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The structural control of a landslide development and functioning of a lake geoecosystem in the catchment area of the Hucianka Stream (the Outer Carpathians, Beskid Niski)

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Abstract: The landslide in Huta Polańska (Beskid Niski/Lower Beskids) is an example of a particular lake geoecosystem. The largest inter-colluvial depression forms a lake basin constantly filled with water, with a natural outflow in the form of a watercourse. Three drainless sink-holes constituting places of periodical accumulation of water and organic-mineral sediments were localized within the landslide. The direction of the landslide movement and its wedge-like shape are determined primarily by the fault surface located in its south-western part. It also forces the linear course of the streams and the cascade location of depressions between colluvial ramparts, seasonally or permanently filled with water. The inventory of minor tectonic structures and the morphotectonic analysis indicate tectonic conditions of this landslide lake geoecosystem. The structures located within the fault surfaces are indicative of shear stresses and their orientation determines the direction of rock movement (Zuchiewicz, 1997a; Szczęsny, 2003). The morphological analysis and correlation of landslide forms indicate the combined rotational-translational motion. It was ended by mud and debris flow which divided the valley longitudinal axis and damming the waters of the Hucianka stream. The result is a landslide dam lake, whose effects are visible within the floodplain above the former landslide dam. In order to formulate the final conclusions regarding the morphotectonic analysis and the slope transformation phases, laser scanning photos were also used.

Key words: structural control, mass movements, landslide lake, landslide dam, Flysch Carpathians

Introduction

Landslide processes are common in the Flysch Carpathians (Ziętara 1969; Jakubowski 1974; Bober 1984). They are favoured by geological conditions, predisposing many places in the Beskid Mountains to form large landslide areas. Their location is uneven, and sometimes landslides cover up to 50% of surfaces of the slopes (Ziętara 1969). The difficulties arising from the impossibility of encapsulating them in a universal classification resulted from their large diversity (Kleczkowski 1955; Ziętara 1969; Bober 1984; Margielewski 2001a, 2009). However, during the research recently conducted in the Flysch Carpathians it was discovered that *"all rock landslides have structural control of development"* (Margielewski and Urban 2000; Margielewski 2001a). In many cases, these are also *"complex"* type forms made up of a few kinds of gravitational movements, (Margielewski, 2009). The possibility of determining the mechanics and type of landslides in the Carpathians is provided today by the morphotectonic analysis (Bajgier 1994; Margielewski 1994, 1998, 2001a; Margielewski and Urban, 2000).

Research into the determinants of landslide development in the Beskid Niski was initiated in 1936 by Teisseyre. It was continued by Bober (1977, 1984) who analysed 50 structural landslides of different types in the central part of the Beskid Niski (Lower Beskids). Both Teisseyre and Bober connected the location of landslides with increased structural disintegration of rocks, due to the occurrence of joint surfaces within a slope. Strong structural anisotropy determines block disintegration of thick bedrock sandstone during the mass movement. It is then that the transformation of the landslide area resulting in both its flattening and variation occurs. As a result, not only the relief changes, but also the future directions of erosion are determined. This affects the formation of specific landslide geoecosystems determining the existence of wetlands, and even the development of permanent or periodic lakes (Margielewski 1999; Alexandrowicz and Margielewski 2010).

Current state of knowledge on landslide lakes

The study of lakes in Poland concerns many aspects. However, comprehensive lists based on the components of the abiotic environment, including in particular structural features, are rarely developed. Most often lake sink-holes, the bedrock, sediments and water chemistry are analysed in the majority of studies. Organic matter‑develops in water and in the top sediment layers. All these factors interact with each other, forming a complex lake geoecosystem. Some landslide lakes are sometimes filled with sediments even completely. Sediments of these lakes can be divided into three major groups based on their petrographic composition. The first are clastic sediments formed from fragments of older rocks varied in size, e.g. gravel, sand and dust or clay. The second are sediments developed in a biochemical or chemical way. The third group is made up of organic sediments (Rutkowski 2007).

Landslide lakes occur within sealed drainless basins. Their division refers to their location with respect to the morphological parts of the landslide. Those that are located within the landslide area are divided into lakes below the head scarp, those filling colluvial depressions, and those within rifts (Margielewski 1999). Reservoirs located directly below landslide scarps are usually characterized by relatively large dimensions and depths. It is also the most common type of landslide lakes. These lakes, both the active ones and those converted into wetlands, occur in almost every range in the Polish Flysch Carpathians. The lake depression is framed on one side by a scarp, and on the other by a colluvial rampart which obstructs the outflow of water from the reservoir (Margielewski 1996). Lakes located within the plateaux and the rampart of the landslide colluvium may develop during the primary or secondary movements. Sediments accumulated in lakes between colluvial swells are characterized by high variability depending on the seal of the bottom, the force of water flow, and the position within the landslide. Sediments of reservoirs located below landslide scarps are characterized by a large volume of mineral material and the high volatility of its deposition in time. This is due to the location of the lake below the landslide scarp cut by seasonal or permanent tributaries of the lake. Sink-holes formed within the colluvium are filled with sediments rich in mineral components, derived from the colluvial material forming the landslide. However, the variability of the sediment deposition is much lower than the first type of lake characterized (Margielewski 2006). A separate type of landslide lake is landslide dam lakes, which are formed as a result of obstruction of the water flow by the colluvial tongue. This part of landslides is called a landslide dam, or a transom, damming the waters from the water flow, thus resulting in the formation of a lake. These reservoirs are usually short-lived, and their size and depth depend mainly on the height of the transom damming the waters from the water flow, the longitudinal profile of the valley, and its width (Costa and Schuster 1988; Malarz 1993). Destruction of the colluvial transom depends on its resistance and the kinetic energy of the swollen water flow. Lakes formed at streams of larger flow tend to have the shortest life (Nowalnicki 1971).

Much more space has been devoted in the Polish literature to lakes between colluvial swells than to landslide dam lakes. The earliest studies of these objects are associated with the landslide in Duszatyn, in 1907, and relate to the estimation of their surface (Schramm 1925). In the later period, they were also verified and comprehensively expanded by the exact measurements of bathymetry, coastline, physical properties of water, and overgrowing processes (Kardaszewska 1968). Currently, research on landslide lakes in the Carpathian Mountains is mainly concentrated on the assessment of landslide age and recording the climate change within their sediments. Such measurements were performed in many places in the Western Beskids, using palynological (Cabaj and Pelc 1991), malacological (Alexandrowicz 1985) and radiocarbon methods (Haczewski and Kukulak 2004; Margielewski 1996, 2001b, 2006). Layers of sediments in landslide lakes also contain information about the conditions in which they were formed. Malacological, palynological, lithological, and sedimentary analyses, as well as those of seeds contained in these sediments, allow changes occurring in the natural environment in the Carpathians over the postglacial and holocene periods to be reconstructed (Margielewski 1996). An increase in the mass movements in the Carpathian Mountains was associated with more humid phases of the climate during the last 14,000 years. The debris flow and rinsing which occurred then supplied a greater amount of mineral material into the landslide sink-holes. Landslide wetlands, particularly those occurring in drainless depressions, are thus a good recorder of hydrometeorological changes (Starkel 1960; Alexandrowicz 1996; Margielewski 2006).

Study area

An example of a large landslide accompanied by water ecosystems is located in the area of Huta Polańska, in the central part of the border range Beskid Niski (Lower Beskids), and in the southern part of the Magura National Park (Fig. 1). The range in this area is formed from rocks of the Magura Unit. It consists of overlapping tectonic scales, built primarily of Magura bedrock (sandstone from Wątkowa), over-Magura sandstone and, in a minority of freaked slates with Ciężkowice sandstone (Kopciowski 2000) (Fig. 2). The bedrock is monoclinic in the whole research area. The overlapping surfaces of the Czerteź tectonic scale on the Huta Polańska tectonic scale is approx. 40°. A clearly visible dichotomy can be observed in the Magura bedrock formations in the Beskid Niski. In the lower part of the Wątkowa sandstone, there is

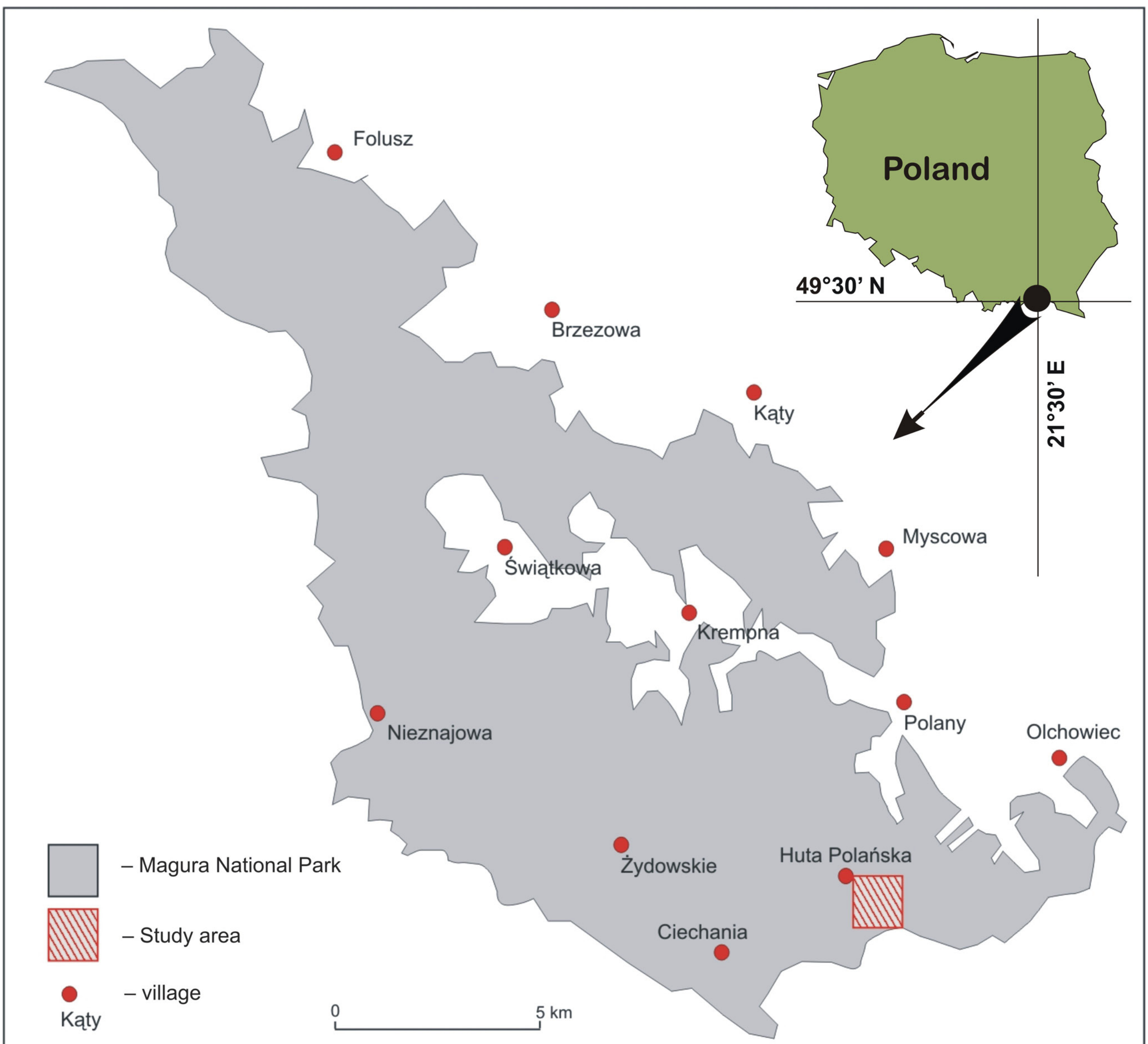


Fig. 1. Location of the study area

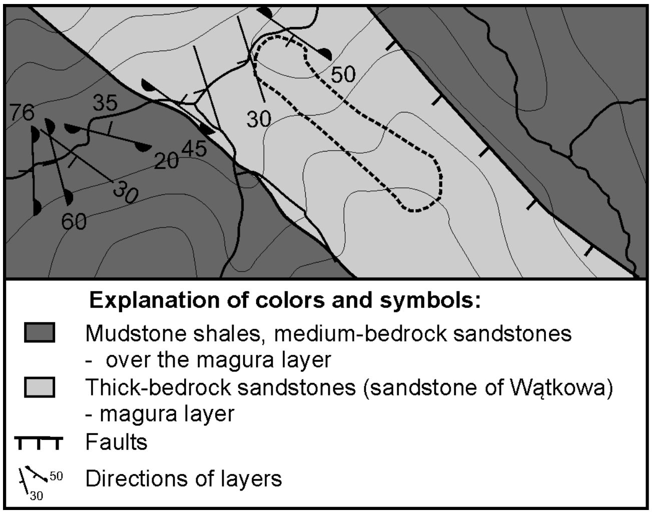


Fig. 2. Geological map of the research area (according to Kopciowski 2000)

a great diversity of lithological types. They are mainly medium and thick-bedrock, grey-ashen massive sandstone, usually without structures, medium and thick-grained. Macroscopically, mainly quartz, minor feldspars and many glauconite grains are observed in the sandstone. Grey-green, thick-cleavable mudstone sometimes occurs between the bedrocks of sandstone. Their share in this part of the geological profile generally does not exceed 10% (Kopciowski 2000).

Hydrologically, the landslide is located in the Hucianka Stream catchment area, with its tongue head reaching as far as the bottom of the valley, which classifies it as a slope-valley landslide. It has distinct structural features of development. With respect to the arrangement of layers in the substrate, it represents the subsequent type of landslide, parallel to the lines of the bedrock course. The landslide has the contour of an elongated trough of the NW-SE course, reaching the bottom of the Hucianka Stream valley (Fig. 2). Its longitudinal axis is 624 metres long, and it is 85-109 metres in width. The marginal zone of this landslide, in its south-western part, is formed by a rock wall with a length of approx. 500 metres, and 5-30 metres in height. The tectonic structures and the tectonic mirror located within it indicate the rejuvenation of the fault surface, which is the result of landslide movement (Świderski 1952). The orientation of minor tectonic structures determines the local surfaces of rock movement (Fig. 4).

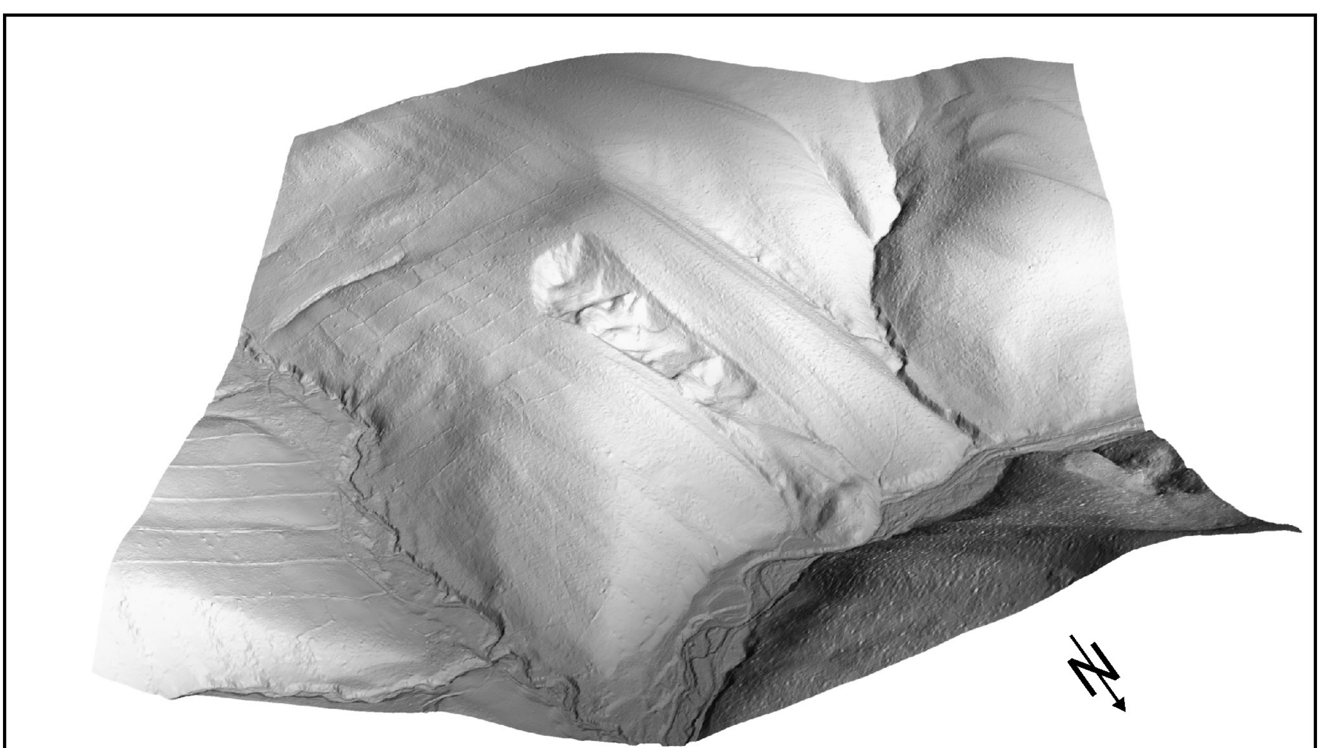


Fig. 3. Digital laser scanning elevation model of the upper part of the Hucianka Stream catchment area

The upper part of the landslide is formed in an earthy scarp which is10-30 metres high. A small-size drainless sink-hole is located below, with a diameter of 8 metres, filled entirely with organic-mineral material. It is limited by a colluvial rampart which is 5-10 metres wide. There is another transversal colluvial rampart below, which is 5 metres high and 10 metres wide. A large landslide lake with a diameter of 40-50 metres, and a maximum surface of 4200 m^2, occurred behind another colluvial swell. Its depth varies between 0.25 and 1.50 metres, which in periods of drought becomes even shallower. In the NE part, the lake is transformed into a fen. The whole lake basin is limited in the north by a colluvial rampart, built of debris with a diameter of 15-30 centimetres. It cuts the permanent watercourse flowing out of the lake. After approx. 100 metres, it flows into a wetland filled entirely with organic material. It is limited in the north-west by the land-

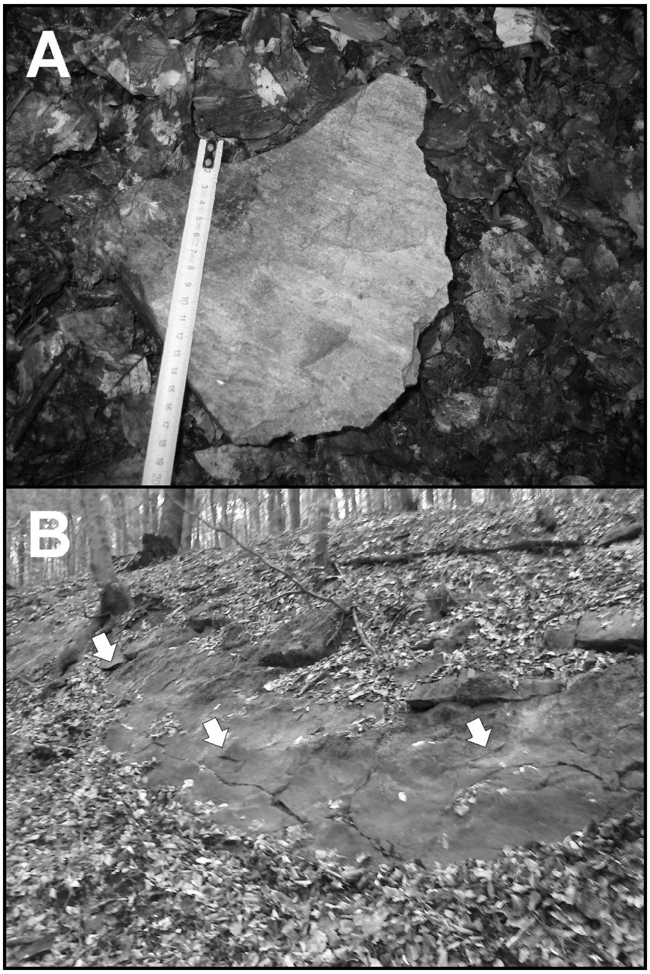


Fig. 4. Structures demonstrating shear stresses within the rock wall of the landslide (A – tectonic mirror, B – minor tectonic structures; the orientation of minor tectonic structures determines the local surfaces of mass movement)

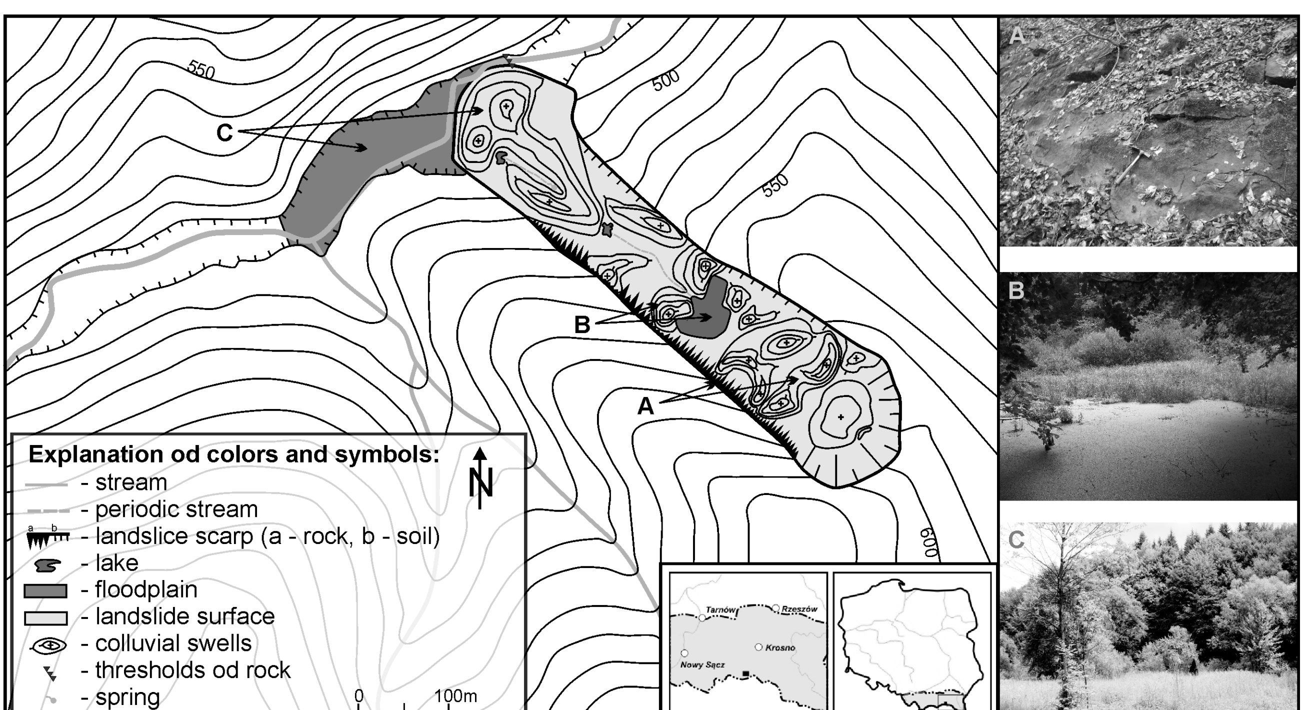


Fig. 5. Geomorphological plan of the landslide in Huta Polańska (A – a rock wall along the edge of the landslide and the rotated colluvial block, B – lake within the landslide surface and a wedged colluvial rampart, C – floodplain and landslide dam)

slide tongue, which falls steeply in the direction of the main axis of the Hucianka Stream valley (Fig. 5). A periodic watercourse and a spring, which flows after approx. 50 metres into a small wetland completely filled with clay, are located within its area. A characteristic narrowing of the valley axis at the landslide tongue head indicates damming which occurred there. The riverbed of the Hucianka Stream in the area of the narrowing is covered with river gravels, and a few metres below, erosion rock outcrops corresponding to the local geological structures (bedrock) are visible. Exposed rock thresholds indicate an increase in the erosive activity after unblocking the flow of water. Certainly, the landslide tongue formed a 10-20-metre-high landslide transom, which swelled the waters of the stream. There is a floodplain 253 metres in length, and 50-62 metres in width, above the place dammed by the landslide tongue. An area of increased erosive and accumulative activity can be distinguished within the floodplain (Fig. 6). River gravels occur in the substrate in the erosive part, and fens filled with organic material are observed in the accumulative part. The accumulative and erosive areas can be also distinguished in the transversal cross-sections made across the floodplain (Fig. 7).

Elevation models, representing the contour of the lake basin and the location of shallow waters, were made within the largest contemporary lake of this landslide (Fig. 8). Three zones of varying flow and groundwater level were determined on this basis. Mineral structures, mainly clay ones with inserts of plant detritus, occur in the partially sealed lake bottom. Sandy loam with mud or clay occurs in the fully sealed lake bottom with changes in the water flow. In its northern part, the lake basin is filled with mineral and organic sediments. Organic material in this part is represented by dark silts with wood chaff and plant debris of 4 cm in thickness.

Methods

A field inventory combined with the geomorphological mapping of landslide relief forms was conducted during the research. The geomorphological map of the landslide took into account also the intercolluvial drainless areas acting as lake basins. The wa-

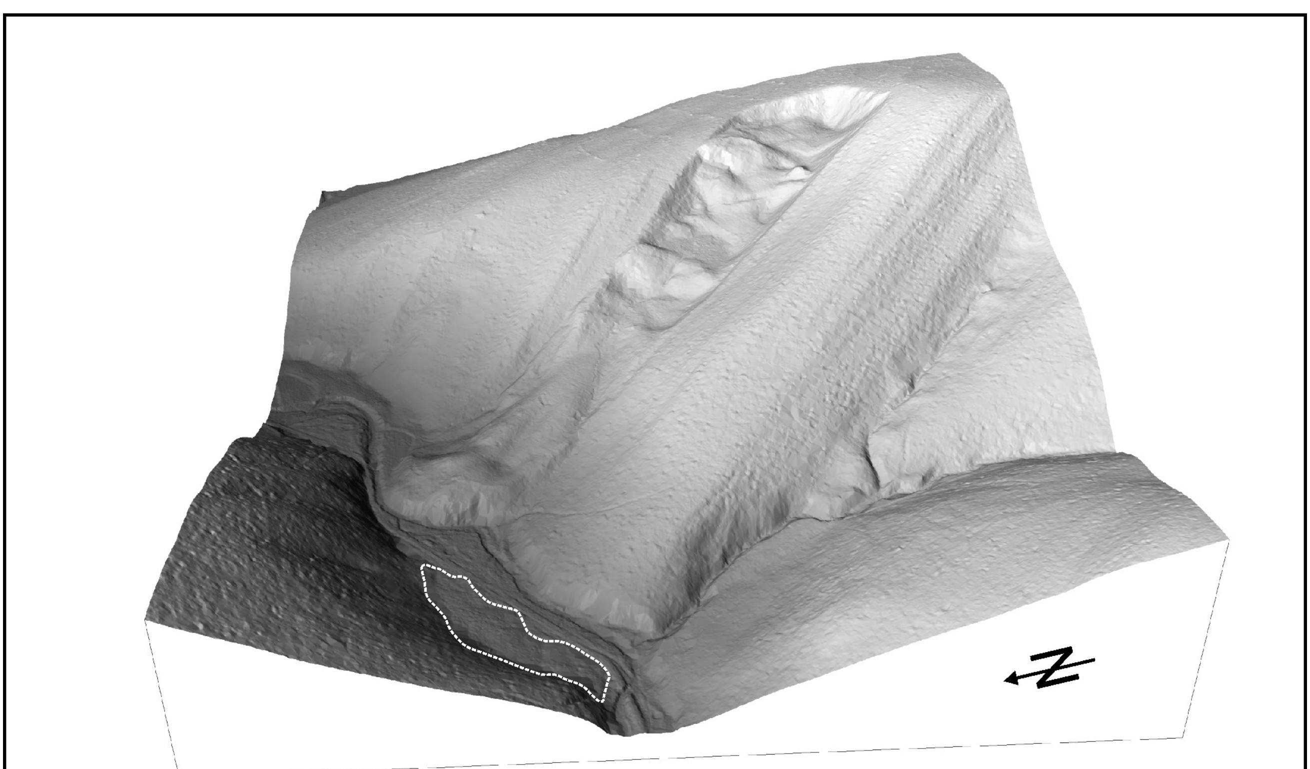


Fig. 6. Digital laser scanning elevation model of the research area (the area of increased accumulative activity within the floodplain has been marked)

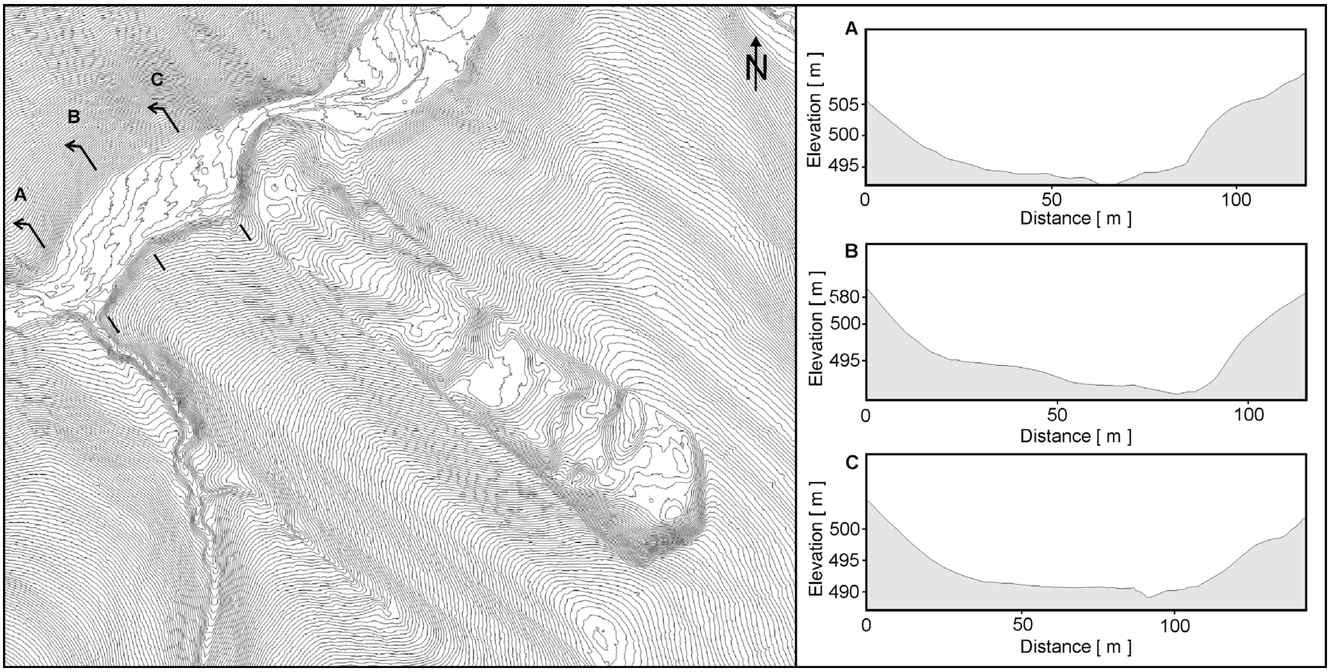


Fig. 7. Cross-sections across the floodplain (the accumulation area can be seen in cross-section B)

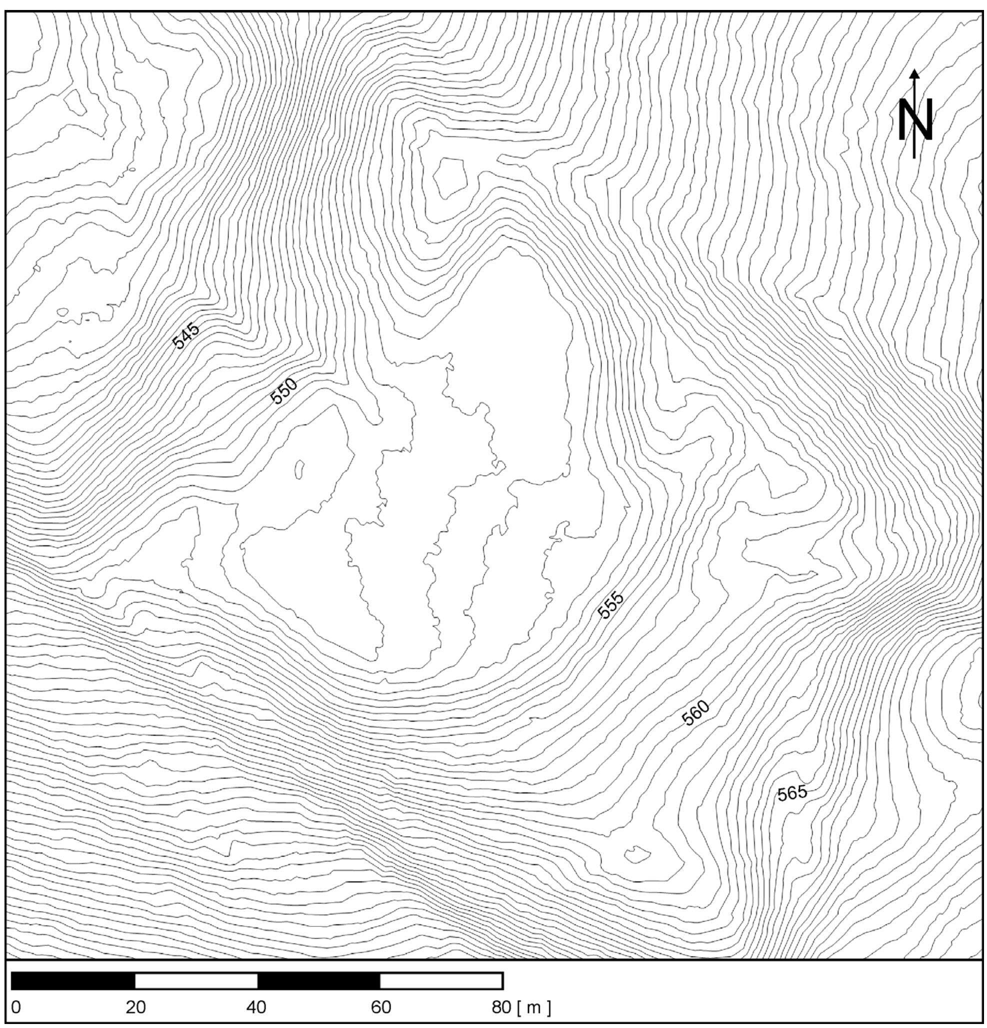


Fig. 8. The inter-colluvial depression in the central part of the landslide (the isolines demonstrate the contour of the lake basin and the location of shallow waters)

ter flow activity occurring in the landslide was also divided into permanent and periodic. In addition, elevation models were used for the morphological analysis and correlation of these landslide forms. They were generated on the basis of data from the digital terrain model, using laser scanning. Three cross-sections and a longitudinal section across the landslide were also made. Another three cross-sections of the floodplain and the measurements of the floodplain performed allowed the potential extent of the landslide dam lake existing before to be established. The area of this largest landslide lake basin was also generated on the basis of the elevation model. Zones of increased mineral supply and places with organic sediments were also determined within it. Also zones of varying water flow and groundwater level were identified during the inventory conducted there. Together with the macroscopic analysis of the clastic sediments within the lake basin, it allowed a potential indication of the direction of water flow and the functioning of this water geoecosystem to be put forward.

A morphotectonic analysis was conducted within the south-western surfaces of the landslide, which is formed by a rock wall. A total of 256 measurements of the discontinuities position were performed. Rock discontinuities were measured using a Freiberg geological compass with an accuracy of 2°. For the purpose of further analysis and proper interpretation, the measurements were divided into four groups, according to their location on the rock wall taking into account the direction of landslide movement. Contour diagrams (a projection of poles onto the lower hemisphere) and rose diagrams (with an accuracy of 10°, in the full range of the circle, from 0° to 360°) were drawn on the basis of measurements of the rock discontinuities. These diagrams were supplemented with the location of the bedrock and the regional names of joint systems, which were adopted after Mastella et al. (1997, 1998): L, L ‘ – longitudinal, $D_{1,}$ D_{2} – diagonal, T – transversal, to the position of the bedrock. Using the morphological and morphotectonic analyses, an attempt was made to determine the phases of landslide movement and the transformation of the fault surface as a result of its motion.

Results

With respect to the arrangement of bedrock in the substrate, the landslide is defined as a subsequent one, i.e. parallel to the course of rock layers. Thick-bedrock of the sandstone in this region of the Beskid Niski is accompanied by systems of longitudinal faults. The rock wall in the SW part of the landslide is covered with a tectonic mirror. Tectonic structures located within the fault surface are indicative of the rejuvenation of its surface as a result of landslide movement. On the basis of the research performed, different phases of landslide lake geoecosystem development were identified (Fig. 9).

The morphotectonic analysis performed indicates strict tectonic conditions of landslide development related to shear stress (Zuchiewicz 1997a, 1997b). As a result of rejuvenation of the fault surface, the exposition of a rock wall covered with a tectonic mirror occurred. Strong structural disintegration within the fault zone predisposed to form a landslide, whose wedge-like contour and direction of movement was determined by the fault surface. However, the flat slip surface was primarily modified by the depth of the landslide of more than 20 metres. In such conditions, the type of movement changes from the formally translational one (with wedge shape and the slip surface located low) into the rotational one (cylindrical envelope of the slip). The landslide was ended by mud and debris flow which divided the valley. Based on the morphotectonic analysis it was found that the central part of the fault surface has been transformed, deepened by colluvial blocks wedging in this part (Fig. 10). This is also evidenced by minor tectonic structures and elongated tectoglyphs inventoried in the narrowest place of the landslide. Rotated colluvial blocks wedged there led to the formation of a large inter-colluvial depression, additionally sealed with impermeable marly slates. This resulted in raising the water table and in changing the water relations within the landslide. The inter-colluvial depressions and small sink-holes were either filled with water, or constantly humid wetlands were formed in them. Below the place of narrowing, the relocated colluvial material was unified. In this part, the landslide had a nature of mud and debris flow movement which led to the damming of the Hucianka riverbed, and the swelling of waters over the section of about 253 metres. The surface of the swollen landslide dam lake could be as large as 1.62 hectares (16,100 m^2). The landslide dam was cut as a result of the erosive activity of the river, a consequence of which is the rock thresholds exposed below the narrowing of the valley. Upon unblocking the water flow, the part with the accumulated sediments was carried out of the floodplain.

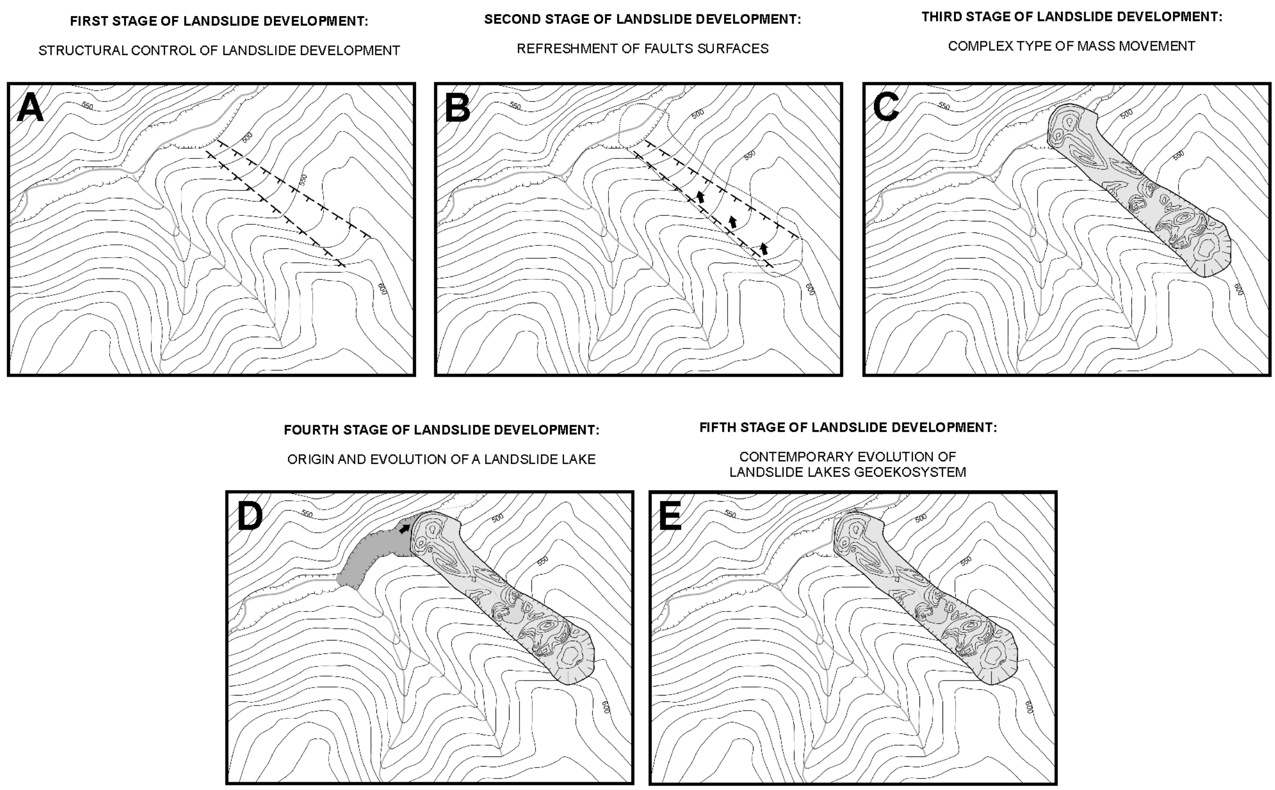
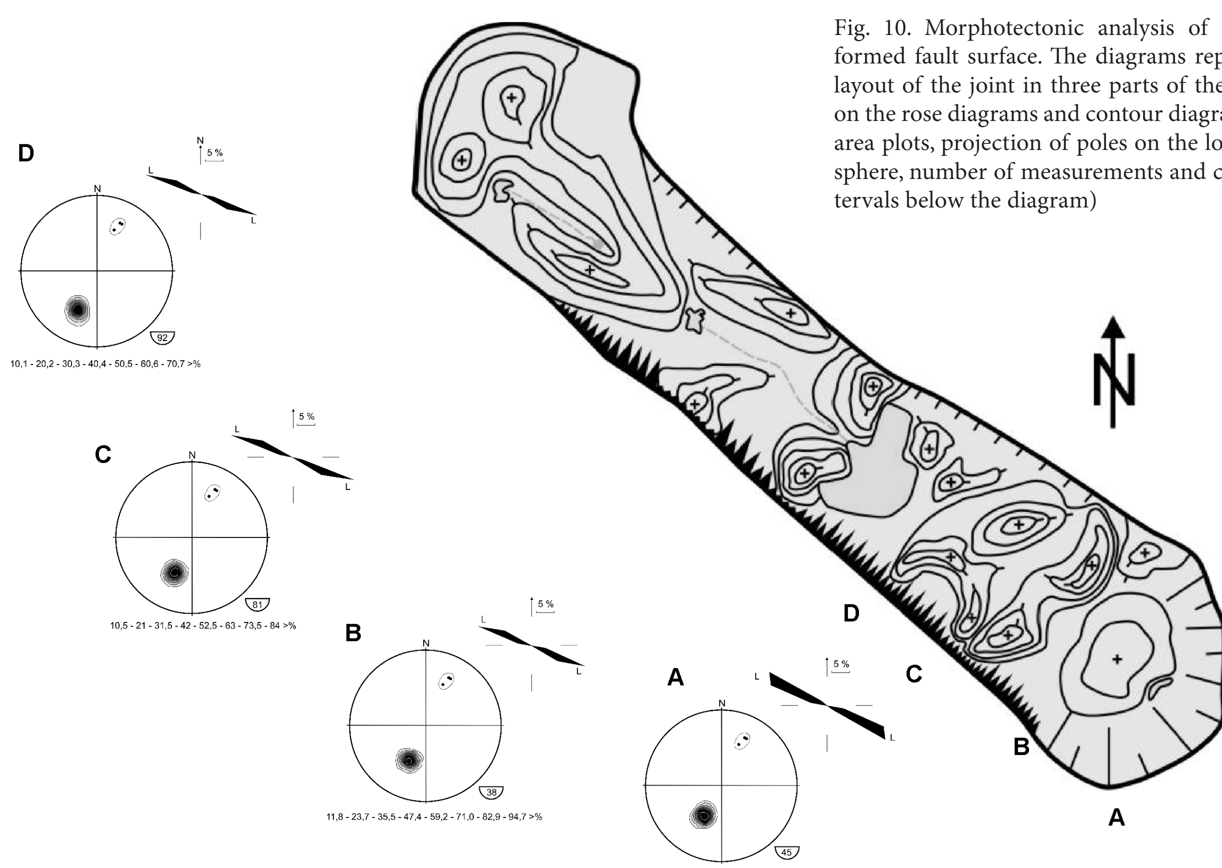


Fig. 9. Phases of the landslide lake geoecosystem development in the Hucianka Stream catchment area

Fig. 10. Morphotectonic analysis of the transformed fault surface. The diagrams represent the layout of the joint in three parts of the rock wall on the rose diagrams and contour diagrams (equal area plots, projection of poles on the lower hemisphere, number of measurements and contour intervals below the diagram)



A preliminary analysis of the sediments and the groundwater level allows the direction of water flow within the central part of the landslide to be determined. The direction of the run-off was determined by the subsequent arrangement of bedrock. In the initial phase of the water system functioning, drainage took place linearly along the elongated fault surfaces. A similar situation, before the landslide activation, is visible in the next valley (Fig. 11). During the movement of colluvial blocks, they rotated along the fault surface determining its direction. This led to the remodelling of the linear system into a cascade one, with inter-colluvial depression or sink-holes filled with water, or with permanently excessively humid wetlands (Fig. 12). A lake basin with a permanent surface outflow developed in the place of narrowing within the landslide trough. The lake is mainly irrigated by waters coming from the drain from the upper part of the landslide. Then, water flows gravitationally to the area of the lake basin's maximum depth, located close to the fault surface, reaching 1.50 metres. After that, it flows through the split in the colluvial rampart, and forms a permanent stream. Due to increased disintegration of the colluvial material in this part of the landslide, water flow disappears after 100 metres into the drainless sink-holes. Then, a few metres below, already within the colluvial tongue, the water flow reappears, but only over a section of 50 metres, and then disappears again. In this case, the landslide performs the function of the drainage surface for the slope. The individual morphological elements of the landslide enforce the stagnation of water and elongate the process of the surface run-off. The model of water circulation in this area is shown in the schema (Fig. 13).

Mainly mineral sediments formed by sandy clay, with organic material, are located on the bottom of the largest contemporary landslide lake. Fens of low thickness occur on this mineral cover in that part of the lake. The dominance of mineral sediments is indicative of a dynamic supply of mineral material from the scarp surrounding the inter-colluvial depression. As shown by previous research, clay sediments with inserts of plant detritus are deposited in this type of landslide lakes, i.e. with a bottom partially sealed and periodically filled with water. In the case of complete sealing of the lake basin bottom, and a variable flow, accumulation of sand with mud and sandy clay occurs. In the case of limited or no flow, sedimentation

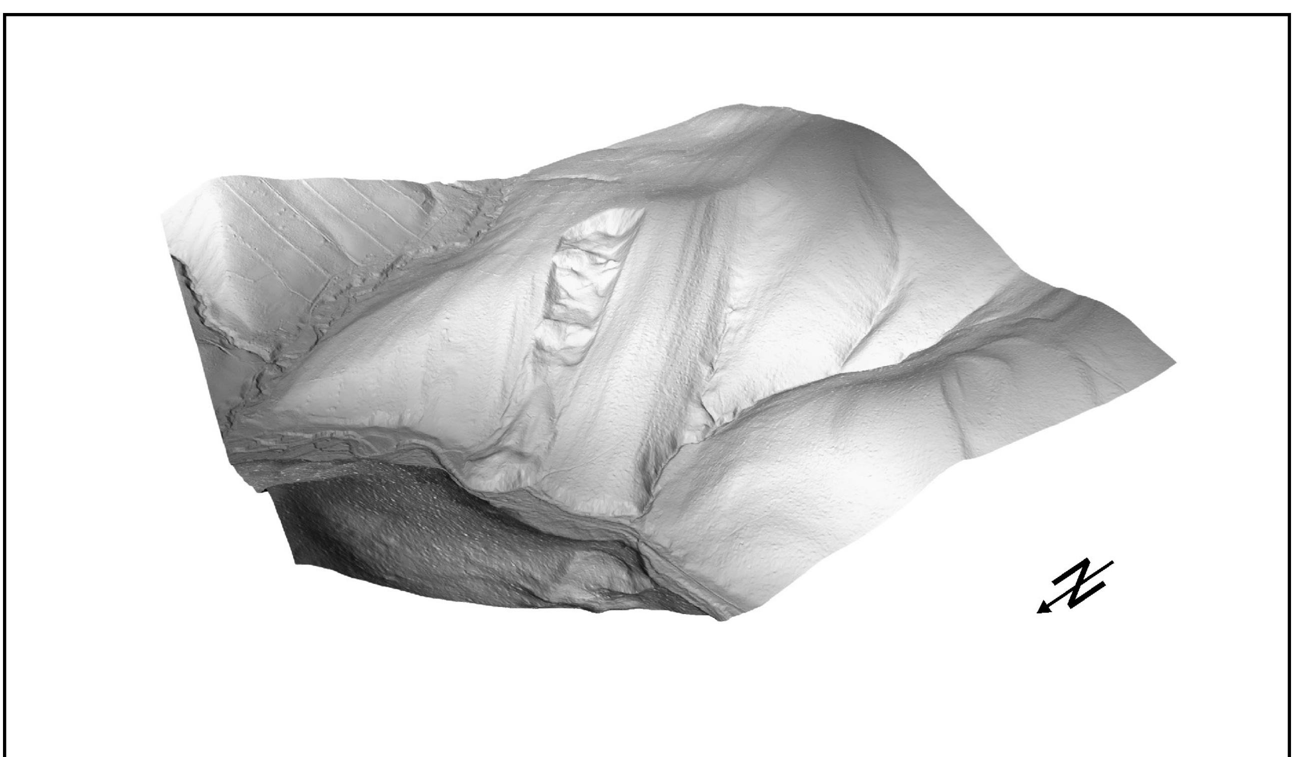


Fig. 11. Digital elevation model of the landslide and the subsequent valley

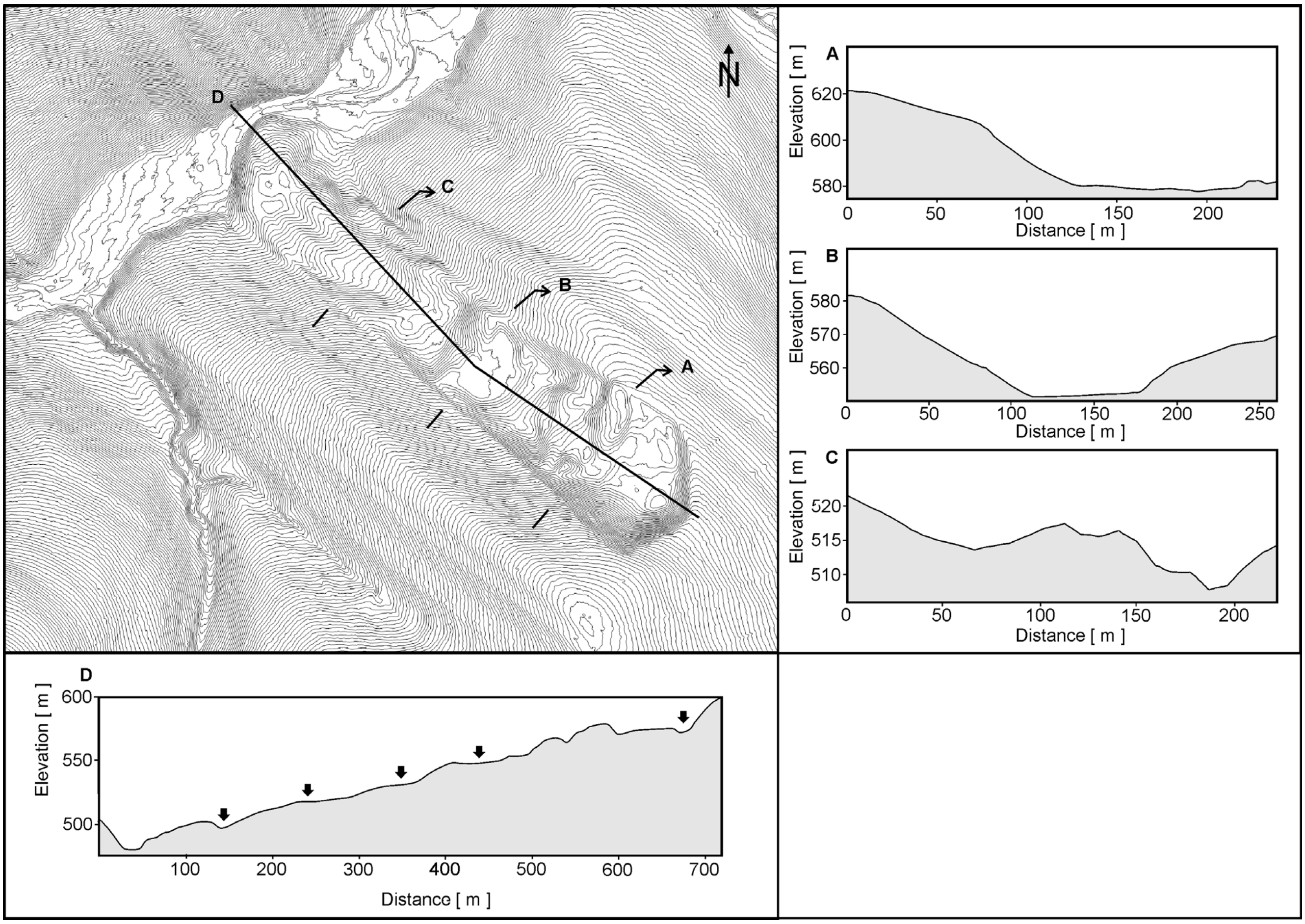


Fig. 12. A cascade layout of the inter-colluvial depression permanently or periodically filled with water. Cross-sections (A-C) and the longitudinal section (D) across the landslide, with marked sink-holes

of organic material occurs. It consists mostly of dark organic silts with wood chaff and plant debris. Ultimately, deposition of peat occurs within overgrowing landslide lakes. The layer of peat often contains a large amount of plant detritus, while in the lower part of peat sediments there are mostly sandy clays, and higher up dark and gelatinous silts with fragments of plant roots occur (Margielewski 1996).

Conclusion

The landslide within the Hucianka Stream valley is an example of a lake geoecosystem associated with structural features. A marginal zone of the landslide is formed by a wall of rock, covered with a tectonic mirror. It determines the wedge-like contour of the landslide and its direction. In addition, the morphotectonic analysis performed enabled the dependence of the development of gravitational forms in relation to geological structure and the transformation of the fault surface to be determined. It also facilitated the reconstruction of the phases of forming this water geoecosystem in relation to structural features. Laser scanning photographs were also used to formulate the conclusions regarding the mophotectonic analysis and slope transformation phases. The morphological analysis and correlation of forms indicates the compound (rotational and translational) gravitational movement which was completed by damming the valley axis, and forming a landslide dam lake. Three drainless sink-holes, being the place of water stagnation and accumulation of organic and mineral sediments, were also located within this landslide. The largest inter-colluvial depression forms a lake basin permanently filled with water. There is also a drain in the form of water flow. As a result of erosive and denudational processes, many gravitational forms lose their distinctness. However, dense plant cover effectively consolidated the landslide relief by delaying the degradation of individual forms. As results from the inventory, deep and

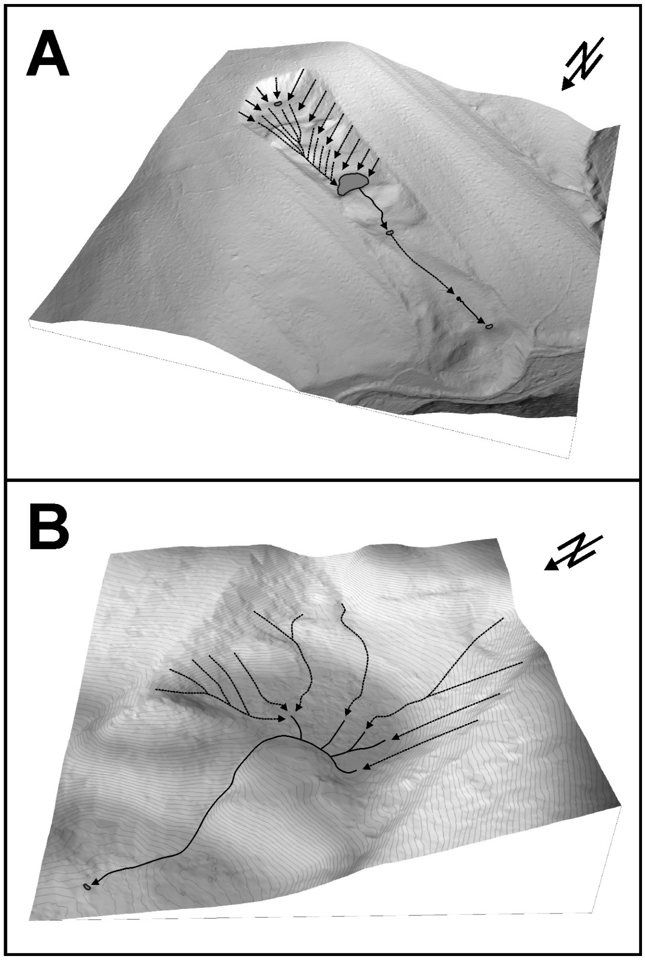


Fig. 13. Model of water circulation within the landslide and in the inter-colluvial lake basin: A – within the landslide, B – within the lake basin, the arrows indicate the direction of water flow

narrow subsequent landslides predispose to develop water-lake geoecosystems, and they are visible in the landscape for a relatively long time. In perspective, the full characterization of sediments in this area will allow them to be adapted to many detailed classifications. Therefore, a wide range of analytical research has been undertaken in this respect.

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