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Catastrophic flood effects in alpine/foothill fluvial system (a case study from the Sudetes Mts, SW Poland)

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Abstract

Depositional effects of two great floods in the Nysa drainage basin have been studied: the alluvial forms and deposits of channels and floodplains. Three types of bars and one overbank form were found in the mountain streams, and four types of bars and three types of overbank forms have been distinguished in main rivers. A specific spatial succession of depositional forms was recognized along the mountain streams, however, no analogous phenomena were noted within the main river valleys. Several types of bars and alluvial lithofacies have been regarded as characteristic effects of the catastrophic flood. The study indicates that the Nysa river is close to the threshold of metamorphosis to a typical braided fluvial system.

Keywords: Fluvial environment; Sedimentology; Flood; Alluvium; Sudetes Mountains; Poland

1. Introduction

In two succeeding years—1997 and 1998—a drainage basin of the Nysa Klodzka River underwent torrential flooding. The Nysa is one of the largest rivers of the Sudetes Mountains in SW Poland. The uppermost part of drainage basin is characterised by a nearly concentric network (Fig. 1). Downstream the river goes across two mountain ranges (Krowiarki and Bardo Ranges), with the large Klodzko Depression located between them. Then the river reaches the foothill area, with two large dammed lakes (Otmuchów and Nysa Lakes). The lakes form the lower border of the upper Nysa drainage basin. Downstream from them the valley floor is strongly affected by human impact.

Both floods took place in July. The 1997 flood was an especially dramatic one, which affected the whole drainage basin. The rainstorm lasted up to 65 h and the total precipitation was 120–480 mm. The maximum rain intensity reached 25 mm h^{-1}. A few flood crests were moving for 18 days with two distinct peaks (maximum phases), each 5 days long. The first flood crest exceeded an absolute historical maximum. The water level of the Nysa River rose 4 m above the bankfull stage and the discharge amounted to 1500–2100 $m^3 s^{-1}$. The flood resulted in fatalities. One year later a large flood took place in the Bystrzyca Dusznicka River (Fig. 1). It was the effect of one torrential rainstorm and lasted only 24 h. However, water reached a level three times higher than the bankfull stage and rose 4 m locally. Both floods destroyed

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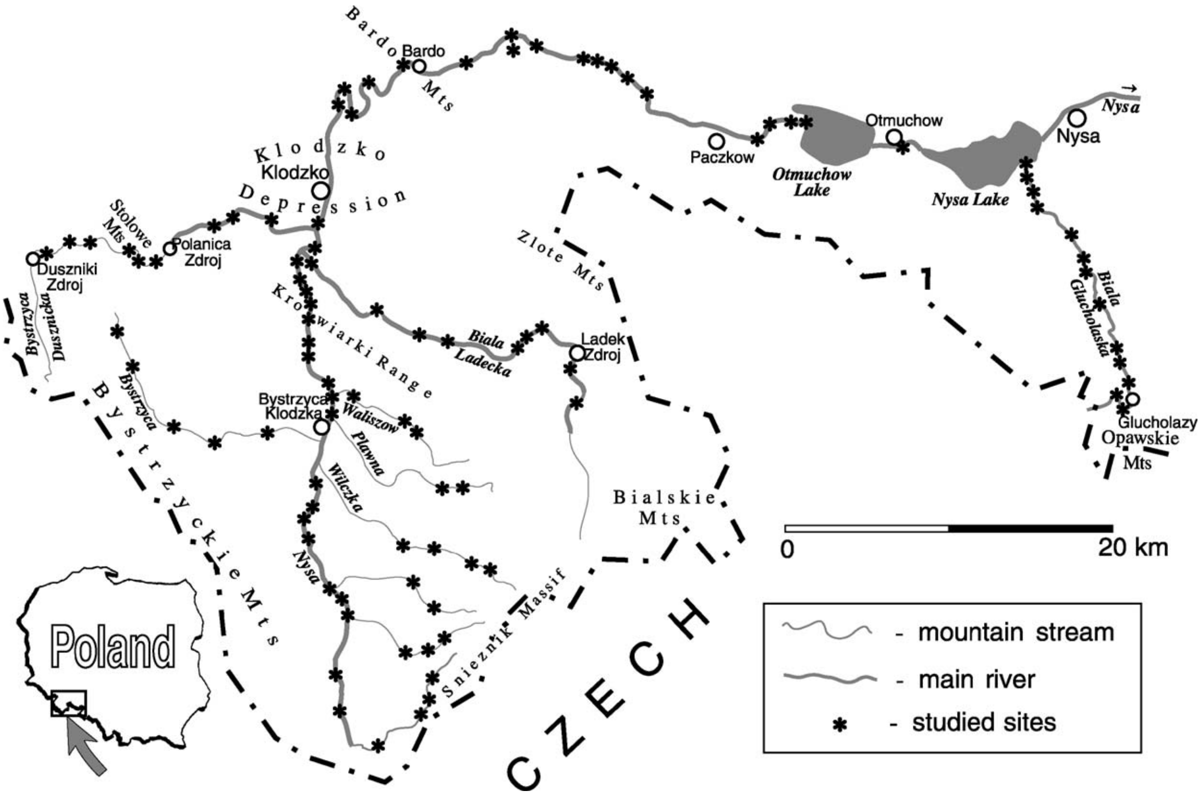

Fig. 1. Map of studied drainage basin.

towns and villages located on the floodplain and nearly all the water plants.

Can these floods be considered as catastrophic processes? Two basic criteria are important from a geological point of view: abruptness and intensity (“energy”) of phenomena compared to average annual floods (cf. Miall, 1996; Reading and Levell, 1996). In each event both criteria were fulfilled. Numerous rocks and fragments of buildings up to 1 m in diameter were eroded and transported by the floods; moreover, the recurrence interval of the 1997 flood is estimated to be between 600 and 1000 years (Dubicki, 1999), and it can undoubtedly be ranked as a catastrophic geodynamic process.

During the floods most waterways became fully active geological environments. The streams and rivers regained their natural character and acted as fluvial systems unconfined by any artificial objects.

2. Subject and method of the study

Ninety-three sites along a total distance of 140 km were studied in waterways of the upper Nysa drainage basin (Fig. 1). Observations were made in 1997 and 1998 after each flood. The shape, location, dimensions and deposits of large depositional forms (bars) were documented. The bars are regarded as megaforms, strictly connected with the alluvial sedimentary style (i.e. depositional processes typical of particular river type). Smaller depositional forms (ripples and dunes) were not investigated because their formation was controlled by local hydrodynamic conditions, and moreover, they were quite rare in the coarse-grained channels.

All waterways were divided into two groups: streams and rivers (Fig. 1). This subdivision was necessary because both qualitative and quantitative character of depositional forms appeared to be differ-

Table 1
Characteristics of depositional forms in the mountain stream valleys (*l*, *w*, *h*—length, width, height)

Suite		Form	Shape and scale	Location	Surface: morphology	Grain size	Subsurface lithofacies	Depositional factor	Indicator of catastrophic flood	Remarks
Mountain stream	channel zone	boulder mound	usually linguoid $5<l<20$ m; $3<w<12$ m; $h<1$ m	in widened valley parts of lower slope; usually in groups, between 2–3 flood channels	convex surface	boulders, without matrix	massive boulder *Bm*, clast-supported	vertical accretion in decreased competence zone, during flood peak	+	typical of the uppermost part of valleys; abundant form
		longitudinal bar	elongated; $10<l<20$ m; $3<w<5$ m; $h<0.4$ m	central part of channel; usually downstream to bend	plane surface	gravel + boulder without matrix, distinct clast imbrication, thin sand layer in distal part	massive gravel + boulder *GBm*, most often clast-supported, long, thin lens-shaped sheets	vertical accretion in decreased competence zone, maximum and initial waning of flood	–	typical of middle and lower stream reaches; usually evolves to side bar; abundant form active during each large flood
		side bar	elongated; $10<l<20$ m; $4<w<8$ m; $0.5<h<0.7$ m	in slightly sinuous channel, alternating, close to convex banks	convex surface	gravel + boulder, fining donwstream to sandy gravel	gravel with boulder admixture *GBm*, possible distal passage to *SGh*	vertical accretion from near-bank secondary currents of slightly meandering flow; waning flood	–	abundant form
	overbank zone	boulder berm	elongated; $l<25$ m; $2<w<3$ m; $h<1.2$ m	in channel/terrace boundary zone, in straight reaches and in the bends	distinctly convex in transverse section	boulder without matrix	massive boulder *Bm*, clast-supported, openwork	accretion due to large gradient of flow velocity in bank zone + secondary currents around trees	+	abundant form

ent in these systems. Flow discharge and channel slope are the two main factors determining sedimentological differences between these environments (Zielinski, 2001). Relatively low discharge and high slopes (S>0.01) are typical of streams. Their channel width is lower than 5–7 m, whereas the river channels are much broader. The rivers flow in broad alluvial valleys with a common terrace system. The streams are often incised into hard bedrock or colluvial deposits, and the alluvial infill of these valleys is very thin, without terraces, or absent.

3. Depositional forms and inferred processes of mountain streams

3.1. Channel zone

Most of the depositional effects in mountain streams are concentrated within the channel.

Boulder mounds are the most typical bar type in the upper reaches of streams (Table 1). Decreasing flow velocity in the areas of channel widening and slope decrease, leads to boulder-mound formation. The mounds are linguoid in planform (Fig. 2). Deposition of coarse-grained material takes place during the flood peak in areas of lower stream power between the main current tracts. During the waning flood the emergent boulder mounds divide the channel into multiple branches. Many of these branches are dry by the time the flow reaches an average condition. Analogous bars are also formed downstream from near-channel landslides. Coarse debris from the landslides is fluvially transported a short distance (up to 50 m), and deposited as a boulder mound. This process shows is similar to reattachment bar formation (Schmidt, 1990), however, reattachment bars are side forms (connected with channel bank), while the boulder mounds are always located in the central part of flood-stage channels. Similar forms, both in their shape and sediment grain size, were noted by Batalla et al. (1999) from mountain torrential streams.

Gravel–boulder longitudinal bars dominate in the lower reaches of streams; these are low and distinctly elongated forms located within the channel (Table 1). Typically, one of the side channels captures most of the discharge and the other one becomes ephemerally abandoned. The bars evolve by successive accretion into flat, gravel–boulder sheets anchored to the channel bank. The growth of longitudinal bars takes place during flood stages only, and well-developed forms are typical of reaches located close to the mouths of steep mountain streams, where the channel slope is usually $0.01 < S < 0.02$.

Gravel–boulder side bars appear in slightly sinuous reaches of stream channels (Fig. 3; Table 1). The bars exist alternately, close to both banks. Average grain size of surficial material decreases downstream most often; sometimes, sandy gravel was found in their distal parts.

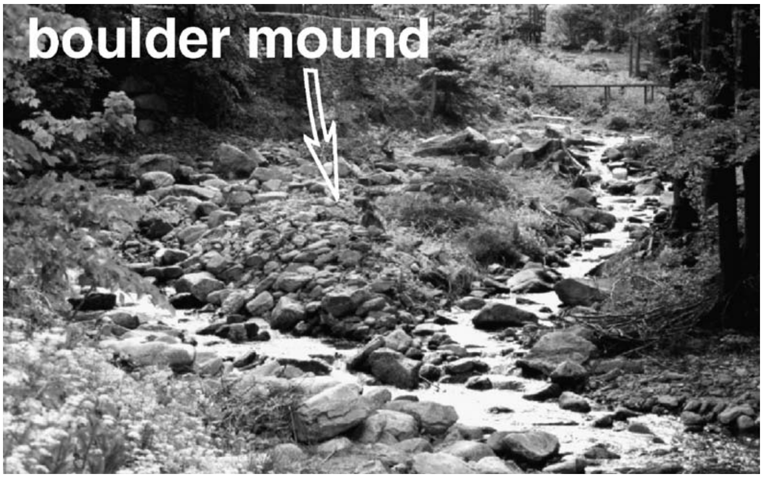

Fig. 2. Boulder mound in the Wilczka stream. Flow towards the viewer.

Fig. 3. Bouldery–gravel side bars existing alternatively along the slightly sinuous channel of Bystrzyca Dusznicka stream. Flow towards the viewer.

3.2. Overbank zone

Overbank depositional forms of streams are relatively rare. *Boulder berms* (sensu Stewart and La Marche, 1967) are characteristic of large floods (Fig. 4; Table 1). A boulder berm is a coarse-grained levee formed immediately above the bank crest, in the zone of large velocity gradients during the flood peak. Berms are built of openwork boulders. The Sudetes' forms are analogous to the boulder berms studied by Carling (1987), who interpreted them as the effects of torrential hyperconcentrated flows. Comparable accumulation forms have also been documented in the Tatra Mts streams (Kotarba, 1998) as the result of the same flood event of 1997. All these facts suggest that boulder berms can be regarded as depositional forms indicative of catastrophic fluvial phenomena in alpine environments.

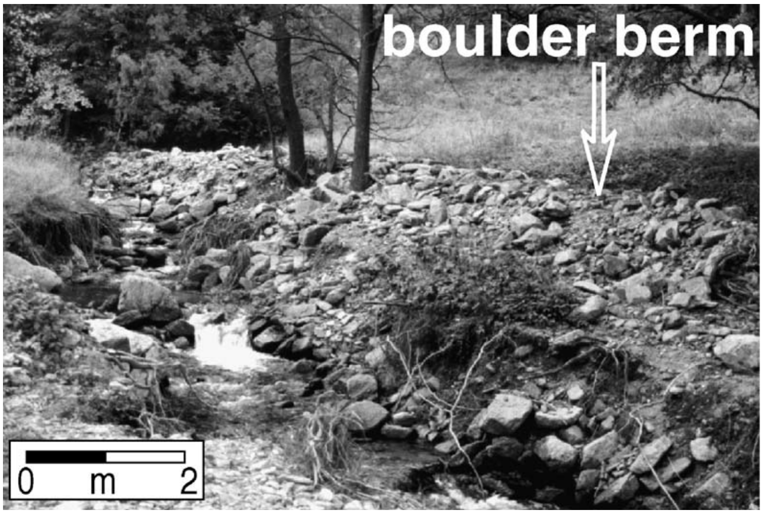

Fig. 4. Boulder berm along the channel of the upper Plawna stream. Flow towards the viewer.

4. Depositional forms and inferred processes of main rivers

4.1. Channel zone

Longitudinal bars are formed in the central part of river channels. Their planform is elongate, oval or rhomboid (Fig. 5; Table 2). Compound bars containing boulders and cobbles belong to a group of large forms, whereas small forms are of unit (simple) type and contain finer material (gravel). Large compound bars commonly develop in wide zones of nearly straight channel courses. On the other hand, unit longitudinal bars result from deposition in crossover zones—the shoals passing diagonally through the slightly sinuous channel.

Unit longitudinal bars are low and flat. Local sand veneers have been noted in their distal and middle parts and were deposited in final phase of waning flood.

Compound longitudinal bars most often include two or three platforms (plane hypsometric levels, separated each other by short steep slopes). Successively, lower platforms are progressively finer-grained, indicating that the bars grew by lateral accretion (mainly distally) during the falling stage.

Over the course of one or a few flood cycles, one of the side channels surrounding the bar becomes dominant and the second is filled-in with gravel, and finally sand. Through this process the longitudinal bar becomes anchored to the bank and evolves into a side bar. In this instance, deposits of the primary longitudinal bar (i.e. gravel and cobble) form the coarsest, core part of the side bar.

Large numbers of bar assemblages were formed in the lower reach of the studied Nysa course, where floodwaters overflowed onto broad valley floor. In the waning flood stage the interbar channels were filled-in with gravel and sand. Then, all these forms were merged to the lowermost overbank area (terrace) during an average stage. This was the most spectacular example of alluvial plain developing from bar sediments of a braided river due to a catastrophic flood.

Undoubtedly, longitudinal bars play a significant role in the process of braiding. They diverge the current (Fig. 5), and enlarged, compound bars lead to new channel growth. The nature of bar development suggests, that only three conditions are necessary to be fulfilled, for the Nysa River to change its pattern from meandering to braided (i.e. anabranching fluvial system containing low-sinuosity channels). These conditions are as follows: 1° increase of flood frequency; 2° increase of flood duration; 3° increase of flood discharge (as the effects of enlarged precipitation within the drainage basin).

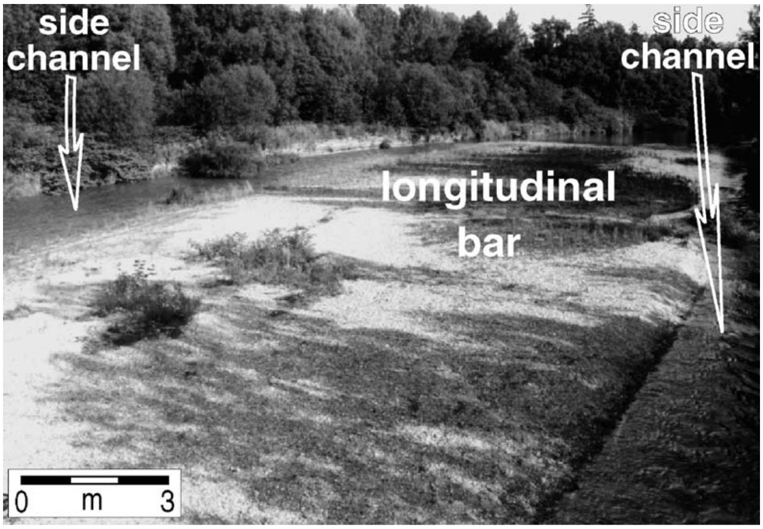

Fig. 5. Gravelly longitudinal bar dividing flow into two equal channels. The lower reach of Biala Głucholaska river. Flow towards the viewer.

Table 2
Characteristics of depositional forms in the main river valleys (*l*, *w*, *h*—length, width, height)

Suite		Form	Shape and scale	Location	Surface: morphology	Grain size	Subsurface lithofacies	Depositional factor	Indicator of catastrophic flood	Remarks
Main river	channel zone	longitudinal bar unit-type	elongated (oval rhomboid); $l<70$ m; $h<0.8$ m	central part of channel riffle or downstream of obstacle	flat surface	gravel, distally fining tendency	massive gravel and boulder (*Gm*, *BGm*), usually clast-suppoted, imbricated, in sheet-beds; subordinately: sandy gravel (*Gm*, *Gh*)	instantaneous vertical accretion from traction carpet in first phase of waning flood	–	evolution of single bar to side barform, and set of bars to alluvial plain fragment; typical factor of braiding phenomena
		compound-type	$l=100$ m; $1.0<h<1.5$ m	widening of straight channel	two or three platforms with parasitic linguoid bars	uppermost platform: boulder and gravel; lowest: gravel and sand			+	
		diagonal bar	elongated; $25<l<130$ m; $15<w<35$ m; $h<1$ m	attached alternatively to banks, downstream of slight bends	slightly convex surface; shallow channel close to bank	boulder and gravel, distally fining tendency; gravel and sand in side channel		vertical accretion from side velocity gradients from slightly sinuous flow; waning flood	–	typical of slightly sinuous channel; abundant form; sometimes derived from central bar
		side compound bar	irregular elongated; $l<150$ m; $w<40$ m; $h<4$ m	near to bank, in channel widening zone	several platforms—large linguoid bars	upper platforms: gravel and boulder, lower ones: sand and gravel; locally sand covers	thick, long beds of cross-stratified gravel and boulder (*Gp*); thin sand beds (*Sh*)	intense lateral accretion in decrease competence zones; waning flood	+	typical of gravel-bed braided river; generally of sporadic occurrence
		point bar	lunate; $l<70$ m; $20<w<40$ m; $h<2.5$ m	close to inner bank of sharp bend, sometimes downstream to tree jam	few platforms with secondary bars and channels	platform: gravel and boulder; secondary bars: boulder-to-sand	erosional bases; lower boulder/gravel bed (*BGm*); upper gravel beds (*Gp*) with sand intercalations	erosion followed by deposition from secondary currents controlled by local morphology	+	most often in sharp bends constrained by bedrock outcrops; generally of sporadic occurrence
	overbank zone	gravel levee	elongated; or $l<70$ m; $w<10$ m; or $h<1$ m	terrace along the channel bank	slightly convex surface in transverse section	gravel	massive gravel (*Gm*) with traces of bedding; clast-supported atop	vertical accretion from velocity gradient in channel/terrace boundary	?	most often in sinuous channel reaches; generally of sporadic occurrence
		coarse-grained sheet	irregular or fan-shaped $150<l<350$ m; $30<w<150$ m; $0.3<h<1.3$ m	on outer bank of bend or in channel confluence zone	usually flat; large sheets with parasitic bars	boulder, gravel, sandy gravel; distal finning tendency	gravel/boulder of gravel/sand thin sheet beds, massive (*GBm*, *GSm*)	vertical accretion from supercritical sheetflow deceleration	+	quite abundant in channel reaches of increased sinuosity
		overbank linguoid bar	linguoid; $15<l<30$ m; $7<w<15$ m; $h<1.7$ m	in assemblages usually, in lows of terrace often	always with distal steep slipface	gravel	thick beds of gravel or sandy gravel with tabular cross-bedding (*Gp*)	distal accretion from deceleration of concentrated overbank flow	?	typical of alluvial plain of large gravel-bed braided river

The absence of lateral accretion slipfaces in the studied longitudinal bars indicates that the bar accumulation is strongly connected with upper-plane bed, supercritical (or transitional) flow conditions. Longitudinal bar origin is linked with the rising flood and flood crest. On the other hand, compound bars presumably developed from the unit forms, during waning flood phases. It seems clear that the longitudinal bar represents the most characteristic depositional macroform of gravel-bed braided rivers (cf. Williams and Rust, 1969; Ashmore, 1993; Ferguson, 1993).

The group of side bars consists of several types of macroforms. All of them are elongated and attached to the bank. The bars of this group were distinguished on the basis of scale, planform shape, grain size, and mode of accumulation.

A *diagonal bar* (Table 2) is the most abundant and characteristic macroform from the group of side bars. Its planform resembles an asymmetric (diagonal) tongue attached to the bank. Diagonal bars are typical of river channel reaches characterized by slight sinuosity. They exist alternatively close to both channel banks, immediately downstream from gentle bends (Fig. 6A). Proximal parts are coarser (bouldery–gravelly) than distal ones (gravelly). It is quite common for a secondary shallow channel to exist in the contact zone between the bank and the bar. This channel is filled-in by fine-grained material: granule/pebble, sand, or even silty sand (Fig. 6B). In the author's opinion, the diagonal bar is an indicative macroform of a natural, relatively shallow and wide alluvial channel, i.e. the channels transitional between meandering and braided ones.

The following scenario of diagonal bar origin has been interpreted. During peak flood stage the river flow was uniform, and acted within all wide channel zones as well as the overbank area adjacent to the river. In the falling stage flow became less uniform: the main current (thalweg) became slightly sinuous. At the same time, large velocity gradients prevailed in the marginal zones of thalweg, and intensive deposition of boulders and gravels occurred. The bars grew in a downstream direction simultaneously with progressive decrease of stream power. In this stage the distal, finer-grained (gravelly) parts of the bars also were formed. Finally, after flood recession, flow was enclosed into a regular network of alternate, coarse-grained diagonal bars. Some diagonal bars could also evolve from the central longitudinal bars by side-channel abandonment. The presence of secondary, near-bank channel in Fig. 6B suggests this mode of bar formation.

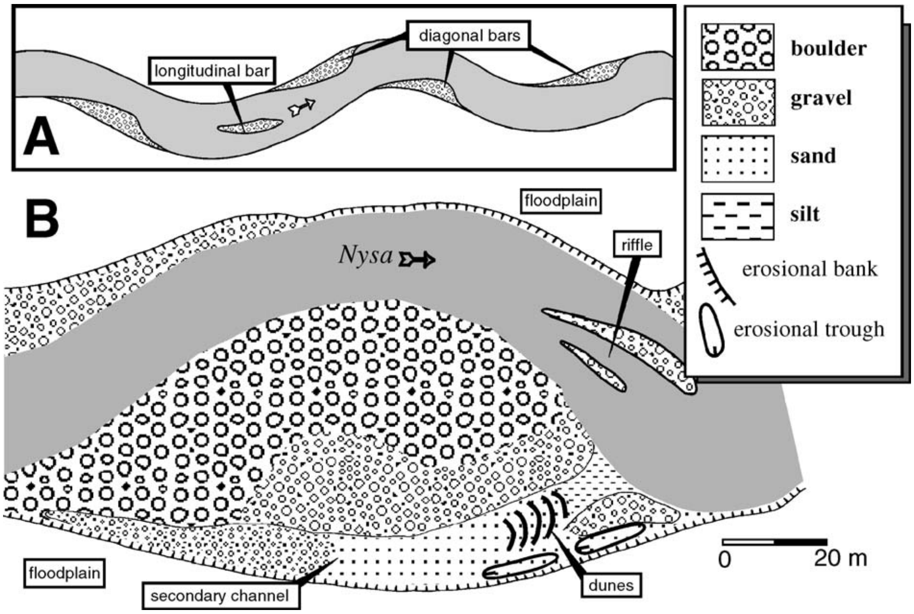

Fig. 6. (A) Sketch of slightly sinuous river with diagonal bars. (B) Diagonal bar in the Nysa river near to Bardo.

To conclude, the macroforms mentioned above can be classified as true diagonal bars. The following features support this suggestion: the bar location close to the inner bank of gentle bend, nearly flat bar surface, presence of near-bank abandoned secondary channel, gradual grain-size fining in downstream direction (cf. Bluck, 1974; Hein and Walker, 1977; Teruggi and Billi, 1997). It is commonly accepted that diagonal bars are typical forms of wandering rivers, i.e. gravel-bed ones of transitional character between meandering and braided pattern (cf. Ferguson and Werritty, 1983).

A *side compound bar* (Table 2) is the second type of the bar distinguished within the group of side macroforms. This is a large-scale bar that exists in the zones of channel widening. These bar types were only noted in channels with tendency for braiding. Such a situation (subdivision into a few branches) was common in the foothill zone in the lower part of the studied river reach (i.e. downstream from Bardo town in Fig. 1). A typical side compound bar consists of a few platforms, each of which is a large, gravel linguoid bar with high (up to 2 m), steep slipfaces of microdeltaic type (Fig. 7). The lower platforms are progressively finer-grained, suggesting their origin during intermittent, successive stages of huge flood recession.

The presence of well-developed microdeltaic (i.e. of lateral accretion) slipfaces is an important feature differentiating this bar type from all the other types mentioned above. From this point of view the side compound bar is analogous to a macroform called the foreset bar (Miall, 1977). Considering its morphology, location, and relation to lateral accretion, the compound side bar ought to be identified as the macroform typical of aggrading braided river environment (cf. Church and Gilbert, 1975; Rundle, 1985). It is characteristic that this bar type was not common in studied river reaches. This fact supports the conclusion that the typical braided river style of sedimentation during large flood was spatially restricted to the lowest Nysa River course, i.e. to the foothill zone. This zone favoured redeposition of alluvium, and the lower valley slope enabled intensive aggradation as well.

A *coarse-grained point bar* (Table 2) is the next characteristic type of side macroform. It differs from other side-type bars by location in the channel, morphology, and mode of accumulation. Point bars exist in sharp bends (i.e. where inflowing and outflowing channel segments make the angle lower than 110°). Simple (unit) bars are small; their length is up to 30 m. The large forms, 50–70 m long, are most often of compound type. Unit bars contain only one, low platform built up of gravel or gravel and sand. Compound bars usually have two or three platforms. The lower platforms are progressively finer-grained: from boulders to sandy gravel (Fig. 8). Secondary "parasitic" bar forms (bouldery, gravelly, or sandy) have been noted on the surfaces of large compound point bars. Sometimes large bars of unit type were also found. They comprise one, however broad platform, which is distally bordered by several languoid progradational slipfaces (microdeltas).

To conclude, there are no uniform rules of morphologic and lithologic development of point bars. Only one necessary condition must be fulfilled for their origin: the presence of sharply curved bend. Both their depositional processes and resultant shapes are controlled by local, highly variable hydrodynamic

Fig. 7. Gravelly–bouldery upper platform of the side compound bar. The Nysa river reach downstream from Bardo.

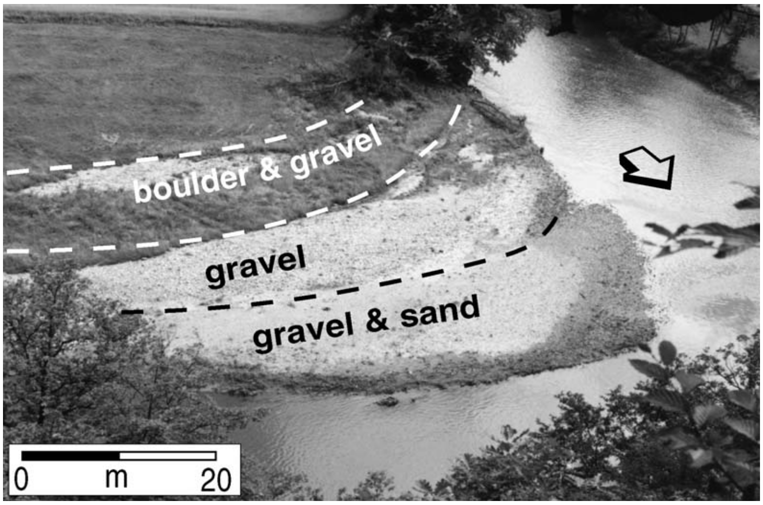

Fig. 8. Point bar in the sinuous channel of the Nysa river. The boundaries of three bar platforms are marked and flow direction is indicated.

conditions. Best-developed point bars were noted in the Nysa River gorge within the Bardo Mountains, where the network of bedrock outcrops causes sharp channel bends. In all the other, unconfined river reaches; the point bar frequency was rather low.

4.2. Overbank zone

A gravel levee is formed on the lowermost terrace, close to the channel bank (Table 2). Sometimes its formation was caused (or enhanced) by the stems of trees growing along the river channel. Most frequent and best-developed levees have been noted in the Nysa River gorge in the Bardo Mountains, where the river course is highly sinuous. In comparison with the boulder berms of mountain streams, the levees adjacent to river channels are less frequent and contain finer deposits (gravel).

Coarse-grained overbank sheets (Table 2) are formed in places where strong current passes from the channel onto the terrace. In the sense of their origin the sheets are comparable with crevasse splays, however crevasses develop rather sporadically. Three different cases of sheet formation have been recognized.

An elongated gravel sheet located along the channel bank (Fig. 9A) is partly comparable with the gravel levee. This form is up to 0.5 m thick and is composed of sandy gravel (surficially reworked to the gravel pavement).

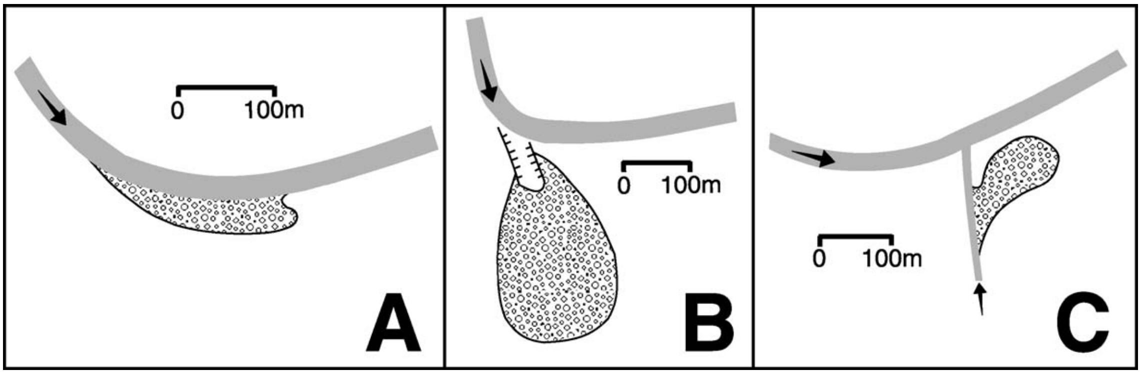

Fig. 9. Three types of coarse-grained overbank sheets.

A coarse-grained, fan-shaped sheet lies on the terrace, out of the channel bend. Flood flow eroded the short channel, which resembles a large-scale crevasse. This flood channel passes into the sheet (Fig. 9B). These are the largest overbank forms; studied sheets attained the length of 350 m and width up to 150 m. They contain boulders and gravels in their proximal parts, which fine distally to gravel and sand (Fig. 10).

The third case of coarse-grained sheet formation was rarely noted. This type of sheet originated in the confluence zone of the main river and a tributary. During flood the tributary flow was shifted in a down valley direction out of the previous channel and to the floodplain area by the stronger current of the main river. In this way, gravel–boulder fan-like sheet was formed in overbank zone (Fig. 9C).

Overbank sheets, especially the coarsest-grained (gravelly–bouldery) ones, are unique forms typical of catastrophic flooding. This assertion is supported by the fact that all previously documented overbank sheets (crevasse splays) are built of evidently finer material—sand or gravelly-sand (cf. Rust, 1972; Klimek, 1989; Reinfelds and Nanson, 1993).

In addition to the sheets, other, smaller scale forms were also found—*overbank linguoid bars* consisting of gravel (Table 2). They typically exist in assemblages and have characteristic steep, distal slipfaces of microdeltaic origin. Therefore, it is clear that these forms developed by distal progradation, not vertical accretion as in the case of the sheets. Overbank bars have been noted in the lower part of the Nysa course only, in the foothill zone (downstream from Bardo town in Fig. 1). However, the bars were quite abundant there. This is the evidence that overbank linguoid bars are characteristic of large, gravel-bed braided rivers.

5. Lithology of alluvium

5.1. Lithofacies of mountain stream environment

The basic feature of stream alluvium is that lithofacies type is weakly dependent on parent depositional form. Generally, deposits are characterized by:

- very coarse grain size (boulders predominate over cobbles usually—Fig. 11),
- predominance of clast-supported over matrix-supported texture,
- lenticular shape of beds (up to 1.5 m thick and up to 30 m long),
- common massive structure; only the finest-grained deposits (gravelly sand) occasionally show horizontal stratification.

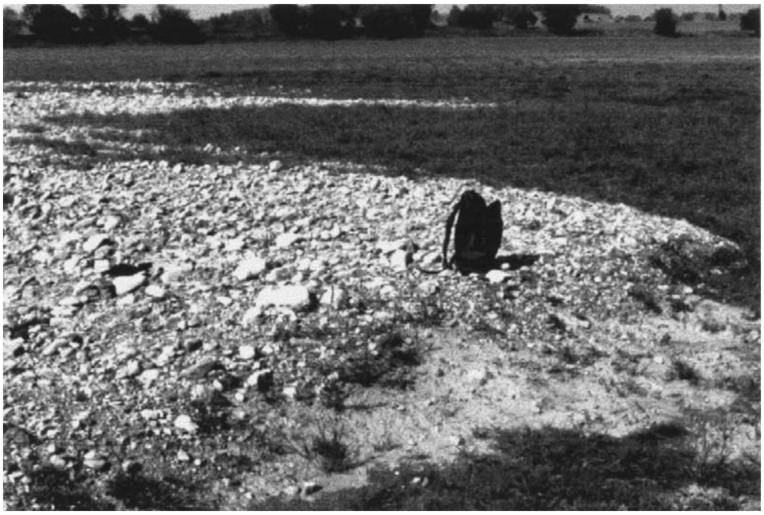

Fig. 10. Distal margin of coarse-grained fan-shaped overbank sheet. The lower reach of Bystrzyca Dusznicka river. Flow was from left to right. Rucksack for scale.

Fig. 11. Deposit of boulder mound. Large imbricated boulders are typical sediment of catastrophic flooding. Flow direction was from right to left. The upper Plawna stream. Rucksack for scale.

It seems important to resolve the problem, regarding which deposits can be qualified as indicative of catastrophic flooding. This study suggests that these are all boulder beds and gravel beds thicker than 1.0 m. Large boulders with abrasion traces (larger than 5 cm in perimeter) play the same indicative role and undeniably prove the intense transport of boulder-sized material by torrential flow.

5.2. Lithofacies of main river environment

All bar-derived deposits of the main rivers studied represent one lithofacies assemblage. This conforms with Brierley's (1991) opinion. He claimed that in a qualitative sense, lithofacies is not dependent on a type of parent bar form, but is strictly related to local hydrodynamic conditions (which temporarily can be the same in subenvironments of numerous bar types).

Gravel and boulder clast-supported beds with massive structure or crude horizontal stratification are the most abundant lithofacies derived from the bars. Within massive beds the clasts are usually well imbricated. Bed thickness is from 0.5 to 1.5 m. As a rule, these are sheet beds. Distal fining is noted in thick beds usually. This feature coexists with distal change from clast- to matrix-supported texture. Gravel beds can be capped by horizontally stratified sand associated with the final, waning flood stage.

Lithofacies of side compound bars evidently differ from deposits mentioned above. Each bar consists of a few gravel or gravel/boulder beds with characteristic, large-scale tabular cross-stratification. This lithofacies (*Gp*) is typical of microdeltaic bar platforms. Flat clasts display pseudoimbricated arrangement (their *ab* planes dip concordantly with palaeoflow direction).

The average thickness of coarse-grained (bouldery–gravelly most often) bar-derived beds is 1.0–1.5 m. Thus, this value can be assessed as mean aggradation ratio per large flood of channel facies in the zones of favoured deposition.

Which lithofacies can be considered as indicator deposits for catastrophic flooding? These are boulder and boulder/gravel, clast-supported beds with sheet shape and massive structure, relatively thick (up to 2 m in channel suite and approx. 1 m in overbank one). As a rule, basal surface is erosional. Boulder–gravel grain sizes gradually fine to gravel in distal direction. One more feature seems to be indicative of torrential flooding; the upper gravel beds are frequently overlain by a boulder lag. Formation of analogous lags has been noted by Rathburn (1993) and Russell and Knudsen (1999) on the surfaces of gravel bars due to catastrophic flood events. Additionally, the present study pointed out that large, convex-down, up to 1.3 m deep erosional surfaces can be regarded as typical features developed within channel facies during catastrophic flooding. Such channel-like structures are interpreted as a record of spasmodic erosional/depositional pulses during extreme floods.

6. Conclusions

- There is a relatively regular spatial succession of depositional processes and forms along the mountain streams. In the uppermost reaches, only erosion takes place. Depositional processes ensue downstream. Formation of boulder mounds and boulder berms take place first. These forms are replaced by longitudinal bars and side bars in lower reaches. Stream energy (principally determined by channel slope) is the main factor controlling this succession.
- One phenomenon was characteristic both of streams and main rivers: the zone of increased deposition always follows the zone of erosion (where they extend from hundreds of metres to few kilometres). Moreover, the ratio of fluvial deposition is proportional to intensity of upstream erosion.
- Both texture and structure of mountain stream alluvium indicate very weak relationship with parent depositional form type. Generally, deposits are characterized by: very coarse grain size (boulder beds prevail over gravel beds), clast-supported texture is more common than matrix-supported, beds are of lenticular shape and their structure is typically massive. All boulder and gravel beds thicker than 1 m can be regarded as deposits derived from catastrophic flooding.
- No regular succession of depositional form types has been noted along the main river courses. Nor is there predominance of one bar type within long channel reaches; the type of bar depends on local channel morphology. On the other hand, channel morphology (pattern) is highly variable in space, which is mainly related to long-term human activity (tree plants, roads, buildings). In this way, the control of natural factors on channel pattern—i.e. the slope—was strongly decreased. Catastrophic flooding caused revitalizing of natural fluvial depositional styles. In straight channel reaches the central longitudinal bars were formed, in slightly sinuous channels—side diagonal bars, and in highly sinuous ones—point bars.
- The most abundant bar types of main rivers are represented by one lithofacies spectrum. The most common lithofacies are clast-supported gravel and boulders with massive structure or crude horizontal stratification arranged in sheet-like beds. Some thick beds reflect distal fining. Lithofacies indicative of catastrophic flooding are coarse-grained (with significant boulder content), clast-supported, relatively thick (up to 2 m for channel facies and approx. 1 m for overbank), and the beds have erosive bases.
- Depositional effects of Nysa River suggest that it is “close” to braided pattern. It can be regarded as transitional river in this sense. It seems that in conditions of increased precipitation in its drainage basin (i.e. increased discharges, duration, and frequency of floods), Nysa would very likely evolve to typical braided river. This conclusion is supported by analysis of erosion processes and forms originated during huge flood (Zielinski, 2001).

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References

Ashmore, P.E., 1993. Anabranch confluence kinetics and sedimentation processes in gravel-bed streams. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers. Geol. Soc. Lond. Spec. Publ., vol. 75, pp. 129–146.

Batalla, R.J., De Jong, C., Ergenzinger, P., Sala, M., 1999. Field observations on hyperconcentrated flows in mountain torrents. Earth Surf. Process. Landf. 24, 247–253.

Bluck, B.J., 1974. Structure and directional properties of some valley sandur deposits in southern Iceland. Sedimentology 21, 533–554.

Brierley, G.J., 1991. Floodplain sedimentology of the Squamish River, B.C.: relevance of element analysis. Sedimentology 38, 735–750.

Carling, P.A., 1987. Hydrodynamic interpretation of a boulder berm and associated debris-torrent deposits. Geomorphology 1, 53–67.

Church, M., Gilbert, R., 1975. Proglacial fluvial and lacustrine sediments. In: Jopling, A.V., McDonald, B.C. (Eds.), Glaciofluvial and Glaciolacustrine Sedimentation. Soc. Econ. Paleontol. Mineral. Spec. Publ., vol. 23, pp. 22–100.

Dubicki, A., 1999. Analysis of maximum stages and discharges of flood flows. In: Dubicki, A., Slota, H., Zielinski, H. (Eds.), The Odra Drainage Basin. Monograph of July 1997 Flood. Institute of Meteorology and Water Management, Warszawa, pp. 89–114. In Polish with English Abstr.

Ferguson, R.J., 1993. Understanding braiding processes in gravel-bed rivers: progress and unresolved problems. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers: Form, Process and Economic Applications. Geol. Soc. Lond. Spec. Publ., vol. 75, pp. 73–87.

Ferguson, R.J., Werritty, A., 1983. Bar development and channel changes in the gravelly River Feshie, Scotland. Spec. Publ. Int. Assoc. Sedimentol. 6, 181–193.

Hein, F.J., Walker, R.G., 1977. Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia. Can. J. Earth Sci. 14, 562–570.

Klimek, K., 1989. Flood plains activity during floods in small mountain valleys, The Bieszczady Mts., The Carpathians, Poland. Quaest. Geogr., Spec. Issue 2, 93–100 (Poznan, PL).

Kotarba, A., 1998. Morphological role of rainfalls in modelling of Tatra relief during summer flood of 1997. Dok. Geogr. 12, 9–23 (Krakow, PL (in Polish with English Abstr.)).

Miall, A.D., 1977. A review of the braided-river depositional environment. Earth-Sci. Rev. 13, 1–62.

Miall, D., 1996. The Geology of Fluvial Deposits. Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer, Berlin. 582 pp.

Rathburn, S.L., 1993. Pleistocene cataclysmic flooding along the Big Lost River, east central Idaho. Geomorphology 8, 305–319.

Reading, H.G., Levell, B.K., 1996. Controls on the sedimentary rock record. In: Reading, H.G. (Ed.), Sedimentary Environments, Processes, Facies and Stratigraphy. Blackwell, Oxford, pp. 5–36.

Reinfelds, I., Nanson, G., 1993. Formation of braided river floodplains, Waimakariri River, New Zealand. Sedimentology 40, 1113–1127.

Rundle, A., 1985. The mechanism of braiding. Z. Geomorphol. N.F., Suppl.Bd. 55, 1–13.

Russell, A.J., Knudsen, O., 1999. Controls on the sedimentology of the November 1996 jökulhlaup deposits, Skeidararsandur, Iceland. In: Smith, N. (Ed.), Fluvial Sedimentology. Int. Assoc. Sedimentol. Spec. Publ., vol. 28, pp. 315–329.

Rust, B.R., 1972. Structure and processes in a braided river. Sedimentology 18, 221–245.

Schmidt, J.C., 1990. Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona. J. Geol. 98, 709–724.

Stewart, J.H., La Marche, V.C., 1967. Erosion and deposition produced by the flood of December 1964 on Coffee Creek, Trinity County, California. Prof. Pap.-Geol. Surv. (U.S.), 1K–22K.

Teruggi, L.B., Billi, P., 1997. Sedimentology of a pseudomeandering river (Cecina River, central Italy). G. Geol. 59, 267–272.

Williams, P.F., Rust, B.R., 1969. The sedimentology of a braided river. J. Sediment. Petrol. 39, 649–679.

Zielinski, T., 2001. Erosional effects of catastrophic flood in the Nysa Klodzka drainage basin during the 1997 and 1998 events (SW Poland). Prz. Geol. 49, 1096–1100 (Warszawa, PL (in Polish with English Abstr.)).