Fig. 7. Eversion hole in the cutting of the unpaved road

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The Czarny Dunajec River, Poland, as an example of human-induced development tendencies in a mountain river channel

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Abstract: The Czarny Dunajec is a typical river originating in high mountains (the Western Tatras). Over the entire Quaternary era the river laboured carrying material away from the Tatras and depositing it in the form of a typical braided channel at their foot. At the end of the 19th century, river management projects and quarrying operations located directly in the very channel set off a rejuvenation process that was further accelerated at the end of 1960s. The activities resulted in the damaged several sections in their natural form and considerably deepened the channel. Measures taken to restrict the amount of material entering the Czorsztyn Dam have largely failed. From the geomorphologic and environmental points of view a continued transformation of the Czarny Dunajec river channel should be regarded as highly adverse.

Key words: mountain river channels, fluvial processes, human pressure, Western Carpathian Mts.

Introduction

The contemporary diversification of river channels is a result of long-term processes covering the entire catchment basins. As active channel sections indicate the current stage of a river channel evolution, a description of the entire river channel system helps understand the principles of how it works (Choeley, Kennedy, 1971). Information on the entire channel systems is mainly supplied by field research, supplemented by maps and aerial photographs (Mosley, 1987; Thorne, 1998; Kamykowska *et al.*, 1999). However, as most of the research has focused only on selected river sections, little is known about river channel systems at the scale of entire mountain ranges or even larger catchment areas.

Similarly, treated as a whole, the upper Vistula-catchment system is unquestionably under-researched. Meanwhile, as several Carpathian rivers are subject to management schemes and their channels dug for building aggregates, their systems have not been properly investigated. The research carried out so far shows that alterations made to one river section can lead to changes, which are difficult to predict in others (Osuch, 1968; Klimek, 1983). In order to determine their current status and to try to predict the development tendencies (Wasson *et al.*, 1993; Chełmicki and Krzemień, 1999), therefore, it is very important to evaluate the entire systems. Channel structures should be evaluated first and only then can changes be made. The Czarny Dunajec river is a very worthy object of such an investigation, as its river channel has been subject to intensive human-induced transformation involving river management and aggregate extraction, especially after the Second World War. These activities are still being carried out despite the official declarations of the relevant authorities that no further river management work is planned and the extraction of the material from the river being legally prohibited.

The research project conducted in the Czarny Dunajec catchment basin was aimed at understanding the structure of the channel system and demonstrating the natural and human-induced causes of its transformation.

Research area

The Czarny Dunajec catchment area covers c. 473 km^2. Geomorphologically, it is located in three topographic units, the Tatra Mts., the Podhale region and the Western Beskidy Mts. Its complex geology includes metamorphic rocks, graintoid, quarzite, limestone, sandstone and *flysch* shale (Fig. 1). The catchment area is located in five regions, i.e. the Western Tatras, Rów Podtatrzański (trench), Pasmo Gubałowskie (ridge), Kotlina Orawsko-Nowotarska (mid-mountain basin) and the Działy Orawskie (Klimaszewski, 1972, Fig.1).

The river is the resultant of three converging streams: Chochołowski, Kościeliski and Lejowy. Both in terms of the geomorphology and hydrology (Krzemień, 1991) the Chochołowska valley is its source valley. This paper pays particular attention to the channel pattern at the foot of the Tatras. The structure of the Chochołowski stream has also been described elsewhere (Kaszowski and Krzemień, 1979; Krzemień, 1981; 1991; Rączkowska, 1983).

The Czarny Dunajec river channel is 30 to 50 m wide with stretches of up to 200 m wide, and its flood plain is 100–500 m wide. The flood plain, rises 1–3 m above the river bed, is transected by multiple abandoned channel-systems and is mostly overgrown with bushes and trees. The channel rubble varies as to the type of rocks and the mechanical composition (Borowski and Kociszewska-Musiał, 1959; Nawara, 1960). It consists mainly of granite and quartzite clasts, up to 20 cm in diameter. The proportion of granite increases from the source down to the village of Chochołów, and then falls towards Nowy Targ. The converse is true of quartzite. The largest-size material comprises granite and quartzite varying from 40 cm maximum in the upper course, 30 cm in the middle course to 20 cm in the lower course of the river. The maximum high water on the Czarny Dunajec is normally associated with continuous summer intensive rains falling between June and August. A maximum discharge of 870 m^3/s was recorded in 1934, and a minimum of 0.85 m^3/s in 1964. The natural structure of the river channel, developed over a long period of time, was that of a typical braided channel running across gravel. At the end of the 19th century it began to shrink in width and deepen at the same time (Krzemień, 1981), the process intensifying, particularly in the 1970s.

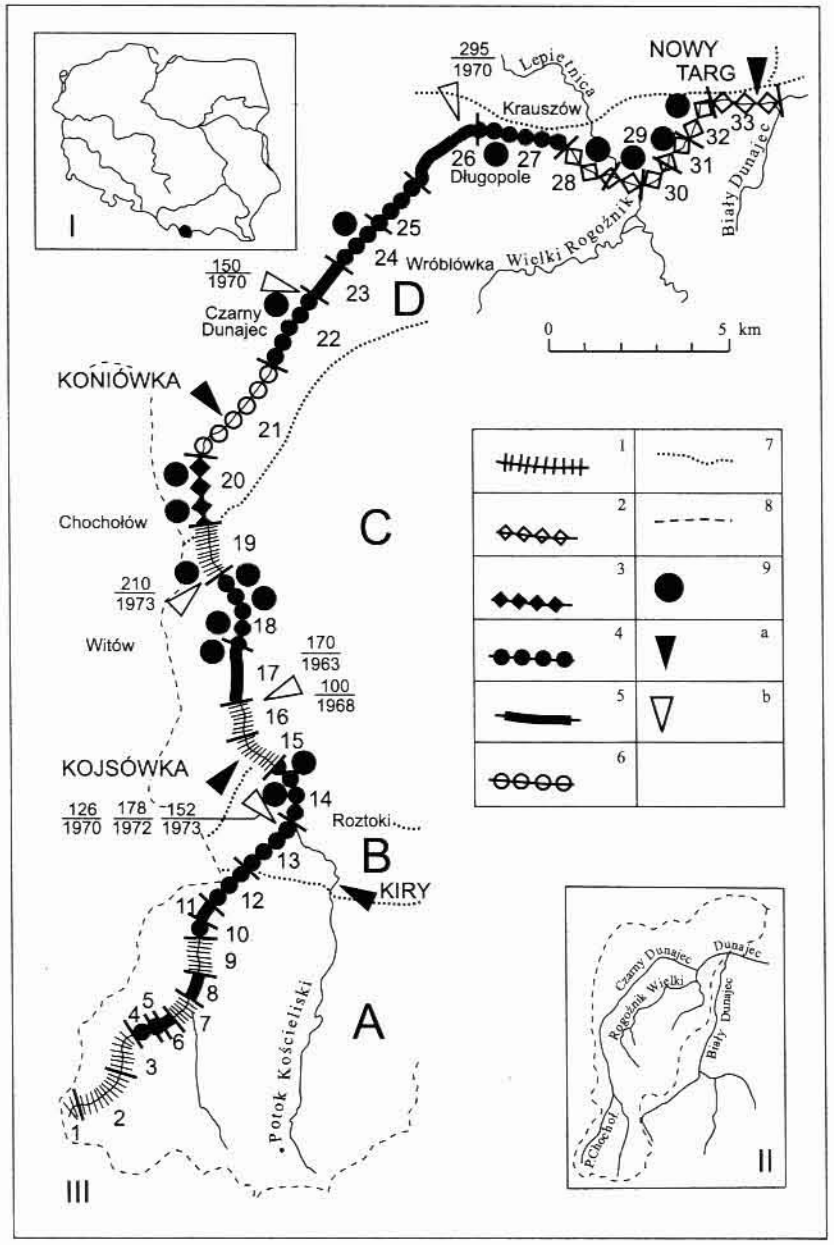

Fig. 1. I – The Research Area, II – Czarny Dunajec Catchment, III – Types of morphodynamic reaches in 1977

1 – erosion reaches modelled primarily by downcutting, 2 – erosion reaches modelled by lateral erosion and downcutting, 3 – erosion/re-deposition reaches, 4 – re-deposition reaches modelled by re-deposition and lateral erosion, 5 – transportation reaches, and 6 – deposition reaches; 7 – regional boundaries, 8 – a watershed, 9 – major rubble extraction points; a – watermarks, b – highwater marks on bridges: date and height above the bed in cm; A – the Tatras, B – Rów Podtatrzański, C – Pogórze Gubałowskie (foothills), D – Kotlina Orawsko-Nowotarska (mid-mountain basin)

Research methods

Field research in the area started in 1975. Investigation into the structure of the channel employed a special register form and an instructions manual developed in the Geomorphology Department of the Institute of Geography and Spatial Economy, Jagiellonian University (Kamykowska *et al.*, 1999). So far, the entire Czarny Dunajec river channel system has been mapped twice (1977 and 1999) and a detailed investigation was carried out into the fluvial dynamics in the upper course of the river (Krzemień, 1981 and 1991). Additionally, 19th- and 20th-century maps and aerial photos were used to analyse the channel system development trends.

The fundamental channel reaches were defined on the basis of the channel pattern and the features and marked on a map and aerial photos. They were then described in a standardised way involving the quantitative and qualitative characteristics of the channel, its features, the rubble and the degree to which the channel was managed. Also, the flood plain was described and analysed.

In total, 13 reaches of the Potok Chochołowski (11.8 km) and 20 of the Czarny Dunajec (37.6 km) were mapped and characterised.

Morphologically active channel types

In 1977, a typology of the channel reaches was developed on the basis of the collected data describing the channel, its ground features and the fluvial rubble, and the use of calculated indices (Fig.1). The analysis of the Czarny Dunajec channel system was based on features providing direct or indirect information on the dynamics of the channel, i.e. those processes, which form and transform the channel. Thus, river channel processes were selected as the basic criterion for the definition of separate channel reach types. The analysis took into account the following:

1) geology (bedrock, bedrock-and-rubble and alluvial reaches);

2) horizontal channel pattern;

3) channel bed mobility;

4) bar index in m^2 per 1 km;

5) largest material size in the channel rubble;

6) channel wildness index, i.e. medial bars and islands per 1 km;

7) channel shape index, i.e. mean width/mean depth;

8) width of the floodplain;

9) river-management index, i.e. number of facilities per 1 km.

Next, the following reaches were defined on a map:

- transecting coarse moraine material; fluvio-glacial, bedrock or alluvial covers; cutting all the way to the bedrock, thus indicating a tendency to downcutting;
- braiding, indicating a tendency to deposition, re-deposition and lateral erosion;
- with the largest index of undercut bank area indicating a tendency to lateral erosion;
- other (all not defined according to the applied criteria) grouped as transporting reaches.

Generally speaking, major morphological processes were identified by looking at particular sets of features, i.e.:

- **downcutting** was identified by the existence of bedrock channels and alluvial channels with rocky outcrops in the river bed;
- **lateral erosion** was identified by the high values of the bank undercut ratio and by lateral migration of the channels;
- **deposition** was identified by high thickness of alluvial formations and high alluvial surface ratio values;
- **redeposition** was identified based on high values of the alluvial surface ratio and the 'wild' ratio, as well as based on 'wandering bars' moving over regulation structures or into vegetated areas;
- **transportation** (transportation reaches) was identified when there was no clear dominance of one ratio over the others or when the values of the alluvial surface and bank undercutting ratios were very low. The transportation reaches, in general, could by otherwise referred to as transit reaches because the movement of the rubble does not cause any major changes of the channel morphology. Such reaches can be very stable for years.

In 1977, this material served as the basis for defining 6 dynamic channel types (Fig.1): 1) erosion reaches produced primarily by downcutting, 2) erosion reaches driven by lateral erosion and downcutting, 3) erosion/re-deposition reaches, 4) re-deposition reaches produced by re-deposition and lateral erosion, 5) transportation reaches, and 6) deposition reaches.

The Czarny Dunajec/Potok Chochołowski is a complex type of channel system (Fig. 1). As far as Reach 10, the Potok Chochołowski channel is shaped mainly by weak downcutting, which is typical of a stable channel system in valleys that were not glaciated other than during the Pleistocene era (Krzemień, 1991). The only exception to this is the braided reach running through the Polana Chochołowska (clearing), dominated by relatively small-scale re-deposition and lateral erosion (Fig. 1). Such reaches are normally found in glacial valleys above recessional moraines or glacial thresholds (Krzemień, 1999). Below the junction of the Chochołowski and Kościeliski streams, the downcutting-driven reaches were located in the top section of the Czarny Dunajec (Reaches 14–16 and 19). Reach 20 was modelled by re-deposition. Downstream, the channel was modelled mainly by lateral erosion and downcutting (Reaches 28–33). Deposition has taken place above rubble-barriers in Reach 21. Other reaches were dominated by re-deposition, lateral erosion and deposition, as well as by transportation. These two morphologically-active reach types alternated with each other. Transport dominated in regulated channel reaches with bankside management facilities, but a weak tendency to the channel returning to its wild form was found for example in Reaches 23 and 26. In 1970, the Czarny Dunajec channel underwent management work along its entire length. The plan pattern was altered by efforts to straighten the channel, with bankside and cross-current facilities lateral regulation facilities erected. The lateral facilities comprised six systems of concrete thresholds up to 2.5 m high (Reaches 21 and 23), while the bankside facilities included bands of broken rock up to 300 m long, netting and faggoting, as well as a system of revetments to strengthen the river banks. They were located either individually or in sets alternately along the right and left bank.

The Czarny Dunajec river channel was also intensely used as a source of natural stone aggregate (Fig. 1). This began after WW2 and was enlarged in the 1970s, just as in other Carpathian river channels (Augustowski, 1968; Osuch, 1968; Klimek, 1983 and 1987; Wyżga, 1991). The extraction operations were either large-scale businesses using machinery or small-scale scattered ventures. They involved the extraction of smaller rock and boulder material from the bar surfaces or all material found in the channel. The exploitation gradually removed the channel armouring and increased its channel depth. Reaches located above such areas were subject to increased retro-erosion in the channel bed.

In 1999, the channel was mapped again in the same reaches as defined in 1977 and only Reach 21 was reclassified so as to define a separate Reach 21a. This material formed the basis for a typological procedure similar to that from 1977. As a result, seven reach types were defined (Fig. 2): 1) erosion reaches produced mainly by downcutting, 2) erosion reaches produced by lateral erosion and downcutting, 3) erosion/re-deposition reaches 4) re-deposition reaches driven by re-deposition and lateral erosion, 5) transportation reaches, 6) deposition reaches, and 7) re-deposition/deposition reaches produced mainly by re-deposition.

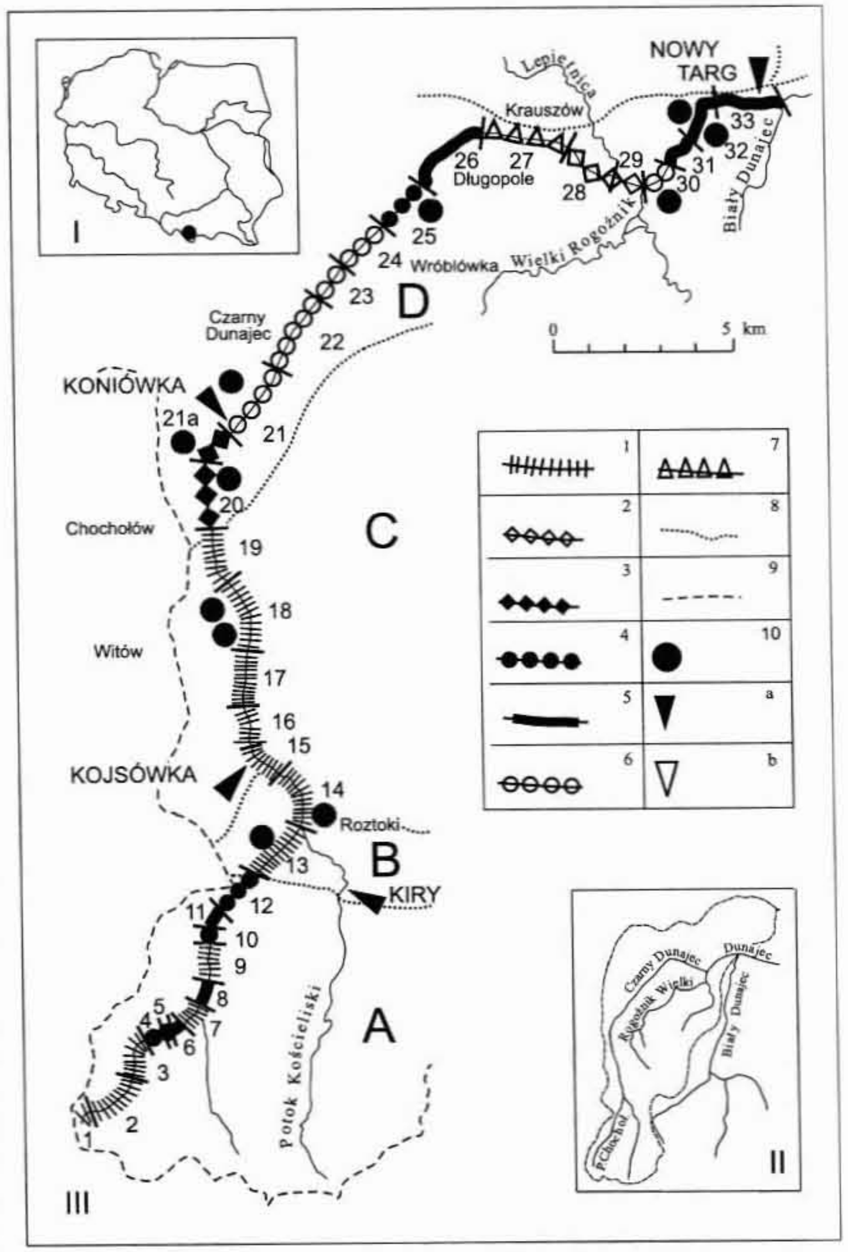

Fig. 2. I – The Research Area, II – Czarny Dunajec Catchment, III – Types of morphodynamic reaches in 1999

1 – erosion reaches modelled mainly by downcutting, 2 – erosion reaches modelled by lateral erosion and downcutting, 3 – erosion/re-deposition reaches, 4 – re-deposition reaches modelled by re-deposition and lateral erosion, 5 – transportation reaches, 6 – deposition reaches, and 7 – re-deposition/deposition reaches modelled mainly by re-deposition; 8 – regional boundaries, 9 – a watershed, 10 – major rubble extraction points; a – watermarks, b – highwater marks on bridges: date and height above the bed in cm; A – the Tatras, B – Rów Podtatrzański, C – Pogórze Gubałowskie (foothills), D – Kotlina Orawsko-Nowotarska (mid-mountain basin)

After 22 years, the structure of the Potok Chochołowski channel had not changed in any visible way within the Tatras. Only at the foot of the mountains, had downcutting increased significantly in Reach 13, which is located on an alluvial fan where the channel had downcut all the way to the *flysch* bedrock (Fig. 2). However, downstream from here, the Czarny Dunajec channel had undergone a dramatic change. The bedrock-reaches increased in length by almost 80%; the downcutting-driven reaches now start right from the foot of the Tatras in Reach 13 and continue all the way to the end of Reach 19 near Chochołów. This was at the expense of the braided reaches, the length of which was considerably reduced. The river training structures destroyed the typical braided Reach 24, despite the declarations of the authorities responsible for river channel management that the Czarny Dunajec channel would not be subject to further regulation. Only in Reaches 21a and 25 did the braided channels develop in any significant way; the number and area of bars, and undercuts increased (Figs. 4 and 5). Compared with 1977, the length of regulated reaches, i.e. narrower and either with strengthened embankments (longitudinal regulation) or with concrete steps (lateral regulation) increased. The recent additions to the lateral regulation features are somewhat different: instead of the concrete steps (up to 2.5 m high) built in the past, wedge-shaped steps following the channel cross-section were built flush with the channel bed, or low steps protruding just 20–30 cm from the bed. This method is less expensive, more effective in stabilising the plan pattern of the channel and less destructive to the original channel. Those reaches, which had been regulated before have shown clear signs of accumulation between the thresholds. In the lower course of the river, above the town of Nowy Targ, the banks are more stable and transportation has taken over as the dominant process.

The channel is still used as a source of aggregate, although to a lesser extent than in the 1970s, as evidenced by less material in the channel bed and by fewer extraction pits. Legally prohibited, such operations are still very much a reality even along the regulated reaches. They have an extremely adverse effect when the bank stabilisation and the huge spending on the regulation of the river are taken into account. Judging by the size of the operations, it certainly seems that opposition from the controlling authorities is largely ineffective. Houses are still being built on foundations of this material that is also stored in heaps waiting for the next house to be built. The rubble is normally dug in two stages; the excavated material is first stored near the channel and then taken to the building lots. The scale of the problem is shown in the larger number of houses completed and under construction.

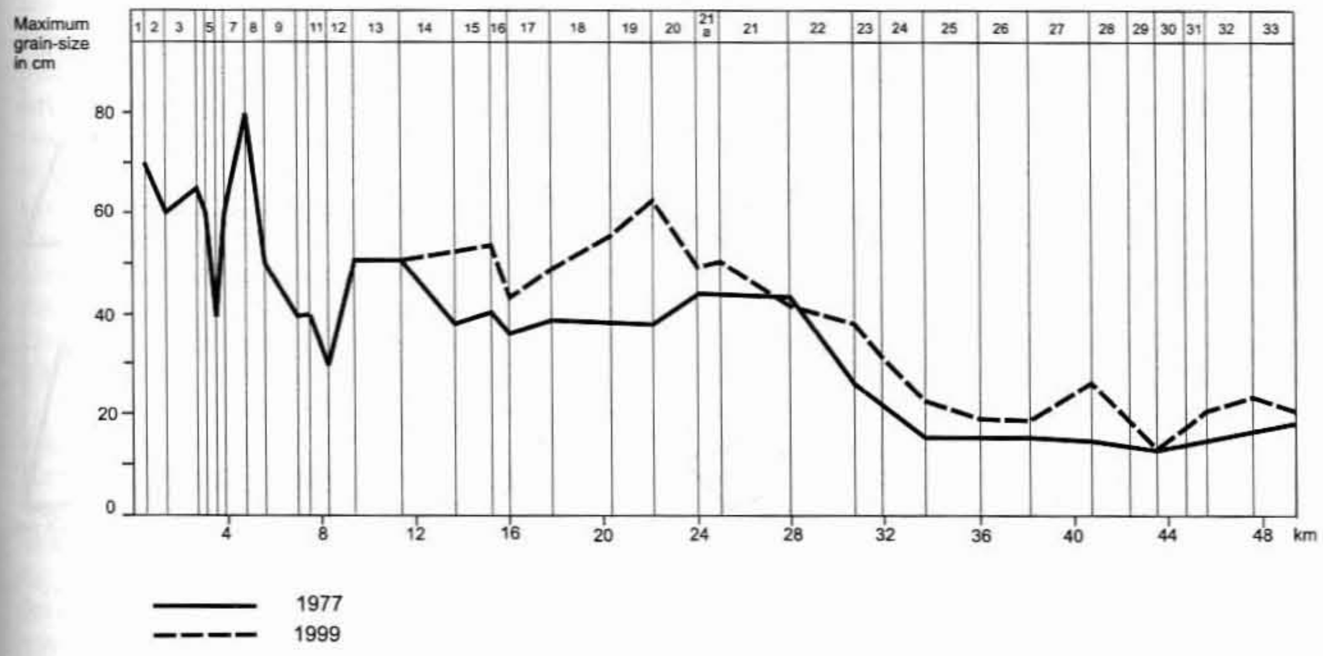

Fig. 3. The maximum size of material (in cm) in the Czarny Dunajec river channel system in 1977 and 1999

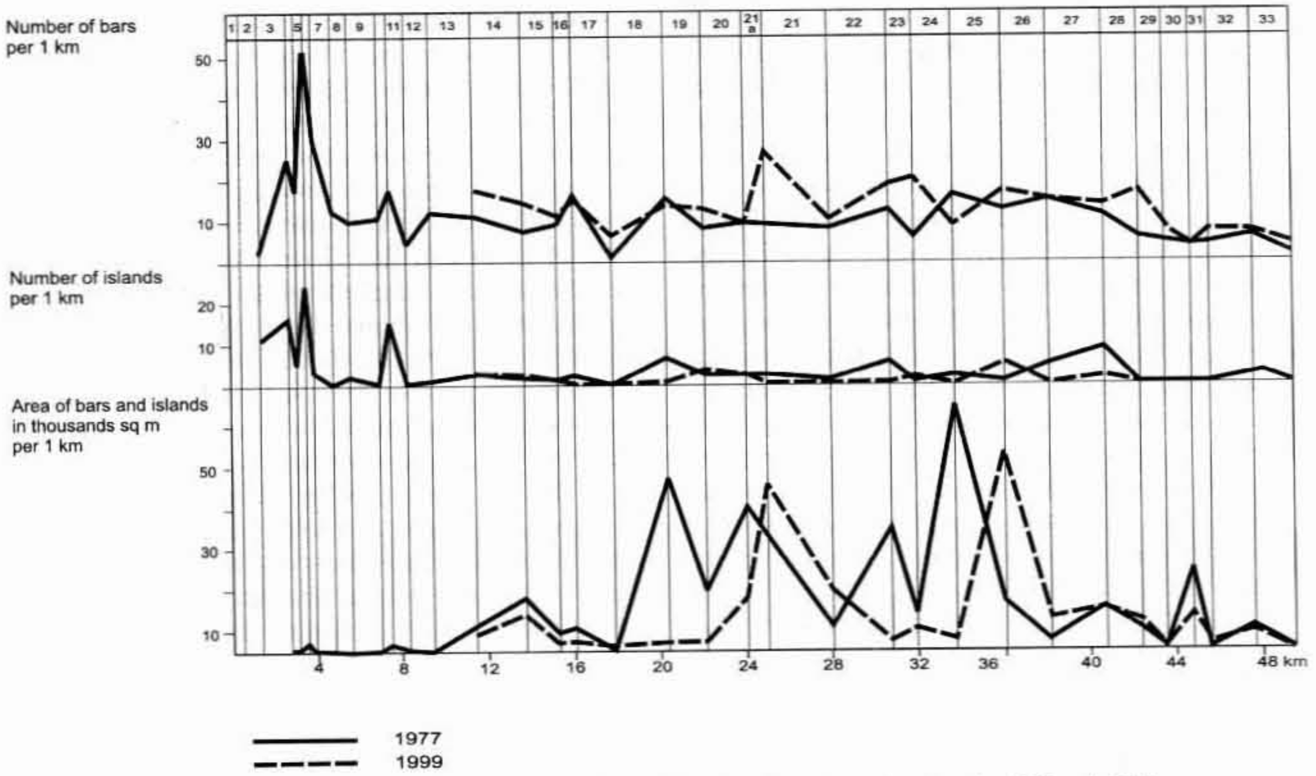

Fig. 4. The number and area of bars and islands in the Czarny Dunajec river channel system in 1977 and 1999

The differences between the channel in 1977 and in 1999 are better shown in Figs. 3 through 5. In the long profile of the river, the maximum size of the material has increased (Fig. 3), the only exception being the regulated Reaches 21 and 29 where this trend was not obvious. The larger maximum size of material down the river indicates primarily the river's increased energy, but also reflects the straightening of the channel, dissection of the underlying material and uncovering of larger boulders. Such boulders occur as individual pieces of rounded rock scattered throughout the river and in the bedrock-reaches are rarely taken out partly because they are difficult to access.

In the long profile of the river there are more small bars, particularly in previously regulated reaches (Fig. 4.). The deepening of the channel has also resulted in the reduced number of islands and the square area of the numerous small bars.

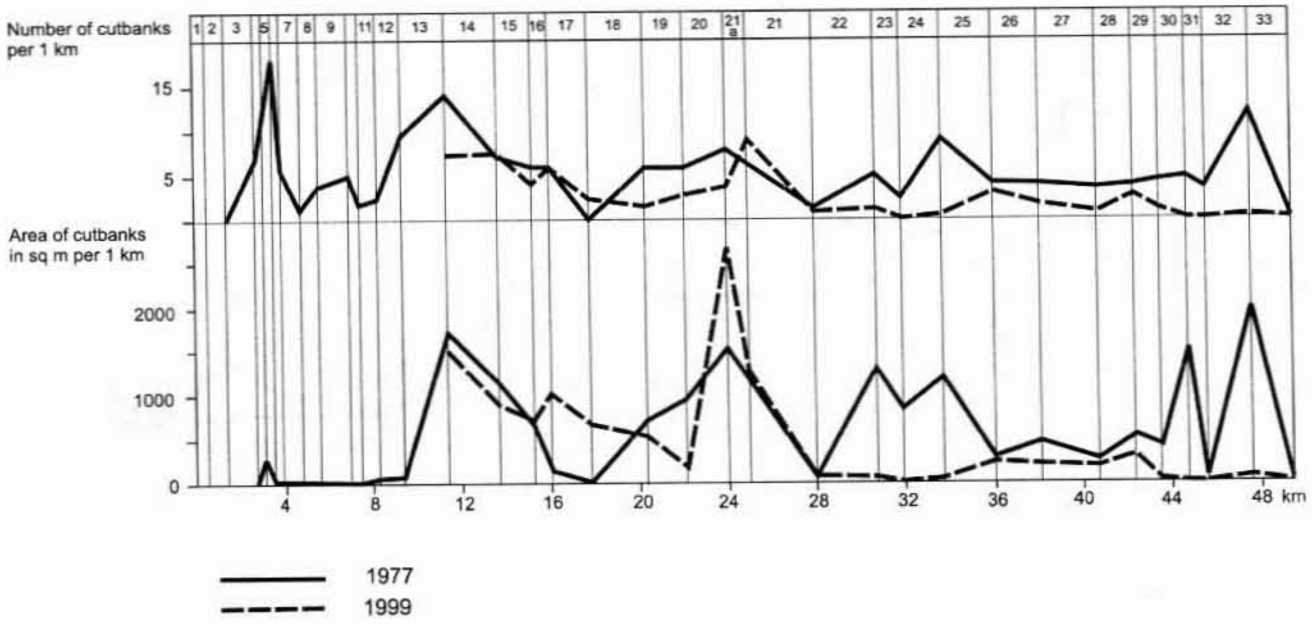

Fig. 5. The number and area of undercut banks in the Czarny Dunajec river channel system in 1977 and 1999

These features would suggest that the regulation methods formerly used have failed to reduce the amounts of bedload material, that the concrete thresholds are subject to intensive abrasion and destruction, and that the channel may have a tendency to return to the wild original form between the thresholds. Indeed, the regulated reaches slowly tend to revert to the old, natural modelling tendencies. Only in the braided reaches does the area of islands and bars increase, indicating that the remains of the braided channels have been shaped by natural processes (Fig. 4).

Another difference is the reduced number of undercut banks (except Reaches 14, 16, 20, 21a and 21), particularly in regulated reaches. The channel banks are generally better stabilised, whether in regulated reaches or not (Fig. 5). This would suggest a huge drop in the amount of material from the undercuts and therefore that the material found in the channel must have come from bed erosion. This is particularly clear in the reaches located at the foot of the Tatras, in the Roztoki area, but also in the lower course of the river below Długopole. The lower course of the Czarny Dunajec shows a tendency to channel deepening followed by increased housing development in the near vicinity, as clearly in evidence near Długopole. Similarly in Nowy Targ, once flood embankments had been erected, buildings are being constructed much closer to the river, causing new problems in the valley, which are further aggravated during catastrophic high water levels.

The straightening of the channel, its narrowing and the reinforcement of the banks, compounded by the excavation of the aggregate increased the river's energy which was then applied mainly to downcutting and deepening. This process was supposed to be addressed by the river management, which has clearly failed. For this reason further excavation of material from the river channel should be fully prohibited and the prohibitions strictly enforced. In other regulated Carpathian rivers their energy also was found to have had increased, but in the larger rivers it was detected much earlier (Klimek, 1983; 1987).

We have recently observed a new wave of support for protection of natural river channel forms (Chełmicki and Krzemień, 1998; 1999; Verbraak, 1999). The Czarny Dunajec, however, is still being destroyed. Therefore, there is a need to protect the remaining semi-natural reaches of its channel (Dąbrowski, 1998) in order to save the very valuable (as well as some of the last) gravel-bedded braided channels in Poland.

Conclusions

The natural structure of the Czarny Dunajec river channel had developed over a long period of time at the foot of the Tatras, a high mountain range. Beginning in the Pleistocene era and throughout the post-glacial period, the river carried material out of the mountains and deposited it at their base, leading to the development of a typical braided river channel. The natural processes involved lateral channel migration and limited material transportation. At the end of the 19th century, however, the channel began to grow narrow and deep again. This process further accelerated at the end of the 1960s and has continued to the present day. Efforts to curb lateral erosion have only managed to channel the river energy into downcutting, in many of the reaches, further intensified by the extraction of the channel-bed material. The gravel and cobble excavation has led to the removal of the channel armour and deepening of the excavation areas. Additionally, upstream reaches have been suffering from retro-erosion, which, already active at the foot of the Tatras, may in the future migrate headwards (as indicated by the newly exposed bedrock at the accumulation fan of Potok Chochołowski, at Siwa Polana). The river management accompanied by channel material prospecting has contributed to the destruction of the natural channel structure and to its deepening, but has not stopped the movement of the clastic material. Indeed, the amounts of material deposited in the Czorsztyn Dam may have actually increased. From the geomorphologic and environmental point of view, the transformation of the Czarny Dunajec river channel must be viewed as highly damaging.

In view of the adverse changes in the Czarny Dunajec channel system, the extraction of the channel rubble should be strictly prohibited. Furthermore, those unique semi-natural channel reaches that have not yet been destroyed by man should be protected. Examples of such protection schemes can be found for instance in Scotland. The research into the Czarny Dunajec river channel should provide a warning signal against excessive human activity, which could mean irreversible damage to a fluvial system, without ever achieving the original aim of reducing the transport of clastic material into a water reservoir. So far, the river management has restricted the natural lateral channel migration and markedly increased downcutting, all of which has been affecting the natural environment in many ways, including increased ground water drainage.

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The depositional conditions of longitudinal dunes based on investigations in the western part of the Lublin Upland, SE Poland

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Abstract: The development of longitudinal dunes depends on three overlapping factors: the strength and direction of winds, the amount of supplied sand, and the occurrence of vegetation which can fix the rising forms. It is assumed that longitudinal dunes in Polish territory were mainly formed from the arms of parabolic dunes, as a result of the deflation of the central parts of these dunes. However, it is possible that some longitudinal dunes in Poland could also have developed as primary forms.

The detailed studies of longitudinal dunes in the western part of the Lublin Upland have revealed an important structural differentiation resulting from various development conditions of each particular form. Three models of development of longitudinal dunes are derived from these investigations:

1) They are formed by undirectional winds deflating the central parts of parabolic dunes, when sand supply is small, and vegetation fixes the rising forms.

2) They develop after a change of wind direction by 90°, in consequence of transformation of a single transversal dune or a set of parabolic dunes formed in front of or on an obstruction.

3) They are primary forms originating at obstructions, when eolian material is transported by bi-directional winds from a narrow (up to 90°) sector.

Key words: longitudinal dunes, date Pleistocene, the Lublin Upland

Introduction

In many papers dealing with the formation conditions of inland dunes in Poland, the origin of longitudinal dunes has never been the principal concern. They have mainly been considered to be created by the deflation of the central parts of parabolic dunes (Galon, 1958; Wojtanowicz, 1969). It was also suggested that longitudinal dunes were primary forms which could develop into parabolic dunes (Dylikowa, 1969). Observations of longitudinal dunes being formed at present (Hack, 1941; Bagnold, 1954; McKee & Tibbits, 1964; Verstappen & Delft, 1968; Brookfield, 1970; Fryberger, 1979; Lancaster, 1980; Tsoar, 1983, 1984) reveal that shifting, bi-directional winds from a sector of <130° are the main factor stimulating their development; winds from the dominant direction have much lower velocities than those from the secondary direction – which are not necessarily frequent but strong. Longitudinal dunes appear to originate most often from barchans, but the possibility that they develop from parabolic or transversal dunes cannot be excluded. The occurrence of various obstructions, mainly vegetation, and small supply of eolian sand are also important for their development.

Complex studies of eolian forms in the western part of the Lublin Upland have revealed an important structural differentiation of the distinctive longitudinal dunes and an attempt was made to explain this phenomenon. The aim of this paper is to determine the origin of longitudinal dunes, i.e. to show the dependence of dune-forming processes on environmental conditions, and to classify the longitudinal forms.