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GEOMORPHOLOGICAL ASPECTS OF THE FLOOD OF JULY 1997 IN THE MORAVA AND ODER BASINS IN MORAVIA, CZECH REPUBLIC

INTRODUCTION

Extreme precipitation at the beginning of July 1997 was the cause of a disastrous flood. Its course and effects, evidenced by meteorological, hydrological, and geomorphological records, suggest an extraordinary event unparalleled in this century in the Czech Republic. The magnitude of the flood in terms of discharge and storm runoff as well as low frequency has surpassed the historical memory of the inhabitants. The flood of 5–9 July 1997 killed 50 people and caused 60 thousand million Czech crowns worth of damage. In the course of the same month the effects of this "most remarkable event of the century" were further amplified by another flood event, although one rather less pronounced, from July 17 to 21.

Rivers in the distressed areas of the Western Carpathians and the Eastern Sudetens transported huge amounts of suspended sediments and bedload in their channels, on valley bottoms, and on the adjacent slopes. This brought about drastic erosion and massive deposition of transported sediments. In lowland regions vast areas of floodplains were flooded. The power of flood flows has carried out much geomorphological work, the evaluation of which in choice sites has contributed to the knowledge of floodplain development and ± channel bedforms generation.

AN ABBREVIATED PHYSIOGRAPHIC CHARACTERISTIC OF THE REGION AFFLICTED WITH FLOOD

July 1997 was an exceedingly wet month. This fact has made itself felt by precipitations of extreme magnitude and duration and has caused, in the North Moravian and Silesian rivers, peak discharges over a long period of time. The floods arose in the mountains of North Moravia and Silesia and affected the rivers of the Morava and Oder basins. The catchments of both rivers include Carpathian and Sudeten parts which meet together in the meridionally oriented Carpathian foredeep formed by the Ostrava basin, by the graben of the Moravská brána (Moravian Gate), and by the Hornomoravský úval (Upper Morava Graben) (Fig.1). A part of the Oder basin is, on the Sudeten side, seperate from the Opava, Opavice, and Moravice rivers, as well as the Bělá (Biała), which is a tributary of the Nysa Kłodzka in Poland. From the Carpathian part of the Oder basin and the flysch mountains of the Western Carpathians flow the Olše, Ostravice, Jičinka, and Lučina rivers, as well as other smaller tributaries. Both parts of Oder basin, the Sudeten and the Carpathian, meet in the Moravian Gate and in the Ostrava basin. Into the Morava flow, from the worst affected part of the high Eastern Sudeten, the tributaries of Desná, Branná, and Krupá, from the Carpathian side Bečva. Both parts of the Morava basin meet in the Upper Morava graben in Middle Moravia. The Oder basin in North Moravia and Silesia covers 6,791 km^2, that of Morava in Kroměříž 7,014.44 km^2. The channel slopes of the Carpathian rivers are steeper, in some places up to twice that of the rivers in Sudeten. This fact most likely makes itself felt by channel deepening during large floods.

EXTREME PRECIPITATIONS

The first precipitations, of a small yield of some 20–50 mm, fell in the affected area of the Oder and the Morava basin as early as the end of June and the beginning of July. There was no response to that in the discharge amount, but the capability of soil to further infiltrations got affected. Over the following days of July 1997, then, extreme rainfall came in two subsequent waves.

On 4 July 1997, Bohemia and Moravia were affected by rainfalls due to a cold front passing from the northwest to the southeast and to a subsequent passage of a cyclone from the western Mediterranean towards the northeast, to southeastern Poland and Ukraine. The abundant rainfall first affected a narrow strip of territory stretching from northern Austria through the western part of the Carpathians to the eastern Sudeten. The return of the cyclone from Ukraine to Poland from 5–9 July, 1997, can be seen as an anomalous phenomenon. The rainfall has thus come back to Northern Moravia and Bohemia. The situation resulted in the so called shear movement, in which the wet warm air from the Mediterranean flowed in the upper layers, while the cool air remained low at the earth's surface. The mountain windward sides of the northeastern border region supported the condensation. The windward effect of the air flow could be felt first on the southern and later on the northeastern sides of the Eastern Sudeten, as well as in the Western

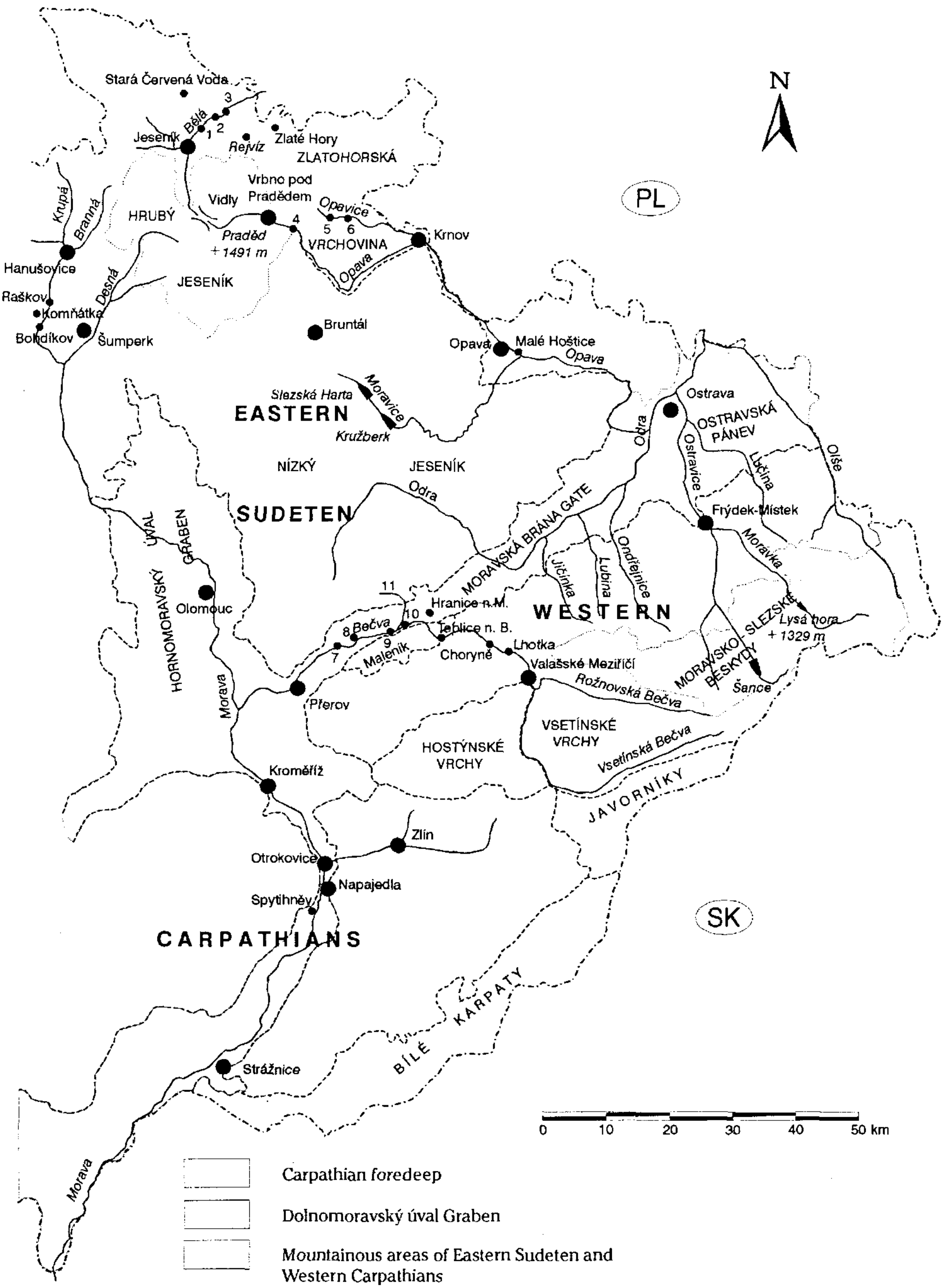

Fig. 1. Location map of the territory affected by flood on July 4 to 9, 1997, in northern Moravia and Silesia in the Czech Republic. Some of communities and water streams mentioned in text. 1. Česká Ves, 2. Písečná, 3. Studený Zejf, 4. Karlovice, 5. Spálená, 6. Holčovice, 7. Osek nad Bečvou, 8. Lipník nad Bečvou, 9. Familie-Hráz, 10. Rybáře, 11. Uhř ňovšk poťok

Carpathians. The worst affected in the Carpathians were the uplands of the Moravsko-slezské Beskydy Mts (M-S Beskydy), the Vsetínské vrchy Mts, the Hostýnské vrchy Mts, the Javorníky Mts, the uplands of Hrubý Jeseník Mts in the eastern Sudeten, the Nízký Jeseník Highlands, and the Orlické hory Mts. The disastrous effect of floods in connection with orographically intensified rainfalls in the northeastern frontier area of the Czech Republic is well known (Hrádek et al. 1997).

The largest amounts of precipitations in the period between 4–9 July, 1997, were recorded in the M-S Beskydy (Šance Dam on the Ostravice River 617 mm, Lysá hora 586 mm, Frenštát pod Radhoštěm 491 mm) and in the Hrubý Jeseník Mts (e.g. Rejvíz 511 mm, Jeseník 512 mm, saddle of Vidly 501 mm, Praděd 455 mm). The highest single-day precipitation total was recorded on 6 July 1997 in the Beskidy Mts (Lysá hora 234 mm, Šance Dam-Ostravice 230 mm, Frenštát pod Radnoštěm 206 mm), and in Hrubý Jeseník (Zlaté hory-Rejvíz 214 mm, saddle of Vidly 199 mm). A majority of the above locations are situated in the Oder basin i.e. in the area characterized by the most frequent occurrence of extreme precipitation in the Czech Republic. On Lysá hora, for example, a single-day total of 100 mm was surpassed 30 times from 1900 to 1980. The precipitation total of 617 mm within six days (July 4 to 9) at the Šance Dam is the highest ever recorded on the territory of the Czech Republic.

In the latter half of July a similar phenomenon occurred in which two frontal systems intersected in Central Europe. Here, too, an important role in the formation of rainfall was played by a windward effect that could be better felt in the mountains of Krkonoše and Orlické hory. The rainfalls which caused a second flood wave after 14 July reached a level comparable to that of the first wave in the Krkonoše Mts.

IMPACTS OF EXTREME RAINFALLS ON THE RATE OF DISCHARGE AND ON GEOMORPHOLOGICAL PROCESSES IN RIVERS

One result of the extreme rainfalls in the Moravian Sudeten and Carpathian mountains was an intensive overland flow from slopes with subsequent storm runoff and a sudden rise of discharges (Q) in the rivers of the Oder and Morava basins. Due to the saturation of soils with water from rainfalls at the end of June, the capability of infiltration by water from further rainfalls after 4 July decreased, which resulted in increased runoff. Dissected mountain relief reduced the capacity for infiltration. The result was a mountain flood characterized by a swift and steep rising limb of the flood hydrograph (Fig. 2). The soil saturation and the amount of rainfall have also triggered numerous landslides, debris flows, and other mass movements, more intensive in the Carpathian than in the Sudeten mountains.

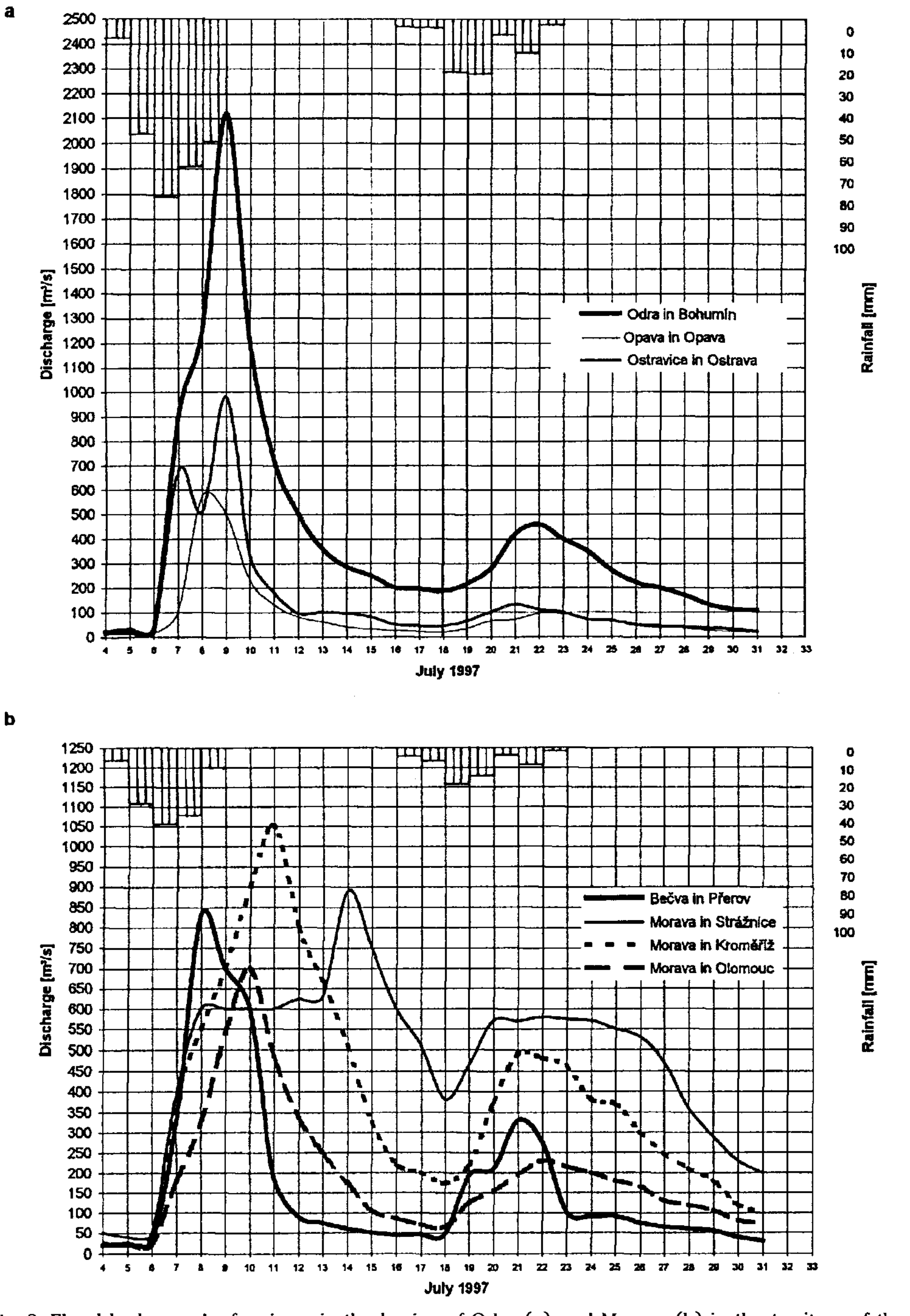

Fig. 2. Flood hydrographs for rivers in the basins of Oder (a) and Morava (b) in the territory of the Czech Republic. For both basins is typical the steep rising limb of the flood wave, in the basin of Oder the downstream increasing volume of the flood, and in Morava basin its delay

Runoff caused by extreme rainfalls along with water flow power had an impact not only on the discharge of rivers, but also on their susceptibility to erosion, entrainment, and accumulation. A great degree of erosion took place on valley bottoms and river beds, in riparian zones, on floodplains, and on valley sides of rivers. In the narrowed mountain valleys the flood effects increased through interaction with the steep slopes of the valley sides. Upon the latter were transported, as result of mass movements, large amounts of sediments, either carried by mountain flood in suspension or as bedload, or dragged on the bottom or on the surface of the floodplain. In most cases the total amount of suspended loads transported in July 1997 surpassed the average yearly transport total of the period 1976–1995. Along with the suspension of mineral particles, huge amounts of wood (trees, logs, shrubs, wood debris, building material, etc.) were carried along by the water. This, together with coarse gravel, clogged some bridges and culverts, making barriers and causing rivers to wander and form new channels. Transport of bedload had a special importance.

The geomorphological work of rivers during the flood could be characterized as the erosion of channels, the remarkable stripping of floodplains, and the interaction with valley sides. In the individual river basins, with regard to the underlying rocks and to the anthropogenic adjustments of channels, can be peculiar local features observed, such as channel incision or bank undercutting. The flood was generally characterized by bank erosion leading to channel widening. The floodplains were eroded, partly or in their entire widths, and then completely or partly stripped. The process was usually triggered by bank undercutting and falling. In zones of banks with trees channel widening was markedly supported by fallen trees and their root systems in the channels. There were local differences in the magnitude and effectiveness of the fluvial processes between the Oder and Morava basins and between their Sudeten and Carpathians parts.

ODER BASIN IN EASTERN SUDETEN

The rivers of the Sudeten part of the Oder basin have their sources on the slopes of the Bohemian Massif. From there they flow down either directly to the Silesian Lowland, such as Bělá (Biała), or first to the Moravian Gate and to the Ostrava basin in the Carpathian foredeep, such as Opava and the upper course of the Oder.

In the Oder basin, where the highest totals of precipitation were recorded, the geomorphological effects of the flood were large and numerous. On the Oder the discharges (Q) in the initial and torrential reaches of the tributaries in the mountains increased in level from Q_5 to Q_{10}. The river channels were well fitted for such discharges in these reaches, as the mountain flood water was led to the main valleys with no particular problem. Downstream the maximum discharge was combined as consequence of the long duration of the rainfalls, and in the middle reaches hydrograph levels of Q_{100} were surpassed. This was above all the case in the Moravice basin upstream from the Slezská Harta Dam, which, as a whole, was less affected (in the order of Q_{20} to Q_{50}). The retention effect of the reservoir was clearly visible. On the Oder itself, upstream from the Odry in the upland of Nízký Jeseník, the discharges were also lower (cca Q_{50}). A Q_{100} was reached on the Oder in the Moravian Gate after confluence with Jičinka and other rivers from the M-S Beskydy. The Oder discharge, at the point of departure from Czech territory at Bohumín on 8 July, 1997, reached 2,160 $m^3 \cdot s^{-1}$.

In the area of the Hrubý Jeseník Mts most rivers soon reached the Q_{100} level. In the Czech section of Bělá (Biała in Poland), discharge level reached $Q_{max} = 216\ m^3 \cdot s^{-1}$ ($Q_{100} = 168\ m^3 \cdot s^{-1}$). The source area of Bělá at taheight of 920 m under the saddle of Vidly was affected by mass movements, above all by slides and earthflows. Downstream the Bělá already triggered bank erosion which damaged near by communications and buildings. At Jeseník the floodplain terrace fell victim to bank erosion. The existing channel was widened. Downstream from Jeseník, at Písečná, the Bělá was subjected to river wandering and formed new arms after channel clogging. Besides bank erosion there were also an accumulation of coarse and fine grain overbank sediment deposits. Upstream from Jeseník (at Adolfovice), the floodplain was silted by sand accumulations of as much as 0.5 m. At Česká Ves below Jeseník the floodplain surface became covered by fine-grained sediments of about 0.5 m.

The extent of the flood of July 1997 can be seen when making comparison of the hydrographic marks preserved. In gap valley of Bělá at Písečná-Studený Zejf there are height marks of significant floods of the last one hundred years preserved on a rock wall. The record contains peak marks of flood of July 29, 1897, and July 9, 1903. Now, there is also that of July 1997, being the highest placed by far and thus witnessing the remarkable extent of that years deluge. Lower situated is the marking of the 1903 flood, and the July 1897 big flood mark is the lowest placed. Concerning the 1903 data (Kakos 1997) it is to be noted that in one day, at the near Stará Červená Voda, there were 240 mm of precipitations; this record-making one-day precipitation total has not been surpassed yet, not even in 1997. The marks also show that in so called century floods, and in other major ones, the water level height in the narrowed gorge can reach as much as 6 m.

On Opava with its Opavice tributary the maximum discharge surpassed the hundred-year level already in its upper stream (at Opava it featured $Q_{max} = 647\ m^3 \cdot s^{-1}$, $Q_{100} = 360\ m^3 \cdot s^{-1}$), and from here up to the confluence with Oder. An investigation of geomorpological effects was carried out in the valley of upper reaches of Opava and Opavice. The flyschoid Lower Carboniferous slates of Opava catchment are less resistant to erosion. This fact influenced in some places the formation of 4–5 m deep gullies with wide alluvial fans (Photo 1). In the source area of Opava below the saddle of Vidly and at Vrbno pod Pradědem the strong rainfall generated slides.

The Opavice floodplain in its upper reach at Hynčice is as much as 60–70 m wide. The original channel width was 3–6 m. After the flood the channel was widened to even 25 m in some places. Along a wide belt the fine grained floodplain the slackwater deposits of about 1 m of thickness were wholly stripped as deep as the underlying coarse gravel on the surface of which was added further gravel by the flood. The coarse channel bed gravel loaded the stream to the extent of giving rise to braiding in the

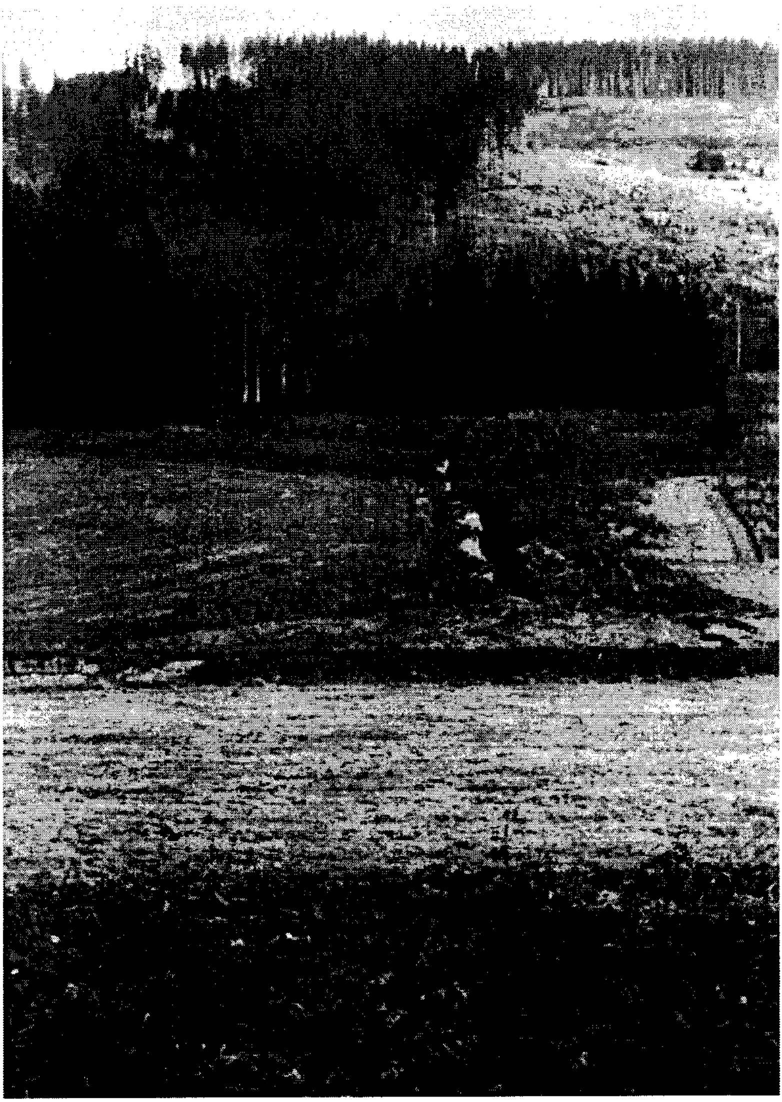

Photo 1. In Sudeten mountains the heavy unremitting rainfalls triggered gully erosion. An up to 4 m deep gully in the figure cut the sides of Opavice valley of Lower Carboniferous flyschoid slates. Note the broad alluvial fan at the foothill of gravel debris

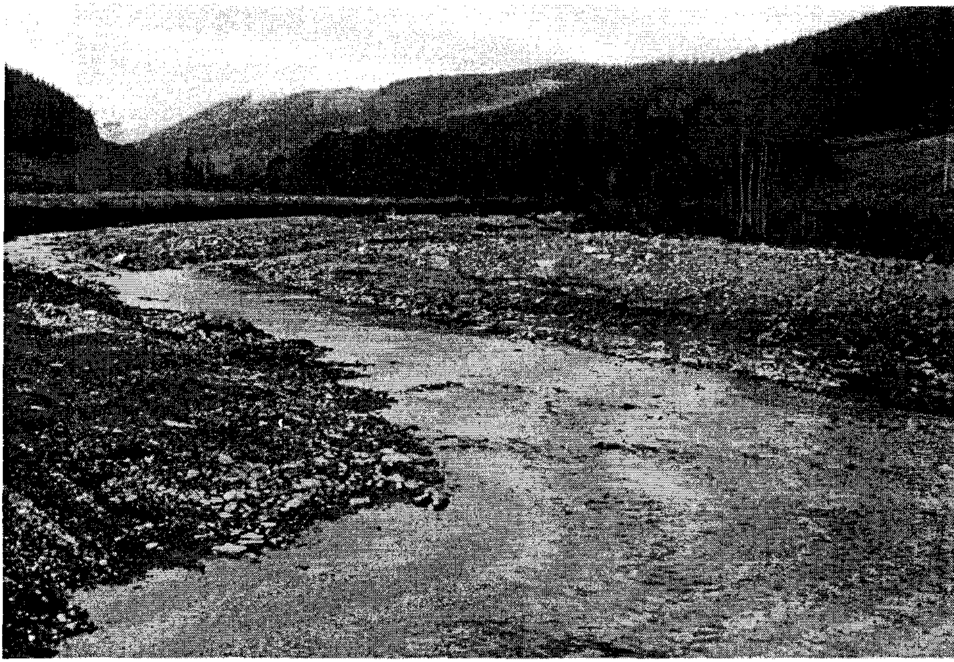

Photo 2. After stripping of fine grained floodplain deposits the reach of Opavice at Spálené with widened channel turned into a coarse-bedload stream and thus became convenient for river braiding

widened channel bed (Photo 2); the river recurred to its stage of braiding as it probably had been the situation there before 14th or 15th century. These are namely the times from which we have records on the end of panning-off for gold in the area with the formation of alluvial placers along the river course which prove the existence of coarse bedload streams still with no thick fine grain floodplain sediments. In the undercut bank wall of Opavice the alternation of coarse gravel layers with finer overbank deposits was well visible as evidence of preceding flood events.

The river Opava in its upper reaches, starting from Vrbno pod Pradědem, passes through a forested mountainous terrain of Hrubý Jeseník Mts and Zlatohorská vrchovina Highland. Here, to, lateral erosion of undercut banks prevailed, accompanied with higher slope processes (slides of water-saturated soil and slope debris). A particular feature of the area was a huge number of logs and wood debris transported by the storm flood, which completely clogged the bridge profiles and stream channels in many places. At Karlovice a log jam blocked a bridge profile and, consequently, the Opava channel on a length of 400 m, for its part, brought about the formation of a new, braided and anabranched channel system within the reach of the floodplain (Photo 3). In the catchment of upper Opava the transport and accumulation of wood debris were a significant geomorphic factor which influenced the dynamic of river beds at times of flood. Wood debris barriers along with trapped gravel divided

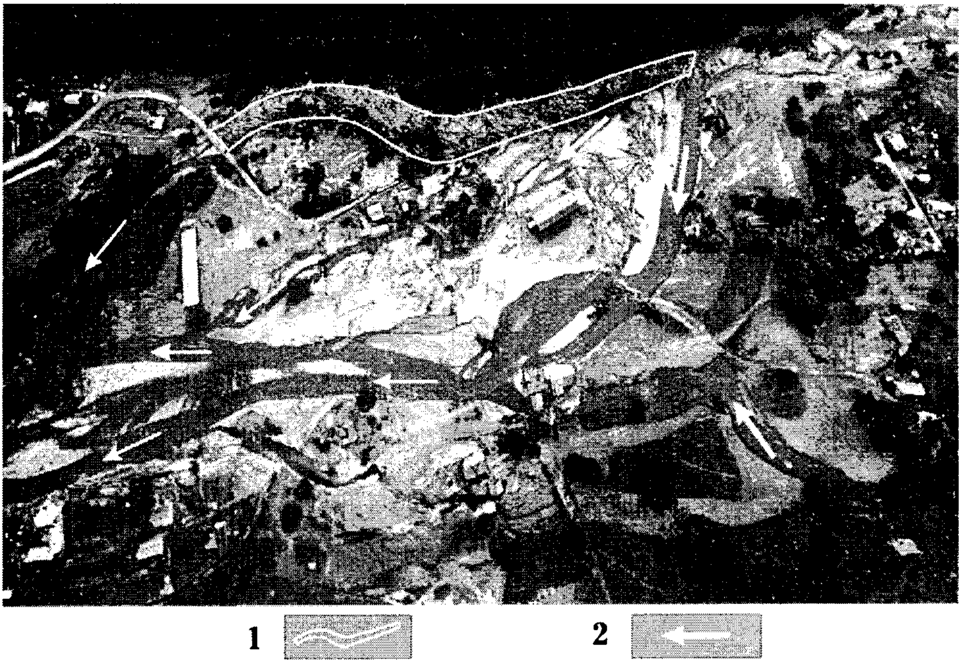

Photo 3. A four-hundred-meter-long of log jam and wood debris clogged the bridge profile of Opava in Karlovice [Sudeten]. The increasing barrier in the natural channel caused a wandering of the river and its braiding and anabranching. 1 — Log jam barrier, 2 — Direction of flow

the original channel into branches and also led to specific forms of wandering and anabranching of Opava. The burst of the temporary dikes made of logs and wood debris at places situated before artificial or natural barriers resulted in the formations of break waves with intensified effects both on the bottom and banks of the channel and in the destruction of buildings. Some sections of original channels as well as the surface of the flood plain, however, were silted even with coarse gravels.

Several years of investigations of channel beds in the Eastern Sudeten have shown that e.g. on Bělá (Biała) there was a long time stable coarse gravel channel bed pavement (Kališ, 1963–1968). Before the flood, and all the time before its start, the one-sided gravel grind indicated a long period of channel bed stability being just traces of bottom bedshear and abrasion, with no significant scour nor aggradation. This stability was broken at the extreme discharges in July 1997 when the channel bed pavement were lifted from the bottom and set into motion. The other part of the bedload came from undercut banks and participated in the geomorphic work of the rivers.

The total length of the floodplain reaches of Sudeten rivers in the Oder basin damaged by erosion and accumulation is 70 km. Specific feature of this region were, beside the huge amounts of suspended wood debris, a surprisingly big volume of bedload which was not envisaged here.

Opava forms, after the confluence with Opavice near Krnov, a broad flood plain which became overflowed. In some sites an erosion of the floodplain occurred, such as near Malé Hoštice at places of an overbank flow of the river onto the flat alluvial plain. Its surface was scoured here by a system of parallel grooves of as much as 1 m of depth that were partly filled with coarse gravel. Opava was still carrying remarkable amounts of coarse gravel in this piedmont lowland area.

The broad flood plain of Oder was inundated also in the Ostrava basin in its section from the Jičínka mouth to the Ostrava area of river confluences. After the flood recession there was the start of slackwater sedimentation in those areas where the inundation lasted the longest. The flood was intensified by the burst of protective dikes, pond dams, and of railway and road fills and causeways. The Ostrava mining region has suffered, moreover, a flooding of sinking basins in undermined areas.

THE ODER BASIN IN THE WESTERN CARPATHIANS

In the Carpathian part of the Oder basin the decisive stream during the July 1997 flood was Ostravice that drains the largest part of M-S Beskydy Mts. The hydrograph of flood demonstrates two peaks, which was a response of the rainfall totals (Fig. 2). The peak flow of flood culminated on July 9 with $Q_{max} = 111\ m^3 \cdot s^{-1}$ and then it was transformed in the Šance Dam. With regard to the risk of landslide of water-saturated flysch foothills of Lysá hora Mt into the reservoir its content was decreased in spillways giving water off at a rate of $Q_{max} = 230\ m^3 \cdot s^{-1}$. Although Ostravice drains particularly that part of M-S Beskydy which attains the highest precipitation values, including Lysá hora Mt, the flood runoff of this river became altered by the retention of water in Šance and Morávka Dams. Down the stream the discharge values were mostly of the magnitude of cca Q_{50} to Q_{100} (Ostrava $Q_{max} = 978\ m^3 \cdot s^{-1}$, $Q_{100} = 1167\ m^3 \cdot s^{-1}$). The frontier area river of Olše had lower discharges, of magnitudes Q_{10-20}. As consequence of water management adjustments performed (reservoirs, channelisation) the rivers in M-S Beskydy remainded bankfull and, with a few exceptions, did not overflow. Most damage occurred in the river channels and their vicinity. The hillslope terrains of the district of Frýdek-Místek had records on 28 landlides. In the upper reaches of some rivers in the piedmont area below M-S Beskydy, such as Lučina, was recorded an incision of the channels.

In the mountainous Ostravice basin of M-S Beskydy the transport of suspended load is being monitored since 1976. In July 1997 were reached the highest concentration values of 36.02 $g \cdot l^{-1}$. The suspended load runoff reached 91,000 tons on that day, i.e. 39% of the total July value and 29% of the yearly value of 1997. Most suspended particles from the upper reaches of Ostravice are deposited in Šance Dam. The high concentrations of the suspended sediments evidence the large extent of soil erosion, as well as of the gully and path type of it, as they occurred after extreme rainfalls (Buzek 1998).

Based on estimates the discharge at Oder below the mouth of Olše was cca 1.4 thousand m^3 of water in July 1997 (= cca three quarters of the total of the yearly outflow). Out of that cca 54% goes to the very Oder and Opava basins and 46% (26% in Ostravice and 20% in Olše) to the rivers in the Carpathians. In terms of water column of the hydrograph at the beginning of July 1997 (days 6 to 12 of the month] the discharge of Ostravice basin was cca 257 mm (0.21 thousand million m^3], the respective data of the Olše basin being 149 mm (0.17 thousand million m^3). This quantification does not fully reflect the differences between the Carpathian and the Sudeten regions, the Odra basin being partly formed also by Carpathian rivers. It is still obvious that the flood outflow total from the Carpathians surpassed that of the Sudeten. This does not conform, however, to the size of the geomorphological work of the rivers of both areas. The Sudeten rivers seem to have carried out more work than those of the Carpathians. The most visible reasons of the fact may lie in the construction of water reservoirs and in the rather large extent of river channel adjustments that were made in the Carpathian streams.

MORAVA BASIN IN THE EASTERN SUDETEN

In Sudeten, in conditions of identical or similar lithology, the differences in geomorphological effectiveness of the flood, as observed in the Morava and Oder basins, were particularly due to the discharge magnitude and precipitation totals.

The discharges in the upper Morava basin corresponded to the changing magnitude of rainfalls. The sudden rise of their values reached its peak in the morning of July 7 (Raškov $Q_{max} = 335\ m^3 \cdot s^{-1}$, $Q_{100} = 146\ m^3 \cdot s^{-1}$), a secondary lower peak of hydrograph having been reached in the evening of July 7 as a reflection of a six hours lasting rainfall in the area of Praděd Mt (a total of 50 mm) and the flood wave in Morava tributaries (Krupá, Desná).

In upper Morava and its tributaries (above all Desná), in their flood peak flows, occurred bank undercutting, overbank flow, floodplain overflow, and, in some places, even channel wandering. In the Morava basin the bank erosion disturbed channels in a total length of 226 km, the volume of accumulations deposited in the channels being estimated at 280 thousand m^3.

In narrow reaches of upper courses the floodplain was completely eroded, e.g. in Morava valley near Hanušovice or in the valley of Branná. In some parts it was covered by coarse gravel deposits. Although the Sudeten part of the Morava basin has no feature of an active landslide region there were several cases of the latter, rather to a vast extent, at Hanušovice, closely related to the flood. The sizeable infiltration into soils and colluvial deposits has brought about, in places of undercut concave banks, mostly planar slides and debris flow. On the forest-covered mountain slopes, e.g. along the upper Desná river, there were features of so-called path erosion taking place in conditions of an overland flow.

In the wider valleys of Morava and its tributaries the geomorphological consequences of the flood have often been influenced by linear road and railway networks on the valley bottom. Near Raškov the mountain flood was at 335 $m^3 \cdot s^{-1}$ of discharge separated by the body of railway fill into two branches. A torrent flow from lateral valley near Komňátky was helpful in the formation of confluent scours, on the surface of the alluvial fan on the bottom of the main valley; the scours turned their courses in the direction of the flood progress. After the confluence both valley streams, near Bohdíkov, a floodplain erosion took place in a belt of some 30 m of width, with flood sediments becoming completely stripped away. The junction of the torrential tributary with the arm of flood flow of Morava resulted in a back water effect. Its role in confluence scours origin is probably important.

Confluence scours turned into stripped belt of floodplain with reduced thickness of fine grained slackwater sediments were cca 0.7 m. Below them, there were coarse river gravels of the valley bottom modified by the flood into a clearly imbricate structure. The geomorphological process which led to the full or partial removal of floodplain slackwater deposits was erosion/stripping by means of shear dragging of coarse bed loads (abrasion). This can be observed in the way of floodplain erosion going on in parallel deep grooves/scours separated by narrow longitudinal blocks and excavated by flood-

Photo 4. Stripping and erosion of the Morava floodplain below the junction of one arm of flood flow with a small torrent near Raškov. Scours separate margin of floodplain into the narrow blocks

dragged coarse gravel which filled them partly (Photo 4). The floodplain stripping and erosion was undoubtedly helped also by the pressure expansion of water in the hollows of rodent burrows. In the recession period of the flood the lowest places of the coarse gravel surface became covered by slack water transverse ripple marks of fine sand. Erosion of the floodplain has opened new space for sedimentation of fine grained slack water depopsits.

Geomorphic effectiveness in valleys of the Oder and Morava basins increased in general as the flood magnitude was rising.

MORAVA RIVER BASIN IN THE WESTERN CARPATHIANS

The principal Carpathian stream of the Morava basin and the first tributary of Morava from the Carpathians is Bečva. In its importance and its position it reminds of Oder river from which it is separated, in the central part of the Moravská brána (Moravian Gate), by the main European divide.

The upper reach of Bečva is formed by two branches, the Vsetínská Bečva and the Rožnovská Bečva. Both branches and the combined Bečva flow down from the Western Carpathian slopes to the Moravian Gate, the latter being a part of the Carpathian foredeep belt in Moravia. Rožnovská Bečva, situated in the close neighborhood of the rainfall centre near Lysá hora Mt, became the more flood-affected of the two. Both branches of Bečva combine at Valašské Meziříčí. The peak of the flood was reached here as early as July 7, with its $Q_{max} = 489\ m^3 \cdot s^{-1}$ ($Q_{100} = 405\ m^3 \cdot s^{-1}$). The renewed rainfall of July 8 has not surpassed the above Q_{max} any more. Vsetínská Bečva reached $302\ m^3 \cdot s^{-1}$ which is a rough equivalent of Q_{20}. In the direction of confluence of the two Bečva branches the discharge became balanced.

The upper parts of the basin, above all Vsetínská Bečva, were the worst affected by mass movements. The reason of this fact consists in the rather high presence of claystones within the lithological structure of the flysch and in the effect of interaction of water channels with saturated valley sides. In this way a large amount of suspended load got into the channels.

The combined Bečva flows westwards, generally transverse to the bedding of nappes of the sub-Silesian unit of the Paleogene flysch displaying an alternation of sandstone and claystone layers. The decreased resistance of the claystone led to the formation of a broad floodplain of Bečva reaching as much as 2 km here. Below Valašské Meziříčí this wide floodplain became overflowed by the flood. At present the Bečva channel is mostly straight and, here and there, it was even artificially realigned. The extent of the flood was influenced by railway and roads fills networks.

The main geomorphological change trigged by flood in the upper reach of the combined Bečva was a local channel widening as consequence of bank erosion. There was a complete stripping of slackwater floodplain deposits as well as of coarse fluvial sediments and a concurrent erosion of the upper part of the underlying strata of flysch layers. Channel widening and entrenchment

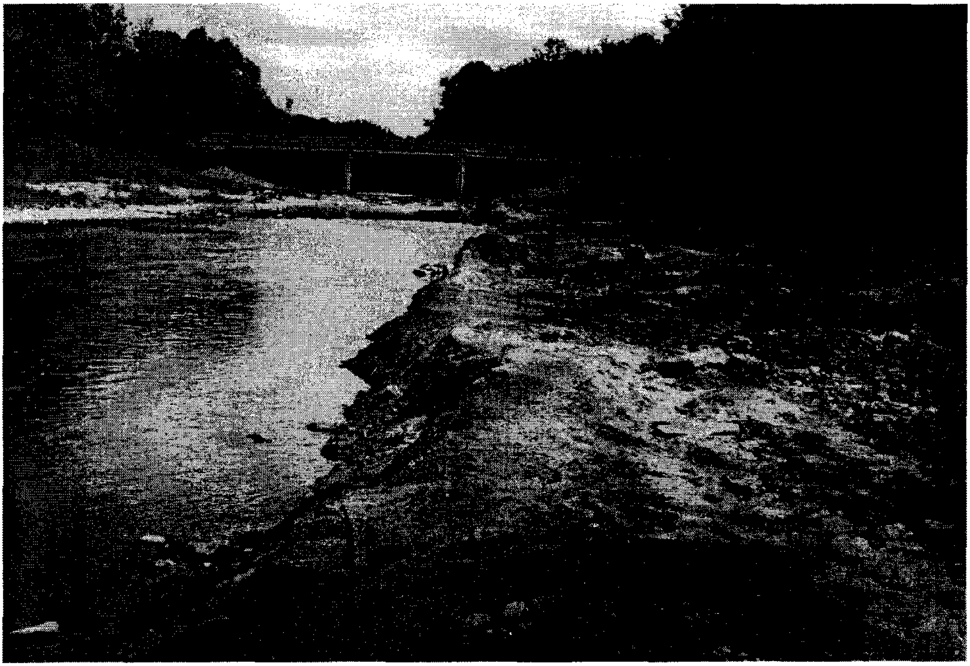

Photo 5. A simple two-stage channel of Bečva in a straight river reach at Choryně. Raised left lower bank is made up of flysch claystone equally as bed of upper channel. Depressions of the latter are discontinuously covered by coarse pebbles and cobbles. The upper part of the upper bank is made of fluvial gravel

led to the formation of a lower and upper channel in a cross-section that consist of two stages (Photo 5). The bed of the widened upper channel forms a berm with jutting outcrops of flysch sandstones. Bečva cuts oblique to the strata of the Frýdlant group of layers dipping steeply, with Strážov-type of sandstones emerging from soft claystones. At the contact between the active lower channel and the upper flood channel there are prominent harder sandstone obstacles. The flysch bedrock of the upper channel was covered by a non-continuous fresh accumulation of coarse gravel. The bank of the lower channel is low, reaching up to 1 m of height; it is higher in the upper one, cca 3 m. The width of the upper channel bed at Lhotka [together with active channel] is up to 53 m. This indicates the possibility of a local channel widening to nearly 40 m. In the September 1998 minor flood the lower channel became bankfull. The upper flood channel remained at Lhotka dry, downstream in other places (Choryně at bridge] was overflowed, too. The widening of a nearly straight channel in this reach of the combined Bečva is answerable to the power of flood discharge.

Before Bečva enters the Moravian Gate the flood discharges, in the narrow gorge at Teplice nad Bečvou, reached the value of 892 $m^3 \cdot s^{-1}$ (Q_{100} = 768 $m^3 \cdot s^{-1}$).

The Moravian Gate is a tectonic graben filled with Miocene sediments and plays the role of the Carpathian foredeep. It separates the uplands of Nízký Jeseník on the Bohemian Massif side from the block of Maleník on the side of the Western Carpathians. The River Bečva crosses it in a 30 km long reach and in southwestern direction, from Hranice to Přerov, where it empties into Morava. The tributaries from the dissected upland relief of Nízký Jeseník and Maleník bring, above all in case of floods, coarse gravel. Roads and railways fills and dikes of large ponds determined the extent of inundation in times of flood. The floodplain of Bečva has a width here of as much as 2 km, with features of meandering in the meander belt, and with ox-bow lakes on the sides.

During the flood the alluvial plain in Moravian Gate was partly reduced. Among the main geomorphic changes which appear to have occurred belong channel widening and maybe deepening as well in some reaches. The widening was mostly left-sided and was accompanied by the stripping of a part of the floodplain deposits in a belt of flood thalweg. The process of widening, which is responsible for the two-stage channel origin, started from undercut banks. The left-sided development of the two-stage channel differs from the above mentioned channel reach below Valašské Meziříčí. After the flood it was possible to distinguish the upper and the lower channel there. The widened upper channel is limited by the upper channel banks and could be bankfull only at times of extreme floods. The lower channel existed here before the flood and it is limited by the lower channel banks; it became filled at the lower bankfull.

In the middle section of the Moravian Gate (Familie-Hráz) the Bečva river channel has already features of the two-stage channel. The left part of the channel was considerably widened and is limited by the upper bank. The right bank was influenced by bank erosion during the flood, too, partly interfered by destructive activity of widespread tree collapse. Along the left upper bank was preserved a dry and shallow depression of the upper channel. Between the bed of the upper channel and the present active lower channel a mid-channel bar of gravel and sand has been preserved, confirmed in conditions of minor flood lower bankfull (in autumn 1998). The width of active channel on the right site of the studied cross-section is 38 m, the gravel bar between the lower and the upper channel being 13.5 m wide. The upper channel width developed in coarse gravels reaches 43.5 m. The left upper bank of floodplain silts in this part is 2 m high.

Unlike the situation near Valašské Meziříčí the underlying strata of flood-plain deposits stayed untouched by channel widening. We have not known original channel width before the flood but we suppose it was approximately half, i.e. cca 45 m.

In the southeastern part of the Moravian Gate, in the reach from Lipník nad Bečvou to Přerov, can still be seen rests of ox-bow lakes in the intensively land-used

Photo 6. A composite two-stage channel of a lower meandering reach of Bečva at Osek nad Bečvou. In the foreground there are lower channel bedforms consisting of an abandoned channel with fossil logs, a lower mid-channel bar and a new active channel bounded by the left lower bank of cross-bedded gravels. In the background there is the upper channel with a mid bar separated by a dry channel from left the upper bank

lowland riverside country. At Osek nad Bečvou the right bank of the channel underwent an artificial adjustment. On the left side the channel became widened during the flood and the undercut bank is present in a length of up 1.5 km. The width of the new channel is as much as 150 m. The original active channel was left, and covered by slackwater deposits. A new active channel was formed in the middle of the present widened one. Between the original active channel, and the present active one, limited by the left lower bank, there are rather low, slightly convex lower mid-channel bars of coarse channel gravels under which are laid clays with abundant organic rests and with buried fossil tree logs. This kind of organic matter obviously filled the original ox-bow lakes of the meander belt.

Near Osek the widening formed a composite two-stage channel (Photo 6) consisting of the lower active and inactive channels and the upper widened channel limited by the upper bank. The left lower bank of the active channel uncovers cross-bedded channel gravels. The raised surface of the upper channel gravels forms a mid-channel bar at the edge between the lower active channel and the shallow depression of the upper channel. The widened upper channel is limited on the left side by the bank of the upper channel. It consists of slackwater flood silts.

In the lower reach of Bečva in the Moravian Gate in relationship to the flood of July 1997 is preserved another characteristic bedform. It is scour-associated with the confluence of Uhřínovský potok Brook and Bečva near Rybáře. Similarly as scours mentioned here at confluence of nameless tributary with Morava an important role in its origin is played back water effect together with the ability (strength) of the tributary flow to entrain quantities of bedload. The flood thalweg of the mentioned brook was due to back water effect, pushed by the stream of Bečva to the side, and ran parallel with the thalweg of Bečva. The 2 m deep and the first tens of meter long scour has been entrenched in the floodplain below the point of confluence. An other example of scours is the presence of a crevasse splay at Osek nad Bečvou.

The widening of the meandering channel in the lower reach of Bečva formed local conditions for a composite channel origin with channel bars in two stages. An important role in the undercuting of upper banks of the channel is played by strength of flood flow in the thalweg accompanied bank inflow, and the vortex of plunging water from floodplain together with crevasse splay origin during flood recession.

THE MIDDLE AND LOWER MORAVA VALLEY

Near Přerov the River Bečva leaves the Moravian Gate and empties into the Morava in the Upper Morava Graben. Morava constitutes the axis of both Moravian grabens, the Upper one and, more to the south, the Dolnomoravský úval (Lower Morava Graben). Starting from Přerov in central Moravia there is often the kind of situation in which the peak flood wave of Bečva precede the upper Morava flood wave by two or three days (Soukalová et al. 1997). In July 1997, however, on Bečva arose a flood wave not only of a high peak discharge but also of a large magnitude with its slower recession. This permanently high discharge of Bečva coincided with the peak discharge of upper Morava. Below the Bečva and Morava confluence in central Moravia there were large overflows after their flood waves combined. In Kromeríž, where still on July 5 the Q_d equalled 35.5 $m^3 \cdot s^{-1}$, there was Morava peak on July 10 of $Q_{max} = 1000\ m^3 \cdot s^{-1}$ ($Q_{100} = 725\ m^3 \cdot s^{-1}$).

Due to vast overflow the flood wave below Kroměříž featured a kind of time course that was difficult to foresee. The width of overflow belt was up to 10 km and its depth was up to 3 m. The flooding of vast alluvial areas brought about a transformation of the flood wave and a sizeable delay in the time course of its peak (between Spytihněv and Strážnice the delay reached 69 hours). Along the broad floodplain of Morava there are networks of railway and road embankments, that, together with protective dams, retained and raised the water of flood. In a number of places these protective dikes and embankments yielded to burst and to additional uncontrollable overflow.

Erosion, namely of flysch claystones in the course of the channel widening as well as of intensive slope processes, in Western Carpathians caused the transport of quantities of suspended load. The total runoff of them in July 1997 at Strážnice in the lower Morava represented 328,238 tons, which is a 26th multiple of the average monthly runoff of suspended load in the last ten years.

CONCLUSION

The flood of the beginning of July 1997 became the first-rate natural disaster in the Czech Republic of the 20th century thanks to extreme rainfalls which, in their six-day duration, reached a magnitude not arrived at so far, in the mountainous areas of Eastern Sudeten and Western Carpathians, and which influenced the infiltration, the storm runoff, and the geomorphic changes in channels, floodplains, and valley sides.

A comparison of the individual components of the storm runoff made it possible to find differences in the magnitude of the flood event in the individual basins. Flood hydrographs both Oder and Morava basins show steep rising limb, to start with, show two stages of the event. In the Morava basin can rather be felt rise of discharges after the Morava confluence with Bečva (Kroměříž), and delay in peak flood flow due to its transformation by overflow in the lowland alluvial plain (Strážnice). While there was a continuous increase of the flood flow in the course of the rainfall in Oder basin, in that of Morava there was a successive transformation and decline. The flood arose as a mountain flood with all attributes of storm runoff. The hundred-year discharge in both mountainous basins has been surpassed.

The scope of geomorphic effects of the flood amplified generally downstream as the discharge increased, and in dependence on lithology and on the degree of anthropogenic adjustments in floodplains and river channels. This fact has made it possible to compare the magnitude of fluvial geomorphic processes on the basis of found changes both in Oder and Morava basins, as well as in their Carpathian and Sudeten parts.

Both mountainous regions of Sudeten and Carpathians appear to have experienced large geomorphological changes. It is more difficult, however, to compare the quantity of changes than their quality. From this point of view both regions have expressed their typical changes. The unmistakably strongest geomorphological effects were those suffered both by the Sudeten part of the Oder basin, followed by the Sudeten part of the Morava basin, and the Carpathian part of the same basin. The least changes have been recorded in the Carpathian part of the Oder basin.

To the most typical geomorphological changes both in the Sudeten and the Carpathian region belongs channel widening. This widespread phenomenon expresses, nevertheless, in both these regions its special feature. In Sudeten it has implication for downstream increasing discharge in straight channels. The extent of floodplain was reduced by bank erosion. A special example of floodplain erosion and stripping comes also below confluences with tributaries, that has a general feature both in the Sudeten and in the Carpathians. Widening of channels (up to five times) of coarse bedload streams free of fine grained slackwater deposits became convenient for river braiding as found in Opavice. A quite specific question of the Sudeten is the channel blockage by log jams and wood debris having influence on river wandering and anabranching.

In Carpathians the channel widening (twice up to three times) was accompanied by contemporary incision and rise of two-stage channels. There are two examples of widened and deepened channels. The first, with simple two-stage channels as in the upper reach of Bečva, and the second, with composite two-stage channel featuring the lower reach of Bečva. It depends from whether the stream is straight or meandering. The straight streams gave rise to the simple type of two-stage channels where the crucial role in it development was played by strength of the flood flow. In the transition to lowlands in flooded meandering Bečva created a widened two-stage composite channel also partly due, besides the power of the flood discharge and the lateral inflow, to vortices driven by water from floodplain plunges into the channel. It is evidenced also by contemporary formation of crevasse splay. Aggradational bedforms as channel bars are developed in the lower and upper stages.

The cause of channel incision could be found in the lithological composition of flysch and the higher slope gradient of channels. There is also a questionable problem whether the channel incision in the Carpathians is comparable with the lifting of stable bed pebble-cobble pavement of some Sudeten rivers.

Large volume of transported bedload in Sudeten resulted also in an erosion and stripping of floodplain by abrasion bearing features of shear stress and drag force, with marks of dragging of coarse gravels during the overbank flow. A typical Carpathian feature here was the transport of suspended loads indicating a strong erosion and slope processes.

The reasons of the differing geomorphic activity of flood making itself felt in the Sudeten by simple channel widening, by lifting of gravel beds and massive transport of bedload and, in the Carpathians, either by deepening and widening of channels or by their widening only, by the rise of simple or composite two-stage channels, and by transport of suspended load, are to be looked for, in our view, first of all in the well known differences between the Sudeten and Carpathian lithologies and in the more than twice as high a channel slope in the Carpathian mountains. Other factors of geomorphological effectiveness such as the channel profile and its roughness which exert influence on the speed of flow in the given profile have not been explored so far.

The major regulatory interventions in the bed performed and the construction of valley dams in the Carpathian part of the Oder basin have slowed down and weakened the geomorphic effects of the flood.

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REFERENCES

Aichler J., Pecina V., 1998. *Documentation of landslides connected with the flood in 1997 in the Jeseníky area (in Czech).* Geologické výzkumy na Moravě a ve Slezku v roce 1997. Masarykova universita 5, Brno, 94–96.

Blažek V. D. (ed.), 1998. *Předběžné hydrologické vyhodnocení povodní v červenci 1997.* Vodní hospodářství 6/98, 128–134.

Buzek L., 1998. *Plaveninový režim v povodí horní Ostravice nad vodárenskou nádrží Šance v letech 1996 a 1997.* Universitas Ostraviensis, Acta Fac. Rer. Naturalium, Geographia-Geologia 168, 8, 7–17.

Hrádek M., Kolejka J., Švehlík R., 1997. *Czechia and Slovakia,* [in:] *Geomorphological Hazard,* (eds) Embleton C. and C. Elsevier, Amsterdam-Tokyo, 61–90.

Kakos V., 1997. *Hydrometeorologická analýza historické povodně v roce 1897 ve vztahu ke katastrofálním záplavám v Čechách na začátku září 1890 a na Moravě v červenci 1997.* Meteorologické zprávy 50, 6, 191–196.

Kirchner K., Krejčí O., 1998. *Slope movements in the flysch Carpathians of eastern Moravia (Vsetín district) triggered by extreme rainfalls in 1997.* Moravian Geographical Reports 6, 1, 43–52.

Květoň V., Srněnský R., Veselý R. 1997. *Rozložení srážek při povodních v červenci 1997.* Meteorologické zprávy 50, 6, 172–177.

Maníček J., 1998. *Povodeň 1997.* Povodí Odry, a.s. Ostrava, 32 pp.

Pavlík J., Sandev M., 1997. *Synoptické hodnocení povětrnostních situací v průběhu povodně 1997.* Meteorologické zprávy 50, 6, 164–171.

Soukalová E., Řehánek T., Šiftař Z., 1997. *Odtoková situace za povodně v červenci 1997 v povodích Odry, Moravy a Labe.* Meteorologické zprávy 50, 6, 183–190.

Kališ J., 1963-1968. *Závěrečné zprávy výzkumu splaveninových režimů říčních tratí.* VVÚ VHS Brno.

Vít J., Aichler J., Pecina V., 1998. *July flood in the Jeseniky-reason, course and after-effects (in Czech).* Geologické výzkumy na Moravě a ve Slezku v roce 1997. Masarykova universita 5, Brno, 118–121.

STRESZCZENIE

M. Hrádek

GEOMORFOLOGICZNE ASPEKTY POWODZI W LIPCU 1997 W DORZECZU MORAWY I ODRY NA TERYTORIUM MORAW, W REPUBLICE CZESKIEJ

Katastrofalna powódź na Morawach w lipcu 1997 była spowodowana długotrwałymi i wyjątkowo wydajnymi opadami, nie notowanymi w XX wieku na terenie Czech. W dniach od 5 do 9 lipca zginęło 50 osób, a zniszczenia spowodowane powodzią wyceniono na 60 miliardów czeskich koron. W tym samym miesiącu wystąpiła ponownie powódź w dniach od 17 do 21.

Na terenie Karpat Zachodnich i Sudetów Wschodnich rzeki objęte powodzią transportowały wielkie ilości materiału w postaci zawiesiny i ładunku dennego, a na stokach wystąpiła erozja i ruchy masowe. Rozległe dna dolinne i kotliny zostały zalane. Najpowszechniejsze zmiany geomorfologiczne na terenie Sudetów polegały na poszerzaniu koryt rzecznych nawet pięciokrotnie, a w niektórych miejscach powstały blokady koryt zbudowane z transportowanego gruzu drzewnego i mineralnego, w którym brały udział całe drzewa powalone do koryta wskutek erozji bocznej. Powodowało to zmiany biegu koryt i formowanie koryt rozgałęziających się (ang. anabranching channel). Natomiast w Karpatach koryta były poszerzane 2–3 krotnie oraz rozcinane. Powstały dwustopniowe profile poprzeczne koryt. Różnice w sposobie przekształcania koryt w Karpatach i Sudetach są związane ze zróżnicowaną budową geologiczną i rzeźbą tych obszarów.