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EVOLUTION OF THE LOWER MSZANKA CHANNEL SECTION AFTER TRAINING USING STAGE CORRECTION METHOD

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Summary

Stage correction is currently the most frequently used type of the Carpathian streams training. It aims at decreasing the channel slope and limiting the bottom erosion, which over the last years led to a considerable channel deepening. The aim of the paper is the analysis of the stage correction effect on changes of the channel development and its functioning against its evolution during an over a hundred-year period. The investigations were conducted in the lower section of the Mszanka channel, a right tributary of the Raba River, which was wholly trained by means of stage correction. The training was conducted in three parts in the years 1977-2013. Available archival cartographic and photographic records, results of geomorphological research, etc. were used for the analysis. Information about the present functioning of the channel was obtained from geomorphological mappings conducted in 2004 and 2015. In result of training works, formerly braided Mszanka channel became transformed into a single thread and sinuous channel. 25 concrete drop structures and many steps were constructed in the bottom. The riverbanks were reinforced. In result of stage correction application the bedload was caught between the drop structures, whereas the channel below was underloaded with material. Therefore it became deepened. At this point the next stage of training was started and finally the drop structures were constructed until the river mouth. However, it did not stop the erosion process, although slowed it down greatly. At present the riverbed at this point is incised to the bedrock. Downcutting and lateral erosion play the main role in its development. The channel is unstable and the hydraulic structures are being destroyed, particularly during floods. The greatest error of the training was too big shortening, straightening and narrowing of the channel at simultaneous cutting it off from the material supply source.

Keywords: stage correction, drop structures, channel evolution, channel deepening, mountain streams training

INTRODUCTION

Channels of Carpathian rivers and streams have been particularly intensively trained since the second half of the 20th century. During the first period, lasting until the 80ties, mainly longitudinal structures were erected (Korpak 2007a, 2012). Debris dams and weirs were also constructed. In result of the transformations carried at that time braided channels became single thread, meandering, greatly shortened and narrowed. The outcome of the training was a considerable increase in bottom slope and progressing channel downcutting (Klimek 1987, Wyżga 2001, Korpak 2007a). In the eighties of the 20th century, long channel sections were trained by means of stage correction in order to prevent their deepening. Today it remains the most popular and recommended method of Carpathian river and stream training (Ratomski 2013). The Mszanka River has been trained in this way along ca. 30% of its length. There is a similar proportion of the sections subjected to stage correction on the other rivers within the Raba catchment, e.g. the Porębianka River (ca. 28%) or Krzczonówka River (ca. 32%). Despite the popularity of this type of river training, few investigations have been conducted so far on its influence on channel development and functioning. It has been known that bedload transported by the watercourse is stopped before the steps, which causes its deficiency in the section below (Jansen *et al.* 1979). Because the steps are usually higher than 0.7 m and they lack fishways, they are an obstacle in the Salmonid migration to spawn (Bojarski *et al.* 2005). Thus, stage correction breaks the river continuity concerning the bedload transport and free movement of organisms. It is not in compliance with the guidelines of the Water Framework Directive and makes difficult for rivers to reach good ecological state (Rozporządzenie Ministra... 2011). The channel trained with drop structures is not adjusted to changeable flows characteristic for mountain streams and rivers. During the low-flow periods a single threaded flow regulation route usually proves too wide, which results in very low water stages, their overheating and oxygen deficiency leading to a drastic deterioration of living conditions for aquatic organisms. During the flood periods, trained channel is too narrow. Floodwaters cause considerable damage within the flow regulation route, and the steps are usually covered by the debris (Korpak 2008) .

There are no investigations on the stage correction functioning over a longer period of time. How is the channel adjustment advancing several, many and several dozen years after training? What are the determinants of the channel further development? What is the durability and efficiency of training after a longer time of its exploitation? The paper strives to provide answers to these questions. The analysed object was the lower Mszanka River section, along which 25 concrete drop structures were constructed. The channel evolution was analysed along this river reach over the last 135 years with the special regard to the role of stage correction.

STUDY AREA

The investigations were conducted in the channel of gravel bed Mszanka River, a right tributary to the Raba River. The river is 19.5 km long, its catchment is situated in the Beskid Wyspowy and Gorce Mts. (Fig. 1). The catchment area is 175 km^2. The Mszanka divides little lithologically diversified flysch deposits of the Magura series and Mszana Dolna tectonic window. Shales and sandstones of the Krosno layers, poorly resistant to denudation, occur along a major part of the channel length. The Mszanka is a mid-mountain river with a considerably big slope and considerably range of annual flows. Mean annual flow is 3.27 m^3/s. Mszana Dolna gauging station located at 3.1 km of the river course (counting from the mouth) has been collecting hydrological data since 1954.

A detailed analysis covered the lower Mszanka section from the debris dam at 5.724 km of the river course to its outlet to the Raba River. This whole section has been trained by means of stage correction and its banks are reinforced. The channel width in this place is little diversified and ranges from 25 to 35 m.

METHODS

The available archival records were used to recreate the evolution of the analysed river reach, including:

- Austrian topographic map of 1879, in 1:75 000 scale,
- aerial photographs of 1963, 1977, 1993 and ortophotomap of 1997,
- multi age technical documentation of the training obtained from the Cracow's Regional Water Management Authority, comprising land survey and height map, channel longitudinal profile and cross-sections, photographic documentation of the performed works,
- results of geomorphological studies conducted in the Mszanka channel in 1975 and 1992 by Krzemień (1984) and Komędera (1993).

The cartographic materials were subjected to rectification process in order to obtain the uniform frame of reference and the same scale.

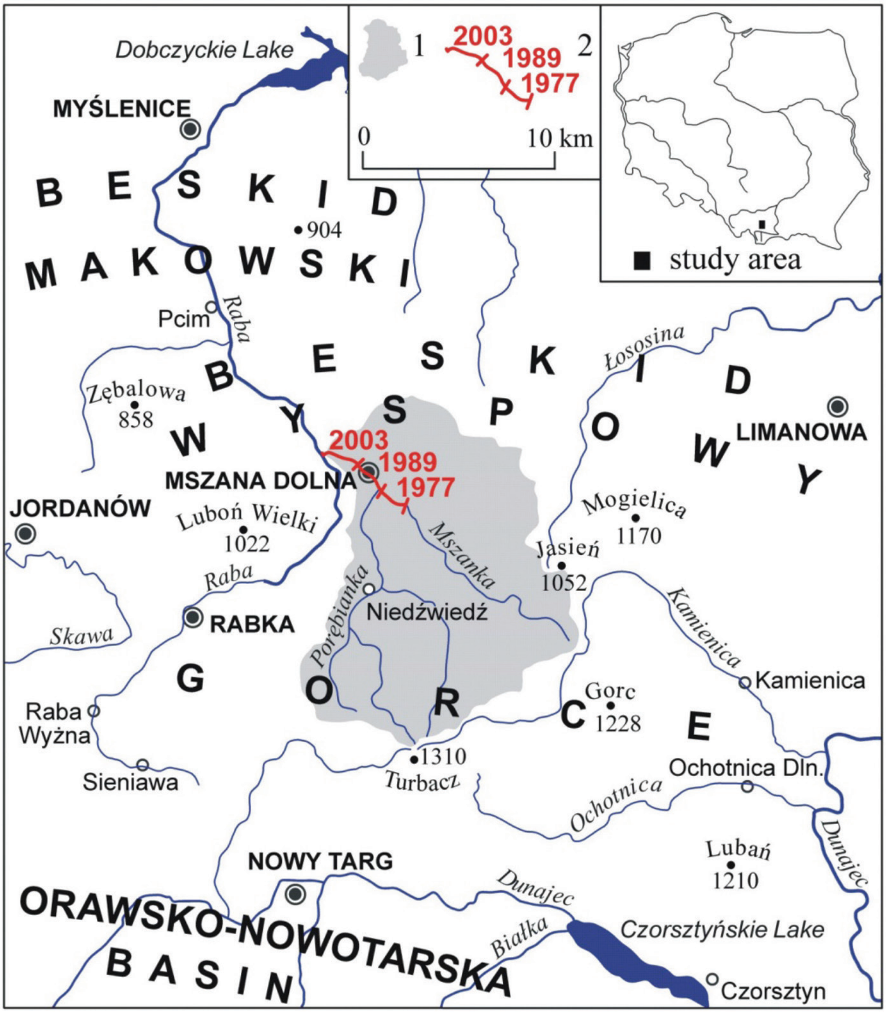

Figure 1. Location of the investigated area. 1 – the Mszanka sections with drop structures from three training periods

A long-term series of minimum annual water stages at the Mszana Dolna gauging station was used to determine the tendency to river bed incision. The method was used many times to investigate the changeability of the vertical channel configuration in Carpathian streams and rivers (Punzet 1981, Krzemień 1984, Soja 1984, Wyżga 1991, Łapuszek and Ratomski 2006). The data series used in this paper came from the Institute of Meteorology and Water Management.

Geomorphological mapping according to the “River channel mapping instruction” (Kamykowska *et al.* 1999) was done in 2004 to learn the present structure and dynamics of the channel. Three sections trained at different time were identified in the analysed lower Mszanka course for which information concerning the kind, number and area of the river-bed forms and the state of river regulation structures was accumulated. The investigations were repeated along the same sections in 2015, providing valuable comparative material.

DEVELOPMENT OF THE LOWER MSZANKA SECTION PRIOR TO THE TRAINING BY MEANS OF STAGE CORRECTION

By the end of the 19th and at the beginning of the 20th century the channel in the lower Mszanka course was braided, alluvial with large central and lateral bars, some of which were utilised as pastures or arable lands (project no 11/90/8, 1910). The channel width exceeded 100 m, in some places reaching even 300 m (Fig. 2a, b). The river loading at this section considerably exceeded its transport ability, as evidenced by the deposition of carried material. Uplifting channel bottom posed a flood hazard for the adjoining agricultural lands. To stave off this problem, a decision was made to construct a debris dam which would arrest the transported material. The project was a part of the plan of systematic channel consolidation along a 12.5 km long Mszanka River reach, developed by the Commission for River Training in Galicia at Imperial-Royal Governorship in Lvov in 1910 (project 11/90/8, 1910). The project was never completed. The dam was constructed in 1934 at 5.724 km of the river in the valley necking. The channel was 20 m wide. The dam, one of the oldest in the Podkarpacie region was a stone structure with a height of 3.3 m. The fishway was situated on the right bank of the river. The dam reservoir capacity was 78,000 m^3. In the subsequent years the structure was destroyed several times (by floods in 1964, 1970 and 1997) and renovated (the last time in 1999, project no. 1750, 2000). The dam broke the continuity of the fluvial system and divided the channel into two sections, which from that time were developing differently. Deposition dominated above the dam, whereas erosion below. The erosion undoubtedly occurred along about several hundred metres long section, situated immediately below the structure. Such length of the erosive section was suggested by the research on other channels below dams with similar dimensions (Korpak 2007b, Korpak *et al*. 2008). Deposition of material prevailed below this reach, as evidenced by the aerial photograph of 1963 (Fig. 2c). In this place the channel still remained braided, of a smaller width than at the turn of the 19th and 20th century, but still very wide (up to 160 m). Values of the minimum annual water stages reveal alternativeness of brief aggradation and degradation episode causing that until 1964 the channel at this cross section revealed vertical stability (Fig. 3).

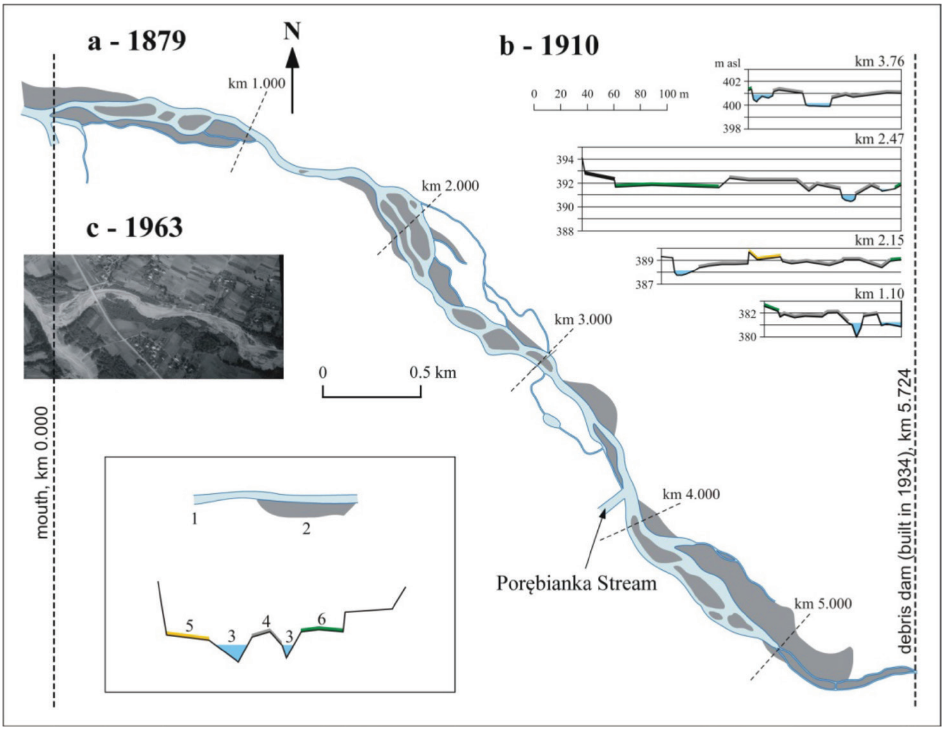

Figure 2. Development of the lower section of the Mszanka channel before regulation: a – in 1789 (on the basis of the Austrian topographic map), b – channel cross sections in 1910 (according to the project no. 11/90/8, 1910), c – in 1963. 1 – water, 2 – bar, 3 – channel with water, 4 – bar, 5 – pasture, 6 – shrubs

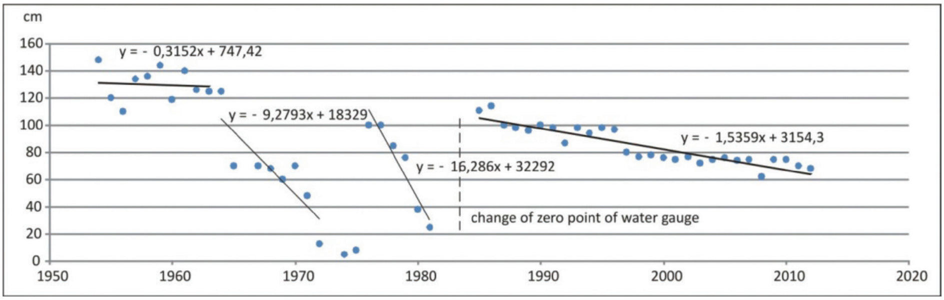

Figure 3. Lowering of the minimum annual water stages of the Mszanka River at the Mszana Dolna gauging station as an indicator of incision rates

STAGE CORRECTION AT THE LOWER MSZANKA RIVER SECTION

The subsequent projects of the lower Mszanka River section training were developed in response to a rapid channel bed lowering below the dam (Korpak *et al*. 2008). The main objective of the projects was reduction of the channel slope, which has been achieved by means of stage correction. Bank erosion, which posed an additional problem, was prevented by bank reinforcements. Construction of stage correction was realised during three periods (Fig. 1). First, stage correction was constructed in 1977 at 5.724-3.840 km of the river, then in 1989 at 3.688-2.100 km section (acc. to project no. 3337, 1977) and in 2003 the steps were commissioned at 2.140-0.000 km (acc. to project no. 1750, 2000). Unfortunately, none of the working plans for the first stage of the construction survived.

The first stage of construction, completed in 1977, lasted for 10 years. 10 concrete drop structures were made and the channel between them was profiled, whereas both river banks were armoured with prefab bands (Zestawienie... 2004).

The second stage of training by means of stage correction was carried out in the eighties of the 20th century. Nine drop structures were constructed along the 3.928-2.140 km section and a trapezoidal, 30-34 m wide channel was formed. According to the project the drop structures were to have 1 m slope but the as-built inventory revealed the incompatibility of the execution with project (project 4175). The bottom between the drop structures was protected wit use of concrete steps. In 1998 both riverbanks along the whole 3.928-2.140 km river section were reinforced with prefab bands (Zestawienie... 2004).

The third stage of training was completed in 2003. The channel was profiled and the width of the flow regulation route is 34 m. In order to reduce the slope of the delineated route it was partitioned by 6 concrete drop structures with height of 0.8 m. A rip-rap was made along the length of 6 m below the structures and finished with boulders of minimum 1 tonne, placed in the previously prepared trench. Concave riverbanks and sites particularly prone to lateral erosion were reinforced with a rip-rap band. A longitudinal dike (in the form of live pole drains with rip-rap) constructed in the mouth zone on the left bank directs the Mszanka waters according to the Raba course. The training was carried out in response to the destruction of previous bank reinforcements by the flood in 1997 and later in 2001.

THE CHANNEL RESPONSE TO TECHNICAL INTERVENTION

Period until 1977 – the first stage of training

The objective of the first stage of training by means of stage correction was decreasing the channel slope and preventing an excessive erosion along the river reach below the debris dam. According to the minimum annual water stages at the Mszana Dolna gauging station, channel deepening at that time was very intensive. At various points of the longitudinal profile the bottom lowered by 1-3, usually by ca. 2 m (project 3337, 1977, Fig. 3). Information about the first period of stage correction realisation may be found in the aerial photograph of 1976 (Fig. 4a). It shows that the channel was levelled and its shape and bottom structure were destroyed. Subsequently, a new single-thread flow regulation route was constructed along the artificially delineated course line. Subsequent drop structures and steps were erected towards the river mouth. Width of the active channel decreased considerably.

At that time the riverbed below the Porębianka River mouth was alluvial and locally divided into several arms, while its maximum width reached ca. 100 m (Fig. 5a, 6a). The river showed tendency for a lateral migration and going wild (Fig. 5a, 6a). Longitudinal training was conducted at several river sections to protect its banks against erosion (project no. 3337, 1977). The training is visible in aerial photographs (Fig. 6a).

1977-1993 period – the outcome of the first and second training periods

The channel section included in the 1st training stage revealed a relative horizontal and vertical stability. Fragments of the former active channel, which were "cut off" due to the training and narrowing, were transformed into a floodplain and in some place even into a terrace (Fig. 4b).

A lack of stability characterised the river section below the Porębianka mouth. Erosion occurring at this section caused the bottom deepening and banks widening. The 2nd stage of training was planned in order to inhibit erosion, limit the bedload transport and to provide flood protection for the adjoining areas, municipal facilities, bridges and roads in the city of Mszana Dolna. The training works were completed in 1989 and the last drop structure was constructed at the 2.140 km of the river. The works comprised levelling of the channel bottom, which totally disturbed the armour layer of bedload and destroyed all channel forms (Photo in Fig. 5b). The artificial flow regulation route was formed (Fig. 5b). The as-built inventory conducted after the works completion revealed considerable differences between the project and real state (project 4175, 1989). The height of the drop structures was not 1 m as planned, but ranged between 0.63 and 1.21 m. The value of channel gradient, instead of expected 5.5‰ along the whole reach, differed between the structures (2.7-4.7‰). The results of considerable reduction of the flowing water volume and negligence of the executor became apparent quite soon. Numerous damages of the new route (acc. to project no. 4175, 1989) were noted already after a small flood wave passing in May 1987 (i.e. even before the works were completed). Potholes up to 1 m deep formed before some drop structure crests. The bottom basins armouring of gabion rock mattresses was damaged or totally destroyed and in these places 0.3-1.1m potholes formed. Concrete steps were scoured and 0.2-1.3 m deep potholes were forming below them. Some concrete steps and bank reinforcements were damaged or destroyed (Photo in Fig. 5b).

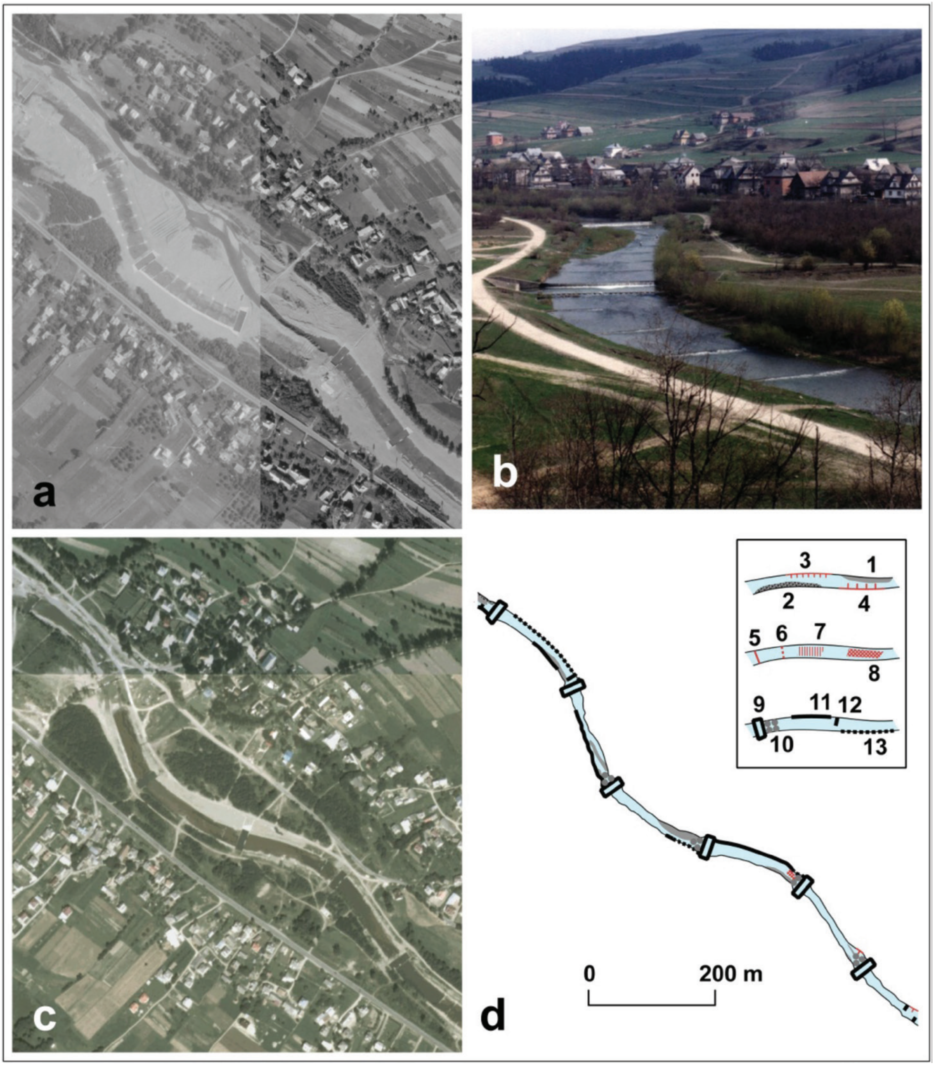

Figure 4. Change of the Mszanka channel morphology at the section regulated during the first training period : a – 1976, b – 1992 (Photo M. Komędera), c – 1997, d – 2015 (on the basis of the terrain mapping). 1 – bar, 2 – vegetated bar, 3 – cutbanks (height >2m), 4 – cutbanks (height 0-2 m), 5 – rocky step, 6 – boulder step, 7 – riffle, 8 – rocky outcrop, 9 – concrete drop structure, 10 – oversize boulders, 11 – embankment of concrete elements, 12 – concrete step, 13 – rip-rap.

In its final, mouth section, so far not included in training by means of stage correction, in 1993 the channel was single thread and narrow. Its width did not exceed 25 m (Fig. 6b). It was the result of training conducted in the 1970s using groynes and longitudinal dikes.

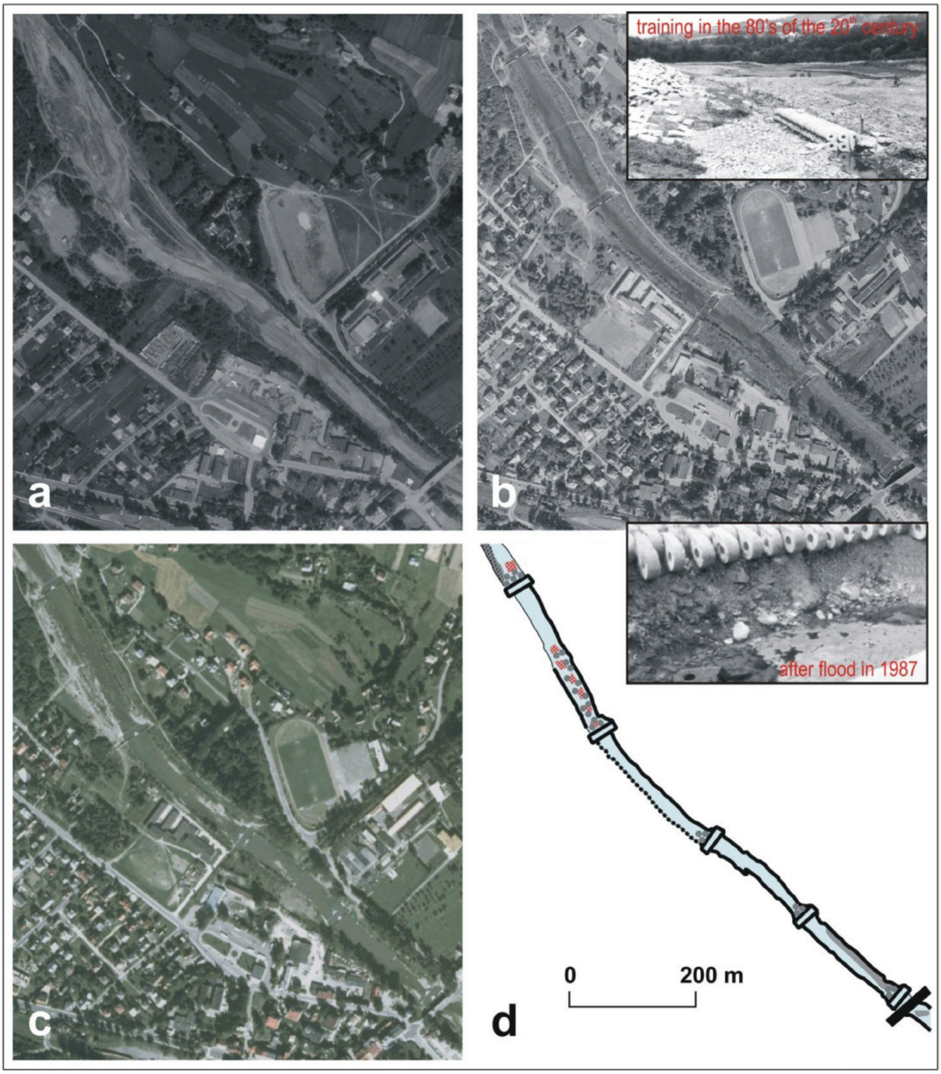

Figure 5. Change of the Mszanka channel morphology at the section regulated during the second period of training: a – 1976, b – 1993 (photographs of the as-built inventory of the flow regulation route acc. to project 4175), c – 1997, d – 2015 (based on terrain mapping). Legend as in Fig. 4.

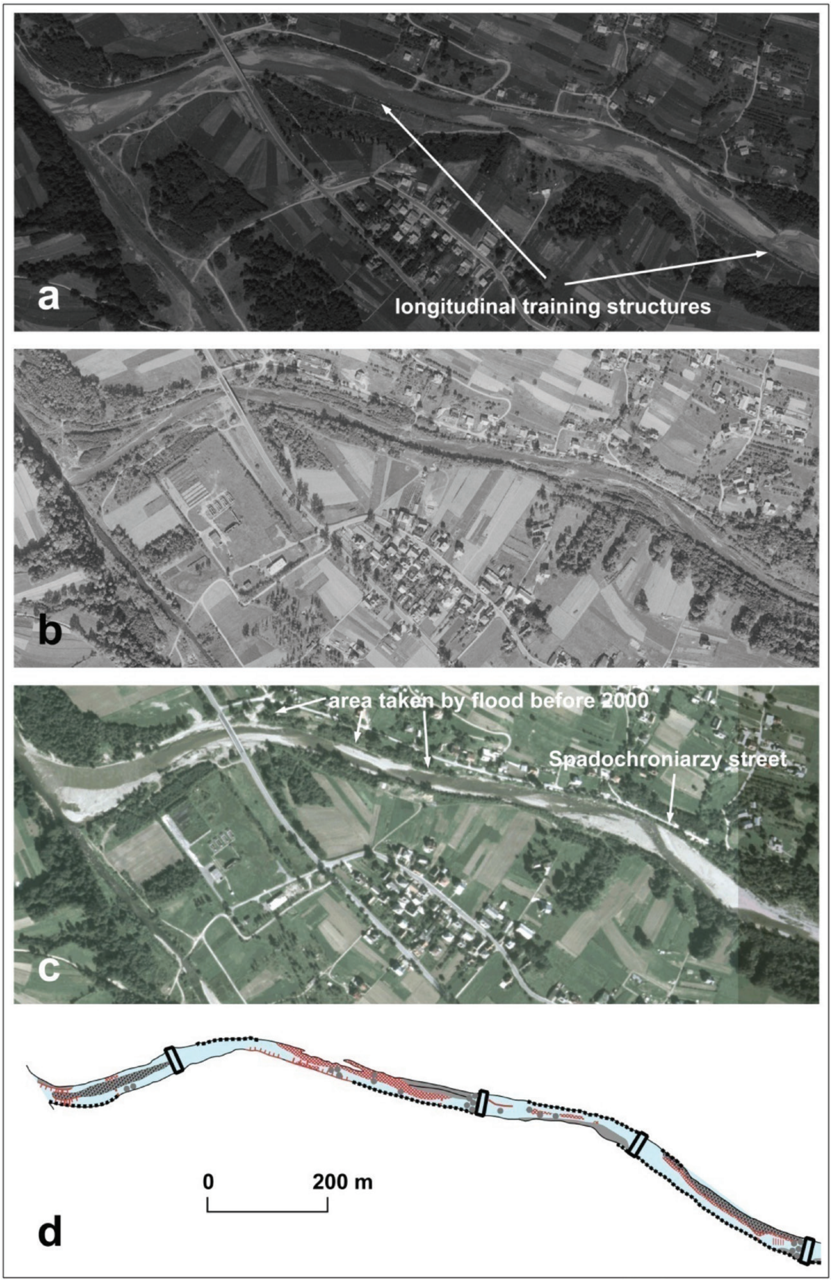

Figure 6. Change in the Mszanka channel morphology at the section regulated during the third period of training: a – 1976, b – 1993, c – 1997, d – 2015 (based on the terrain mapping). Legend as in Fig. 4.

Figure 7. Development of the Mszanka channel in 2004 and 2015: a – the channel in 2004 without any fluvial forms after freshly conducted training, b-d erosional channel in 2015: b – rocky outcrops between drop structures, c – cutbanks within the flow regulation route, d – destroyed concrete steps between drop structures

1993-2003 – period of high floods and 3rd stage of training

Serious changes in the channel morphology were the result of a high flood in July 1997. However, renovation works were conducted immediately in the channel, as may be seen in the aerial photograph taken only a month after the flood. The section from the debris dam to the Porębianka mouth was almost wholly cleared and the banks, especially concave ones, were renovated, which evidences intensive activity of lateral erosion during the flood (Fig. 4c).

Numerous bars, visible in the channel bed below the Porębianka mouth were mostly deposited during the flood (Fig. 5c). Many drop structures were partly or wholly covered by the bedload. Concave banks were undercut, which caused their local scouring and destruction of bank reinforcements. Renovation of the analysed channel section (3.928-2.140 km) was carried out in 1998 (acc. to Zestawienie... 2004). Both banks were armoured with concrete prefab bands and the channel was cleared by removing the accumulation forms. Subsequent renovation works were conducted after the flood in 2001.

The final, mouth section of the Mszanka River was considerably widened in August 1997 in comparison with its state in 1993 (Fig. 6c). The floodwater, overflowing the artificially narrowed channel, destroyed bank reinforcements.

The channel width after the flood was already 35-70 m. The subsequent floods between 1997 and 2000 caused further damage to bank reinforcements, the majority of which were suitable for demolition. Tendencies for the river lateral migration were apparent, due to which between 1997 and 2000 the channel widened considerably, in some places even 3 times. It reached its maximum width of ca. 100 m before the bridge (project 4175, 1989, Fig. 6c). During one of the floods the river took away ca. 35 m wide wooded bank strip which separated it from the Spadochroniarzy street (Fig. 6c). From that time the channel adjoined the road, which threatened its destruction during the next flood. Therefore, in 2000 the third part of training works using stage correction was planned at the section of 2.140 – Mszanka inflow into the Raba River. The construction was completed in 2003. The channel was narrowed to 34 m and at the same the active channel area was diminished ca. twice. Six concrete drop structures were constructed. The building works levelled the channel bottom and destroyed all accumulation forms (Fig. 7a).

2004-2015 period

During the analysed period the channel was regulated along the whole length from the debris dam at 5.724 km to the river mouth. During the terrain mapping in 2004, almost none fluvial forms were spotted at this section (Tab. 1). They were artificially removed from the section situated closest to the mouth during the recently completed 3rd stage of the training, whereas the section above it was cleared after the recent floods. Quite numerous but small bars occurred only in the section immediately below the debris dam. Their presence was undoubtedly caused by the fact that the dam reservoir was already filled with bedload and some of it got out through the dam spillway.

The terrain mapping repeated in 2015 revealed considerable changes in the channel morphology. Along its whole length the river was incised into the bedrock. A thin and discontinuous alluvia layer was present only in some places. Numerous rocky outcrops appeared in the bottom (Fig. 4d, 5d, 6d, 7b). A small, comparable number of bars occurred at each river section, whereas the forms differed considerably with their sizes (Table 1). At the section trained during the first two periods of training, the bars were small and usually lateral (Fig. 4d, 5d). The section regulated in 2003 revealed the presence of large bars, of which the biggest were central forms (Fig. 6d). Big cutbanks appeared at this section (Fig. 7c), as well as rocky steps with an average height of ca. 0.25 m. Few and small erosion forms visible as cutbanks were observed also at the river section closest to the dam. The least of the forms were in the central river reach, which has undergone renovation works in 2013 (City Office Mszana Dolna, 2013). Engineering structures along the whole lower Mszanka section are damaged or even destroyed. It refers particularly to the bank reinforcements, which slide and fall into the river. Almost all concrete steps constructed between the drop structures were removed (Fig. 7d).

Table 1. Development of the lower Mszanka channel section in 2004 and 2015

Morphology characteristic	Channel reach, km					
	5.724 – 3.928		3.928 – 2.140		2.140 – 0.000	
	2004	2015	2004	2015	2004	2015
Channel length in km	1.796		1.788		2.140	
Number of rocky steps per 1 km	0	0	0	0	0	1.9
Number of cutbanks per 1 km	0	1.5	0	0	0	3.3
Area of cutbanks in m^2 per 1 km	0	21	0	0	0	289
Number of bars per 1 km	7.2	6.7	0	6.2	0	6.3
Area of bars in m^2 per 1 km	3,152	1,715	0	3,025	0	5,914
Braiding ratio	3.1	2.1	0	2.5	0	1.4

FUNCTIONING OF THE MSZANKA RIVERBED SUBJECTED TO STAGE CORRECTION

Stage correction was developed in response to increased channel slope and its rapid deepening after construction of the debris dam at 5.724 km of the river. The strongest deepening occurred in the years: 1964-1972 and in 1976-1981 (Fig. 3). Training works were conducted between these periods, so the values of the minimum stages are incomparable. Each of the training stages comprised the channel narrowing, its straightening and cutting off lateral meanders, which considerably diminished the flow cross-section. The channel along river section trained with drop structures revealed a relative horizontal and vertical stability, whereas it was very unstable below. Problems appeared particularly during flood water flow. Flood water was flowing with a high velocity through the narrowed flow regulation route and strongly eroded the bottom and channel bank. Engineering structures were also damaged during floods. The training conducted to limit erosion did not eliminate the problem but moved it closer to the mouth. Therefore, sometime later a decision was made to train the next section. Finally the stage correction covered the whole length of the Mszanka lower course. However, the problem of erosion remained. The diagram of minimum water stages shows that the tendency for channel deepening lasts continuously in the channel, although the process is less intensive (Fig. 3). Strong erosion occurs in the Raba channel below its junction with the Mszanka. According to the course on minimal annual water stages over the last 100 years at water gauging station

Kasinka Mała, situated at 95.8 km of the Raba course, the period with the strongest erosion started in the mid-eighties of the 20^{th} century and lasts until now. The rate of the bottom deepening is ca. 4.8 cm per year (data from Institute of Meteorology and Water Management).

Geomorphological research conducted in the Mszanka channel in 1975, 1992, 2004 and 2015 revealed constantly decreasing role of the deposition process in the analysed channel. In 1975, at the section from its junction with the Porębianka to its mouth, there were 15.8 bars/km in the Mszanka channel with a total area of 16,063 m^2/km (Krzemień 1984). In 1992, when the drop structures occurred only from the conjunction with the Porębianka to 2.140 km of the river, the number of bars increased slightly (to 24.5 bars/km), but their area decreased even 11-fold (to 1,470 m^2/km) (Komędera 1993). The channel function below the Porębianka inflow to the Mszanka changed from redepositional-erosional in 1975 to erosional-redepositional in 1992. In 2004 the channel was fresh after training and renovation works, during which all fluvial forms were artificially removed. At the same time the armouring layer was destroyed, which provided a natural protection of the channel bottom against scouring. Subsequent floods (particularly in 2010 and 2014) caused a removal of alluvia and uncovering of the solid substratum. The channel, which in this place was always alluvial, now is incised into bedrock. Downcutting and lateral erosion is mainly responsible for its transformation. In 2015 at the section from the conjunction with the Porębianka to the mouth, there were only 5.1 bars/km (some of them deposited on the rocky outcrops) with an area of 4,658 m^2/km. The value may be slightly overestimated because the research was conducted at very low water stage. The dominance of erosion causes numerous damages along the flow regulation route which requires constant repairs and financial outlays.

CONCLUSIONS

The channel in the lower Mszanka section is erosional and incised to the bedrock, despite applied stage correction, which was meant to prevent downcutting. The main cause of this state is too excessive narrowing of the previously very wide channel at simultaneous preventing material supply to the channel. The material cannot get through either from the reinforced banks or from the upper parts of the riverbed where the obstacle for the bedload transport is the debris dam. The river transport capacity considerably exceeds its loading. Energy of flood waters which cannot be held in the channel focuses on eroding its bottom and banks. Engineering structures become gradually damaged. The riverbed is greatly unstable. The adjoining terrain is threatened with erosion, particularly the developed right bank area. It turns out that it is impossible to design a durable and efficient river training without ensuring a free bedload flow.

How can the channel state be improved to help the river regain its balance? Examples may be sought from the currently renaturalised Krzczonówka River whose inflow to the Raba River is situated about 10 kilometres below the Mszanka mouth. At this point the decision was made to lower the debris dam and re-build it in the form of a cascade composed of several steps (Lenar-Matyas *et al*. 2015). In this way the channel continuity was recovered making possible the bedload transport. Concrete drop structures below the dam on the Mszanka could be rebuilt as artificial rapids. Such constructions also decrease the channel slope, but unlike the drop structures, do not pose any obstacle difficult to pass for fish. Water ecological quality of the Mszanka River renaturalised in this way would most probably improve, what is compliance with the guidelines of the Water Framework Directive. Obviously, the purposefulness of these activities in a given place must be tested by a number of interdisciplinary investigations.

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