Research Article

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The influence of river training on the location of erosion and accumulation zones (Kłodzko County, South West Poland)

https://doi.org/10.1515/geo-2020-0031
received August 05, 2019; accepted December 02, 2019

Abstract: The channels of the main rivers in the Kłodzko County, South West Poland, have been strongly influenced by human activities since the end of the nineteenth century. The reasons, type, and time frame of these changes are very similar to those which occurred in other European mountain regions but the magnitude is different. Kłodzko County is an area with a well-developed river network. Since the Middle Ages, human activities were noticed in the river valleys of this region. The main cause of the most anthropogenic transformations of the river channels was changes in the volume of sediment supply and, thus, the channel load and its erosive and transport capacities. The ultimate effects of human impact are manifested in the changes of channel pattern, depth and sinuosity, and the location of erosion and accumulation zones. Morphological transformations are most intensive immediately after the regulation works. The influence of channel training is noticeable; however, there is no clear correlation between the occurrence of engineering structures and the development of channel forms. The channel changes are mostly local. The highest efficiency of channel processes is observed in the direct vicinity of the damming objects and in the peripheral fragments of bank-protection structures. Below the damming structures, the rate of channel downcutting increases because of sediment retention in dam and weir reservoirs, and above the transversal structures bed aggradation takes place; lateral erosion intensifies below the bank reinforcements, and sediment shadows are common below the transversal structures. The types of morphological changes observed in the regulated channels of the Kłodzko County are in most cases similar to the effects of training works in other mountain river systems in Poland and around the world; however, the scale of morphological influence is much smaller, which indicates greater stability of the river channels of the Sudetes than the Carpathian and Alpine river channels.

Keywords: river training, channel changes, erosion, accumulation, fluvial system, human impact, fluvial processes, hydrotechnical objects, Kłodzko County, Sudetes

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1 Introduction

River systems all over the world are transformed in different ways by human activity, e.g., by channel regulation. These actions are in many cases necessary, but they cause a number of significant, often adverse, effects on the natural river environment. Understanding the relation between human activity and the reaction of the fluvial system to changes in it allows us not only to recognize the processes and phases of the contemporary evolution of fluvial systems but also to identify potential further directions of morphological transformations of river.

Over the last two centuries, river channels were rapidly and substantially transformed in response to various types of human activities [1–5]. The response of rivers to human impact was often analyzed, showing that remarkable channel changes, such as vertical adjustment and changes in channel width and pattern, generally take place [4–9]. These changes are often larger than those that could be expected to result from natural channel evolution.

The major transformations that have taken place comprise changes in channel patterns, channel depth (deepening or shallowing), and channel width (narrowing or widening). These transformations can produce many environmental and social effects, such as undermining or damaging of bank-protection structures, bridges and weirs, loss of groundwater resources, loss of agricultural land, concentration of flow in regulated, narrow channels with increased flow velocity, reduction in floodwater retention on floodplains and thus an increased risk of flooding in downstream sections, riverbank instability, and loss of habitat diversity.

A large number of mountain rivers, including the Sudeten, were affected by training works in the last 200 years. In Poland, in the second half of the twentieth century, the most intense regulatory works in mountainous fluvial systems were carried out in the Carpathians and on a much smaller scale in the Sudetes. As a result of channel regulation, the channel pattern of Carpathian rivers was changed from braided to single thread and the rivers displayed a tendency toward incision [10–13]. The main process modeling Carpathian rivers today is downcutting, but the timing of the increased erosion, its magnitude, and the rate vary among the rivers [14,15]. In addition to training works, morphological transformations of Carpathian rivers were also caused by in-channel gravel mining and land cover change [15,16].

The Sudeten rivers and streams were regulated much earlier, most intensively at the turn of the nineteenth and twentieth centuries, when this region was a part of Germany. The influence of Sudeten river training on channel changes has been neglected; to date, the literature lacks detailed studies discussing the geomorphological role of specific channel regulation systems. This subject was discussed marginally during studies of the geomorphological effects of floods [17–20] and analyses of changes in the natural environment related to population and settlement changes [21,22]. So far, few works have focused solely on the impact of training works on mountain channel changes in the Sudetes [23–25].

Our studies have shown that the main changes in the morphology of the regulated river channels in the Kłodzko County are (1) channel pattern changes caused by training works, (2) channel depth increase below regulated channel sections and dam structures, and (3) increase in the intensity of bank erosion in the areas of contact between natural and regulated river banks. Anthropogenic transformations of river channels are mostly caused by changes in the volume of sediment supply and, thus, the in-channel sediment load and its erosive and transportation capabilities as well as the location of erosion and accumulation zones in the channels.

The purpose of this work is to analyze and explain changes in the distribution of erosion and accumulation zones caused by river training works. The intensification of channel processes during extreme events and the influence of technical condition of hydrotechnical objects on morphological changes in the channels are also considered.

2 Study area

The research was conducted in the Kłodzko County, where extreme floods have occurred over the last two decades, a period in which regulation structures have had a significant influence on channel morphology. Moreover, there is a well-developed river network in this area, which is related to long-standing human activities, and, thus, numerous examples of channel regulation exist. The Kłodzko County has a rich history of land use changes (mainly reflecting socioeconomic changes that have taken place in the region, including total population exchange after the World War II and changes in land use), which has affected the functioning of river systems.

Kłodzko County, with an area of 1,643.37 km^2, is located in South West Poland, in the central part of the Sudety Mountains (Figure 1). The morphology of this area is very varied and shares the main morphological features of the entire Sudeten region (numerous isolated mountain ranges and massifs separated by valleys of various origins and foothill areas). The river network is well-developed. River valleys in many cases are directly related to lithology and refer to the course of tectonic structures and the resistance of the ground rocks. The main morphological features of all the valleys studied are similar. In the highest parts of the slopes, river channels have the form of slope streams. The valleys are poorly developed. Streams often flow through several undeveloped low-flow channels upon the slope surface. Below the headwater sections, they flow in shallow channels incised into the boulder lag deposits. Low bedrock or boulder steps are found in these channels. The height of steps is often increased by accumulation of organic materials, mostly small wood debris. The bed of most channels is formed of medium- and coarse-grained mineral sediments, which are the product of selective slope erosion mainly transported during floods. The characteristics of river channels changes in the foreland of the mountain ranges and within the mid-mountain basins.

Draining of rivers and streams surrounding the mountain ranges flows to the northerly oriented valley of the Nysa Kłodzka River. This river is the hydrographic axis of the region. It has numerous tributaries, e.g., Biała Lądecka with Morawka, Bystrzyca Dusznicka, Bystrzyca Łomnicka, Ścinawka, and Wilczka. The hydrological and physiographic characteristics of the analyzed rivers are summarized in Table 1. These rivers vary in channel

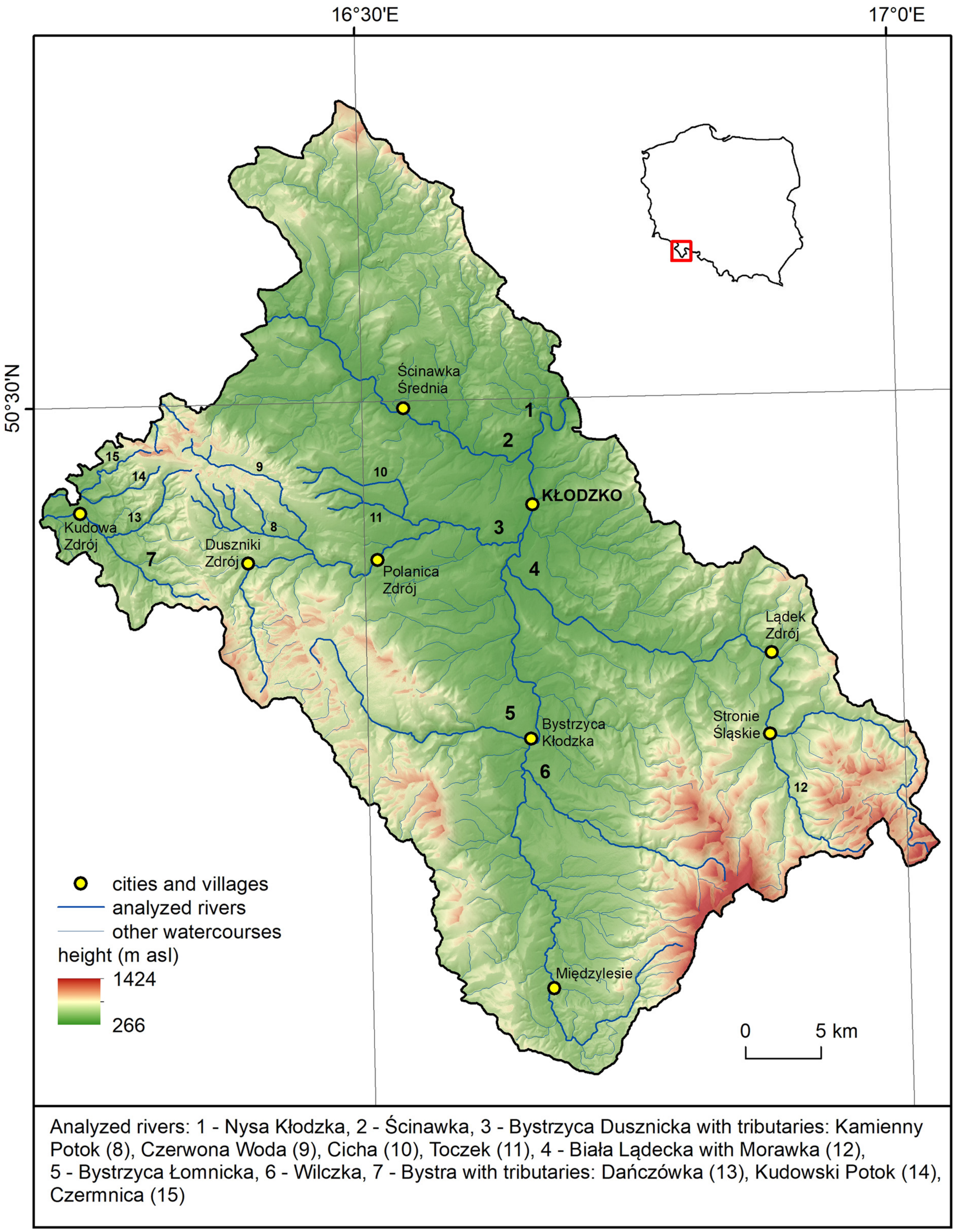


Figure 1: Study area: Kłodzko County with analyzed rivers.

slope and the amplitude of water stages. During spring snowmelt and summer rainstorms, extreme flood events occur, which are very dangerous, especially in the Kłodzko Valley.

The morphology of most channels, especially in the middle and lower sections, has been significantly anthropogenically changed (regulated). Nowadays, all the analyzed river channels are trained along around 30% of their

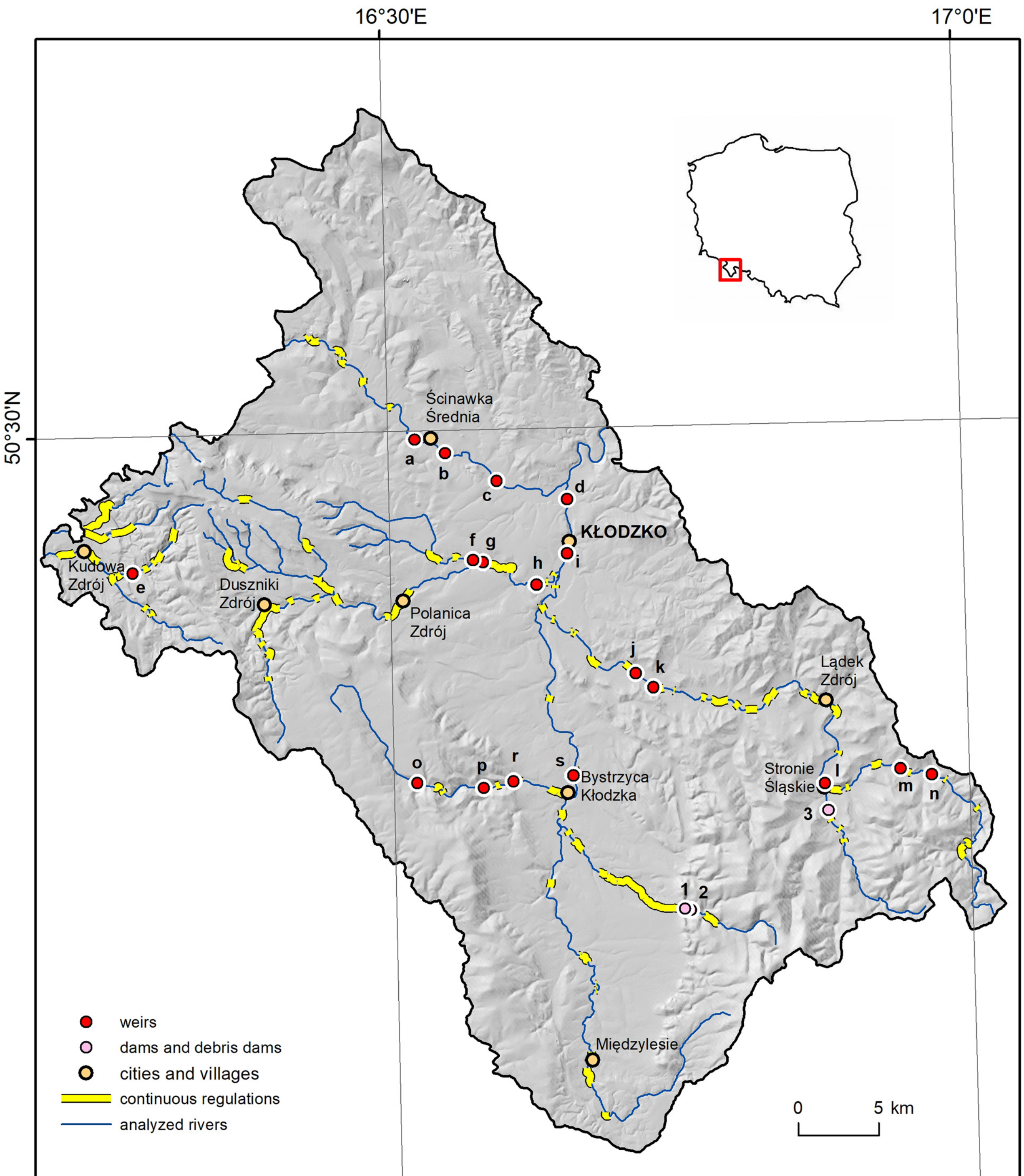
Table 1: Hydrological and morphological characteristics of analyzed rivers

River	Channel length (km)	Drainage basin area (km^2)	Mean channel slope (‰)	Channel width (m)	Mean annual water stages (cm)	Maximum water stages (cm)	Mean annual discharge (m^3 s^{-1})	Maximum discharge (m^3 s^{-1})	$Q_{1\%}$	$Q_{0.5\%}$
Nysa Kłodzka	126.6	1500.0	5.09	1.0–35.0	97.2[1]	655.0[1]	12.84[1]	1340.0[1]	862.0[1]	1062.0[1]
Biała Lądecka	52.7	314.6	15.3	1.0–25.0	66.0[2]	430.0[2]	4.99[2]	700.0[2]	386.0[2]	453.0[2]
Wilczka	17.2	47.0	47.0	1.0–8.0	86.8[3]	360.0[3]	0.88[3]	150.0[3]	58.9[7]	68.8[7]
Ścinawka*	24.0	520.0**	3.2	5.0–15.0	71.6[4]	450.0[4]	4.63[4]	364.0[4]	225.0[4]	256.0[4]
Bystrzyca Dusznicka	35.0	205.0	16.8	1.0–13.0	31.4[5]	318.0[5]	2.17[5]	214.0[5]	150.0[5]	172.0[5]
Bystra	15.0	67.1	28.3	0.5–5.0	233.9[6]	380.0[6]	0.68[6]	16.4[6]	–	–

Gauging station: [1]Kłodzko, [2]Żelazno, [3]Wilkanów, [4]Gorzuchów, [5]Szalejów Dolny, [6]Kudowa-Zakrze ("zero" of this gauging station is different than at other stations), [7]measured at the mouth of Wilczka to Nysa Kłodzka.
*Ścinawka was analyzed from border in Tłumaczów.
**The area of all Ścinawka drainage basin.

length (Figure 2 and Table 2). Changes in the settlement development in river valleys have been observed in this region since the Middle Ages [26]. It was then that the first hydrotechnical constructions appeared in the channels. These objects were initially related to basic human needs such as water supply (small dams and water reservoirs) and communication (fords and bridges) and later to rapidly developing economic activity. From the eighteenth century, water mill construction was intensive in the Kłodzko County, and later came other types of industries using flowing water. Training works have been undertaken on a larger scale since the beginning of the nineteenth century. Channels were changed most intensively at the turn of the nineteenth and twentieth centuries. Various types of transversal and longitudinal training structures were built, e.g., weirs (about 1.5–2.5 m high), drop structures (up to 1.0 m high), hydroelectric power plants, leats (millraces), artificial channels, and different types of bank reinforcements (Figure 2). The next stage of systematic training works began in the early 1960s. These were projects mainly concerning bank protection (retaining walls) and new road bridges. The course of many channel sections was changed at that time. They were straightened, shortened, and narrowed. Transversal structures reduced the channel gradient and bed load transport. The verification of the functionality of the most hydrotechnical and bridge constructions in the channels came with the extreme floods in 1997 and 1998. Many facilities were destroyed or seriously damaged and had to be rebuilt. There was a short but intense period of training works after these events. Some objects were rebuilt using new technologies. Many training works have been started since 2007 as part of projects financed by the European Union and in fulfillment of *The program for the Odra 2006*. Some works are still in progress.

Nowadays, the rivers in the Kłodzko County area are regulated mainly for flood protection purposes. Training works comprise channel straightening and deepening and construction of hydrotechnical facilities and bank reinforcement (retaining walls, ripraps, and gabions). The number of hydrotechnical objects and the length of longitudinal structures vary among channels and even along sections of specific rivers (Table 2). An increase in the number of river and civil engineering structures is closely related to the settlement network and the main roads in the region. Facilities associated with old industrial activities are usually concentrated in the middle and lower sections of the channels. In the upper parts of the channels, regulated sections are mostly located in the vicinity of settlements (present as well as those already depopulated).



Weirs: a - Ścinawka Średnia, b - Gorzuchów, c - Piszkowice, d - Ławica, e - Dańczów, f - Szalejów Górny, g - Szalejów Dolny, h - Kłodzko Zagórze, i - Kłodzko, j - Ołdrzychowice Kłodzkie I, k - Ołdrzychowice Kłodzkie II, l - Stronie Śląskie, m - Stary Gierałtów, n - Bielice, o - Młoty, p - Wójtowice, r - Stara Bystrzyca, s - Bystrzyca Kłodzka
Dams: 1 - Międzygórze, 3 - Stronie Śląskie
Debris dams: 2 - Międzygórze

Figure 2: Location of the most important hydrotechnical objects and channel sections with continuous regulations (beginning from 2018).

Table 2: Hydrotechnical facilities and training structures in the analyzed rivers

River	Channel length (km)	Percentage of bank reinforcements relative to channel length	Number of objects	Number of objects per 1 km	Number of large damming objects (weirs, dams)	Number of small damming objects (steps, cascades)	Number of road and railway bridges
Nysa Kłodzka	57.0	14.9	153	2.68	4	32	79
Biała Lądecka	52.7	26.1	125	2.37	6	33	57
Wilczka	17.0	49.0	81	4.76	2	41	22
Ścinawka	24.0	9.8	42	1.75	3	2	26
Bystrzyca Dusznicka	35.0	33.5	198	5.66	9	96	67
Bystra	15.0	22.3	86	5.73	1	9	36

3 Methods

The contemporary morphology of the channels was studied between 2008 and 2015 during a river channel mapping. Many different quantitative and qualitative characteristics concerning the bedrock lithology, channel geometry, fluvial forms, and anthropogenic facilities were described. Where possible, the length, width, and height of fluvial forms were measured in the field with a tape or laser range finder. Others features, such as channel width and certain fluvial forms, were measured on orthophotomaps. On the basis of the form–process relationship, the main processes modeling specific channel sections were identified. The assumption was made that the dominance of specific channel forms identifies the process that models channels or sections of channels: (1) an alluvial channel with numerous large cutbanks and bars indicates lateral erosion and redeposition, (2) an alluvial channel with large bars indicates redeposition and deposition, (3) a bedrock channel with bedrock steps, outcrops, and evorsion forms indicates downcutting, (4) a bedrock channel with small bars and cutbanks indicates downcutting and initial redeposition and lateral erosion, and (5) lack of dominant forms indicates a channel modeled predominantly by transportation.

General changes in channel patterns and course as well as the land cover were analyzed using an orthophotomaps at a scale of 1:15,000 and 1:10,000 produced from aerial photos taken in 1958/1959, 1975, 1994, 2000, and 2015; German topographic maps Messtischblatt 1:25,000 available for the years 1883–1940; and Polish topographic maps at a scale of 1:10,000 (edited 1977–1983, 1998) and 1:25,000 (edited 1983, 2000). A comparison of these sources showed changes in channel patterns as well as changes in the distribution of erosion and accumulation zones. All cartographic materials were registered in ArcGis 10.5.2 software. Channels were digitized and compared. As a result, changes in the course and pattern of the channels between 1884 and 2015 were determined.

4 Channel changes in the Kłodzko County river systems

River channels in the Kłodzko County are transformed by humans in two ways: (1) the channels are trained by the so-called continuous regulation (retaining walls, stone claddings, ripraps, and drop structures), which usually results in their shortening and straightening and changes the longitudinal profile and (2) point objects such as weirs, debris dams, and artificial steps are built, which interrupt channel continuity; also objects related to road infrastructure are constructed. At present, continuous regulations (channel sections of a minimum length of 100 m with uninterrupted bank reinforcements) affect about 27% of the 300 km examined channels (Table 2). A considerable number of these structures were built before the World War II and in the 1970s and 1990s. Bank and bed reinforcements have been made in channel sections especially exposed to the negative effects of lateral and vertical erosion (strongly urbanized areas, the vicinity of hydrotechnical objects, and strongly meandering sections of the channels located in the vicinity of buildings or road embankments). In the channel sections affected by intense bed degradation (below damming objects), drop structures were built, and in some corrected sections, the channel bed in the vicinity of bridges or urbanized areas was stabilized. The last group of anthropogenic objects comprises structures related to road infrastructure. Field observations have shown that during base flows these objects do not usually affect the quality and intensity of morphological processes in the channels. Most often, the cross-sectional shape of a channel is changed as a result of channel profiling. Road structures are major obstacles in the river during flood flows. In the vicinity of these objects, significant changes in the functioning of the channels, such as the formation of flood channels or the intensification of lateral erosion, are possible. The effects of all these transformations are manifested in changing (1) channel patterns, (2) channel depth, (3) channel sinuosity, and (4) the location of erosion and accumulation zones.

5 Changes in downcutting

The process of vertical erosion in natural channels most often affects the upper sections of rivers or sections with an increased channel slope. The intensification of vertical erosion in regulated channels is primarily related to the location of transversal hydraulic structures, especially damming objects (debris dam, weirs, high steps, and drop structures [Figure 3 and Table 3]). The structures reduce channel gradient and bed load transport. All dams interrupt channel continuity and modify the longitudinal profile and sediment transport. In the upstream of these structures, the sediment is retained; while in the downstream, the energy of the flow increases and channel downcutting occurs [4,5,11,15,27–29]. This process dominates below damming structures. Downcutting was most efficient in the short-term after the construction of most objects and its intensity increases during extreme floods. At some objects, several zones of channel deepening occur. These structures have additional transverse elements that change the longitudinal profile of the channel (weir Ołdrzychowice Kłodzkie I and II on the Biała Lądecka River and weir Gorzuchów on the Ścinawka River). A maximum bed incision of 1 m was observed below the highest weirs in Kłodzko (Nysa Kłodzka River), Szalejów Górny (Bystrzyca Dusznicka River), and Ołdrzychowice II (Biała Lądecka River). Incomplete historical data prevent estimation of the rate of this phenomenon. However, even without precise measurements, it is clear that bed degradation in the channels of the Kłodzko County rivers was much slower than in Carpathian or Alpine rivers. Incised channel sections are relatively short, up to 1 km downstream of the damming structures (weir in Bystrzyca Kłodzka, Nysa Kłodzka River). Because of the increased channel incision downstream of many transversal structures, it was necessary to reinforce the bed, e.g., with drop structures. The longest river sections with drop structures are part of the Nysa Kłodzka channel below the weir in Bystrzyca Kłodzka (0.6 km) and sections below dams in Międzygórze (Wilczka River, over 0.2 km) and Stronie Śląskie (Morawka River, over 0.15 km). In many cases, downcutting was so intense that channels incised to bedrock (below the weir in Szalejów Dolny, Bystrzyca Dusznicka River, or Stronie Śląskie, Biała Lądecka River). In such a situation, the possibility of further downcutting is limited and the process ceases. Natural bedrock steps and changes in the longitudinal profile below the damming structures are the result of the downcutting. The analysis of archival aerial photographs and descriptions of the channel condition during training works indicated downstream extension of the zone of bed degradation. Therefore, the channel sections with drop structures were gradually extended (Bystrzyca Kłodzka, Stronie Śląskie, Międzygórze). In the analyzed channels, downcutting also results in the destruction of some training structures. Significant damage was observed in the downstream parts of hydrotechnical objects as well as in their reinforcement structures (e.g., weirs in Gorzuchów, Ołdrzychowice Kłodzkie II, Kłodzko). Downcutting is intensified below the already damaged objects and those in poor technical condition (e.g., old weirs in

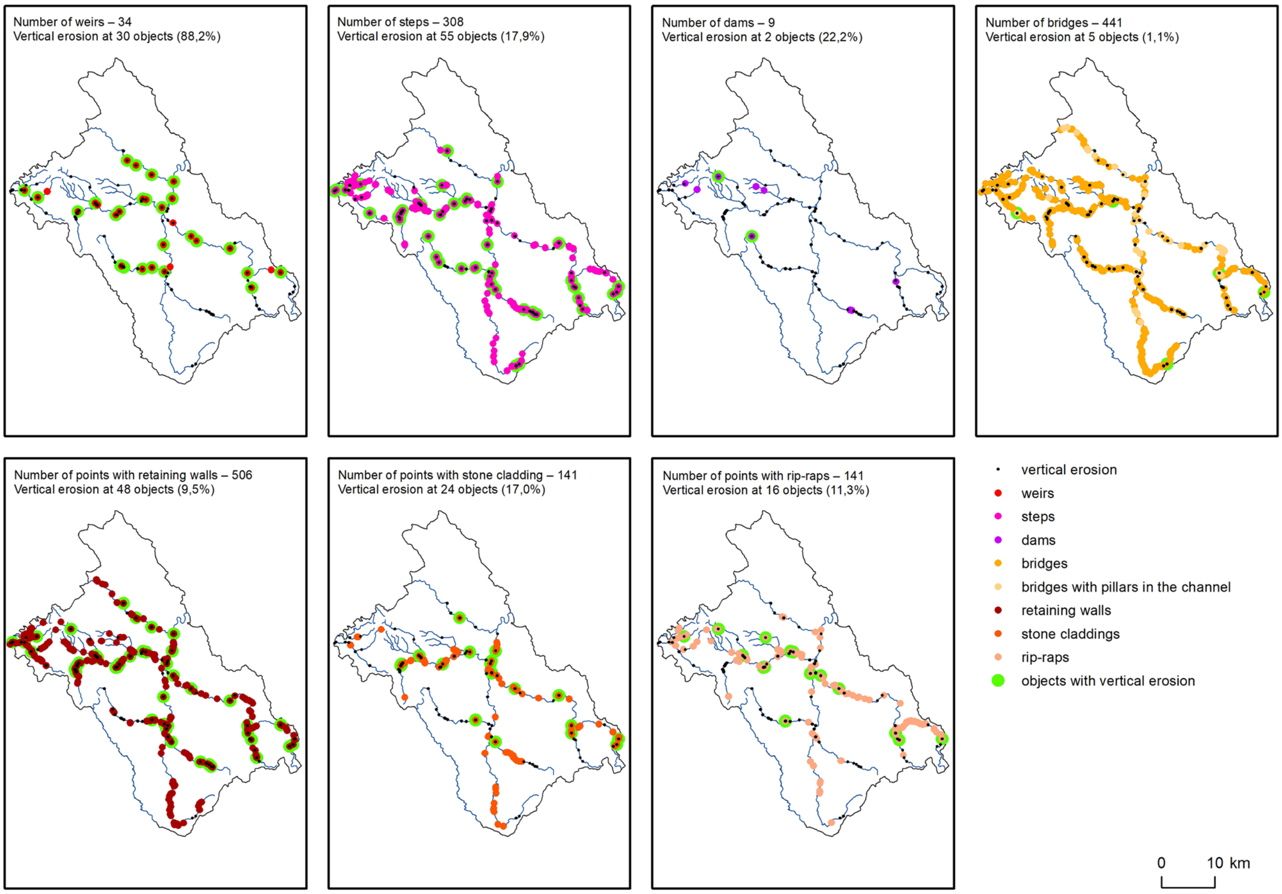


Figure 3: Location of the objects affected by vertical erosion.

Bielice, Stary Gierałtów, Biała Lądecka River). Bed-level lowering results in the exposure and undermining of bank-protection structures (retaining walls in Radochów, Biała Lądecka River) and pillars and abutments of bridges. In river sections where bed reinforcements (e.g., concrete slabs) were used in the vicinity of damming structures, displacements of structural elements below the current level of the bed are observed (weirs in the center of Kłodzko and Ołdrzychowice Kłodzkie II).

Intense downcutting is also observed downstream of the regulated channel sections, especially those with drop structures wherein increased bed erosion can be caused by several factors as follows: (1) removal of bed material or disturbance of the bed during training works, which may cause greater susceptibility of the material to entrainment (during some training works heavy machinery was used directly in the river channels, e.g., in Nysa Kłodzka and Biała Lądecka); (2) retention of some volume of the sediment above the steps (sections with drop structures) which increases the river's ability to erosion downstream of the regulated sections; (3) limited sediment supply to the channels caused by bank reinforcement construction; and (4) increase in flow velocity in the regulated channel sections. The highest values of channel incision of 0.5 m were observed in Nysa Kłodzka and Bystrzyca Łomnicka channels; Duszniki-Zdrój, Szczytna, and Polanica-Zdrój in the Bystrzyca Dusznicka channel; Biała Lądecka channel in Trzebieszowice; and also below the new training structures in the Wilczka channel in Wilkanów.

A relationship was also observed between the size of the erosional bed forms and the length of time since the construction of regulation structures. Channel incision is definitely more intense in the downstream of older structures. In the downstream of the sections with new regulations, no erosional bed forms were generally observed. The only exception is the Wilczka channel in Wilkanów, where only 2 years after the completion of training works, initial erosional bed forms were visible. In some cases, erosional bed forms were also found directly downstream the small drop structures, e.g., in the Wilczka channel in Wilkanów. These forms were observed below 18% of all the steps in the investigated

Table 3: Relation between anthropogenic objects and the occurrence of channel forms

Object	Number of objects	Objects with vertical erosion	%	Objects with lateral erosion	%	Objects with mid-channel bars	%	Objects with downstream obstruction bars	%	Objects with bars near the bank	%
Weirs	34	30	88.2	5	14.7	12	35.3	11	32.4	7	20.6
Dams	7	2	28.6	0	0.0	1	14.3	0	0.0	0	0.0
Debris dams	2	0	0.0	1	50.0	1	50.0	0	0.0	1	50.0
Steps	308	55	17.9	26	8.4	9	2.9	4	1.3	41	13.3
Cascades	8	2	25.0	2	25.0	0	0.0	0	0.0	1	12.5
Bridges	401	5	1.2	91	22.7	34	8.5	1	0.2	80	20.0
Bridges with pillars in the channel	40	0	0.0	12	30.0	4	10.0	12	30.0	15	37.5
Footbridges	202	7	3.5	27	13.4	4	2.0	1	0.5	28	13.9
Points with retaining walls	506	48	9.5	60	11.9	43	8.5	17	3.4	118	23.3
Points with stone cladding	141	24	17.0	18	12.8	16	11.3	7	5.0	26	18.4
Points with riprap structures	141	16	11.3	28	19.9	14	9.9	5	3.5	23	16.3
Gabions	60	9	15.0	7	11.7	5	8.3	0	0.0	8	13.3

channels (Figure 3 and Table 3). In four study sites (in the Dańczówka, Wilczka, and two sites in the Biała Lądecka channels) below the drop structures, the river incised to bedrock and the bedrock steps were observed. In the Kłodzko County river channels, downcutting is ineffective during normal flows. This process intensifies during flood events.

6 Changes in lateral erosion

In the regulated channel sections in the Kłodzko County, lateral erosion is not very apparent. However, this process currently models almost all river channels in this region. The lack of erosional forms in regulated sections of the channels shows that bank reinforcements generally successfully protect the riverbanks from lateral erosion. Exceptions are sections with old or partly damaged training structures. In these sections, undermining of retaining structures is observed, leading to the collapse of the bank reinforcements. Lateral erosion in regulated channel sections takes place most intensively in channel stretches with riprap. This type of bank reinforcements is least durable. Cutbanks were identified at 20% of test areas with riprap, 13% of places with stone cladding, and 12% with retaining walls (Figure 4 and Table 3). The highest number of damaged riprap structures was observed in the Nysa Kłodzka channel, where over 45% of all test areas (in this channel) with this type of bank reinforcement is found.

A characteristic phenomenon observed in peripheral sections of bank reinforcement in all analyzed channels is the intensification of lateral erosion in the areas of contact between protected and natural banks (Figure 5A and B). The occurrence of zones of increased lateral erosion was observed for nearly 90% of such areas [23,25]. In these places, new cutbanks were formed. These forms vary in scale, ranging from several centimeters to 1.5 m. In most cases, only the intensification of erosion takes place; cutbanks are larger than those in other fragments of regulated channel sections (Figure 5A). However, there are places where lateral erosion below the regulated sections is so strong that the retaining walls break and sometimes collapse (Figure 5B). Some undercuts are stable; during the period of observation, no signs of bank retreat were noticed. Most erosional forms, however, are constantly active, with progressing bank retreat. In the undercuts, landslides occur and turf overhangs and the exposed roots of trees growing on the banks are visible. Although

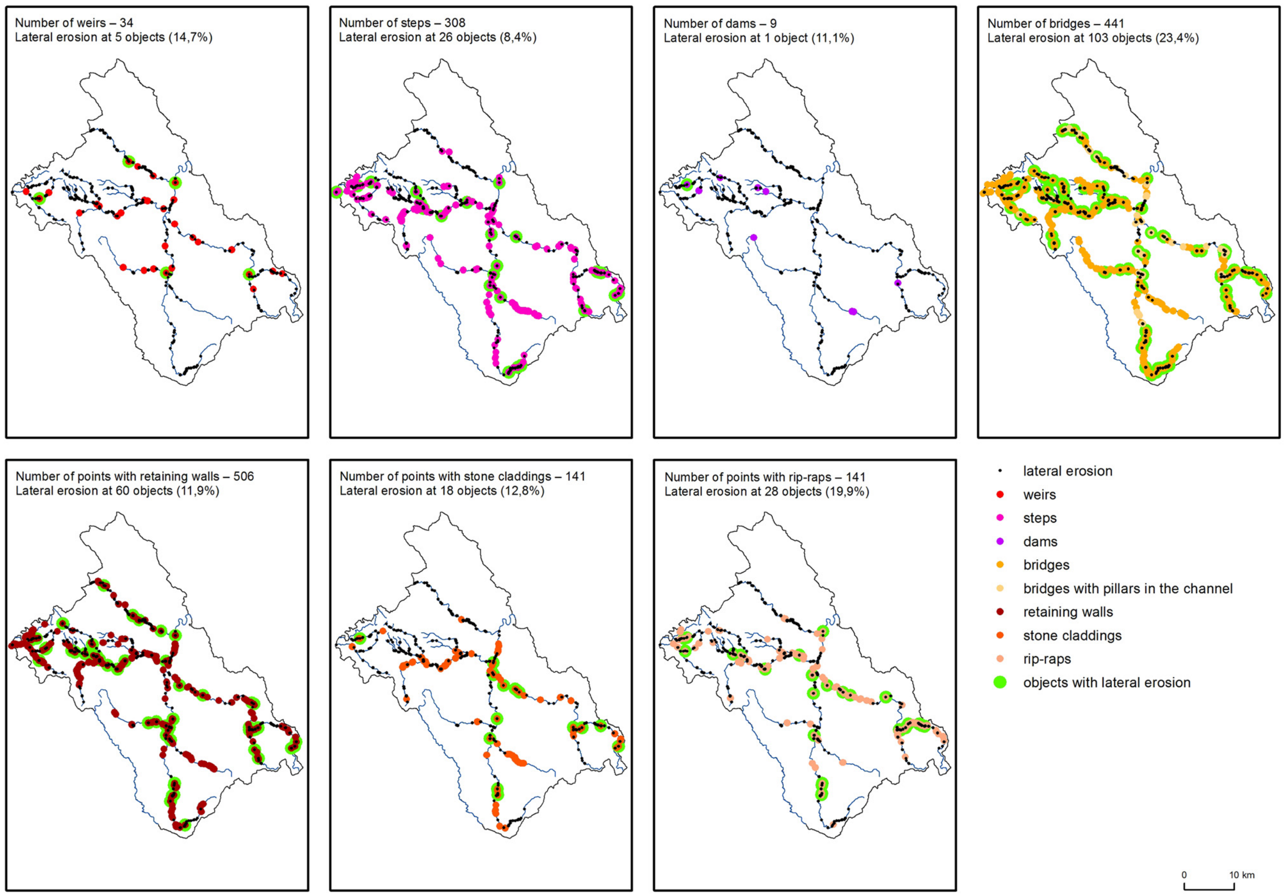


Figure 4: Location of the objects affected by lateral erosion.

lateral erosion is the dominant process currently modeling the analyzed channels, its progress is stopped in many places by construction of bank reinforcements. These structures, however, do not completely eliminate adverse effects of lateral erosion but only move the erosion zone downstream [18,25].

Additional zones of lateral erosion are formed in the vicinity of hydrotechnical and road structures. In its cross sections, intensification of lateral erosion on the contact of protected and natural bank is observed. This situation is similar to that described above from channel sections below hydraulic structures. Here, the undercuts reach significant dimensions – up to 10 m in length. The formation of larger forms of lateral erosion in the vicinity of hydrotechnical objects is the result of flow concentration and increase in flow velocity. In cross sections of damming objects, the riverbanks are usually reinforced with retaining walls whose continuity is varied. Some objects are located in continuous bank reinforcements. In these situations, intensification of lateral erosion generally is not observed at all, thus proving the effectiveness of the bank reinforcements. In some cases, mainly in the vicinity of the objects located in upper river sections of the channels, undermining of bank reinforcements was observed. This mainly concerned old, partially destroyed training structures. Zones of intense lateral erosion were observed at 15% of the damming objects analyzed (Figure 4 and Table 3). In the most spectacular cases, the channels widened by 50% of their width. Lateral erosion forms are formed directly below the cross section of the objects with retaining walls. In the vicinity of other hydrotechnical structures, small changes in the course of banks occur; however, the erosional forms do not reach considerable dimensions.

Erosive processes have their strongest effect in the vicinity of partially neglected objects, where damage of bank reinforcements has already occurred. Undercuts are intensely modeled here, especially during higher water levels. The rates of undercut retreat equal to about 10 cm in 4 years for the weir Ołdrzychowice II (Biała Lądecka River) and over 20 cm for the weir in Ścinawka Średnia (Ścinawka River). The erosion zone near the weir in Ścinawka expands not only downstream but also

Figure 5: (A) Intensification of lateral erosion in peripheral sections of bank reinforcement in Polanica-Zdrój, Bystrzyca Dusznicka River; (B) destroyed retaining wall in Stronie Śląskie, Biała Lądecka River; (C) accumulation zone below the weir in Piszkowice, Ścinawka River; and (D) sediment shadow below the bridge in Tłumaczów, Ścinawka River.

upstream, currently reaching upstream of the bank reinforcements. Destabilization of the river banks affects the foundation of the retaining walls, which systematically fall down. In the case of weirs where channel shortening also occurred, eliminating previous meanders (e.g., the weir in Ławica, Nysa Kłodzka River), increased lateral erosion is observed in the places of removed river bends. Lateral erosion leads to channel widening, which is associated with the river's tendency to return to its previous preregulation channel course. A remarkable intensification of this process is observed during floods (channels widened even twice).

Lateral erosion also gets activated at the anthropogenic objects connected to road infrastructure. Undercuts are observed at almost 23% of all structures (at 37% of bridges with at least one pillar located directly in the riverbed [Figure 4 and Table 3]). Erosional forms occurred at almost all bridges regardless of their location in the channel. In some channels (e.g., Nysa Kłodzka, Biała Lądecka), more forms of lateral erosion are found in the upper river sections. However, these forms are definitely smaller than the undercuts forming in the middle and lower sections. In the studied channels, the undercuts adjacent to channel bars are the most common erosional forms occurring close to the road structures. However, there are also rivers in whose channels these undercuts hardly form at bridge constructions (e.g., in the Wilczka channel undercuts appeared at 10% of the structures of these types). A very important factor determining the formation of erosional forms is the presence of bank reinforcement in the vicinity of bridges. When the pillars of a bridge are an integral part of the retaining walls, the effects of lateral erosion are usually limited to a minimum. Exceptions are objects with old or damaged bank reinforcements, where undermining of pillars is observed. The location of objects, in the vicinity of which no erosive forms were observed, is strongly linked to the course of regulated channel sections (Figures 2 and 4). The best example is the Wilczka channel, especially in Wilkanów, the Bystrzyca Dusznicka in Duszniki-Zdrój, and the Nysa Kłodzka near Międzylesie. If bank reinforcements occur in the vicinity of bridge structures, then lateral erosion is intensified in their peripheral parts. This is a phenomenon similar to that observed in the case of continuous training structures and damming objects. The risk of lateral erosion increases when bank reinforcements were made only in the direct vicinity of bridges. Among the objects analyzed, there were several cases of damage to training structures that protect the pillars of bridges and also to pillars themselves. Such a situation happens mainly at the objects that have not been modernized for a substantial period of time. These structures are usually located in smaller channels or in channel sections outside the urbanized areas. Examples of such objects are bridges in the upper section of Biała Lądecka channel in Stary and Nowy Gierałtów and in Bielice, Bystrzyca Dusznicka channel above Duszniki-Zdrój, Ścinawka channel below Ścinawka Dolna.

7 Changes in accumulation

Changes in the distribution of accumulation zones in river channels of the Kłodzko County are mainly related to the location of damming objects and road infrastructure facilities (Figures 6 and 7). Accumulation forms are generally scarce because of limited sediment supply from the slopes to the regulated sections of channels. It should be noted that the analyzed rivers do not transport large amounts of sediment, and the material accumulated in the channels originates mainly from bank erosion. In fact, lateral erosion in regulated channel sections has been completely stopped; hence, no accumulation forms are observed in these sections.

The accumulation of mineral material is observed above all damming objects (minimum height of 1 m). It leads to siltation of dam reservoirs, thus limiting the retention capacity of the objects and their functionality. This process occurs with varied intensity for different objects. In the case of smaller objects, organic obstructions were also observed, which completely blocked the water flow. As a consequence, even at normal water stages, uncontrolled flooding areas occur above the structure. The rate of siltation of the reservoirs depends primarily on the type and amount of material transported by the rivers. In the Kłodzko County, the objects in the Wilczka and Ścinawka channels are filled fast. The weir reservoirs are usually filled with sandy, sometimes gravel material. It can be supposed that during the period of operation of the industrial facilities for which dams were built, the reservoirs were regularly cleaned of accumulated material to maintain their retention capacity. Currently, some objects no longer have their original function. They are not regularly cleaned and maintained in good technical condition. They no longer

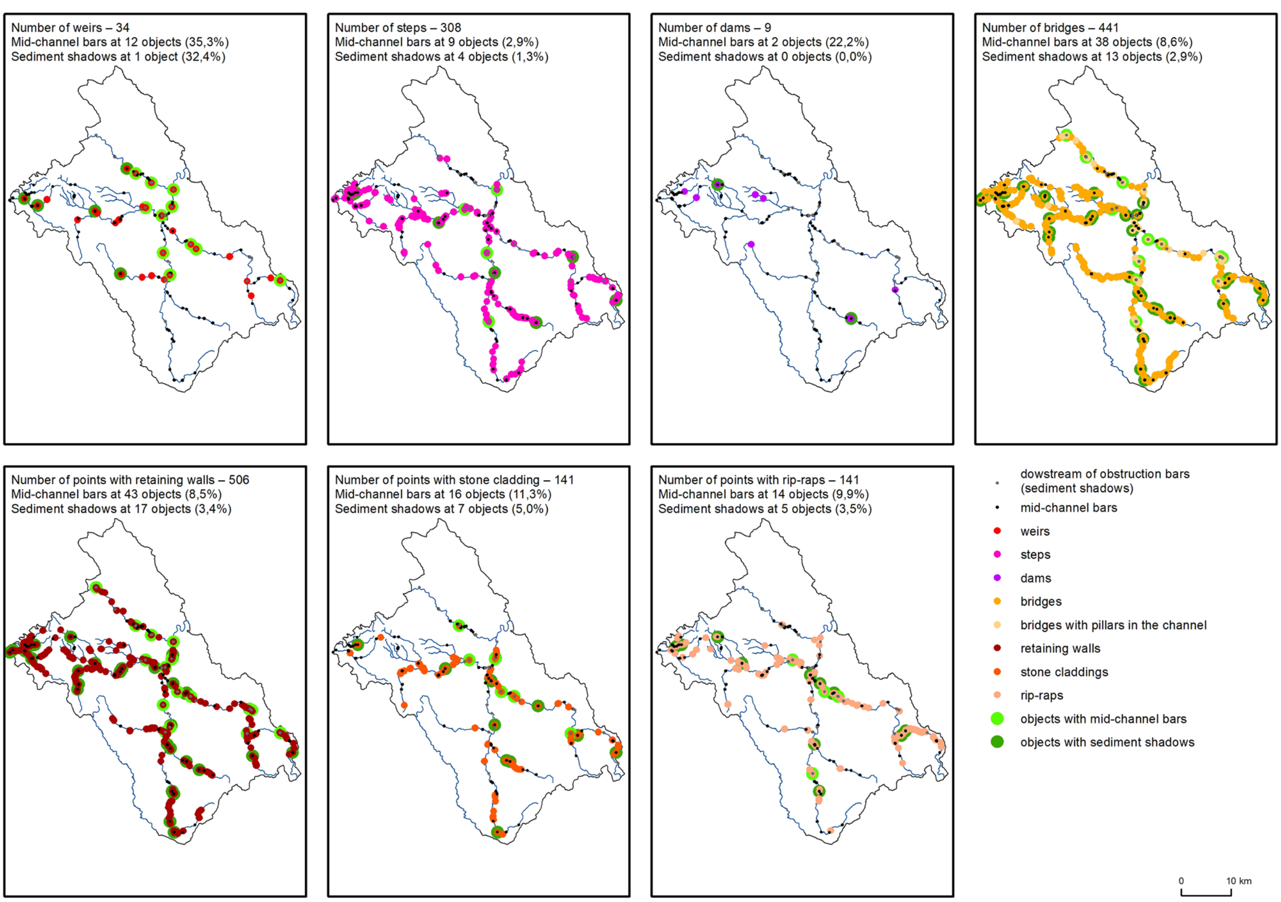


Figure 6: Location of the objects affected by sediment accumulation (mid-channel bars, sediment shadows).

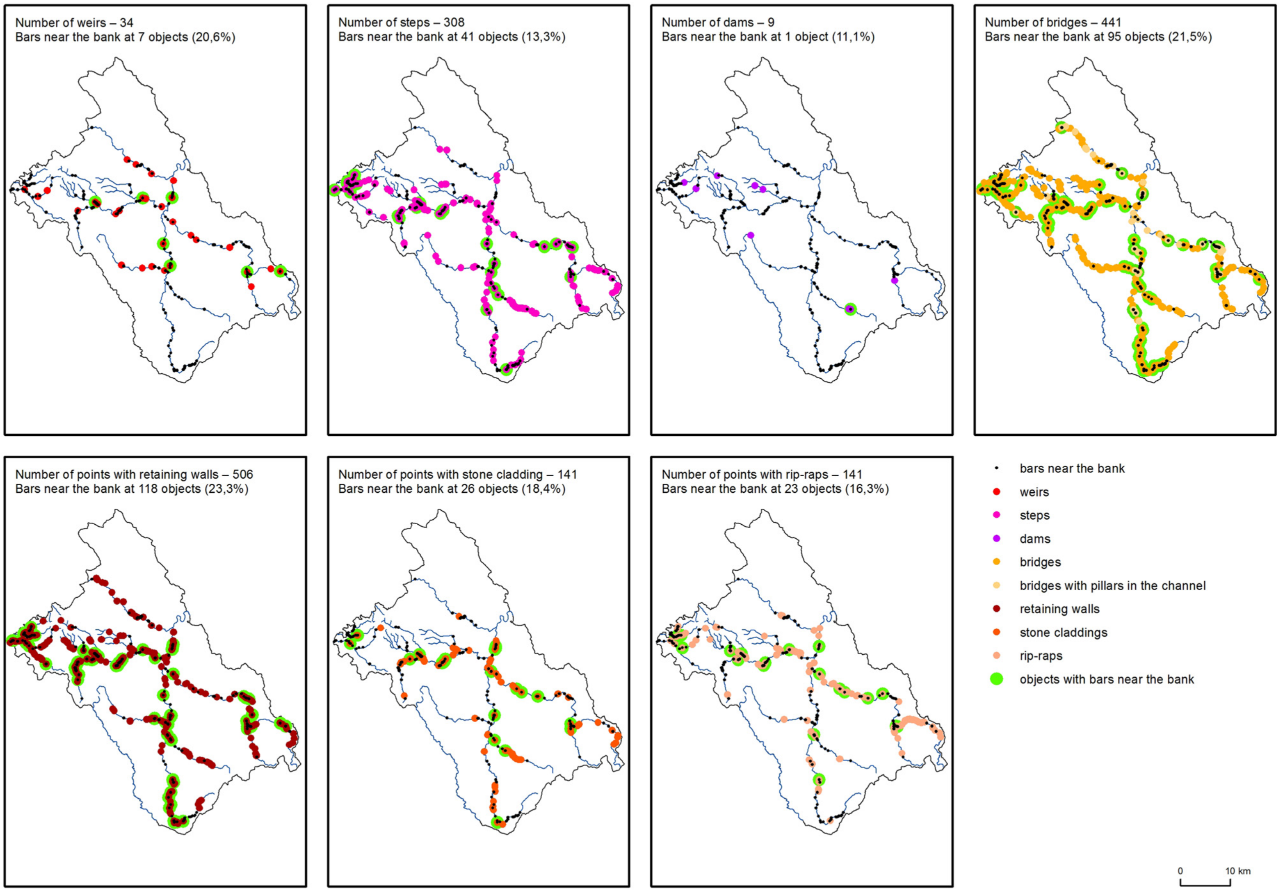


Figure 7: Location of the objects affected by sediment accumulation (bars near the bank).

maintain their retention capacity but also increase the risk of flooding (the bottom level is raised and when the water level is higher, it leads to flood). The most spectacular example of the total siltation of a weir reservoir is the object in Piszkowice (Ścinawka River), where during the base flow conditions, practically all flow are directed to a millrace and only the water leaking through the damaged weir flows into the river channel. During high water stages, water overflows the weir on its whole length, causing additional damage. The weir at Piszkowice is also the best example of bed aggradation. This process also affects a channel section of about 100 m above the weir. Sediment deposition in weir reservoirs is also observed in the objects in Gorzuchów and Ścinawka Średnia (Ścinawka River), Kłodzko Zagórze (Bystrzyca Dusznicka River), Stara Bystrzyca, Wójtowice, and Młoty (Bystrzyca Łomnicka River). The lack of detailed historical data makes it impossible to quantify the rate of bed aggradation. Sediment accumulation above damming objects results not only in weir reservoir siltation but also in the formation of accumulation zones (point and meander bars). These forms are best seen in the vicinity of large objects, e.g., the reservoir of the debris dam in Międzygórze (Wilczka River). Since its construction in 2001, accumulation forms with a maximum height of 1 m have been formed directly above the dam. These forms also have a relatively large area (up to 25 m in width). The short time frame of their formation indicates a very intense accumulation in the reservoir. The debris dam in Międzygórze is located in the upper river course at the mouth of the Wilczka Gorge. The river transports coarse mineral material in this section, which is also important for the accumulation rate above the debris dam. Accumulation forms above damming objects were also observed at the weir in Ołdrzychowice Kłodzkie I (Biała Lądecka River), at the weir above Młoty village (Bystrzyca Łomnicka River), and above the ruins of the weir in Dańczów (Dańczówka stream). Above some objects, accumulation forms, which are completely submerged at the base level, can be observed during low water levels (e.g., the weir in Gorzuchów).

A characteristic feature of most damming objects in the Kłodzko County is the presence of an accumulation zone downstream of these objects (Figure 6 and Table 3). These forms are usually composed of fine materials transferred through the structure and deposited just below it. These bars are usually triangular in shape and elongated in the direction of flow. Some of them have the form of classic elongated channel bars (Figure 5C). As mentioned above, incomplete historical data preclude the estimation of the enlargement rate of these forms. The exceptions are bars formed at the largest weirs, for which it is possible to reconstruct their dimensions from the past, e.g., the accumulation form below the weir in Kłodzko (Nysa Kłodzka River). In general, accumulation zones below the damming objects are not longer than about 50–100 m. In the vicinity of just a few objects (Kłodzko, Bystrzyca Kłodzka, Ołdrzychowice Kłodzkie I – the largest forms approximately 250 m long), these zones are longer, but they do not have a homogeneous compact form. They are rather sets of individual forms of different dimensions. The bars below the damming objects are at various stages of stabilization. In most cases, they are partially covered with grassy vegetation, but there are also forms on which bushes and small trees are already growing (Kłodzko). Accumulation zones below larger damming structures occur near all objects in the Ścinawka channel, nearly 64% of facilities in the Bystrzyca Dusznicka channel and Kamienny Potok, 50% of the structures in the Nysa Kłodzka channel, and around 44% of damming objects in the Biała Lądecka channel (Figures 6, 7 and Table 3). The accumulation zones below the structures are not formed at all objects with a height of up to 1 m, or the bars do not have a compact clear form that can be measured. The results of our observations also reveal the following relationship – these accumulation zones are formed primarily below the damming objects located in the middle and lower sections of the channels, where sediment accumulation is usually more efficient than in the upper sections.

A significant role in the formation of accumulation zones is played by objects related to road infrastructure, in particular bridges, especially those that have structural elements located directly in the channel. The bars adjacent to river banks were most often formed in bridge cross sections (at 34% of all objects), as did mid-channel bars located downstream of pillars situated in the channels (at 30% of all objects) and wood jams (at 25% of all objects [Figure 6 and Table 3]).

It is the type of material from which the river banks and beds are composed, and the possibility of its delivery from the hillslopes to the channel, rather than the type and size of the structure that has the most crucial influence on the formation of accumulation forms in the vicinity of road infrastructure. Most of the large accumulation forms in the bridge cross sections were observed in the Ścinawka channel. Along the entire analyzed section, the river flows in fine sediments. During base water stages, the river mainly transports sandy material. This material forms most of the channel bars. It should also be noted that in the Ścinawka River, the material from bank erosion and hillslopes can be relatively easily delivered to the channel because this river has the smallest percentage of regulated banks – only 9.8% of the length of the analyzed section (Table 2). The relatively frequent channel–slope coupling results in a more efficient sediment accumulation in the channel. Large accumulation forms (up to several meters in length) in the vicinity of bridge cross sections were also observed in the Nysa Kłodzka channel between Bystrzyca Kłodzka and Kłodzko where bank reinforcements are almost lacking. Configuration of some bridges intensifies sediment accumulation. The size of some bridges (in the Nysa Kłodzka, Biała Lądecka, Bystrzyca Dusznicka, and Ścinawka channels) demonstrates that they have elements (pillars and pillar reinforcements) located in the channel, partly under water. These elements narrow the active channel. They are obstacles that obstruct mineral and organic materials. In such bridge cross sections, the channel bars form more often and grow faster. Downstream of obstructions, bars form (the so-called sediment shadows) at bridges with pillars located directly in the channel (Figure 5D). These forms are observed at almost 70% of all bridges with at least one pillar located in the channel (Figure 6 and Table 3). Some of these forms reach considerable dimensions, even up to 30 m in width. In other bridge cross sections, the channels below the bridges are often shallower, which may indicate increased sediment accumulation. Some of the accumulation forms are submerged. Field observations have shown that the location and size of sediment shadows do not depend on the type and size of the structures below which they form. The most important factor for their formation is the quantity and type of material transported in the channel. As in the case of other accumulation forms, most sediment shadows are formed in the Ścinawka channel (Figure 5D). Most of them are composed of sandy material and partially stabilized by vegetation. These forms tend to grow fast but as sand is not cohesive, they are easily eroded at higher water stages, so no systematic enlargement of these forms was observed. In the other analyzed channels, especially in the middle and lower sections of the Nysa Kłodzka and Biała Lądecka rivers, it is also possible to observe sediment shadows; however, they are not so spectacular compared to those in the Ścinawka channel. They are not characterized by so high dynamics as the sand shadows below the bridges at Ścinawka.

8 The geomorphological effects of river training during flood events

Most of the phenomena described above are intensified during flood flows. Sometimes the channel is completely remodeled, and, thus, the number, size, type, and distribution of channel forms change. The primary purpose of the training works was to convey flows through urbanized areas as quickly as possible. However, the result of excessive straightening, shortening, and narrowing of the channels was the initiation of bed erosion downstream of the regulated channel sections during floods. This is the effect of increasing channel slope and flow velocity in the regulated sections. Longitudinal erosional forms are visible on channel beds (the best example is the section of the Biała Lądecka channel in Lądek Zdrój). After floods in 2009 and 2011, several new zones of bed degradation formed directly below artificial steps in the channel sections with drop structures (e.g., Wilczka River in Wilkanów, Biała Lądecka River). The already existing erosional forms enlarged. Also, lateral erosion becomes distinctly stronger during floods. Erosional tendencies in peripheral sections of bank reinforcements are intensified during events. A good example is the flood of June 2009 in the Biała Lądecka channel, during which bank undercuts on the contact of reinforcements with the natural banks significantly increased [30].

The presence of any obstacles in the channels during floods has great importance for safe conveyance of flood flows. This applies to all objects interrupting the natural channel continuity, especially transverse structures (damming objects and bridges). During floods more water flows over the damming objects, and its velocity and, thus, erosive ability increase, which causes more efficient downcutting directly downstream of the object. The most spectacular changes are observed in the vicinity of the structures. A frequent phenomenon is damage to bank and bed reinforcements and structural elements downstream of the objects. Analysis of archival materials, the results of 5 years of field observations, and interviews with local inhabitants allow us to state that the largest morphological changes in the vicinity of damming objects occur during floods. These changes vary in characteristics, from remodeling erosion and accumulation zones in the vicinity of the objects through the creation of new erosion and accumulation zones, cessation of erosion, and (or) accumulation processes in the neighborhood of some structures to channel avulsion triggered by the blockage of water flow in the cross sections of damming objects (the weir in Radochów, Biała Lądecka River, during the 1997 flood).

Bridges are also serious obstacles for flood flows. Many of them are too small for free water flow during extreme flood events. A flood is a test for each bridge verifying whether its construction parameters have been properly chosen. There are many examples of large undercuts of various ages above these objects. This is the result of a backwater effect caused by flow constriction in bridge cross sections. A great example is the bridge in the Ścinawka channel in Gorzuchów. On the right bank, there is a large cutbank formed during floods in 1997, with the bank retreated by several meters. A similar case is the railway bridge on the Nysa Kłodzka River in Kłodzko. A large undercut originated on the right bank and the right bridge pillar was undermined.

During floods in bridge cross sections, not only is lateral erosion intensified but also accumulation of mineral sediment and large wood takes place. In this case, the most important are bridges with structural elements located directly in the channel, because these elements obstruct the transfer of mineral and organic materials. There were several small flood episodes during the observation period, when the formation and enlargement of the already existing accumulation forms were observed.

9 Discussion

Over recent decades, channel changes increased and accelerated as a result of various human activities. Many studies have proved a strong dependence between human intervention in the channels and their reaction to the disturbance and also their adjustment to new conditions [4,14–18]. Changes in channel morphology and functioning occur as a result of direct (channel regulation, construction of hydrotechnical objects, especially damming structures, and gravel mining) and indirect (land use change, deforestation, and urbanization) human interventions. However, the effect is always the same – the amount of sediment delivered to the channel changes, and, thus, the relationship between the load of the river and its transport capacity is disturbed. The most common channel transformations are modifications of channel pattern, depth, and width and changes in the location of erosion and accumulation zones [2,4,31–42]. This situation is typical of most mountain rivers and streams. The same trends are observed in Polish rivers [1,10–12,19,27,43–47].

It is very difficult to present specific values characterizing the morphological changes of channels in the Kłodzko County because of the lack of historical data. Hitherto, no studies of the human impact on channel changes in this region have been carried out. However, available sources and our field studies allow us to indicate consistent tendencies in the channel adjustments to specific anthropogenic transformations. Most of the presented results are therefore qualitative.

Because of a smaller size of the studied rivers and the varying characteristics of their channels, the scale of the occurring phenomena is not so spectacular as in the case of gravel-bed Carpathian or Alpine rivers. A comparison of these fluvial systems indicates that the distribution of erosion and accumulation zones and hence the zones of intensification of these processes are similar; however, in the Carpathian and Alpine areas, the dynamics and spatial extent of the processes are much higher and the reaction of channels to environmental changes is much faster.

In the study area, the dominant process is lateral erosion, and sediment accumulation in base flow conditions is very inefficient, which distinguishes the Sudeten channels from the Carpathian channels, where the main process forming the river channels nowadays is bed degradation [11,13,27,29,45]. The location of channel sections where the process is the most effective in the Kłodzko County rivers corresponds to the distribution of similar zones in the Carpathian and Alpine channels. The incised channel sections were recorded below the highest damming objects and channelized sections of the rivers. Channel incision of 1.3–4 m is very common in the Polish Carpathians [5,10–13,45]. These values correspond to the scale of channel downcutting in mountain catchments worldwide, ranging from 2 to 10 m or more [3,4,8,9,15,32,33,36–38,48]. In rivers of the Kłodzko County, these values are definitely lower, ranging from 0.5 to 1 m below the highest damming objects. A similar depth of bed erosion forms – about 0.6 m – below small debris dams was found in the channel of the Spanish river Rogativa [39]. Bed erosion zones are located in the close vicinity of the objects in both regions. They do not continue for long distances as in the Carpathian [11,27,29,45] and Alpine rivers [4,34].

In the Carpathian channels below hydrotechnical facilities, sections with bedrock steps are common. This indicates very efficient channel deepening [45]. In the Sudeten rivers, sections with bedrock steps are definitely scarcer, which reflects the presence of thicker cover of alluvial sediments in Sudeten channels. This indicates a long-term accumulation trend in these channel sections.

Construction of hydrotechnical objects, especially transversal ones, in river channels disrupts their continuity. The rivers adapt to the new situation. That is why in most transformed channels downcutting occurs directly after the construction of training structures, which is when the process is also most effective [32].

In Carpathian and Alpine rivers, downcutting was accompanied by a narrowing of the channels [4,5,34,45]. In the Kłodzko County, the situation is slightly different. Today, the channels are formed mainly through lateral erosion; however, changes in channel width are usually very small. Effects of lateral erosion are also observed in reinforced channel sections, especially directly below regulated sections as well as in the peripheral parts of bank reinforcements (on the boundary between the reinforced and natural banks) and also in sections with damaged training structures. A similar phenomenon was observed in the regulated river channels in England and Wales [6] and in the Carpathian channels of the Biały Dunajec and Porębianka River [45]. The mechanism of lateral erosion below the regulated channel sections in all regions is the same: the erosional action is limited in the trained sections, so the river directs its energy to erode the banks below the reinforced sections. The scale of this phenomenon is diversified, depending on the region. The process is the least efficient in the Sudeten channels. The changes in river width ranged up to 56% in the channel parts where erosion is most efficient. This concerned mainly the middle and lower sections of the Nysa Kłodzka and Ścinawka rivers. As in the case of bed degradation, such small changes in channel width result from the significant stability of the Sudeten rivers. Changes in channel width of the Sudeten rivers as well as the Carpathian and Alpine rivers vary based on the longitudinal profile. The most significant transformations take place in the lower sections; while in the upper sections, the channel width remains rather stable.

At the base water level, sediment accumulation is not very efficient in the Kłodzko County river channels. In Carpathian and Sudeten rivers, the problem of bed aggradation mainly concerns channel sections above debris dams, weirs, and high steps [5,25,45]. These places favor sediment accumulation because transversal hydrotechnical objects are obstacles in river channels which trap the sediment. This phenomenon occurs on a much larger scale in Carpathian channels, mainly because the Carpathian rivers transport much more sediment, and its supply from hillslopes to the channels is higher and the resistance of river banks and bed to erosion is lower. Channel aggradation above damming objects was also observed in the United States [3] and Spain [39,49].

All the above discussed processes and morphological changes in mountain channels caused by human activities are intensified during floods. Flood events generally accelerate the morphological changes that already take place in the channels. In regulated channels, often with steepened slope, the velocity of flows (and thus their erosive force) is increased, which usually results in channel downcutting downstream of the training structures [27]. Channelized rivers are characterized by changed channel parameters, which together with the bank and bed reinforcements considerably limit the retention of floodwater and the accumulation of overbank sediments. This results in an increase of flood risk in channel sections below the training structures [2,6,27,44,50–52]. Similar cases, but on a smaller scale, occur in Carpathian rivers and in the channels of the Kłodzko County. For example, during the 1998 flood, the training structures in the Bystrzyca Dusznicka channel in Polanica-Zdrój were completely destroyed.

The majority of rivers try to return to their preregulation channel during floods. All engineering structures then become serious obstacles to flow. Very often, they are destroyed or seriously damaged. The best examples are bridges, which are destroyed or cause channel avulsion during floods. This is why the course of the Wilczka channel in Wilkanów changed during the floods in 1997 [20]. When a river tends to return to the former channel pattern, the efficiency of erosion increases. Lateral erosion occurs even in reinforced channel sections, which leads to the destruction of the training structures.

In the Kłodzko County, even during floods, the impact of individual anthropogenic objects on the formation of erosion and accumulation zones is in most cases local and limited to the vicinity of the structures [23,25,53].

10 Conclusion

The channels of the main rivers in the Kłodzko County have been strongly influenced by human activities since the end of the nineteenth century. The reasons, type, and time frame of these changes are very similar to those which occurred in other European mountain regions but the magnitude is different.

The morphological changes were the most intense immediately after the onset of training works in analyzed channels, as in other channelized mountain rivers. Therefore, it can be considered that hydrotechnical objects and training structures are important factors leading to changes in channel morphology and functioning. However, the research conducted showed that it is not the only factor causing channel transformations. As a result of different characteristics of the Sudeten channels and their greater stability, training works do not always cause such drastic effects as in Carpathian or Alpine rivers. Moreover, the research revealed situations where no radical changes in channel morphology occurred after the training works as well as situations in which changes similar to those observed in regulated channel sections were also occurring in nontransformed sections, which suggests a significant impact of natural environmental conditions.

Each channel regulation, especially the construction of transverse objects, interrupts the natural continuity of the channel in the longitudinal profile. This results in the creation of channel sections, which, although located close to each other, often develop quite differently. The efficiency and intensity of the channel processes often change on the boundaries of such sections as the river tends to adapt to the new situation. Channel reactions to specific human interventions have long been recognized. Some rivers are more sensitive to disturbance, while the reactions of others may be even imperceptible. Such a difference in the response to training works can be observed between gravel-bed Carpathian rivers, which had a tendency to braiding in the past, and more stable Sudeten channels. In the Sudeten rivers, both the spatial scale and rate of change are much smaller.

The research conducted in the river channels of the Kłodzko County showed that the influence of river training on mountain channel changes is visible; however, no clear relationship can be found between the occurrence of engineering structures and the development of fluvial forms. In contrast, the coexistence of erosional and accumulation channel forms with some types of hydrotechnical structures was often noticed, and their influence on intensification of morphological processes in the vicinity of the structures was observed, especially during floods [18,20,25]. Hydrotechnical structures in channels undoubtedly influence the formation of fluvial forms and accelerate their development.

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