Landform Analysis, Vol. 4: 75–82 (2003)

Geomorphological effects of the catastrophic drainage of artificial reservoir in the Młynówka valley at Górowo Iławeckie, Poland

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Landform Analysis 2003

Abstract: The problem concerns the catastrophic flood flow caused by the breaking of the dam of the artificial reservoir in the valley of the small river Młynówka Górowska. Extensive studies were focused on the section just below the broken dam, were the geomorphological effects of that event were most noticeable. A number of erosional and accumulative forms have been distinguished. The structure and grain size of the flood deposits have been studied. The occurrence of deposit sequences characteristic of slurry-flows has been found. The rapid fall of the flood wave was associated with the deposition of the coarser deposit fractions on the sides of the valley and of the finer ones on its floor.

Key words: flood, breaking of dam, flood forms and deposits, valley of the Młynówka Górowska river

Introduction

On 3 February 2000, the dam on the river Młynówka Górowska got broken, the water from the higher situated reservoir flowed down, which resulted in a catastrophic flood in the river valley. Within less than four hours ca 250 000 m^3 water outflow through the gap in the dam, inundating the river valley including the part of Górowo Iławeckie situated in it.

Dam disasters are rather infrequence, that is why there is only a small number of studies presenting their actual effects (Scott, Geavlee, 1968, Jarret, Costa, 1986). More attention has been given to theoretical problems, such as the hydrological parameters of the flood wave (among others: Froehlich, 1995; Walder, O'Connor, 1997; Bellos, Hrissanthou, 1998; Kubrak, Ordyniec, 1999). A synthetic survey of the causes and effects of catastrophic floods caused by the breakage of artificial or natural dams has been carried out by J.E. Costa (1988a). Compared with the good understanding of the hydrological effects of this kind of events, the geomorphological changes caused by them in the natural environment of the river valley have not so far been the subject of any extensive studies, which has been pointed out by W. Graham (1998).

The catastrophic flood in the Młynówka valley provided a rare chance of tracing the geomorphological and sedimentational changes in a small young-glacial river valley, caused by processes of extreme (catastrophic) intensity. The object of our field research studies was the description of the progress of erosion and fluvial accumulation in the river channel and in the overbank area following the passage of the catastrophic flood wave. The range of the flood wave has been determined as well as the spread of the particular fluvial forms and their inner structure.

The studies of the geomorphological effects of the flood covered a 0,4 km segment of the river, between the broken dam and the built-up area. That part of the valley floor shows comparatively little anthropogenic transformation. It is characterized by considerable morphological changes in contrast to the regulated part flowing through the town, where the changes are much smaller.

Description of study area

The catchment of the Młynówka Górowska, 48,4 km^2 in area, part of the Pregoła drainage basin, is situated in the region of Wzniesienia Górowskie (Górowo Hills) in the forefield of the end moraine zone of the Pomeranian Phase of the Last Glaciation (Kondracki, 1972). It includes an undulant moraine plateau diversifield with subglacial channnels and kettles. A range of such depressions is incorporated in the Młynówka valley. That is manifested both in the varying gradient of its floor (4,8–9,3 ‰) and in the occurrence of gaps and valley widenings.

The orographic conditions account for the considerable differences in the amount of precipitation. The higher situated Górowo Iławeckie gets an average of 717 mm rainfall per year (*Roczniki IMGW, Opady Atmosferyczne 1956–1980*), which is nearly 150 mm more than Bartoszyce and Lidzbark Warmiński, situated at lower altitudes.

Młynówka is a small watercourse, 20,4 km long, characterized, like other rivers of the western part of Pojezierze Mazurskie (Mazury Lakeland), with an even fluvial regime with a spring and winter flood and ground-rain-snow yield (Dynowska, 1972). The mean value of the unit runoff of the Elma drainage basin, whose part is the Młynówka catchment area, amounts to 7,63 dm^{3}s^{-1}km^{-2} (in 1971–1980).

The natural character of the river channel has undergone complete change as a result of hydrotechnical works carried out at various times. In several places the river has been barred and dammed up by dikes. River training has been carried out in the town part of the river channel. The last act of anthropogenic transformations of the Młynówka valley was the construction in 1977 of a 7-m high dam resulting in the formation of a water reservoir 10,8 ha in area (Fig. 1). The breakage of that dam resulted in a catastrophic flood.

Causes of the dam breakage and progress of flood wave

The direct cause of the dam breakage was the washing away of its crest, resulting from the fact that the permissible ordinate of water level in the reservoir had been exceeded. That situation together with a sudden thaw and rainfalls were conducive to the water flowing over the lowered part of the dam crest. The water flowing down the side of the dam caused its erosion, which weakened its stability and consequently led to its further being washed away. The resulting breach reaching down to the dam's base was 107 m^2 in area (Fig. 2). The breakage of the dam happened at about 0^{30} a.m. on 3 February 2000. The flood wave moved very fast. As follows from the report of Powiatowy Sztab Kryzysowy (the local crisis headquarters), at about 1^{00} a.m. the whole river valley within the town boundaries was under water (Fig 3A). According to estimates, the mean intensity of water discharge through the breach was ca 28 m^{3}s^{-1}. It can be assumed that the maximum values were much higher. The scale of the flood is demonstrated by the value of 1% flood probability, which has been assessed at 10.33 m^{3}s^{-1}, compared with the Młynówka's discharge just before the flood, which amounted to about 0.025 m^{3}s^{-1}. The mean velocity of the water discharge through the breach, calculated on the basis of the equation of the velocity of water discharge through a non-awash opening (Singh, Quiroga, 1988) was 4.1 ms^{-1}. If we assume that, occasionally, the discharge velocity might have been greater, it would have allowed the transport of stones of considerable size. Levelling measurements have shown that the mean range of the flood wave was 3.3 m. There occurred, however, local backwater to 5 m associated with bridge sections of the river channel.

The vehemence of the flood caused not only morphological changes in the river valley but also three death casualties and damages estimated at 14 milion zlotys.

Description of erosional and accumulative forms developed in the flood

The diversity of natural conditions of the valley and the extent of its anthropogenic transformation both affected the amount and the character of the transformations of the river channel and valley floor following the catastrophic flood. The most spectacular geomorphological effects occurred in a section from the dam to ca 400 m down from it (Fig. 3B), where the Młynówka valley is a form with steep sides and ca 15–20 m deep. Its floor does not exceed 50 m in width with a gradient of 9.3 ‰ and is sparsely overgrown with trees and shrubs. The river channel is not very deep and shows a sinuous course.

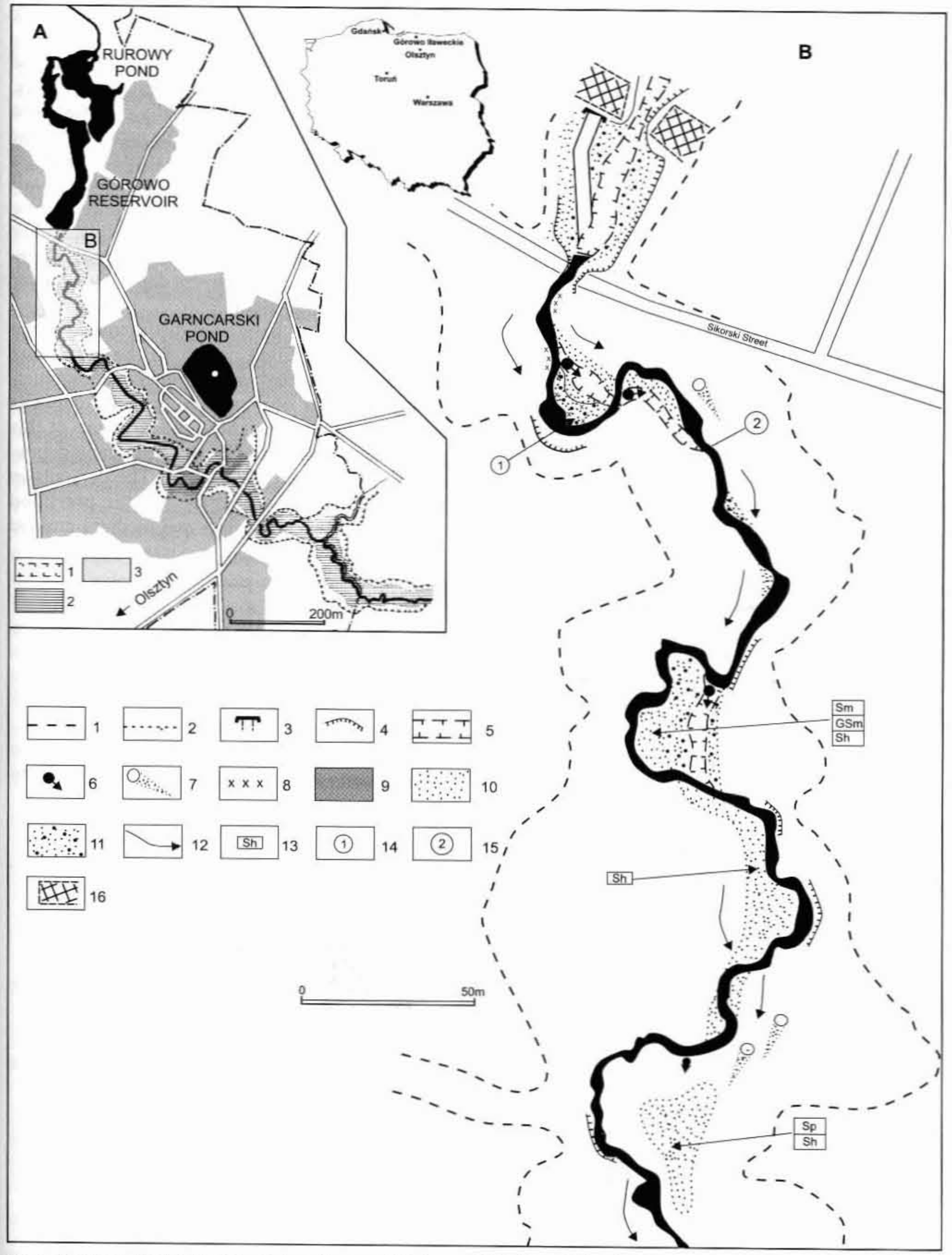

Fig. 3. Range of flood in the Młynówka valley on 3rd February 2000 (A) and sketch of the geomorphological transformations of its floor below the broken dam (B)

A: 1 – upper edge of valley, 2 – range of flood wave, 3 – build-up areas

B: 1 – upper edge of valley, 2 – range of flood wave, 3 – spillway and draining off canal, 4 – bank undercuttings, 5 – erosive and overflow channels, 6 – crevasses, 7 – sandy shadows, 8 – large boulders and fragments of construction materials, 9 – sandy-silty deposits, 10 – sandy deposits, 11 – gravelly-stony deposits, 12 – directions of flood water flow, 13 – lithofacial types of flood deposits, 14 – delta cone from Figs. 6, 15 – cross section from Figs. 8, 16 – broken dam

The geomorphological processes transforming the valley floor decrease in intensity with the increasing distance from the broken dam. That refers in particular to the fluvial erosion process, whose greatest effects have been found in the upper part of the valley section under study. It resulted in the development of a new channel, 60 m long and 0.6 m in mean depth, along the old channel from before the damming up (Fig. 3B). The left, erosional edge of the valley has been considerably transformed. In this case the processes of erosive undercutting of the valley sides were associated with mass movements (falls and landslides). Intense erosion in the river channel resulted in undermining the bridgeheads followed by the destruction of the bridge. Further down the channel the effects of erosion were much slighter. Those were crevasses, sections of overflow channels at the start of the river's meander curve and undercuttings of the valley sides. The erosive transformation of the river channel consisting in its local deepening by 30–40 cm was much smaller compared with the changes in the overbank zone.

The effects of accumulative processes could be best seen in the most sinuous parts of the river. They have overlaid sandy-gravelly material onto fixed point bars in the Młynówka meanders. One of the best developed forms in that site is the delta cone, 23 m long up to 16 m wide and 1.6 m tall at the front, situated several dozen metres below the destroyed bridge (Fig. 3B, Fig. 4). Other accumulative forms are: crevasse cones, sandy shadows and sandy-silty covers deposited all over the flooded valley floor.

Two sequences have been distinguished in the structure of the flood cones. In the lower one horizontally stratified sandy deposits predominated, in the upper one massive gravelly deposits prevailed. A good insight in the structure of this type of forms is offered by the delta cone deposited below the dam (Figs. 5–6). The deposits in its front are clearly bipartite. On the pre-flood deposits there occurred fine- and medium-grained

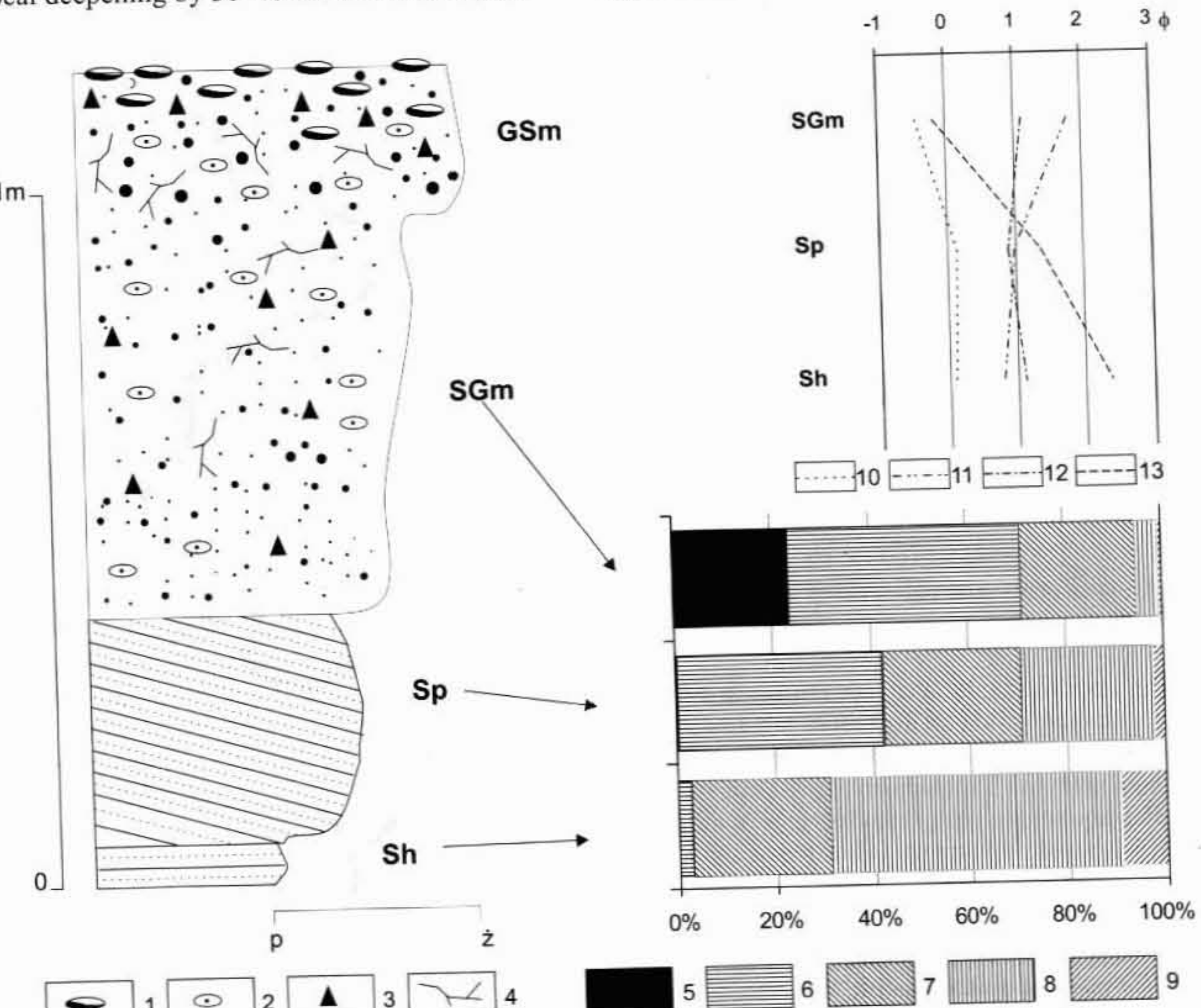

Fig. 6. Structure and granulometric characteristics of delta cone deposits (localization in Fig. 3B)
1 – boulders, 2 – mud-balls, 3 – fragments of construction materials, 4 – plant detritus, 5 – gravel, 6 – coarse-grained sand, 7 – medium-grained sand, 8 – fine-grained sand, 9 – fine silt, 10 – skewness (Sk_1), 11 – standard deviation (δ_1), 12 – kurtosis (K_G), 13 – mean grain size (Mz)

laminated sands with a faint horizontal stratification (lithofacies Sh), changing higher up into varigrained sands with prevalence of coarser fractions cross-stratified (lithofacies Sp). On the other hand, in the top there occurred massive medium- and coarse-grained sands with gravel accessory (lithofacies SGm). In the top part of the cone, 78 cm in thickness, there were numerous mud-balls, 3–8 cm in diameter, as well as pieces of wood, brick, construction materials and plant detritus. The character of the sedimentation points out that the initial stage of cone formation proceeded under sheet-flow conditions, which is documented by the occurrence of homogeneous lithofacies Sh sands in the bottom part of the sequence of deposits. Accumulation was taking place under supercritical flow conditions, corresponding (in transport of material) to the plane bed phase. A similar structure of the bottom part of flood deposits has been described by E.D. McKee *et al.* (1967). In the second sedimentation stage the flow was probably already partly channelled, evidence of which are the cross-stratified sands of lithofacies Sp and the sands and gravels of lithofacies SGm. Evidence of high flow energy and rapid deposition are the mud-balls laid in the deposit as well as the boulders up to 50 cm in diameter and fragments of the bridge construction found on the cone surface. A similar sequence of deposits has been found in other cone forms overlying point bars. Like in the case described above, they are characterized by reversed, and in some cases pensymmetrical, graded bedding. A similar sequence of deposits has also been found in the crevasse cones developed as a result of a breakage of embankments in the flood in the Vistula valley in 1997 (Gębica, Sokołowski, 1999).

With increasing distance from the broken dam the material coming through the crevasses onto the surface of the backland became more and more fine-grained. At their outlets formed crevasse cones made up of sandy material. Those were mostly fine- and medium-grained sands with organic lenses in the bottom with faintly visible horizontal stratification (lithofacies Sh), overlain by similarly grained sands with cross-stratification (lithofacies Sp) (Fig. 3B). The flat cone surfaces and the overbank plain have been diversified by sandy shadows, which were the most commonly occurring accumulative forms in the part of the valley under study. They form behind all kinds of obstructions, mostly trees and shrubs, and their width depends on the width of the obstruction (Zwoliński, 1992). A particularly large form of that type, 8.5 m long, 1.4 m wide and 0.3 m high, was made up of medium- and coarse-grained sands with an accessory of gravels (Fig. 7). Deposition of pebbles and coarse gravel has often been found on the upstream side of the terrain obstructions with sandy shadows downstream.

The bottom and the foot of the valley sides have been covered with a layer of sandy mate-

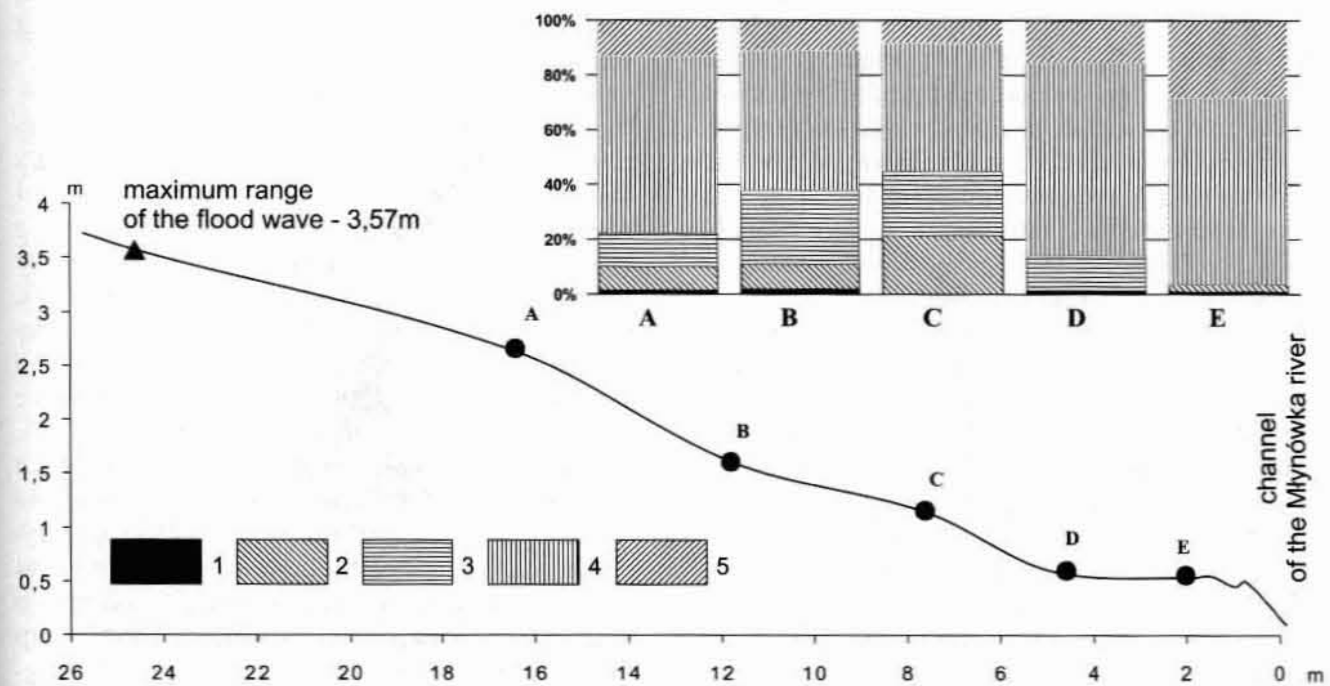

Fig. 8. Granulometric characteristics of deposits of sand covers in cross profile of the Młynówka valley (localization in Fig. 3B)
1 – gravel, 2 – coarse-grained sand, 3 – medium-grained sand, 4 – fine-grained sand, 5 – silt

rial ranging in thickness from 0.5 to 2 cm in the lower part of the slope to 20 cm in the valley floor. That deposit consists mainly of fine-grained sands. On the flat areas close to the channel there occur fine-grained sands with a considerable accessory of fine silts (Fig. 8). As we move away from the channel the material becomes coarser, most of it is medium- and coarse-grained sand. The presence of coarser fraction on higher, downsloping parts of the valley sides as well as the length and set of the lodged grasses are evidence of a considerable energy of the water in the course of flood wave falling. On flatter areas of the valley floor the fraction is finer, which is accounted for by a quieter type of sedimentation. After the waters had flown down into the channel, it was possible for the finest material to decantate in small depressions.

Morphodynamic characterization of the flood

The hydro- and morphodynamic conditions of floods caused by dam disasters differ in many ways from natural floods. The most important difference is the lack of relationship between the processes going on in the river channel and valley and those going on in the river catchment area. Floods of that type are short-lived and violent. The rapid water outflow caused by the breakage of the dam is probably comparable with the release of waters from proglacial lakes (Baker, Nummedal, 1978). The culmination of the flood wave of great energy, preceded by a short period of increased discharges, appears very soon. If the valley is rather small, its entire floor is flooded with a considerable layer of water, and for a short time the valley functions as a channel (cf. Chen, Simons, 1979). The flood wave falling takes much longer than the appearance of its culmination. That is accounted for by the changes in resistance to water flow in the overbank zone and by the development of local backwaters conditioned by the morphology and cover of the valley floor. There are also differences in the way material for fluvial transport is supplied. Besides typical products of erosion of the channel and of the flooded part of the valley a significant source of material is the washed away dam and the reservoir sediments in the part of the reservoir adjoining the dam. A certain part is played by the material supplied from the banks of the reservoir as a result of the stirring up of mass movement processes after it has been emptied.

The forms and sequences of sediments deposited in the part of the valley under study as a result of erosive and depositional processes constitute a clear record of the changes of energy of the waters flowing out of the dam reservoir and of the variations in the sources of supply of the river load transported.

In the initial very short flood phase the valley floor was being gradually filled up with water loaded with large amounts of sandy material derived from the washed away dam. Its deposition, occurring initially in the near-channel zone, consisted in overlaying the upper parts of fixed (old) point bars with a few centimetre thick deposits of cone deltas. The common occurrence of horizontally stratified sands (lithofacies Sh) in the lower parts of the sequences indicates that the sedimentation took place under sheet-flow conditions in the upper plane bed phase.

As more and more water ran off through the breach in the dam, the flood area soon spread over the entire valley. Flat sandy covers were deposited on more distant from the channel inclined areas among grasses and thickets, and elongate sandy shadows formed behind clumps of trees and shrubs. The presence of terrain obstructions and vegetation clumps resulted in a clear channelling of the flood waters flow in the later flow phase and in the formation of cross-stratified sandy-gravelly deposits (lithofacies SGp). The breach in the dam gradually expanded until the dam was completely washed away and that was followed by the flood wave culmination. That in turn led to overloading of the outflowing waters, an increase in their density and the development of hyperconcentrated grain flow (Costa, 1988b). Its characteristic is rapid, short transport. Such was the character of the Młynówka's discharge in the flood wave culmination over a several-hundred-metre-long section below the broken dam. Evidence of that are the slurry-flow type deposits in the top part of the cone (Pierson, Costa, 1987), consisting of massive coarse-grained sands, gravels and mud-balls stuck in the sandy-silty matrix (lithofacies GSm). The above deposits are similar to those described by J.E. Costa (1988b), which represent an intermediate stage between debris-flow and water-flood and develop under conditions of sheet-flow of high density. Evidence of high water flow energy as well as rapid accumulation are the numerous mud-balls deposited in the sediment, boulders up to 50 cm in diameter, fallen tree trunks and fragments of the bridge destroyed in the event. Another evidence of great transporting force are traces of injuries on tree trunks, which indicate

Fig. 1. Bottom of the Górowo reservoir after its catastrophic drainage on 4.02.2000

Fig. 2. General view down the river, in the foreground the broken dam

Fig. 4. Accumulative area of delta cone

Fig. 5. Internal structure of delta cone front. For explanations of deposit sequence see Fig. 6

Fig. 7. Instance of deposition of sandy shadow behind an obstruction consisting of trees and plant jam

saltation transport of stones of considerable size. The source of the transported material, besides the washed away dam and the products of erosion of the newly formed section of river channel down from the dam, was also the material supplied into the channel from the valley sides as a result of stirring up of sliding processes.

The considerable loading of the river channel by the transported sediments and flotation material resulted in its blockage, particularly in places where straight-line channel sections change into meanders. As a result of cutting off meanders and filling up the channel with sediments resistance to flow was reduced. That caused an acceleration of the flow rate and local drops of water level. That relationship has been verified by experimental studies carried out by Y.H. Chen and D.B. Simons (1979). Under the circumstances the conditions of water flow and sediment transportation in the valley were reorganized. Through crevasses and overflow channels formed at that time the bed load of the channel was brought out onto the surface of the valley floor. The drop in velocity of the water flow and the initially slow falling of the flood wave, associated with local backwater in the lower situated part of the valley, resulted in the deposition of the transported material and local erosion of the valley sides. The material of the coarsest gravelly-stony fraction, eliminated from the transport, filled up the river channel and the overflow channels where finer sediment was still being transported. As a result of its later deposition earlier developed forms were expanded. It was then that the facies of crevasse cones and sandy shadows were accumulated. After the flow had been unblocked, the floodwaters started to falling very fast concentrating their flow in the channel. At that time the depositional forms, which had been developed earlier, were cut through, which is evidence of the considerable energy of the waters returning to their channel.

Conclusion

In analysing the geomorphological effects of flood in that part of the Młynówka valley, it must be stressed that the erosional and depositional processes in the Młynówka valley were affected in a decisive way by its morphometric characteristics (gradient, floor width, channel course). The greatest geomorphological changes took place just below the broken dam. The section of the valley running through the town, anthropogenically transformed, suffered the worst economic damages, but was least transformed geomorphologically.

The commonly occurring erosive forms were: crevasses, sections of overflow channels and undercuttings of the channel and valley banks. The erosion of the channel floor did not reach any great proportions thanks to the nature of the bedrock (moraine residuum hard to wash away) and to the fact that the water flow filled the entire valley floor. It must be mentioned that the highest intensity of erosive processes in floods of that type occurs at the time of flood wave falling.

Accumulative forms were represented by: deposits of delta cones overlaying fixed point bars, crevasse cones, sandy shadows and flat sandy-silty covers. A particular instance of accumulative form deposited just below the dam was a delta cone with a pronounced front consisting of material showing characteristics of high energy flow of the slurry-flow type. Evidence of the high energy of flow and rapid deposition were mud-balls, boulders up to 50 cm in diameter and fragments of the bridge construction. The commonly occurring sedimentation structure consisted of fine-grained horizontally stratified deposits in the lower part of the sequence and coarser-grained deposits of massive structure in the top part.

Local occurrence of coarser fractions of material on the valley sides compared with the finer sediment deposited on the valley floor points to considerable flow energy at the time of flood wave falling.

The progress of depositional processes in the valley floor was closely related to the current course of the channel. The accumulation of material was greatest in its sinuous segments. It also should be noted that the set of erosive-depositional forms developed in the course of floods caused by dam disasters is similar to that developed in natural floods. Depositional forms developed under conditions of deep flooding, in narrow deep river valleys show similar morphological and lithofacial characteristics to corresponding forms developed under subaerial conditions. Common characteristics are also ascribed to both the above environments by A.K. Teiseyre (1988).

The progress of fluvial processes, particularly at a short distance from the broken dam, is strongly affected by the deposits building its bank. Their inclusion into the fluvial transport already in the first phase of the flood flow resulted in rapid filling up of the channel with load. That changed the geometry of the channel and the resistance to water flow, which led to increased discharge velocity and increased intensity of erosive processes.

Acknowledgements

The authors wish to acknowledge their gratitude for help with their field studies and for allowing the use of their materials to Mr Leopold Ażgin (Wojewódzki Inspektor Nadzoru Budowlanego w Olsztynie) and to Mr Edward Drymuch (Urząd Miasta w Górowie Iławeckim).

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Landform Analysis, Vol. 4: 83–97 (2003)

Holocene shoreline migrations in the Puck Lagoon (Southern Baltic Sea) based on the Rzucewo Headland case study

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Abstract: The results of the study indicate that the Rzucewo Headland area – a landform located on the western coast of the Puck Lagoon – has been developing under the terrestrial conditions until the end of the Atlantic period. The headland is constructed from sands and silts with organic beds. The end of the Atlantic period saw the appearance of the first pollen grains of plants which indicate human activity (*Chenopodiaceae, Artemisia, Rumex, Plantago lanceolata*). The sediment age and the then sea level of the Baltic Sea indicate that human activity has been taking place before the development of seal hunter's settlement, i.e. the Rzucewo Culture.

A transformation of the freshwater lake into the brackish/marine Puck Lagoon started not earlier than 5500–5000 years BP. In the Subboreal period, cliffs on slopes of the Puck Morainic Uplands started to develop and the accumulation of sands in the Rzucewo Headland began. The pollen grains of the plants relating to human activity (*Chenopodiaceae, Artemisia, Rumex, Plantago lanceolata*) are more numerous in the pollen spectrum. The occurrence of the plants and the approach of the Puck Lagoon shores to Rzucewo coincided with the development of the Rzucewo Culture (seal hunters) c. 4400–3700 years BP. In the last 4000 years or so, average growth of the Rzucewo Headland was c. 100 m^3/year. In the period 1958 –1997, a land growth of up to 50–80 m (on average 1–2 m/year) was noted on the northern part of the Headland.

The analysis of the geological and palynological data from the Rzucewo Headland indicates that its development has taken place under conditions of a long-drawn-out transgression. No evidence indicative of either a phased transgression or a periodical regression was found. A good compatibility of the relative sea level curve of the Puck Lagoon with the curves of the eustatic changes of the ocean indicates only a small range of vertical movements of the Earth's Crust in this area during the Subboreal and Subatlantic periods.

Key words: Southern Baltic, Puck Lagoon, Rzucewo Headland, palynology, radiocarbon dating, sea level changes, coastal processes

Introduction

The Puck Lagoon (also called Little or Inner Puck Bay) and its coast have been subject of the geological, geomorphological and paleogeographical studies for many years (Pawłowski, 1922; Rosa, 1963; Musielak, 1983; Jankowska & Łęczyński, 1993; Witkowski & Witak, 1993; Kramarska *et al.*, 1995, etc.). However there is little detailed information on the Lagoon's age, sea level changes and the development of the coast. The data relating to sea level change in the southern and south-western area of the Baltic Sea in the Middle and Late Holocene (including relatively new recent information) are not explicit and they are very often contradictory. The published curves of the relative sea level changes sometimes show oscillations of sea level of several meters in only short periods. Occasionally, such changes as have been identified have been attributed to different periods and those changes allocated into short time periods are sometimes of different in directions (e.g. Lampe, 1996; Lampe & Janke, 2000; Rot-