapons necessary to effectively conduct operational activities. From the point of view of the ability to manoeuvre, the most important water bodies are rivers, long, linear forms which are difficult or impossible to bypass (Fig. 1). In general, existing road or railway bridges in conditions of active conflict are not a safe place to cross river channels. It is commonly believed that these would be destroyed in the first hours of a war by the enemy's air attack capabilities and as a result of our own delaying actions. The scale of the problem of forcing riverbed crossings during land forces operations in NE Poland can be illustrated by a map showing the density of the river network in this area (Fig. 1).

Despite the significant development of military technology, including the means of crossing rivers, relatively narrow second- and third-order river channels also pose a significant terrain obstacle for mechanized troops (Ostrowski and Utratna-Żukowska, 2023). An example here was the unsuccessful attempts to cross the Donets Siverskyi, Ukraine, river channel in the first half of 2022. Several attempts to cross the channel, which is only 30 m wide, by Russian battalion battle groups near the town of Bilohorivka and Ukrainian troops in the area of Izyum town ended in complete failure (Fig. 2). The river crossing was unsuccessful because of the lithology and probably the low density of the alluvium forming the bottom of the river channel. Despite the small depth and width of the river, crossing it with heavy military vehicles required technical means such as pontoon bridges. On a modern battlefield, in the absence of complete air dominance of the side forcing the river, these are very susceptible to destruction.

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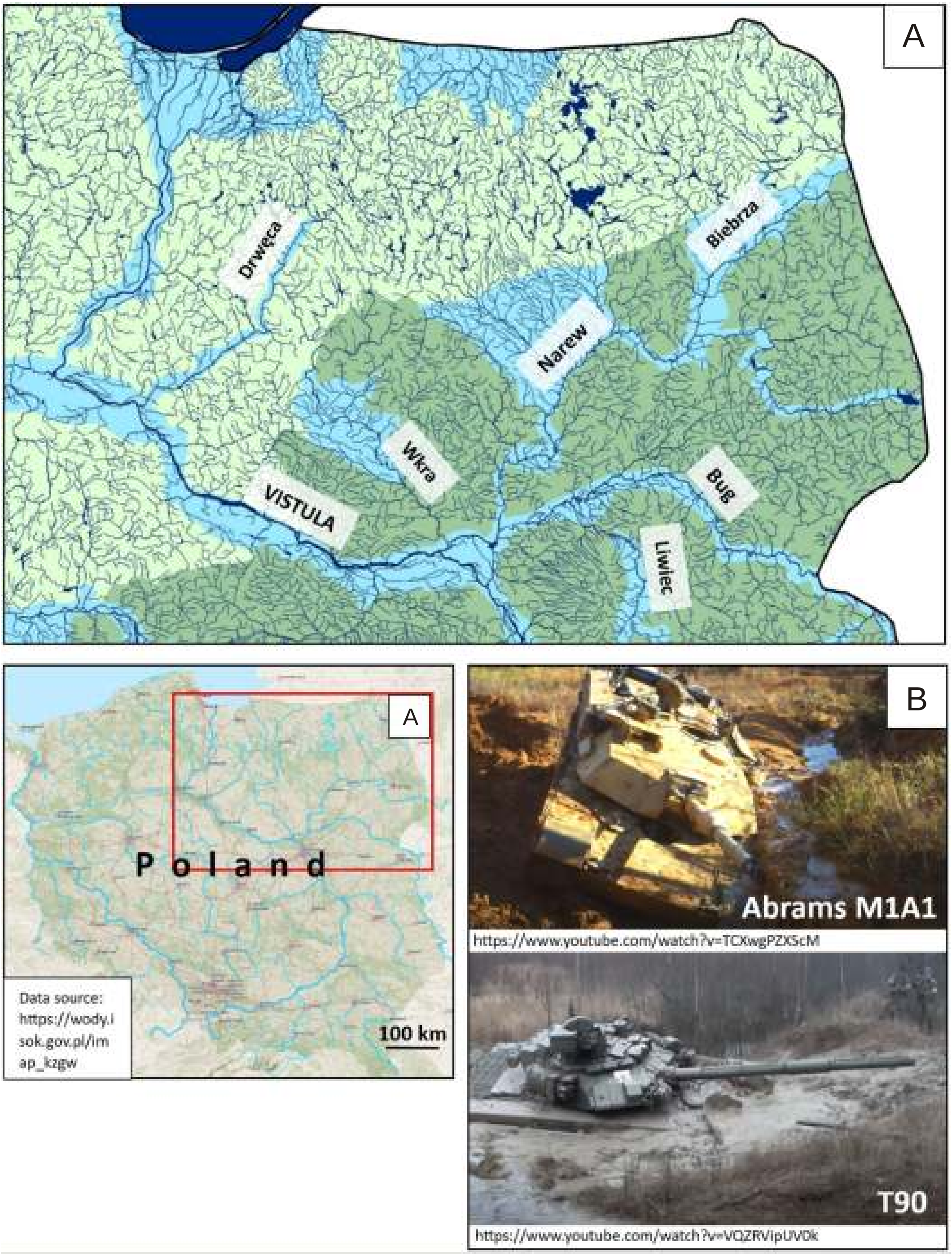

Fig. 1A – hydrographic network of part of the Polish Lowland in the northeastern strategic direction (on the base of MPHP10, part of the ISOK project); B – problem for modern main battle tanks may be crossing even shallow streams a few metres in width

The problem of crossing water obstacles can only be partially solved by using specialized crossing means, e.g. Motorized Floating Bridges (MFB), which are at the disposal of the European component of NATO troops. This is due to the specific nature of the rivers of the East European Plain. In most cases, rivers in the Polish Lowland are characterized by very high flow variability over the hydrological year (Stachý, 1970). The use of crossing equipment is only possible in conditions of high water levels in the channel, which in the case of the Polish Lowlands are relatively brief and are associated with floods (Ostrowski and Utratna-Żukowska, 2023; Fig. 3). This problem is also aggravated by long-term hydrological low flows during the summer months in recent years, in which the conditions make forcing modern river channels extremely difficult. This applies especially to sections with a large thickness of modern channel sediments, which dominate in the Eastern Strategic Direction.

Under low water conditions, the accessibility of Polish Lowland river channels may in many cases be limited, especially for heavy military technology. The maximum wading depth for

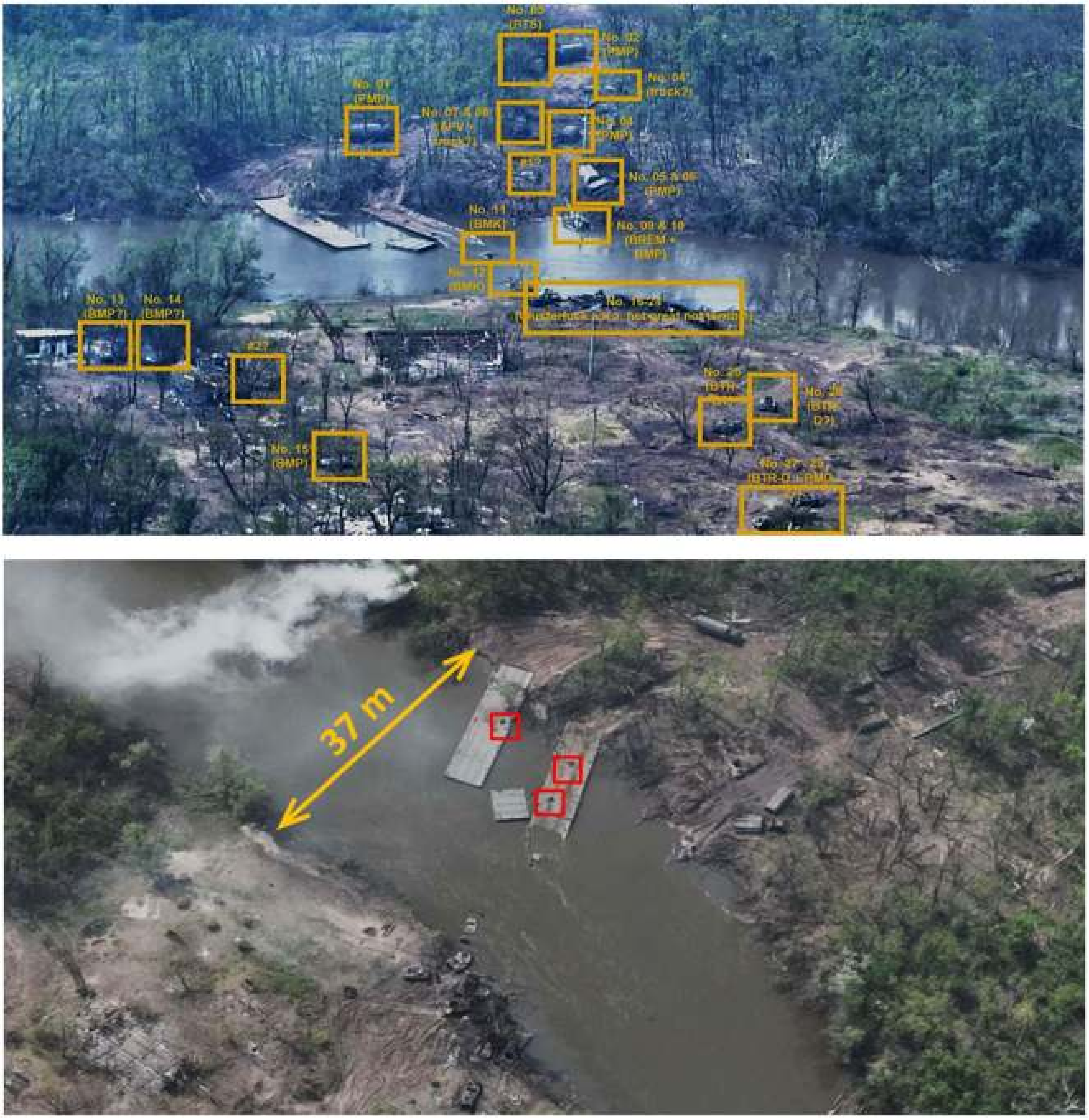

Fig. 2. An unsuccessful attempt to cross the Donets Siverskyi River near the town of Bilohorivka, May 11, 2022; rectangles mark destroyed military equipment (General Staff of the Armed Forces of Ukraine; after Ostrowski and Utratna-Żukowska, 2023)

most types of Infantry Fighting Vehicles (IFVs) and main battle tanks is 2.5 m. Rivers operating in conditions of large differences between extreme flows often have braided channels overloaded with alluvia (Falkowski, 1971; Kozarski and Rotnicki, 1977; Mycielska-Dowgiałło, 1978; Szumański, 1986). Their bottoms are made of alluvium with varying degrees of relative density (i.e. of compaction) (Smaga, 2015). These are often loose sands with low resistance to static and dynamic loads, which are also easily subject to thixotropy, because of their thorough transformation (reworking) during floods (Falkowski, 2007; cf. Leopold et al., 1964). The channel bed deepens during the passage of the flood wave and after this is quickly filled with loose sediment. The location of flood reworking zones is often difficult to determine because, during high water flow, the arrangement of streamlines may change significantly (see Falkowski et al., 2017).

Apart from the channel zones filled with poorly compacted mineral deposits, in the Polish Lowland river valleys, some sections are difficult to cross because of the occurrence in their bottom of organic soils – mainly peat or gyttja. High lithological/morphogenetic variability of individual sections of such a valley, including the occurrence of lacustrine sediments, reflects the diverse genesis of these forms (Falkowski, 1971, 1997; Mojski, 2005).

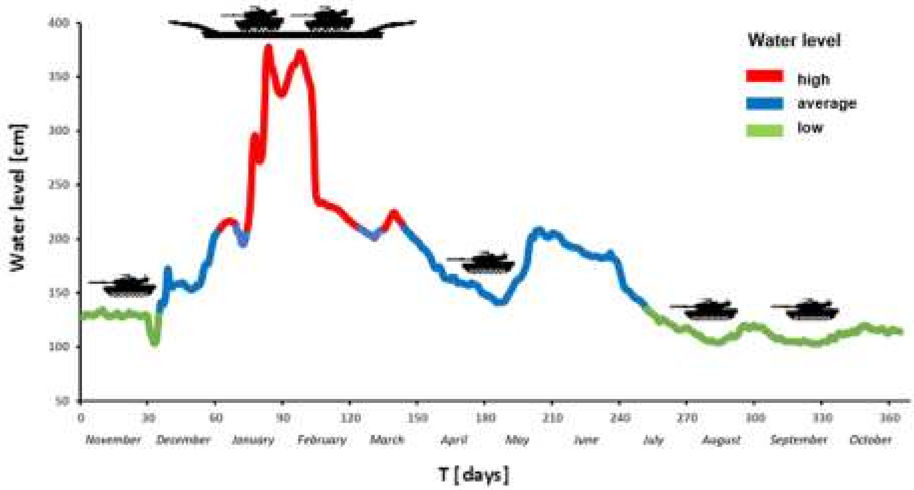

Fig. 3. The possibility of using various crossing means on the example of a section of the Bug River Valley in Małkinia; an example from the hydrological year 2022 (after Ostrowski and Utratna-Żukowska, 2023, modified)

The maximum wading depth for most types of IFVs and main battle tanks is 2.5 m

In the available literature, there are no studies devoted to the methodology of identifying sections of riverbeds suitable for crossing by military vehicles. Available publications mainly concern technical issues and the logistics of crossings (e.g., Headquarters Department of the Army Commandant, US Marine Corps, 1992; Iyer, 2024).

Here, we analyse the specific morphodynamics of individual sections of lowland river valleys to identify zones within their channels that are convenient for crossing by heavy military vehicles.

The examples described in the paper illustrate the complex geological structure of river valley sections in the Polish Lowlands, in areas shaped during the Middle Pleistocene and also of young glacial relief.

A basic assumption is the existence of a relationship between the geological structure of the valley and the morphodynamics of the floodplain surface. As previous studies have shown (Falkowski, 1971), in alluvial sections of river valleys in the Polish Lowland we can distinguish mature sections, with developed erosional bases filled with thick channel alluvia, and immature sections, with an undeveloped erosional base. In the second case, the sub-alluvial bedrock forms stable, morphological forms (Falkowski, 2007), which may constitute fords: places convenient for crossing the river (specific "geological bridges"; Ostrowski, 2022). In conditions of low and moderate water levels (i.e. during most of the hydrological year), the tops of such forms are covered with a thin-layer of channel alluvium, which makes their effective identification using remote sensing methods difficult or even impossible.

However, quick and effective identification of such places can be carried out indirectly based on the features of the valley bottom, especially the floodplain. The occurrence of a stable level in the river channel that does not wash out during floods significantly affects the flood water flows (Falkowski, 2007; Falkowska and Falkowski, 2015; Ostrowski et al., 2021): the inability to deepen the river channel during floods causes water to enter the floodplain always at the same places (Fig. 4), resulting in sets of characteristic erosional and depositional landforms

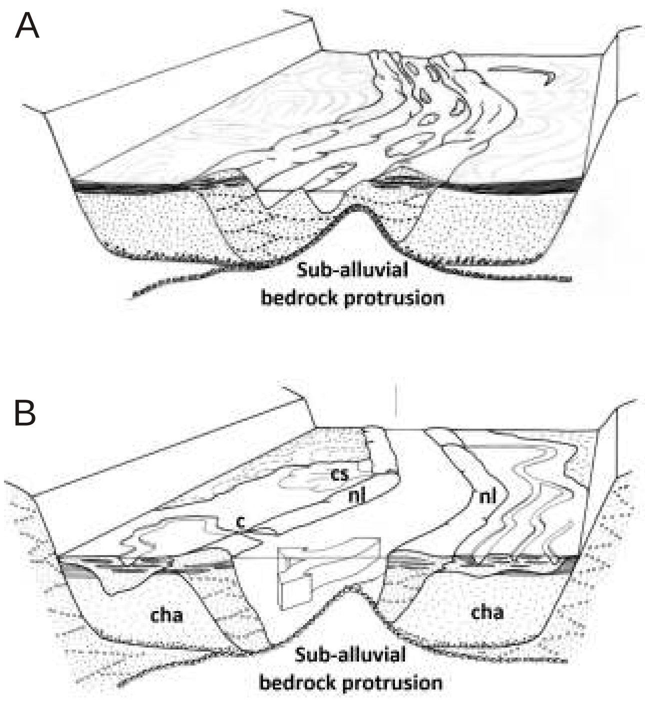

Fig. 4. Sub-alluvial bedrock protrusions' influenceon floodplain morphodynamics (after Falkowska and Falkowski, 2015, changed)

Under low flow (discharges) conditions, the projections of the erosion-resistant substrate are hidden under the alluvial layer. During flood flows, when the energy of the flow increases, the substrate ceiling is exposed, and its relief affects the system of the streamlines. The waters piled up on the substrate convexity invade the surface of the floodplain in the same places each time, creating associations of erosional and depositional forms there; **A** – middle state; **B** – flood flow; c – crevasse, cha – channel alluvia, cs – crevasse splay, nl – natural levee

Table 1

Details of the starting/source materials

River/valley reach	Stream order	Studied valley length [km]	Course	Boreholes		Figs. photo/imagery				Reference
				Type/ Diameter	Number	Year/Date of performance	Resolution [m]	Scale	Type/Source	
Rospuda/ Święte Miejsce-Rospuda Lake	4	10	upper	Cased boreholes/ 90 mm	9 (along the channel) + 16 in 3 sections	2022.05.04	0.25	1:5000	digital aerial imagery, natural colour (NRG) composition/PZGiK*	Jabłońska et al. (2014)
Odra/Cedynia-Bielinek	1	10	lower	Cased boreholes/ 90 mm	46 (along the channel)	2025.01.20	–	–	digital satellite imagery, natural colour (NRG) compositions/Airbus Image, Maxtar Technologies (Google Earth Pro)	Falkowski (2006)
Orzyc/Grzebsk -Janowo	3	15	upper	Cased boreholes/90 mm	38 in 4 sections	2020.06.02	0.25	1:5000	digital aerial imagery, natural colour (NRG) composition/PZGiK*	Falkowska (2015)
Wkra/Nidzica-Strzegowo	3	35	upper and middle	Cased boreholes/90 mm + archival	28 archival in 7 sections	–	–	–	–	Falkowski (1997, 2003, 2006)
Supraśl	3	13	middle	Cased boreholes/90 mm	45 (along the channel) + archival	–	–	–	B/W aerial photo /PZGiK*	Falkowska and Falkowski (1994)
Pilica	3	21	middle	Cased boreholes/90 mm		–	–	–	–	Falkowski (2010)
Wisła/Annopol -Modlin	1	250	middle	Cased boreholes/90 mm + archival	420 in the channel + 142 archival	–	–	–	–	Falkowski (2006, 2007)
Bug	2	27	lower	Cased boreholes/90 mm		–	–	–	–	Ostrowski et al. (2022)

* – State Geodetic and Cartographic Resource (Państwowy Zasób Geodezyjny i Kartograficzny)

(Falkowski, 2007; Falkowska and Falkowski, 2015; Ostrowski et al., 2021).

In sections of mature river valleys (Falkowski, 1971), which have deeply cut erosional bases, such morphogenic flood water features are not concentrated in particular sections of the floodplains.

METHODOLOGY

Research into the relationship between the morphodynamics of the valley floor and the occurrence of stable channel bottom zones (acting as fords) convenient for crossing by heavy military vehicles was carried out in the valleys of lowland rivers of great geostrategic importance: Wisła, Odra, Bug, Supraśl, Orzyc, Wkra, Pilica, and Rospuda. As part of the field research, geological mapping of the surface of the floodplain and the channel zone, drilling boreholes in the river channel, and sounding with a dynamic light probe were performed to assess the relative density of alluvia. Additionally, in different hydrological conditions in the channel, a series of bathymetric measurements were carried out using an echosounder coupled with a Global Navigation Satellite Systems (GNSS) receiver operating in the Real Time Kinematic (RTK) and Real Time Network (RTN) modes, which allowed for the preparation of bathymetric and hypsometric maps.

The geomorphological features of the valley floor were mapped based on remote sensing using aerial photos and satellite imagery and Digital Terrain Model (DTM) based on Airborne Laser Scanning (ALS). The spatial resolution of all materials analysed was 1 m.

The results of field and remote sensing research were jointly analysed in the GIS database, which was the basis for formulating our conclusions. Details of the starting/source materials are given in Table 1.

RESULTS

The valley sections studied are located in areas with different degrees of landscape maturity. The area of young glacial relief is represented by sections of the Rospuda and Odra valleys, and sections of the Orzyc, Wkra, Supraśl, Pilica, Bug, and Wisła valleys represent the area formed in the Middle Pleistocene.

ROSPUDA RIVER VALLEY

Research was conducted on an ~10-km valley section from the site called Święte Miejsce to Lake Rospuda. In this section, the river follows the depression of a subglacial trough (Ber, 1982). Sixteen boreholes were made in the valley floor, creating cross-sections running transversely to the valley. Nine boreholes were also made in the channel bottom (Jabłońska et al., 2014; Fig. 5).

In the Święte Miejsce the valley floor is ~100 m wide. The Rospuda channel reveals boulders and coarse gravels resulting from the winnowing of fluvioglacial deposits that constitute

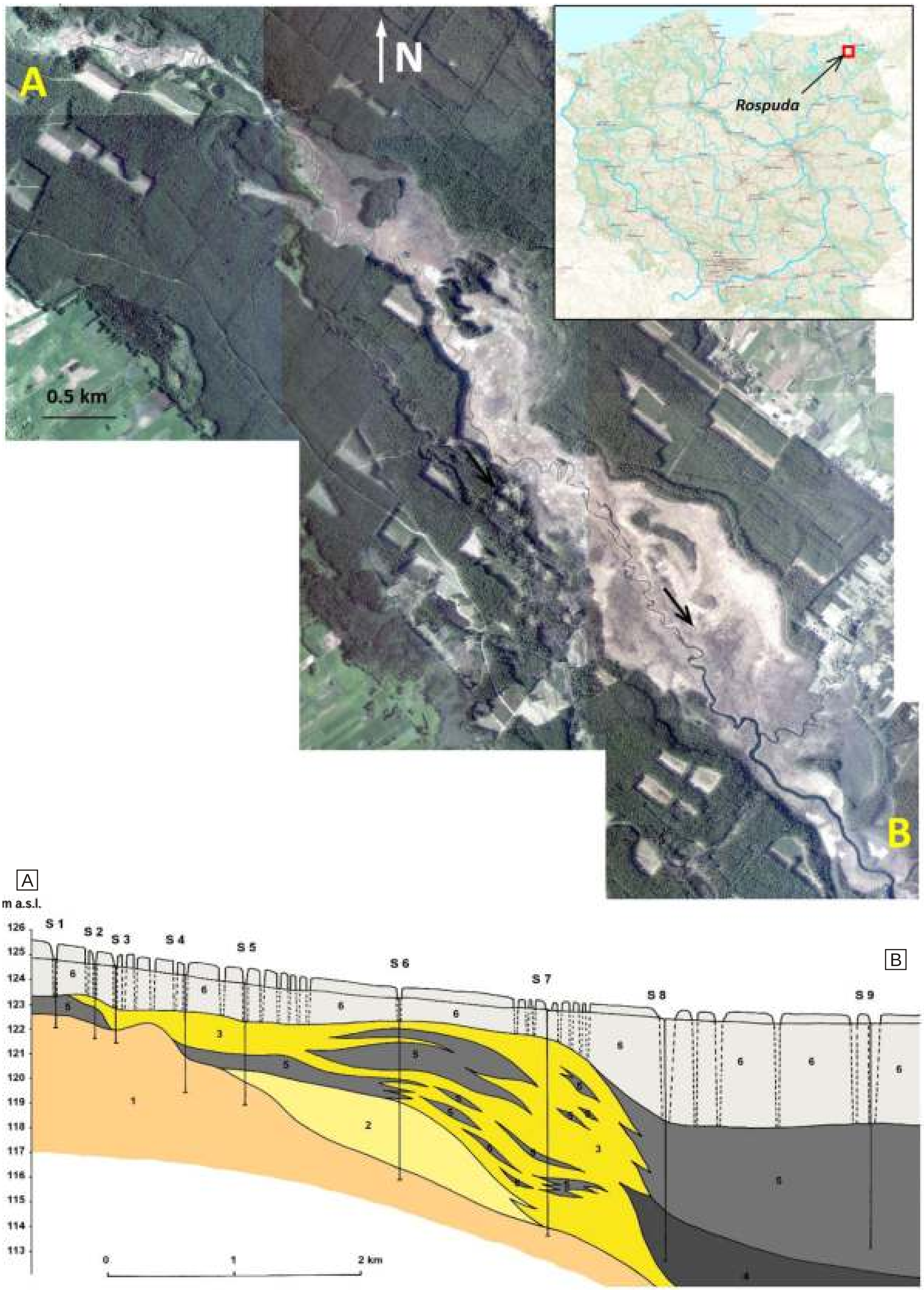

Fig. 5. Lithological cross-section of the Rospuda River Valley zone between Święte Miejsce (A), and Rospuda Lake (B) (after Jabłońska et al., 2014, changed); the cross-section runs through the middle of a winding channel

1 – fluvioglacial sands and gravels, 2 – fine and medium sands, channel deposits, 3 – fine and medium sands with mud intercalations, 4 – organic gyttia, 5 – peat with mud, 6 – organic mud

the valley floor. Downstream from this zone, the valley expands locally to over a kilometre, while the surface of the fluvioglacial deposits constituting the valley floor becomes lower. The valley is filled with peat and gyttja with a thickness exceeding 20 m. In the channel zone, sands intercalated with organic mud, peat, and gyttja were found, overlying the sloping surface of the fluvioglacial deposits. Sands also occur as intercalations and probably as lenses within soft, plastic lake deposits; they were encountered at various depths in boreholes drilled outside the contemporary channel zone.

ODRA VALLEY BETWEEN CEDYNIA AND BIELINEK

The Odra Valley section examined constitutes a distinct extension of the valley (Fig. 6). In the Cedynia area (the polder area called Żuławy Cedyńskie) the width of the valley is almost 4 km. On the floodplain surface are visible traces of a multi-channel system similar to the Narew system between Suraż and Tykocin (Falkowski, 1971; Gradziński et al., 2003). The valley floor is directly adjacent to the slope of the moraine plateau or to the fluvioglacial accumulation terrace. The sands and gravels that make up this form are extensively exploited: on the Polish side, in Bielinek and Piasek, and on the German side, near Hohensaaten.

Forty-six boreholes were drilled in the channel along the mainstream zone (Fig. 6). These showed the presence of a several-metres-thick layer of medium sand and gravel at the bottom of the channel, lying on organic locally carbonates silt and gyttja in a soft-plastic state. The sand thickness increases especially in the vicinity of engineering structures. In the zones of evorsion hollows accompanying groynes, the channel sands reach several metres thick. The bedrock on which organic soils rest is built of glacial tills and coarse-grained fluvioglacial deposits.

ORZYC VALLEY IN GRZEBSK

The Orzyc Valley section examined is an upstream reach, where the river follows a NE–SW-aligned melt-out depression. Downstream from Janowo the valley changes direction to NW–SE on entering the Kurpie outwash plain (Różycki, 1972; Marks, 1990; Mojski, 2005).

The reach of the Orzyc Valley studied is an irregular depression (Fig. 7), of maximum width ~3 km. The valley floor is filled with peats and gyttja lying on glacial sands and tills. The maximum thickness of organic deposits exceeds 8 m (Falkowska, 2015). On the peat surface of the valley floor, traces of a multi-channel system are visible. These are similar to those of the valleys described above. The modern Orzyc flows through an artificial ditch, dug into the peat (Fig. 7).

WKRA RIVER VALLEY

Research in the Wkra River Valley was aimed at determining the diversity of underground outflow conditions (Falkowski, 1997). The analysis included purpose-drilled boreholes in the valley bottom, and the use of drilling records from several engineering-geological projects mostly for bridge crossings (Falkowski, 2003). The Wkra River Valley in the section analysed follows a series of melt-out depressions, transformed to varying degrees during the valley's development (Fig. 8). In the upper reaches, the valley floor is built of organic soils: gyttja and peat with an average thickness of 3–5 m. An artificial, straight river channel is dug into organic soil. The width of valley sections varies from several hundred metres to over 3 kilometres.

Downstream of Nowy Dwór (Fig. 8), the valley turns N-S and runs along the eastern edge of the outwash plain (Różycki, 1972; Marks, 1990; Kotarbiński and Krupiński, 2000). The set of glaciogenic depressions creating the valley was transformed due to the concentrated flow of meltwater during the last glaciation (Falkowski, 1997; Kotarbiński and Krupiński, 2000). In addition to buried lake deposits (Kotarbiński and Krupiński, 2000), evidence of the original genesis of the form comprises also low valley-bottom gradients which favour peat development. The average surface peat thickness is up to ~2 m. However, in the vicinity of Żuromin (Fig. 8), lacustrine soils: sapropel, and peat, buried under fluvioglacial sands, reach a thickness of over 10 m (Falkowski, 1997; Kotarbiński and Krupiński, 2000).

The wide sections of the Wkra River Valley are associated with distinct narrowings. Those reaches of river-gorge type are marked on the longitudinal valley profile by a noticeable increase in bottom gradients (Fig. 8). In such places, in the channel bottom, there are outcrops of erosion-resistant deposits such as morainic tills, ice-dam clays, and coarse-grained fluvioglacial deposits.

SUPRŚAL RIVER VALLEY

Study here was aimed at determining the possibility of expanding the water intake for Białystok in the Supraśl River Valley bottom, including by identifying differences in the aquiclude properties of the surface deposits (Myślińska et al., 1993). In the section examined, the Supraśl River runs along the edge of a wide, irregular melt-out depression (Falkowska and Falkowski, 1994; Fedorowicz et al., 1995). On the valley floor, outside the channel zone, there are peats with an average thickness of ~2 m. The deposits forming the plateau adjacent to the valley, as well as the bedrock of organic-rich lithologies in the valley, are strongly glaciotectonically disturbed. There are folds made of morainic tills, ice-dam lake clays, silts, and coarse-grained fluvioglacial deposits in the valley bottom (Fig. 9; Falkowska and Falkowski, 1994; Fedorowicz et al., 1995).

PILICA RIVER VALLEY

Research took place within an ~12 kilometre section of the middle Pilica River Valley between Inowłódz and Domaniewice (Falkowski, 2010). Twenty five boreholes were drilled in the alluvial bed of the channel, and mapping of the valley floor was carried out. Sub-alluvial bedrock protrusions were detected, composed of morainic clays, fluvioglacial sands with gravels, and ice-dam lake clays in the channel bed, as well as a zone where siliceous sandstones of the Middle Jurassic were exposed in the channel floor (Fig. 10). Between the basement highs, the channel alluvia are up to 10 m thick. The depth of Holocene reworking, marked by a layer of residual lag, is on average 2–4 m. The surface of the valley shows traces of the activity of flood waters that dammed up on these resistant thresholds.

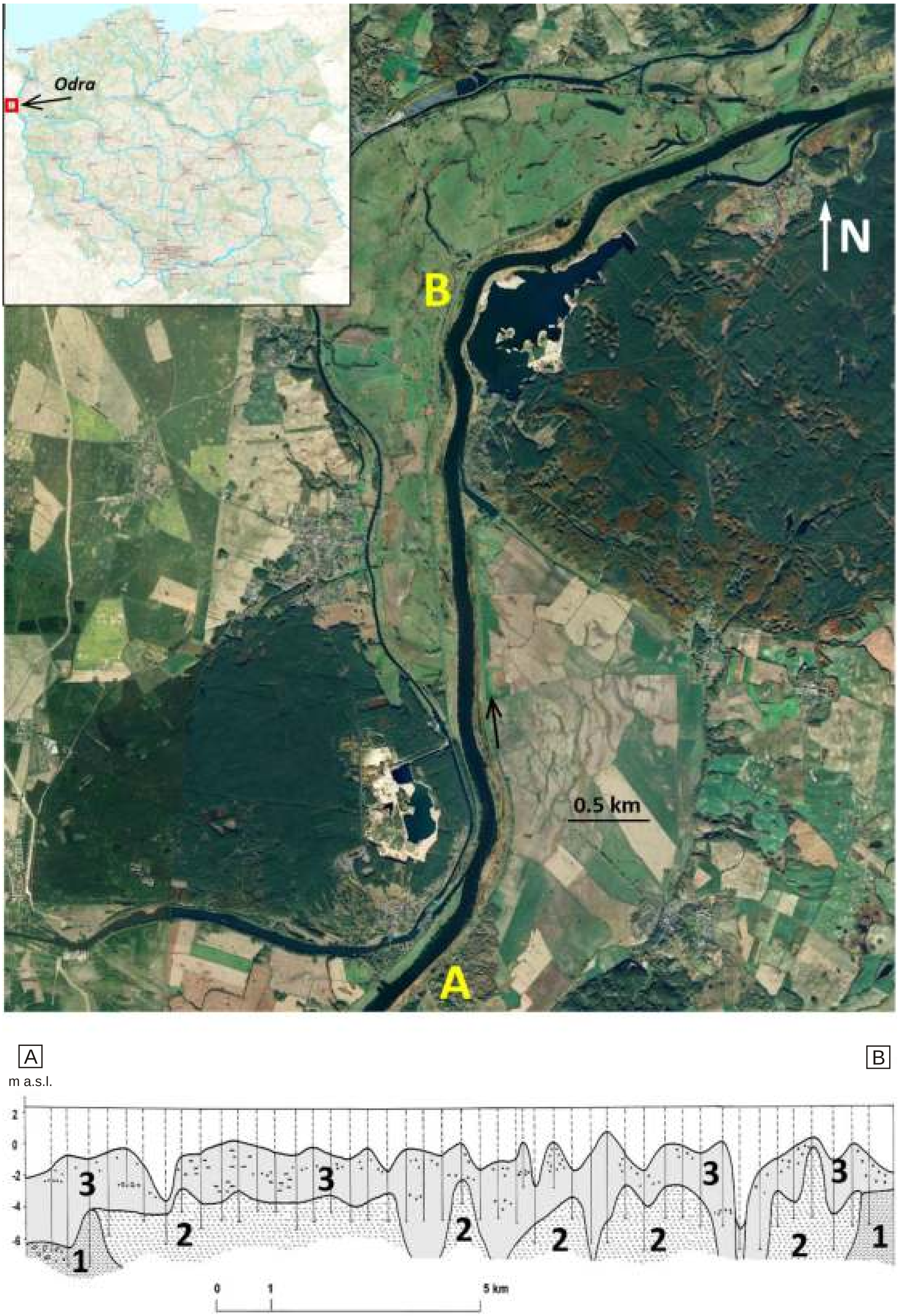

Fig. 6. Longitudinal channel cross-section of the Odra River Valley in the area of Cedynia (A) and Bielinek (B) (after Falkowski, 2006, changed); the cross-section runs through the middle of a channel

1 – fluvioglacial sands and gravels, 2 – gyttia, 3 – channel alluvia

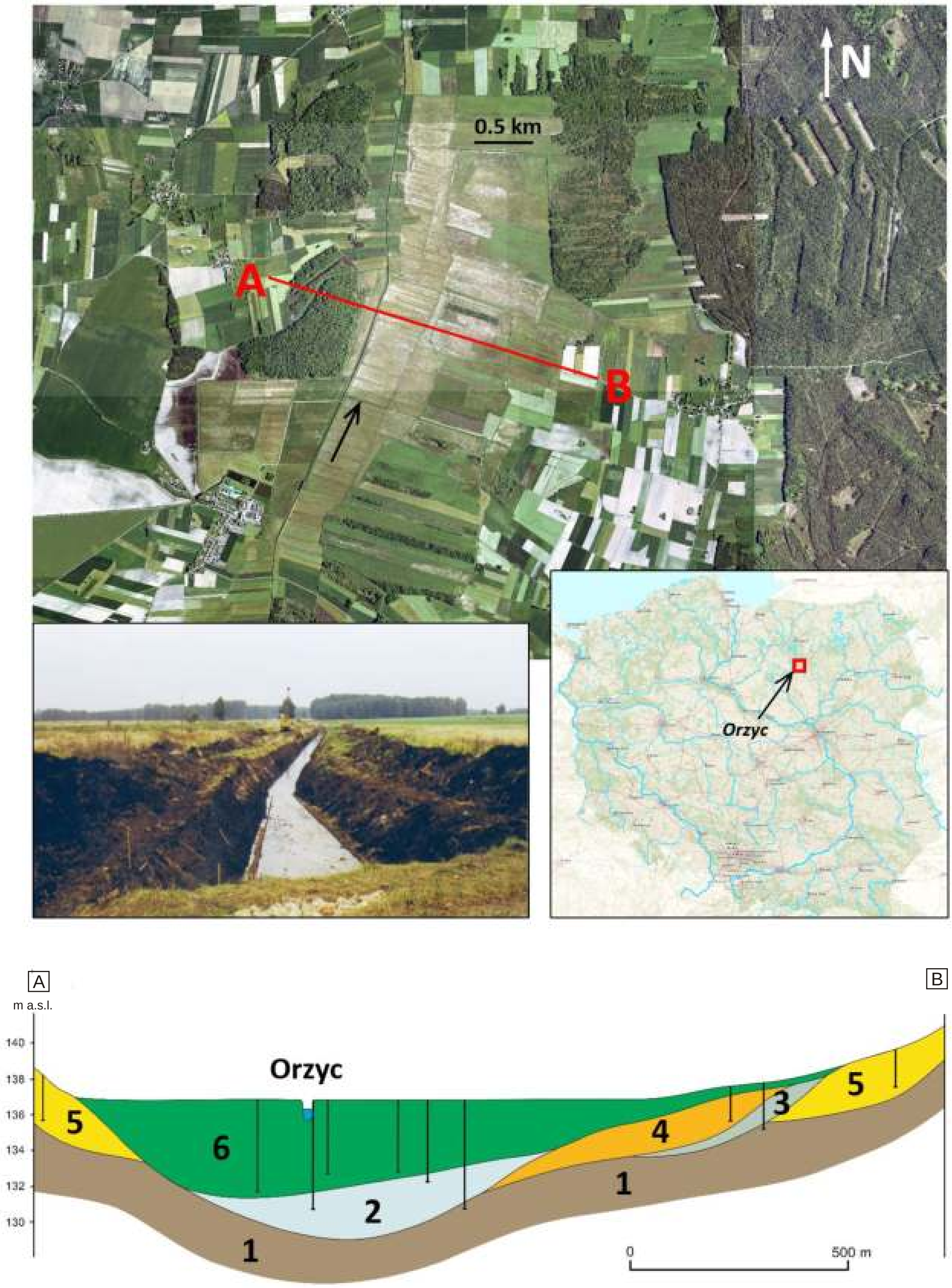

Fig. 7. Geological cross-section of the Orzyc River Valley in the vicinity of Janów (after Falkowska, 2015, changed)

1 – glacial till, 2 – fluvioglacial sands and gravels, 3 – organic mud, 4 – fine sands, 5 – organic gyttia, 6 – peat

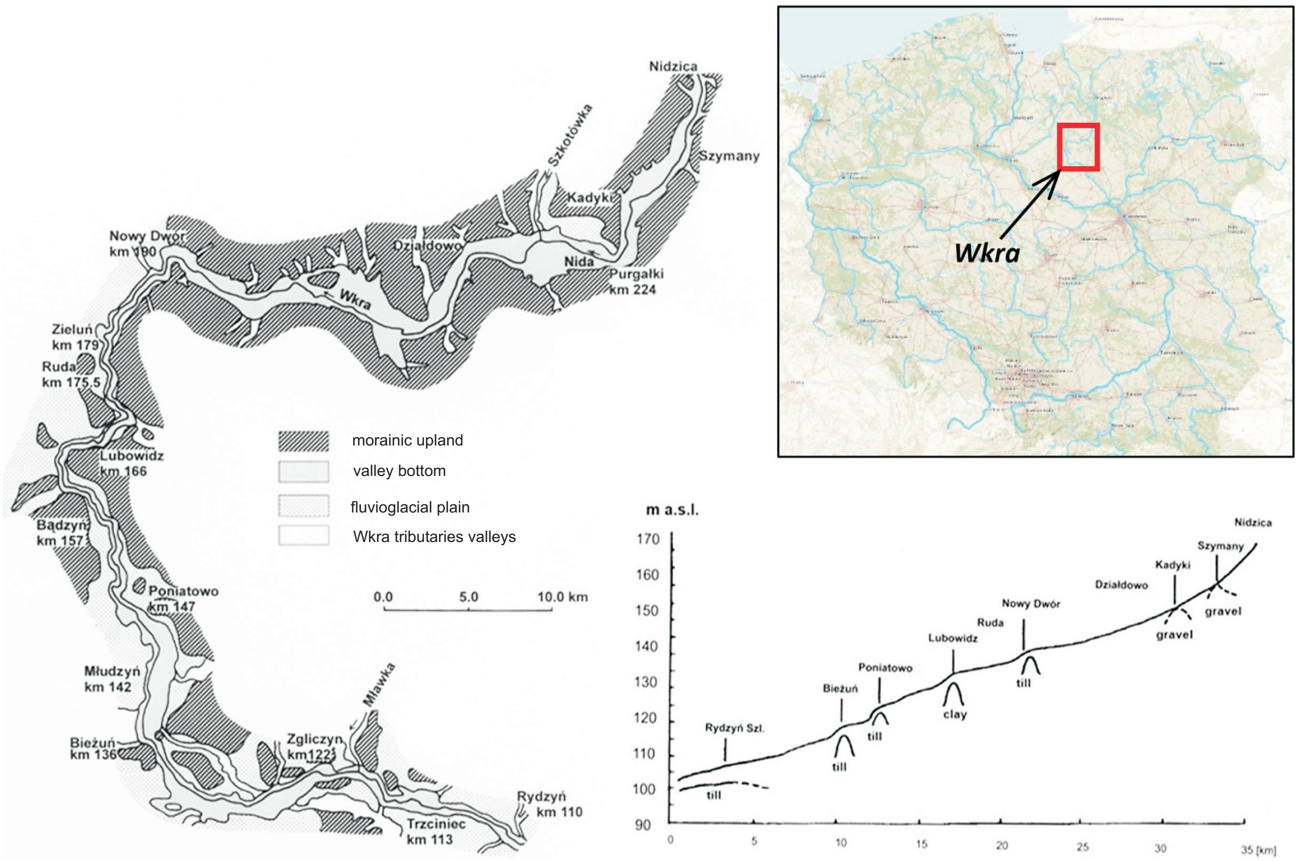

Fig. 8. Geomorphological sketch of the upper course of the Wkra River Valley and longitudinal profile of the valley bottom with location of hinge-points (thresholds) between post-lacustrine valley reaches (after Falkowski, 1997)

This activity partially erased the traces of the river's meandering from the period of the Holocene climatic optimum (Falkowski, 2010; cf. Falkowski, 1971).

MIDDLE WISŁA RIVER VALLEY

The section of the Wisła River Valley studied runs from Annopol to Modlin (Falkowski, 2006; Falkowska and Falkowski, 2015; Falkowska et al., 2016). In sections where evidence of concentrated and repeated floodwater activity was identified on the floodplain surface, drilling was carried out in the channel bed. This showed the presence of sub-alluvial bedrock protrusions. Inside the section of the Vistula River Gorge (Pożaryski, 1953; Kondracki, 2001), such bedrock protrusions are built mainly of Upper Cretaceous carbonate and siliceous rocks and their clay-rich weathering products. Downstream from the gorge zone, they are built of cohesive and coarse-grained Paleogene, Neogene, and Pleistocene deposits. In the section analysed, 21 such zones were found, ranging in length from several to over 20 kilometres (Falkowski, 2006, 2007; Falkowska and Falkowski, 2015; Falkowska et al., 2016; Falkowski et al., 2017). Echosound studies conducted during various river states showed the stability of the current-line system (Falkowski, 2007; Falkowski et al., 2018). This stability sometimes causes the failure of regulatory and flood protection structures (Falkowski, 2007; Wierzbicki et al., 2018; Bujakowski and Falkowski, 2019).

LOWER BUG RIVER VALLEY

Research was carried out in the Podlasie section of the river (eastern Poland) (Ostrowski and Falkowski, 2021; Ostrowski et al., 2023) and the vicinity of Małkinia and Brok (central Poland) (Ostrowski, 2022). This showed the occurrence of a series of sub-alluvial bedrock protrusions. As in the case of the Pilica and middle Vistula valleys, a rich set of flood-flow erosional and depositional landforms was found, related to the presence of resistant thresholds in the channel (Fig. 11) . Some of these were the result of ice-jam floods (as in the valleys of the other rivers studied; cf. Falkowski and Popek, 2000; Fig. 12), evidence of which were found even on the surfaces of higher terraces (Ostrowski et al., 2023).

In subsequent years, changes in the density of channel alluvium in the zones of sub-alluvial bedrock protrusions were also examined. The density index of channel sands in places outside the main current zones increased in subsequent years. This phenomenon contributes to the stabilization of the current lines between extremely high floods.

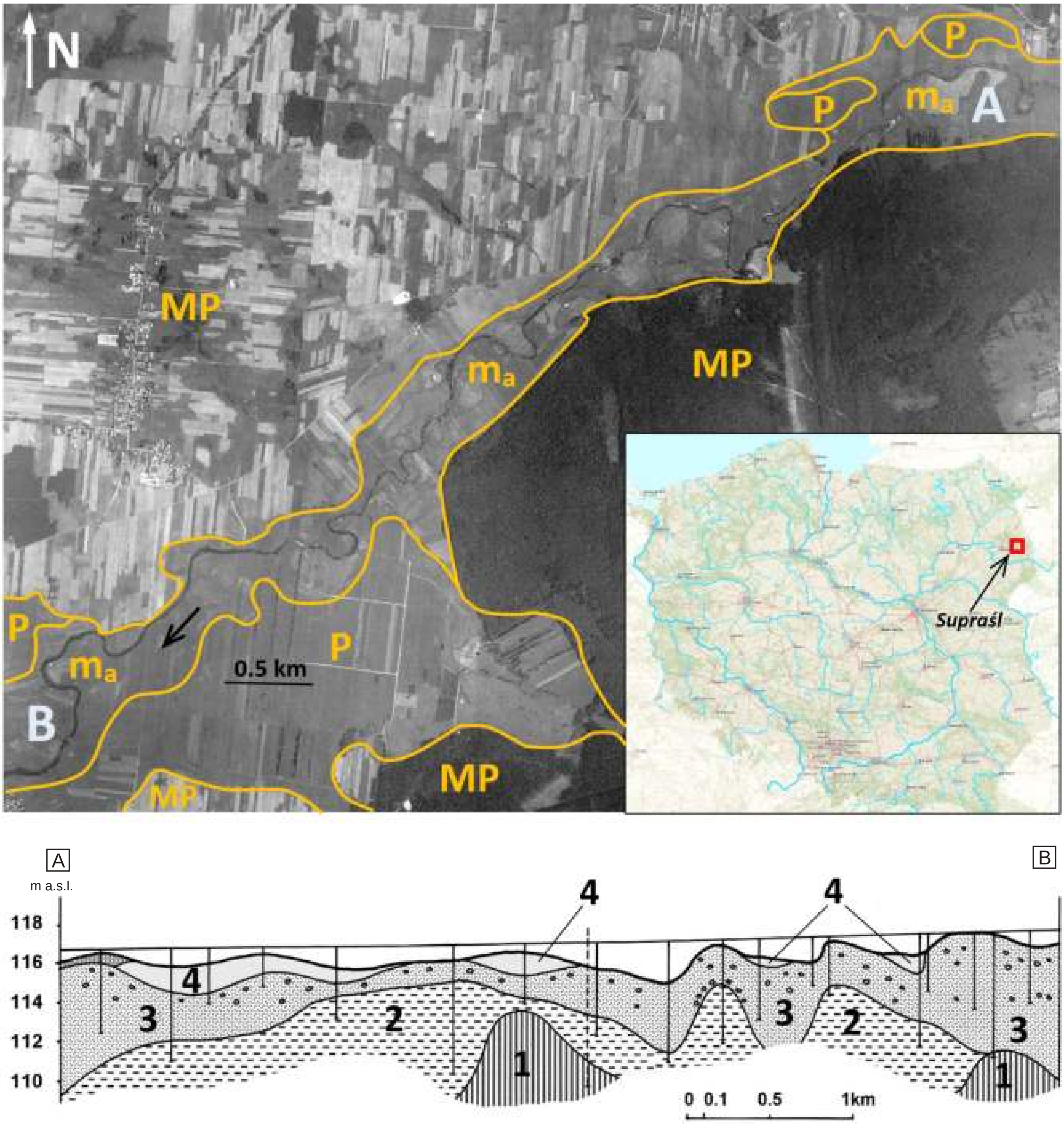

Fig. 9. Geological cross-section along the Supraśl River Valley near Wasilków and simplified photo-geological sketch of the river valley bottom and adjacent plateau (after Falkowska and Falkowski 1994, supplemented); the cross-section runs through the middle of a winding channel

MP – morainic plateau, P – peat, m_a – valley surface built with mineral deposits (alluvial), 1 – glacial till, 2 – ice-dam lake deposits, 3 – fluvioglacial sands and gravels, 4 – Supraśl River Valley alluvia, 5 – organic mud

DISCUSSION

Even though the sections of the river valleys analysed are located in areas with varying degrees of development of denudational processes, their common feature is morphogenetic immaturity, manifested by the lack of fully developed erosional bases. This results mainly from the varied genesis of these forms, traces of which are still visible in the morphology and geological structure of the valley floor (Falkowski, 1971, 1997).

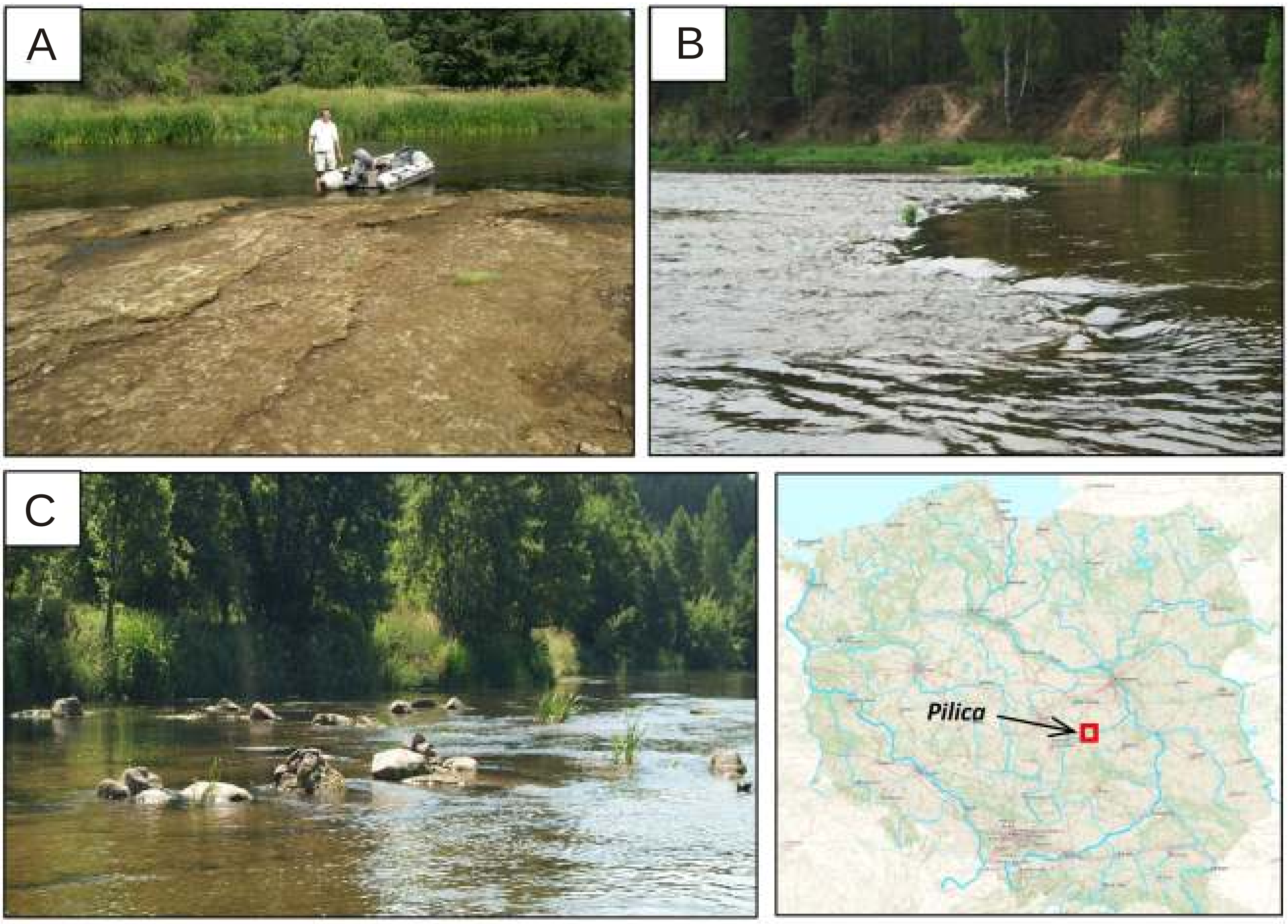

Fig. 10. Thresholds built of erosion-resistant deposits in the Pilica River Valley in the vicinity of Inowłódz; A – siliceous sandstones (middle Jurassic), B – ice-dam lake deposits (Pleistocene), C – glacial till residuum

The river valleys formed after deglaciation include sequences of glaciogenic and thermokarst depressions of various sizes and shapes. The course of their adaptation to the valley largely depended on the size of these forms, the size of their partial catchment, and therefore mainly on the supply of sediment to the valley. In many cases, evidence of the original genesis of valley sections is still visible, both in the shape of the form and in the lithology of its infill (Klajnert and Wasiak, 1989; Musiał, 1992; Błaszkiewicz and Krzymińska, 1992; Kobojek, 1996; Falkowski, 1997; Falkowska, 2015). The survival of evidence of the original genesis of a valley section depends on the age of the form, as well as its size and shape. Most such sections can be found in young glacial relief (Mojski, 2005), but they also occur in areas where the relief was shaped in the Middle Pleistocene (Falkowski, 1971; Musiał 1992).

POST-LACUSTRINE SECTIONS

In polygenetic sections of river valley bottoms outcrops of non-alluvial sediments, often of considerable thickness, are very common. These are mostly weak, organic soils with low load-bearing capacity. Most valley sections of this type can be found in areas of young post-glacial relief. An example is the section of the Rospuda Valley downstream of the Święte Miejsce, where the thickness of peats and gyttja commonly exceeds 20 m (Jabłońska et al., 2014; Fig. 5). Sandy riverbed sediments are being deposited in the delta zone created by the river simultaneously with the deposition of organic sediments. Due to differences in sediment compaction, alluvial deposits sink within lake sediments and can currently be found as isolated bodies at different depths.

The other example is a part of the lower Odra Valley in the area of Cedynia and Bielinek, where the river uses a lake depression filled with peat and gyttja. The channel zone is formed in sands, which the river washed along the cut which was dug at the end of the 19th century (Falkowski, 2006; Fig. 6).

Post-lacustrine valley sections can also be found in areas with more mature relief (Falkowski, 1971), for example in the area shaped during the Middle Polish Glaciations (Lindner, 1988; Lindner and Marks, 2012). Such a form is the section of the upper Orzyc River Valley in the area of Janowo and Grzebsk. The depression adapted to the valley is filled with peats and gyttja with a thickness exceeding 6 m (Falkowska, 2015; Fig. 7).

An example from the history of the defensive war in 1939 in Poland (Kozłowski and Wrzosek, 1984) shows the scale of difficulties that may result from attempts to cross post-lake sections of polygenetic river valleys by subunits of mechanized troops. A modest unit of the Border Protection Corps of the Polish Army

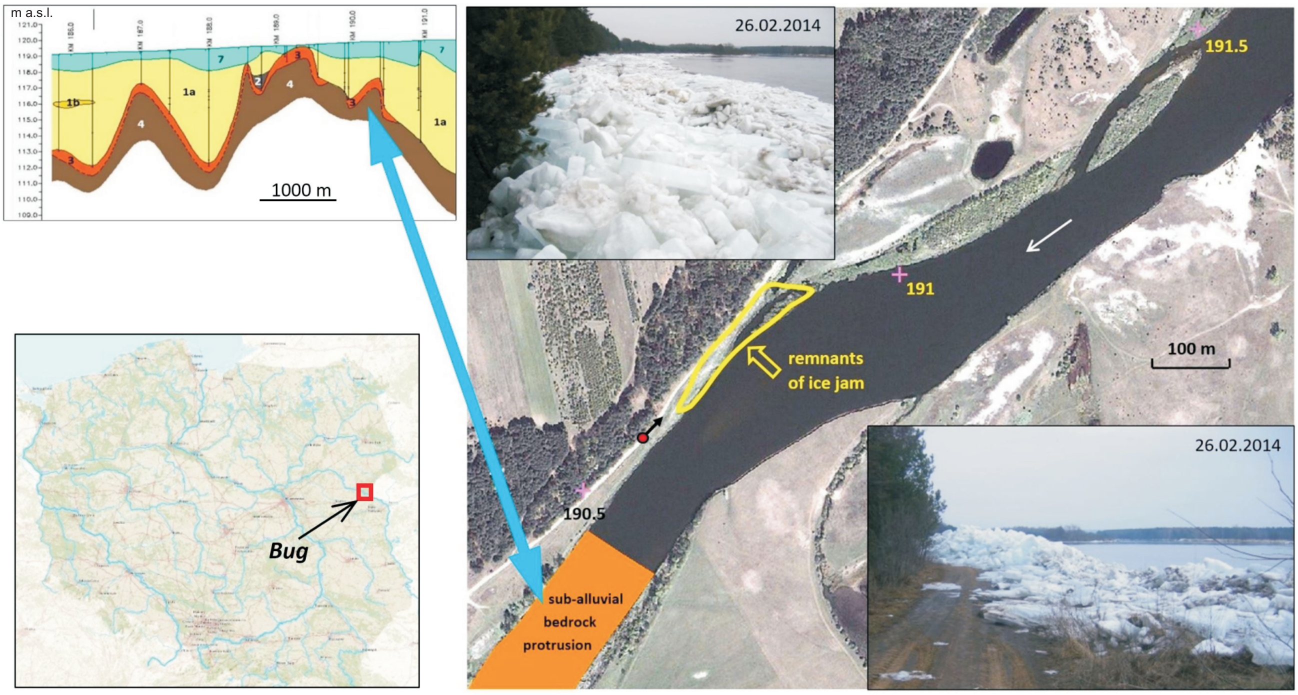

Fig. 11. Remnants of ice jam in the Bug River Valley zone in the Mielnik vicinity and cross-section along the channel reach (after Ostrowski et al., 2021)

1(a, b) – channel alluvia (Holocene), 2 – mud (Holocene), 3 – residual lag, 4 – glacial till, blue (7) – water; 191 – kilometre of the river course

under the command of Captain Władysław Raginis, defending the area where the Biebrza River flows into the Narew River, stopped the 19th German armoured corps commanded by General Heinz Guderian. The entire section of the Narew Valley from Tykocin to Łomża is a melt-out depression adapted to the valley (Falkowski, 1971; Musiał, 1992; Mojski, 2005). A relic of the lacustrine origins of the landform is Maliszewskie Lake, located in the eastern part of the Wizna Marsh, where the thickness of organic deposits exceeds 20 m (Żurek, 1978). The Narew flows through a sandy dyke zone built within this depression.

Bedrock protrusions of stable, load-resistant deposits can also be found within the post-lacustrine reaches. Their presence is usually associated with the complex genesis of the melt-out depressions themselves, which may include glaciotectonic processes (e.g., the Supraśl River Valley; cf. Falkowska and Falkowski, 1994; Fig. 9). Convexities of the mineral substrate of organic sediments can also be dunes (Falkowski, 1971, 1988). Such places, suitable for heavy military vehicle routes in post-lacustrine valley sections, can be located precisely based by remote sensing methods because the thickness of the organic sediment layer is lesser in such areas (cf. Ostrowski and Falkowski, 2016; Ostrowski et al., 2021).

RIVER GORGE SECTIONS

Within polygenic valley reaches, between post-lacustrine sections, there are usually narrow river gorge-like zones. They mark distinct knick-points on the longitudinal profile of the valley floor and river bed (Falkowski, 1997; Ostrowski et al., 2021). Within them, dense and erosion-resistant deposits from the valley substratum are often exposed in the channel. An example is the upper and middle Wkra River Valley, where between the lake sections, coarse-grained fluvioglacial, moraine, and ice-dam lake formations are exposed in the channel bottom (Falkowski, 2003; Fig. 8).

ALLUVIAL RIVER VALLEYS

The lack of a developed erosional base is manifested in alluvial river valleys (see Schumm, 1971) by the occurrence of zones of sub-alluvial bedrock protrusions. These are composed of highly compacted cohesive deposits that are difficult to erode, or highly compacted, coarse-grained fluvioglacial deposits. The sub-alluvial bedrock protrusions are often composed of cohesive Paleogene and Neogene strata (Różycki, 1972; Falkowski, 1990), and even the Cretaceous Chalk (Falkowski, 2006; Ostrowski et al., 2021). In places, the sub-alluvial bedrock highs in the Polish Lowland river valleys are composed of solid rocks or their clayey weathering products. An example is the Pilica River near Inowłódz (Falkowski, 2010) where, in the river bed and adjacent to glacial tills and ice-dam lake clays, siliceous sandstones of the Middle Jurassic are exposed (Fig. 10). Another example is in the Małopolska Vistula Gorge area, where the bedrock protrusions comprise carbonate and siliceous rocks of the Upper Cretaceous (Falkowski, 2006; Falkowska et al., 2016).

The top of the sub-alluvial bedrock is often covered with a layer of residual lag, which effectively increases its resistance to erosion (Falkowski et al., 2017). Such channel sections can be considered convenient for armoured vehicles to cross during low river states. However, such features are often hidden beneath channel alluvia.

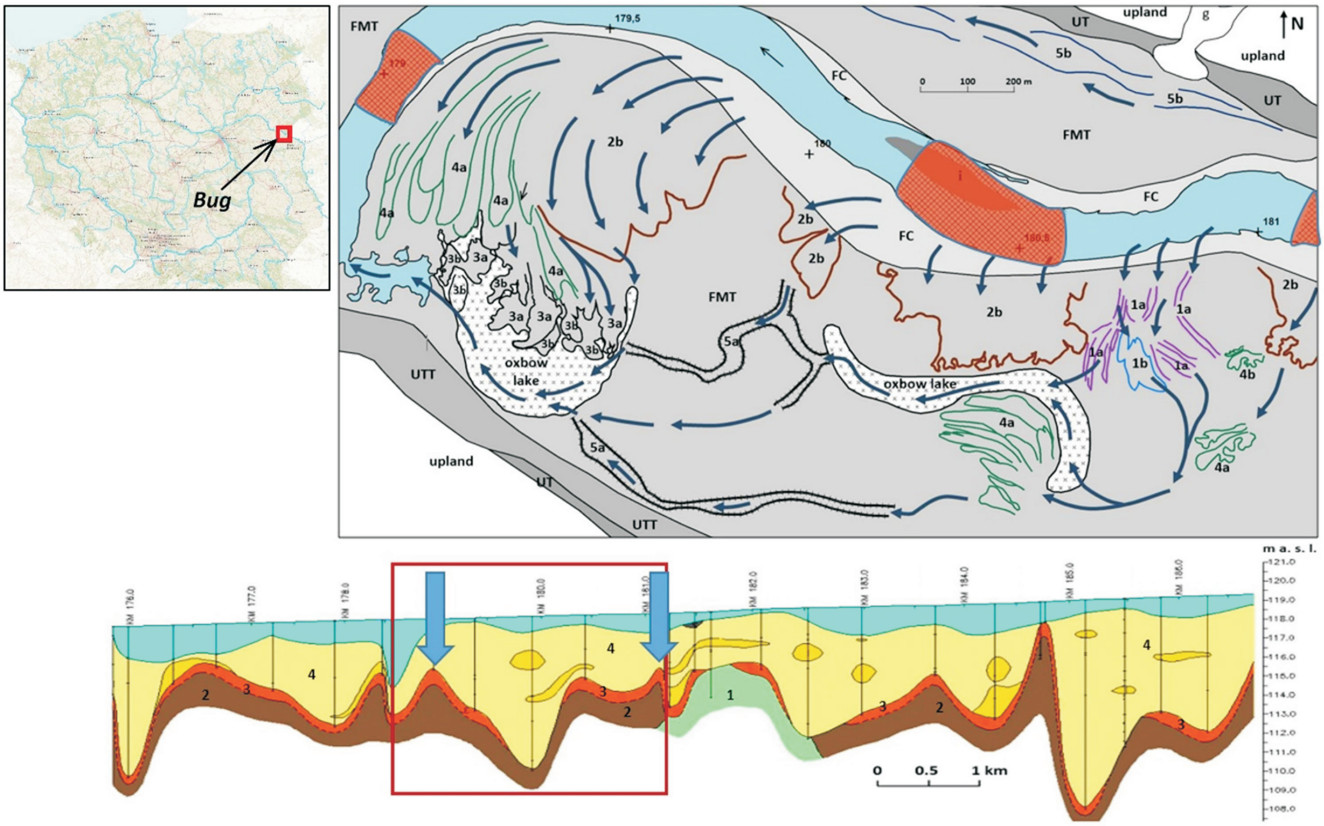

Fig. 12. The morphodynamics of the Bug River floodplain (part) in the vicinity of Mielnik (after Ostrowski et al., 2021, supplemented)

Geomorphological sketch: UT – upper terrace, UTT – upper transformed terrace, FMT – floodplain part created in the meandering period, FC – floodplain created contemporary; depositional features: 1(a, b) – alluvial fans, 2(a, b) – crevasse splays, 3(a, b) – deltas in oxbow lake, 4(a, b) – sand bars; 5(a, b) – erosional troughs; red polygons in the channel – sub-alluvial bedrock protrusions, blue arrows show directions of flood flows derived from geomorphological features distribution; longitudinal channel cross-section: 1 – chalk (Cretaceous), 2 – glacial till, 3 – lag deposits, 4 – channel alluvia (sand with gravelly intercalations), blue- water; the rectangle shows a channel reach of the floodplain area that is shown in the geomorphological sketch (up); the vertical blue arrows – show bedrock protrusions marked on the geomorphological sketch in red

Evidence of concentrated flood flows on the valley bottom may be the basis for searching for zones suitable for crossing channels in alluvial river valleys. This issue has been previously described (Falkowski, 2006, 2007; Falkowska and Falkowski, 2015; Falkowski et al., 2017; Ostrowski et al., 2021; Fig. 4). The inability to deepen the river bed during a flood wave passage in such zones causes water to enter the floodplain in the same places each time. Since channel sections with shallowly located sub-alluvial bedrock protrusions are also ice-jam sections, this morphodynamic pattern also applies to ice-jam floods. In this case, however, the blockage based on such a bedrock high (a heavy or dead jam according to Grześ (1991), or grounded ice jam according to Wiliams and MacKay, 1973) causes blockage of the entire channel. In such cases, evidence of floodwater erosion can be found not only on the floodplain but higher, on the upper terrace surfaces (Ostrowski et al., 2021, 2023).

The location of the bedrock protrusions coincides with places where ice jams formed in the past, including on a section of the middle Vistula (Falkowski and Popek, 2000) and the lower Bug (Ostrowski et al., 2021; Fig. 11). This has also been recorded in the lower Vistula valley (Wierzbicki et al., 2013).

As noted in the introduction, the specific morphodynamics of the floodplain in the zones with sub-alluvial bedrock protrusions are recorded by associations of erosional and depositional landforms, which can serve to identify them (Ostrowski et al., 2021). Evidence of erosion and flood deposition is much more visible in sections of alluvial river channels. In polygenetic, post-lacustrine sections, the morphogenic activity of flood flows is much weaker, mainly due to the large retention capacity of such valley sections.

The inventory of forms that arise as a result of encroachment on the surface of the floodplain in specific zones includes flood erosion channels: crevasses of various sizes and shapes, and crevasse-splays (Falkowski, 2007; Wierzbicki et al., 2013, 2018; Ostrowski and Falkowski, 2016; Ostrowski et al., 2021), or transformed oxbow lakes and related forms (see Falkowska and Falkowski, 2015; Falkowska et al., 2016; Ostrowski et al., 2021; Fig. 12).

The presence of a stable bottom and sub-alluvial bedrock protrusions in the channel, which influences the concentration of flood flows in certain zones, may also be revealed through a considerable lithological diversity of the floodplain surface (Falkowska and Falkowski, 2015; Falkowska et al., 2016; Ostrowski et al., 2021). This may be reflected in the greater habitat diversity of the valley floor than in mature valley sections (Demarchi et al., 2020). These features facilitate the identification of such sections through remote sensing (Ostrowski and Falkowski, 2016, 2020).

A characteristic feature of channel sections in sub-alluvial bedrock protrusion zones is the stability of the streamline system. Very often, this influence is so strong that it may cause repeated failures of hydrotechnical facilities or flood protection structures (Falkowski, 2007; Wierzbicki et al., 2018; Bujakowski and Falkowski, 2019). The impact of sub-alluvial bedrock surface relief is greatest during high water flows when its surface is exposed. However, as shown by the results of serial bathymetric studies of sections of the middle Vistula (Falkowski, 2007; Falkowski et al., 2018) and the lower Bug (Ostrowski et al., 2021, 2023), such stability is also observed in low and medium states and discharges when the bedrock surface is covered with channel alluvia. Channel sediments deposited during rare floods outside the mainstream zone become thicker over time. During medium or low flows, the river finds it “easier” to wash out loose sediments deposited in the mainstream zone during the descent of the flood wave than dense sediments deposited outside it this phenomenon was called “channel memory” by the authors (see Falkowski et al., 2018).

The stability of the mainstream lines system and its relationship with the density of channel alluvium may be the basis for the decision to cross the channels of large braided rivers, e.g. the reaches of the Vistula River in its middle and lower course. The channels of such rivers (the high water channel) are often ~1,000 m wide. Crossing them must be divided into several stages and requires the use of various crossing techniques.

CONCLUSIONS

Our review of research into the bottoms of lowland river valleys indicates a great diversity of geological and engineering conditions in their floodplains and channel zones. The main reason for this diversity is the lack of morphogenetic maturity of valley forms, as well as the nature of the hydrological regime of modern rivers. These show large variations in flow during the hydrological year.

The possibility of using pontoon sets (Motorized Floating Bridge) for crossing river channels is limited to brief periods of high and medium river states. This emphasizes the importance of geological studies of valleys to identify zones convenient for crossing riverbeds by armoured military vehicles. With this as a context, four major conclusions may be drawn:

–Unfavourable conditions for channel crossing occur in post-lacustrine sections of polygenetic river valleys with outcrops of weak, organic soils. Within them, marching routes may follow outcrops of glaciotectonic bedrock highs (protrusions) of glacial deposits that crop out in the channel zone (cf. Jabłońska et al., 2014). The recognition of such structures can be effectively carried out by remote sensing. They are most often associated with narrowings of the valley bottom. Glaciotectonic disturbances are visible most often as a mosaic of outcrops of different lithologies (Falkowska and Falkowski, 1994).

– In the conditions of medium and low levels prevailing in the hydrological year, convenient places for crossing river channels are zones where the sub-alluvial bedrock forms morphological protrusions made of deposits resistant to erosion.

– The presence of stable channel reaches is indicated by the specificity of the floodplain morphodynamics, and the related habitat diversity. These features can be identified using remote sensing methods on aerial and satellite imagery.

– The arrangement of current lines of the modern river channels of the Polish Lowlands in the zones of sub-alluvial bedrock protrusions is stable in medium and low water states when these forms are covered with a layer of channel alluvia.

REFERENCES

Ber, A., 1982. Marginal zones and deglaciation during the North-Polish Glaciation in the Suwałki–Augustów Lakeland (in Polish with English summary). Biuletyn Instytutu Geologicznego, **343**: 71–89.

Błaszkiewicz, M., Krzymińska, J., 1992. The late-glacial lake stage in the Wierzyca valley (in Polish with English summary). Przegląd Geograficzny, **64**: 369–380.

Bujakowski, F., Falkowski, T., 2019. Hydrogeological analysis supported by remote sensing methods as a tool for assessing the safety of embankments (case study from Vistula River Valley, Poland). Water, **11**, 266; https://doi.org/10.3390/w11020266

Demarchi, L., Kania, A., Ciężkowski, W., Piórkowski, H., Oświecimska-Piasko, Z., Chormański, J., 2020. Recursive feature elimination and random forest classification of Natura 2000 grasslands in lowland River Valleys of Poland based on Airborne Hyperspectral and LiDAR Data Fusion. Remote Sensing, **12,** 1842; https://doi.org/10.3390/rs12111842

Falkowska, E., 2015. The significance of morphogenetic analysis in the assessment of soil-water conditions in Quaternary sediments. Geomorphology, **246**: 420–432; https://doi.org/10.1016/j.geomorph.2015.06.039

Falkowska, E., Falkowski, T., 1994. Differences of lithology and sorption properties of surface deposits and their significance in protecting of extend contamination on the glacial relief area in example of Supraśl river valley (in Polish with English summary). Zeszyty Naukowe AR we Wrocławiu, **246**: 47–55.

Falkowska, E., Falkowski, T., 2015. Trace metals distribution pattern in floodplain sediments of a lowland river in relation to contemporary valley bottom morphodynamics. Earth Surface Processes and Landforms, **40**: 876–887; https://doi.org/10.1002/esp.3680

Falkowska, E., Falkowski, T., Tatur, A., Kałmykow-Piwińska, A., 2016. Floodplain morphodynamics and distribution of trace elements in over bank deposits, Vistula River Valley Gorge near Solec nad Wisłą, Poland. Acta Geologica Polonica, **66**: 541–559; https://doi.org/10.1515/agp-2016-0025

Falkowski, E., 1971. History and prognosis for the development of bed configurations of selected sections of Polish lowland rivers (in Polish with English summary). Biuletyn Geologiczny, **12**: 5–121.

Falkowski, E., 1990. Morphogenetic classification of river valleys developing in formerly glaciated areas for needs of mathematical and physical modeling in hydro technical projects. Geographia Polonica, **58**: 55-67.

Falkowski, T., 1988. Effect of morphogenetic units on hydrogeologic conditions in the Nurzec river valley (in Polish with English summary). Zeszyty Problemowe Postępów Nauk Rolniczych, **347**: 135–148.

Falkowski, T., 1997. The importance of recognition of polygeny for the rational utilisation of river valleys in Polish Lowland. Proceedings of International Symposium “Engineering Geology and the Environment”. A. A. Balkema: 107–111.

Falkowski, T., 2003. Influence of the morphogenetic diversity of the Nida-Wkra river valley stretches on the conditions of underground flow. Annals of WAU, Land Reclamation, **34**: 51–64

Falkowski, T., 2006. Factors of natural stability of the Middle Vistula River channel zones (in Polish with English summary). Wydawnictwo SGGW, Rozprawy Naukowe i Monografie, **312**.

Falkowski, T., 2007. Alluvial bottom geology inferred as a factor controlling channel flow along the Middle Vistula River, Poland. Geological Quarterly, **51**: 91–102.

Falkowski, T., 2010. Basement of the alluvia influence on the channel pattern in example of selected reach of the Pilica River. Annals of Warsaw University of Life Sciences – SGGW, Land Reclamation, **42**: 93–104.

Falkowski, T., Popek, Z., 2000. Zones of ice-jams formation on the Middle Vistula River reach in relation to variable of river valley morphology. Annals of WAU, Land Reclamation, **30**: 77–90.

Falkowski, T., Ostrowski, P., Siwicki, P., Brach, M., 2017. Channel morphology changes and their relationship to valley bottom geology and human interventions; a case study from the Vistula Valley in Warsaw, Poland. Geomorphology, **297**: 100–111; https://doi.org/10.1016/j.geomorph.2017.09.011

Falkowski, T., Ostrowski, P., Bogucki, M., Karczmarz, D., 2018. The trends in the maim thalweg path of selected reaches of the Middle Vistula River and their relationship to the geological structure of the river. Open Geosciences, **10**: 554–564; https://doi.org/10.1515/geo-2018-0044

Fedorowicz, S., Laskowski, K., Lindner, L., 1995. Possibility of further extent of the Wisła Glacial in light of the dating of glacial deposits in the northern part of Wysoczyzna Białostocka (NE Poland) (in Polish with English summary). Przegląd Geologiczny, **43**: 941–944.

Gradziński, R., Baryła, J., Doktor, M., Gmur, D., Gradziński, M., Kędzior, A., Paszkowski, M., Soja, R., Zieliński, T., Żurek, S., 2003. Vegetation-controlled modern anastomosing system of the upper Narew River (NE Poland) and its sediments. Sedimentary Geology, **157**: 253–276; https://doi:10.1016/S0037-0738(02)00236-1

Grześ, M., 1991. Ice jams and floods on the lower Vistula River. Mechanism and processes (in Polish). IGiPZ PAN, Warszawa; https://doi.org/10.7862/rb.2017.112

Headquarters Department of the Army Commandant, US Marine Corps 1992. FM 90-13/FMFM 7-26, River Crossing Operations; Washington DC.

Iyer, A., 2024. Bridging through time: from river crossing in World War II to wet-gap crossing today and in the future. Land Warfare Papers, **157**.

Jabłońska, E., Falkowski, T., Chormański, J., Jarzombkowski, F., Kłosowski, S., Okruszko, T., Pawlikowski, P., Theuerkauf, M., Wassen, M.J., Kotowski, W., 2014. Understanding the long term ecosystem stability of a fen mire by analyzing subsurface geology, eco-hydrology and nutrient stoichiometry – case study of the Rospuda Valley (NE Poland). Wetlands, **34**: 815–828; https://doi.org/10.1007/s13157-014-0544-z

Klajnert, Z., Wasiak, G., 1989. Morphological effects of the Warta ice-sheet areal retreat in the zones of the pre-Warta subglacial valleys in the Łódź Plateau (in Polish with English summary). Acta Geographica Lodziensia, **59**: 39–60.

Kobojek, E., 1996. The effect of the Warta Stage glacial processes on the Rawka River valley development (in Polish with English summary). Acta Geographica Lodziensia, **71**: 67–78.

Komornicki, L., 2021. Przygotowanie obronne terytorium Polski: północno-wschodni kierunek strategiczny. Fundacja Instytut Bezpieczeństwa i Strategii. https://www.defence24.pl/przygotowanie-obronne-terytoriu-polski-polnocno-wschodni-kierunek-strategiczny-opinia

Kondracki, J., 2001. Geografia regionalna Polski. PWN, Warszawa.

Kotarbiński, J., Krupiński, K.M., 2000. First localities of the biogenic sediments of Eemian Interglacial at the Urszulewska Plain (Central Poland) (in Polish with English summary). Przegląd Geologiczny, **48**: 596–600.

Kozarski, S., Rotnicki, K., 1977. Valley floors and changes of river channel patterns in the North Polish Plain during the Late Würm and Holocene. Quaestiones Geographicae, **4**: 51–93.

Kozłowski, E., Wrzosek, M., 1984. Historia oręża polskiego 1795–1939. Wiedza Powszechna, Warszawa.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman & Company, San Francisco.

Lindner, L., 1988. Outline of Pleistocene stratigraphy of Biała Podlaska region (eastern Poland) and attempt of correlation with neighbouring area of Soviet Union (in Polish with English summary). Przegląd Geologiczny, **38**: 637–647.

Lindner, L., Marks, L., 2012. Climatostratigraphic subdivision of the Pleistocene Middle Polish Complex in Poland (in Polish with English summary). Przegląd Geologiczny, **60**: 36–45.

Mądrzycki, P., Burek, M., Marcinkowska, M., Rusewicz, M., Ostrowski, P., 2019. The needs to recognize conditions for river crossing operations in the Polish Lowlands by military vehicles in the light of NATO regulations. Journal of KONBiN, **49**: 139–156; https://doi.org/10.2478/jok-2019-0080

Marks, L., 1990. Outline of geology and evolution of the north western Kurpie outwash, Northern Poland (in Polish with English summary). Geological Quarterly, **34**: 489–502.

Mojski, J.E., 2005. Ziemie polskie w czwartorzędzie. Zarys morfogenezy. Państwowy Instytut Geologiczny, Warszawa.

Musiał, A., 1992. Studium rzeźby glacjalnej północnego Podlasia (in Polish with English summary). Rozprawy Uniwersytetu Warszawskiego, **403**.

Mycielska-Dowgiałło, E., 1978. Evolution of the fluvial relief in the northern part of Sandomierz Basin in the light of sedimentological studies (in Polish with English summary). Rozprawy Uniwersytetu Warszawskiego, **120**.

Myślińska, E., Falkowska, E., Hoffmann, E., Stępień, A., 1993. Lithology of soils in the Supraśl River valley (E Poland) and their ability to hold pollution. Geological Quarterly, **37**: 467–484

Ostrowski, P., 2022. Remote-sensing detection of points for the heavy vehicles crossingin the large lowland riverbeds. Journal of KONBiN, **52**: 107–122; https://doi.org/10.2478/jok-2022-0026

Ostrowski, P., Falkowski, T., 2016. The application of Very High Resolution multispectral satellite images (VHR) for the identification of some floodplain landforms (in Polish with English summary). Przegląd Geologiczny, **54**: 810–817.

Ostrowski, P., Falkowski, T., 2020. Application of remote sensing methods to study the relief of lowland river valleys with a complex geological structure – a case study of the Bug River. Water, **12**, 487; https://doi.org/10.3390/w12020487

Ostrowski, P., Utratna-Żukowska, M., 2023. The new concept for the heavy vehicles crossing in the large lowland riverbeds North East Strategic Direction. Journal of KONBIN, **53**: 59–77; https://doi.org/10.5604/01.3001.0016.3239

Ostrowski, P., Falkowski, T., Utratna-Żukowska, M., 2021. The effect of geological channel structures on floodplain morphodynamics of lowland rivers: A case study from the Bug River, Poland. Catena, **202**, 105209; https://doi.org/10.1016/j.catena.2021.105209

Ostrowski, P., Falkowski, T., Kochanek, K., 2023. Reconstructing parameters of the Holocene paleofloods in alluvial lowland river valleys – an example from the Bug valley (East Poland). Journal of Hydrology, **624,** 129930; https://doi.org/10.1016/j.hydrol.2023.129930

Pożaryski, W., 1953. Pleistocene in the Vistula River gorge across the Southern Uplands (in Polish with English summary). Prace Instytutu Geologicznego, **9**.

Różycki, S.Z., 1972. Plejstocen Polski środkowej na tle przeszłości w późnym trzeciorzędzie (in Polish). PWN, Warszawa.

Schumm, S.A., 1971. Fluvial geomorphology in river mechanics. In: River Mechanics (ed. H.W. Shen): 365–417. Water Resources Publication, Fort Collins.

Smaga, A., 2015. Analysis of prognosis of lowland river bed erosion based on geotechnical parameters. Studia Geotechnica et Mechanica, **37**: 57–63.

Stachý, J., 1970. Wieloletnia zmienność odpływu rzek polskich (in Polish). PIHM, Warszawa.

Szelka, J., 2017. Crossing water obstacles in accordance with NATO standards (in Polish with English summary). Journal of Civil Engineering, Environment and Architecture, **64**: 165–177.

Szumański, A., 1986. Late Glacial Evolution and Mechanism of Transformation of a Floor of Lower San Valley (in Polish with English summary). Zeszyty Naukowe AGH, Geologia, **12**: 5–92.

Wierzbicki, G., Ostrowski, P., Falkowski, T., Mazgajski, M., 2018. Geological setting control of flood dynamics in lowland rivers (Poland). Science of the Total Environment, **636**: 367–382; https://doi.org/10.1016/j.scitotenv.2018.04.250

Wierzbicki, G., Ostrowski, P., Mazgajski, M., Bujakowski, F., 2013. Using VHR multispectral remote sensing and LIDAR data to determine the geomorphological effects of overbank flow on a floodplain (the Vistula River, Poland). Geomorphology, **183**: 73–81. https://doi.org/10.1016/j.geomorph.2012.06.020

Williams, G.P., MacKay, D.K., 1973. The characteristics of ice jams. In: Seminar on Ice Jams in Canada. Proceedings, Seminar on Ice Jams in Canada: 17–35. National Research Council of Canada, Ottawa.

Żurek, S., 1978. Development of the fossil Holocene lakes in the Biebrza ice-marginal valley against the background of the Maliszewskie Lake sediments. Polskie Archiwum Hydrobiologii, **25**: 491–498.