S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
vol. LVI–LVII 2022–2023: 51–78 PL ISSN 0081-6434

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KEY CAUSES OF CHANGES IN THE SOŁA RIVER CHANNEL IN THE OŚWIĘCIM REGION OF SOUTHERN POLAND IN THE 18TH AND 19TH CENTURIES

Abstract: The study consisted of an analysis of changes in the course of the Soła River and covered the section of the river situated in the Carpathian foreland. A detailed analysis was performed for a 3.5 km section of the Soła valley in the vicinity of Oświęcim – a midsize city in southern Poland. The aim of the research was to evaluate natural and anthropogenic determinants of runoff formation and the resulting erosion, transport, and aggradation of sediments in the Soła river channel. The study covers the time period from the late 18th century to the late 19th century with a special focus on the years 1812 to 1875 or the final phase of the Little Ice Age. The materials used in the study include detailed maps of the Soła valley (scale: approx. 1:6,000 or 1:8,000) as well as maps at the scale 1:28,800. The detailed maps were created by the Galicia Water Management Bureau in Kraków for local projects associated with river regulation works. Medium-scale maps were produced in chronological order: (1) first military map of Galicia called Mieg's Map during the era of Emperor Joseph, where the cartographic work was managed by the Headquarters of the General Staff, (2) second miliary map of Austria-Hungary created during the reign of Emperor Francis. The present study employs military maps of Galicia and Bukovina created based upon a generalization of available cadastral maps. These materials are characterized by a significant degree of detail and cartometric finesse. Twenty six maps of the studied section of river were used in the study. The research helped to determine changes in the pattern of braided and anastomosing rivers with gravel bed channels flowing across mountain foreland areas. The channel pattern was found to change in the studied section following every high water stage. The changes included shifts in the location of the actual channel as well as variations in depth. In some cases the river channel would become deeper or wider, while in other cases it would become filled in with sediment. Significant changes in the studied river's system were noted as a result of variations in the climate and due to human impact in the Soła river channel and along its tributaries. The width of the Soła channel declined from about 80 m to about 60 m, while maximum depth increased from 2.2 m to 3.2 m, main river channel length declined from 3.48 m to 2.99 m, and the total length of lateral channels declined from 4.20 km to 3.46 km. The sinuosity of watercourses also decreased, while the studied multi-channel river in effect became a single-channel river featuring multiple currents.

Keywords: development of a river channel, watercourse regulation, anthropogenic pressure, river channel pattern, Carpathian foreland

INTRODUCTION

Fluvial processes leading to erosion or aggradation are determined by a variety of different elements of the geographic environment. The most important of these are geology and relief as well climate conditions, vegetation cover, and the water balance. One other crucial part of this picture is human impact leading to changes in vegetation cover due to deforestation and shifts in agricultural production. Additional key factors include forced changes in river channel course – both in the horizontal and vertical directions. Human impact in the form of channel regulation, debris extraction, and the construction of levees, dams, and weirs further affects river channel patterns. All of these determinants are closely connected with one another and together shape fluvial patterns. Such change processes occur slowly in some channel sections and may be quite difficult to alter even due to human impact. In other sections changes may occur rapidly and abruptly even when meaningful human impact is not a regular occurrence (Klimek 1979).

Large Carpathian river channels have experienced many changes over the years related to environmental factors and human impact, the exact nature of the changes depending on the drainage basin in question (Woskowicz-Ślęzak 2012; Wyżga et al. 2013; Krzemień et al. 2015; Witkowski 2017; Krzemień, Gorczyca 2021a). In their natural state Carpathian rivers flowed atop gravel beds and would normally adapt to changes occurring along their tributaries. River channel systems were characterized by different stages of adaptation to new environmental conditions affecting each river channel in its longitudinal profile. Downstream sections of Carpathian rivers tended to be characterized by single-current flow (meandering), both sinuous and braided, as well as by the presence of anastomosing channels. These channels are no longer found in Poland in our times, but can be observed on Austrian and German maps, at various scales, from the 18th and 19th centuries (Woskowicz-Ślęzak 2012; Witkowski 2017; Czaja, Rahmonov 2017).

Cartographic materials from the 18th and 19th centuries make it possible to assess the channel pattern for Carpathian rivers along with its pattern of functioning in this time period (Ingarden 1910a, b, c; Wyżga et al. 2013). According to R. Ingarden (1910a, b, c) rivers in the Beskidy Range experienced changes in their channel pattern up to the end of the 19th century – shifting from a single-channel pattern to a sinuous or braided pattern, thus becoming more natural due to human impact in their drainage basins. R. Ingarden (1910a, b, c) linked this shift towards a more natural flow pattern with rapid deforestation in the Carpathian Galicia region in the years 1848–1860. He also argued that these same rivers had earlier followed a single-channel pattern characterized by narrow channels. Additionally, B. Wyżga et al. (2013) makes the argument that the channel pattern shown on Austrian maps – both for braided and sinuous channels – does not have to reflect the initial state. Instead, the pattern is determined by human impact in the catchment including deforestation and the introduction of potato farming (Klimek 1987).

According to B. Wyżga et al. (2013), as in the case of R. Ingarden (1910a, b, c), the rivers of the Beskidy Range continued to evolve until the end of the 19th century from a pattern of single continuous channels to braided channels due to human impact. A different view is held by V. Škarpich et al. (2016) and K. Witkowski (2018). According to V. Škarpich et al. (2016) research in the Olše river basin in Czechia indicates that significant out-of-channel deposition was associated with Wallachian settlement and resulting deforestation. A similar view is held by K. Witkowski (2018) who believes that braided river channels existed in the Carpathians prior to the 19th century. In his view there exist historical sources that confirm the existence of a braided channel in the case of the Skawa River in the 17th century. He associates this type of Carpathian river channel with the more wet periods of the Little Ice Age and the onset of human settlement in the Carpathians in the 15th and 16th centuries. Finally, H. Keller (1899) argues that intensive logging activity occurred in the Soła, Skawa, and Vistula drainage basins throughout the 19th century. The wood was then floated downriver or shipped by train towards the end of this time period.

In summary the gravel-bed Soła river channel tended to adapt to changes noted in its drainage basin. Its downriver reach was characterized by a sinuous single current that sometimes also followed an anastomosing pattern. In the Oświęcim region major impacts on the Soła river channel included human impact in the form of dam, dike, groin, and reinforcement construction.

AIM OF THE STUDY AND RESEARCH METHODES

The purpose of the study was to assess the reasons for changes in the Soła river channel in the Carpathian foreland area situated in the Oświęcim region of southern Poland. The study examines data for the 18th and 19th centuries in relation to natural and anthropogenic determinants present in the studied catchment. The studied area here consists of the Soła river channel from the Porąbka site to the mouth of the Soła at the Vistula River (Fig. 1). The Soła river channel was examined on a map at a scale of approximately 1:28,000 from the years 1779–1783 and another map from the years 1861–1862 (Originalaufnahmskarte … 1779–1783; Militäraufnahme … 1861–1862; Figs. 2, 3).

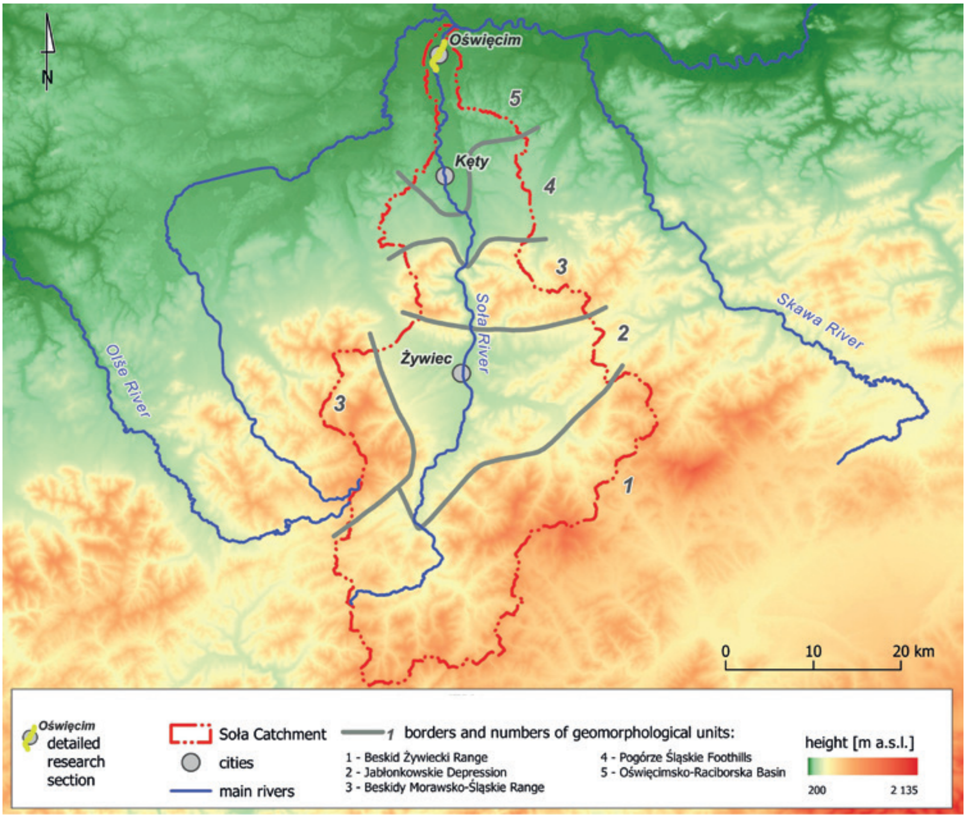

Fig. 1. Location of study area

The Soła river channel was examined using detailed hydrotechnical maps of the Oświęcim area created in the years 1812–1875 (Figs. 4–9). The scale of the maps was approx. 1:6,000 and 1:8,000, while the unit of measurement thereon was the Vienna fathom or approx. 1.9 meters. Only some of the maps are oriented using standard N-S markings and even these are not oriented precisely. Most of the maps are oriented SW-NE relative to the vertical map frame. Three pairs of maps were selected for the analysis in the research study – maps from the years 1812 and 1814, 1822 and 1833, as well as 1864 and 1875. Each pair of maps covered the same relief of the studied valley floor and was created at a similar scale. The said maps were found to contain a wealth of geomorphologic and hydrotechnical content.

The said maps are property of the National Archive in Kraków. A total of 26 maps were obtained for the purpose of the study. The maps covered between 2.6 and 3.5 kilometers of the studied channel from kilometer 84.0 to kilometer 87.5 of the present-day river channel. Maps of the bed of the Soła River were created most often following very high water stages – in some cases

Fig. 2. Soła channel in the section from Kęty to the point of confluence of the Soła and Vistula rivers shown on a map from the late 18th century (Originalaufnahmskarte… 1779–1783)

Fig. 3. The Soła channel in the section from Kęty to the point of confluence of the Soła and Vistula rivers shown on a map from the 1860s (Militäraufnahme…, 1861–1862)

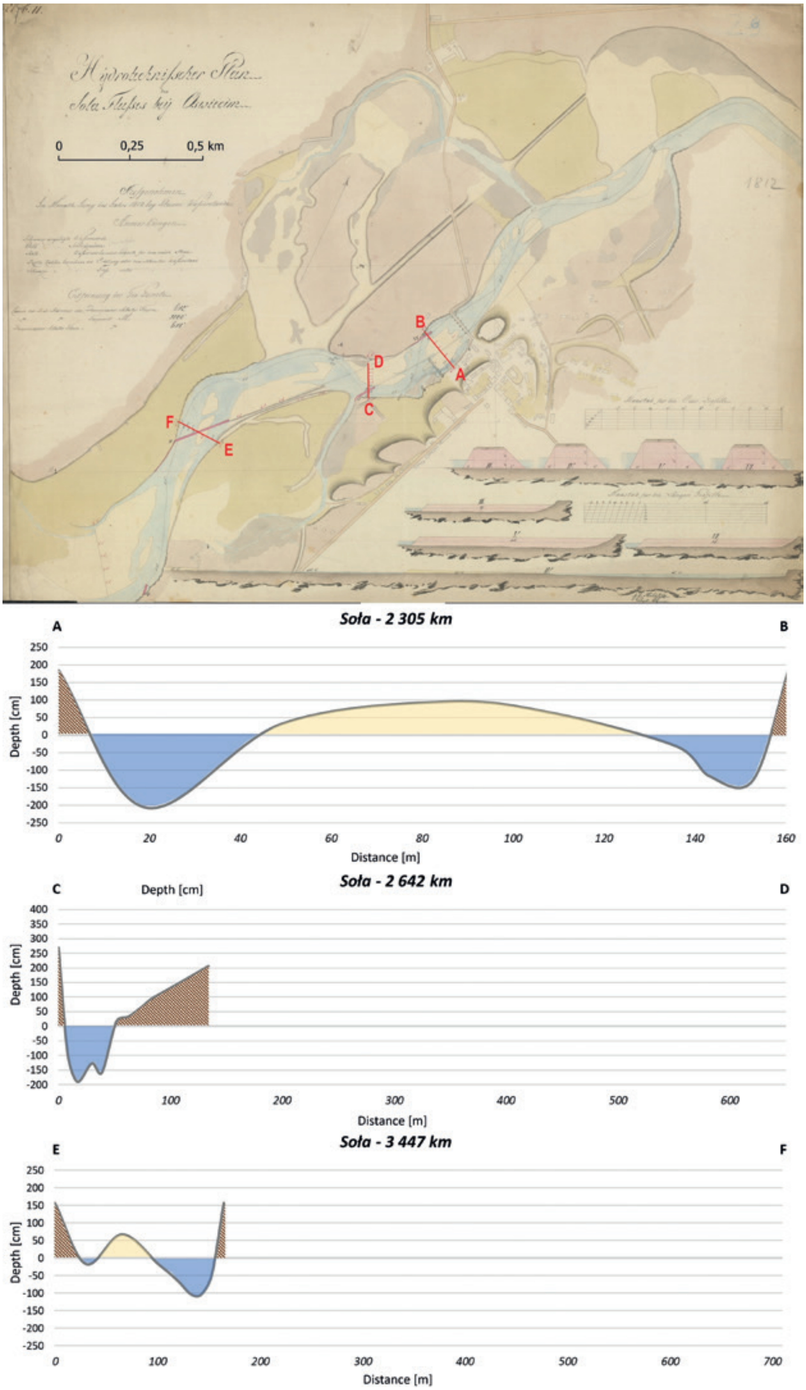

Fig. 4. Map from 1812 of the Soła channel in the vicinity of the town of Oświęcim and cross section of the Soła channel (Hydrotechnischer Plan..., 1812)

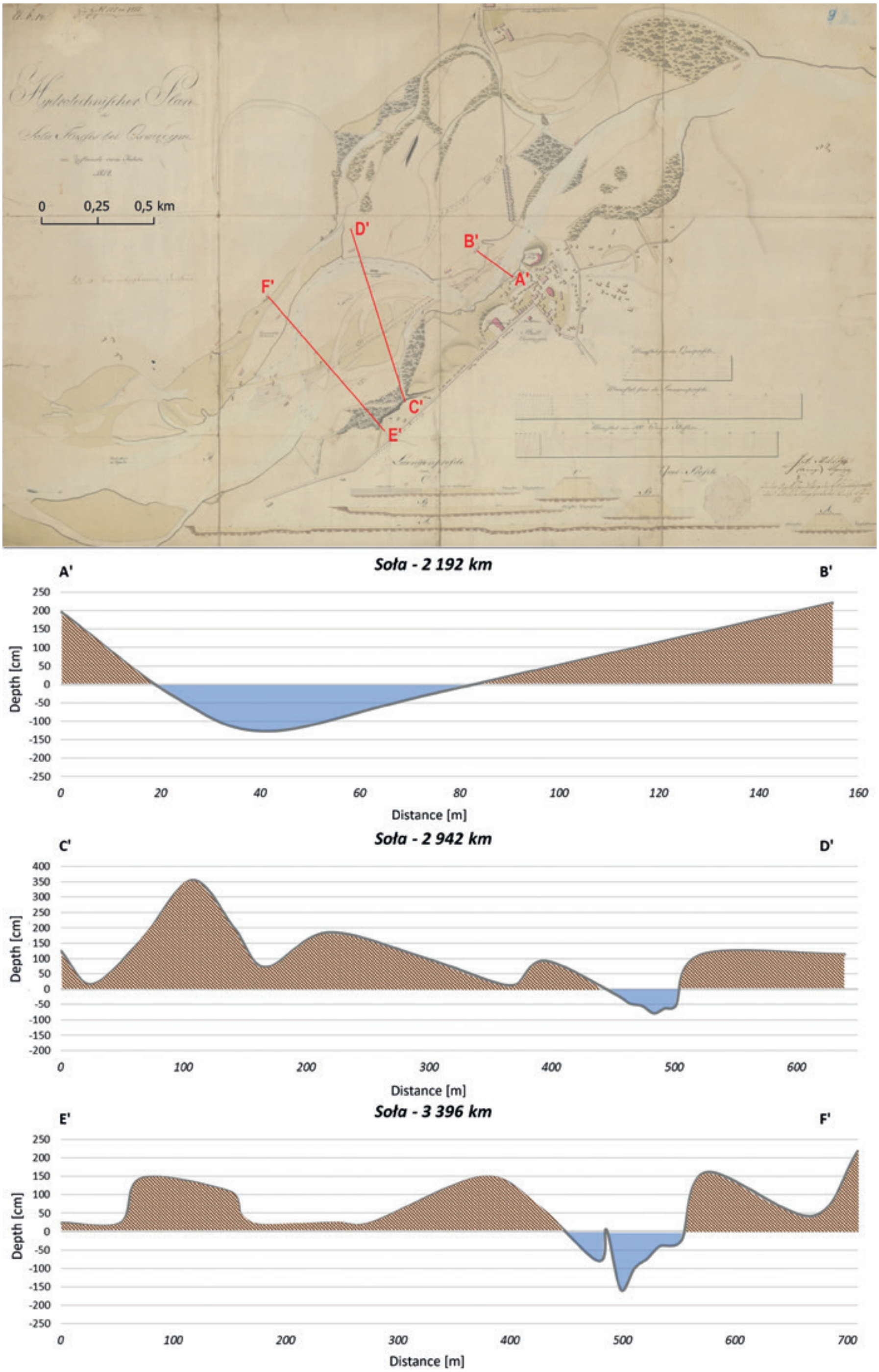

Fig. 5. Map from 1814 of the Soła river channel near Oświęcim and cross section of the Soła channel (Hydrotechnischer Plan..., 1814)

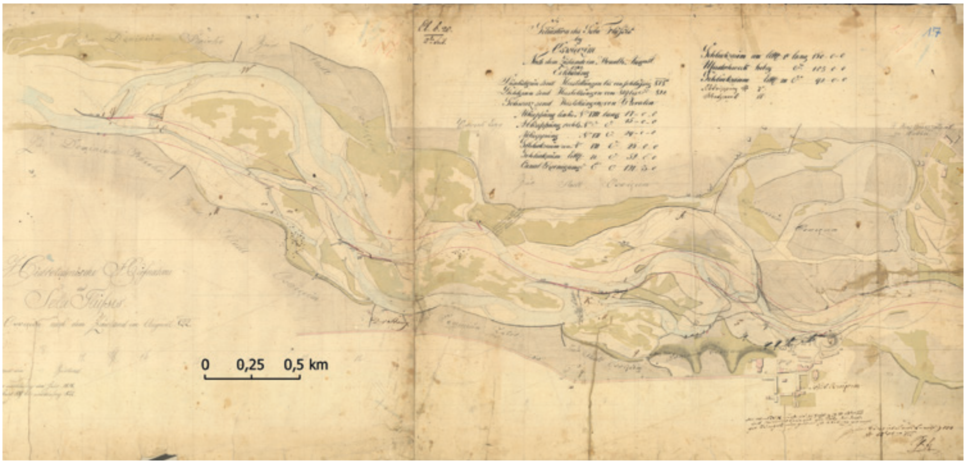

Fig. 6 Map of the Soła channel near Oświęcim from 1822 and cross section of the Soła channel (Situation des Sola…, 1822)

Fig. 7. Map from 1833 of the Soła channel in the Oświęcim area and location of cross sections of the Soła valley (Situation des Sola…, 1833)

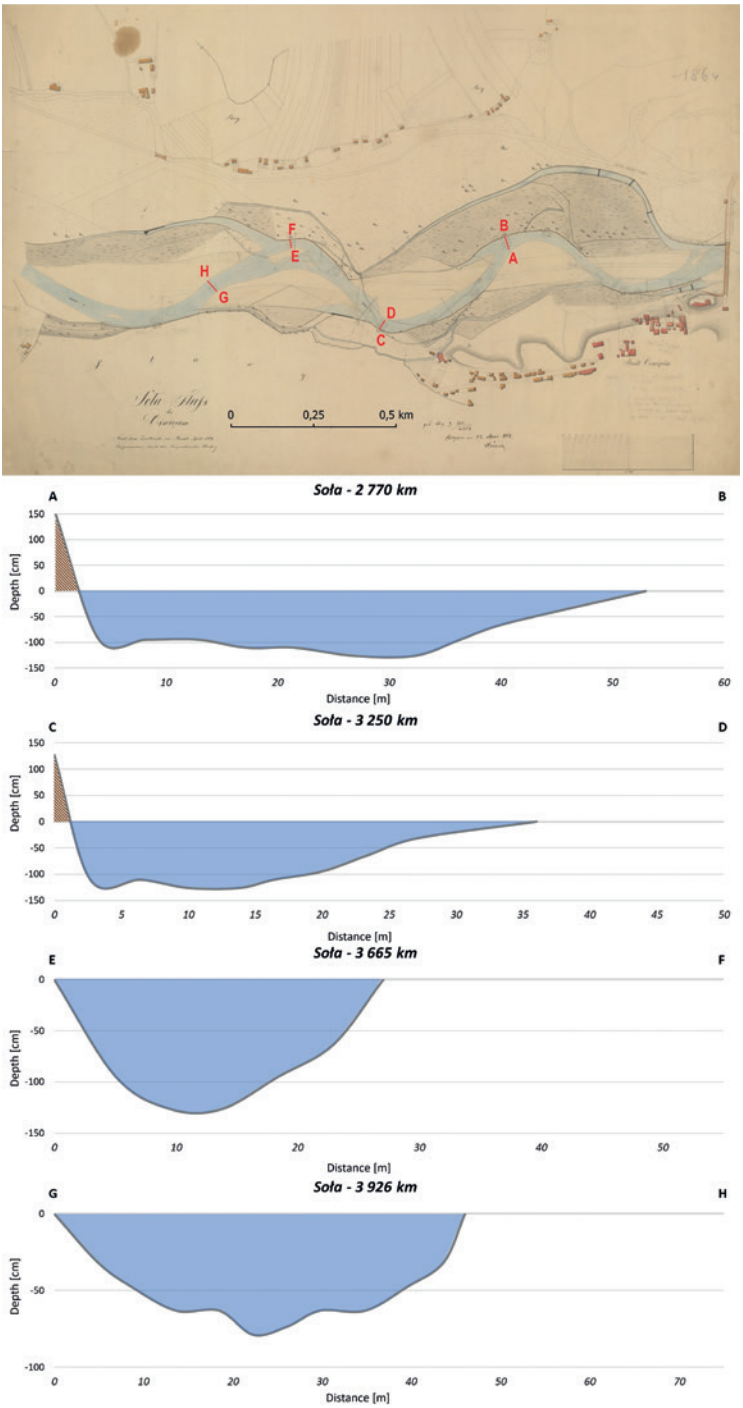

Fig. 8. Map from 1864 of the Soła channel in the Oświęcim area and cross section of the Soła channel (Soła Fluβ bei Oświęcim..., 1864)

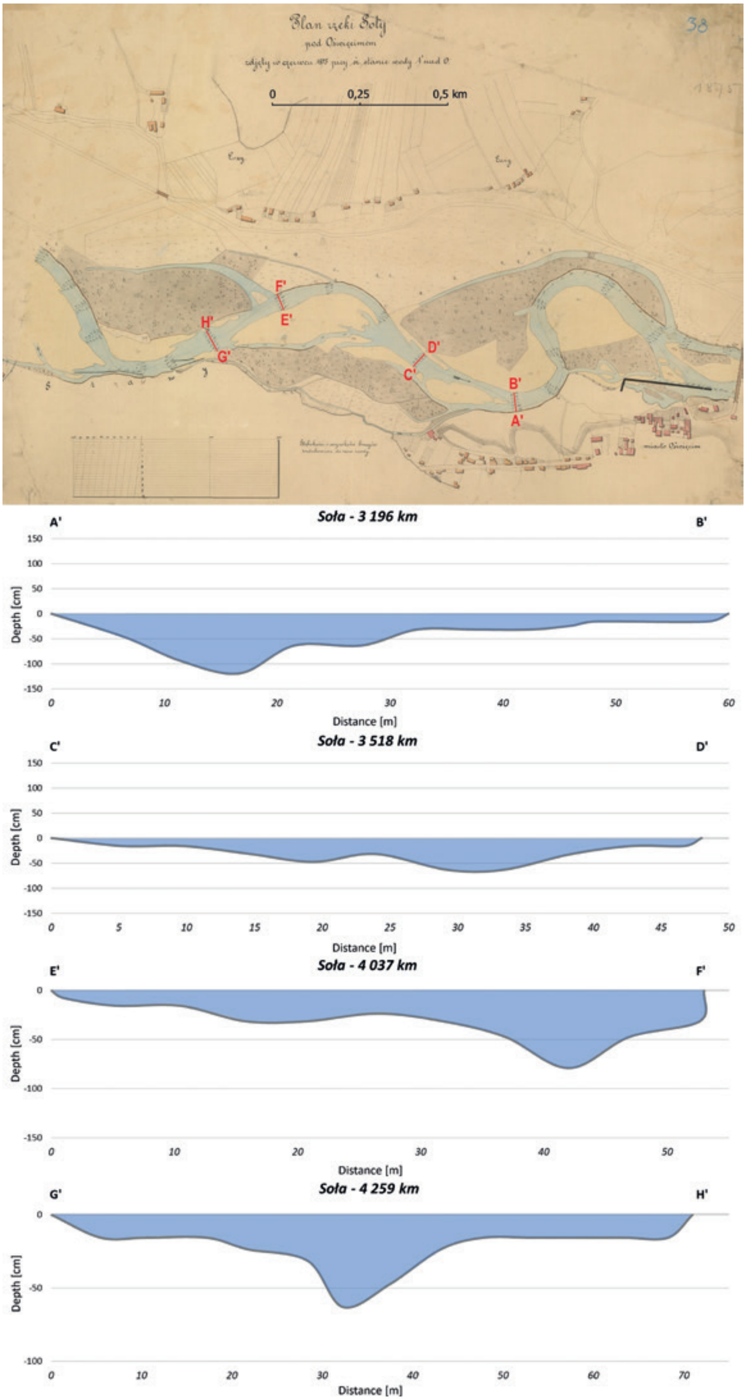

Fig. 9. Map from 1875 of the Soła valley in the Oświęcim area and cross section of the Soła channel (Plan rzeki Soły pod Oświęcimiem…, 1875)

twice a year: in the spring and autumn. The studied reach of the Soła changed its channel pattern almost after every high water event. The said changes included a change in overall channel pattern and depth. Aside from natural factors the studied channel was also affected by river regulation work in the form of weirs, dikes – both longitudinal and cross sectional – and bank reinforcements designed to create a single, wide and deep river channel (Keller ed. 1899). The abovementioned factors helped trigger erosion in some channel reaches and debris accumulation in others. Changes were assessed on the basis of a comparative analysis of river channel cross sections for analogous time intervals.

CHARACTERISTICS OF THE SOŁA DRAINAGE BASIN

The Soła River is a right-bank tributary of the much larger Vistula River with a total catchment surface area of 1,375 km^2. Its catchment borders the spring areas of the Vistula and Olše rivers (a tributary of the much larger Odra River) to the west and the Skawa drainage basin to the east (Fig. 1). The Carpathian portion of the Soła basin is characterized by four distinct geomorphologic units (Klimaszewski, Starkel 1972): the Beskid Żywiecki Range, Jabłonkowskie Depression, Beskidy Morawsko-Śląskie Range, the Pogórze Śląskie Foothills. The pre-Carpathian part of the studied catchment is located in the Oświęcimsko-Raciborska Basin (Klimek, Starkel 1972). Almost 90% of the drainage basin is situated in the Beskidy Range and the Carpathian Foothills; hence, these two regions determine the channel type for the studied river. The average elevation of the studied catchment is 590 m a.s.l. The highest point is Pilsko Mountain found at 1,557 m a.s.l., and the lowest point is the mouth of the Soła in the Oświęcim area at 226 m a.s.l. (Punzet 1971).

The catchment's geology and relief are determined by local tectonics via changes in terrain elevation, valley gradients, local hillslopes, bedrock erosion rates and types of weathering affecting the area. The said determinants create a number of variants of the supply of weathering products into river channels and assure the formation of a certain variety of types of weathering. The Soła catchment is formed of rocks resistant to weathering – it consists primarily of Magura-type sandstone (Stupnicka 1989). It is also characterized by high elevations and large differences in elevation. Weathering products here include boulders and debris of various size. This type of material is then supplied to the Soła channel via steep hillslopes or via tributaries.

The Soła drainage basin is characterized by large differences in precipitation totals on an annual basis. The southern and southwestern parts receive an annual total of more than 1,300 mm, on average. The middle part –

the Żywiecka Basin – receives an average of 800 to 950 mm, while the mouth of the Soła in the Oświęcim Basin an average of 750 to 850 mm per year (Hess 1965; Kozłowska-Szczęsna et al. 1983). The multiyear average precipitation total for the Soła drainage basin is as follows: the summer half-year from May to October receives an average of 500 to 1,200 mm, while the winter half-year from November to April receives 250 to 500 mm. For the warmest summer months of June, July, and August the precipitation total ranges from 50% to 70% of the annual total. The precipitation regime and spring snowmelt pattern produce a strong impact upon the occurrence of high and low water stages in the Soła River.

The Soła River tends to flood in the summer due to heavy rainfall in its region. A large flood occurs along the river every few years. Snowmelt flooding extends over a longer period of time and is less substantial than that in the summer due to differences in elevation ranging from 226 m to 1,557 m a.s.l. The magnitude and frequency of flood events determines the discharge rate of the river and the extent of fluctuations in the water level (Dynowska 1995). High water stages in the Soła occur quite often, and when this is combined with large gradients, the conditions for weathering material transport are quite good. The weathering product types (i.e. boulders and sedimets of various grain size) that affect the river channel lead to the formation of a gravel and boulder bed in the study area, as wide as 500 meters in the Oświęcim area (Malarz 2002). Today the Soła is a gravel-bed river typical of the Beskidy Range Mts.. According to the A.D. Knighton (1984) classification system it is a river cutting into loose material. Its large-grained bedload becomes mobile only in the course of major flood events (Malarz 2002).

Vegetation cover depends on climate conditions, soil type, and land use across a given catchment area, and helps to determine runoff driven by precipitation and the melting of snow as well as the influx of weathering material from valley slopes to the main river channel. It affects fluvial processes in two different ways – directly and also indirectly. Its impact mostly takes the form of regulation of precipitation-driven runoff and the protection of weathering cover from erosion. This is very important in the case of large hillslopes. The direct impact of vegetation cover first and foremost consists of the weakening of erosion of alluvial banks and the acceleration of the aggradation of accumulation flats. The present-day distribution of vegetation in the Soła catchment and its species composition are the result of human impact.

Human settlement in this part of the Carpathian region began in the Early Middle Ages and contributed to significant deforestation of foothills and the use of mountain tops and gentle hillslopes for crop cultivation (Towpasz, Zemanek 1995; Święchowicz et al. 2021). While today the mountainous parts of the Soła drainage basin are largely forested, these woodland areas represent a different species composition than in the past due to tree planting. Human impact in the form of altered plant cover has affected fluvial processes in the study area for centuries. About 18% of the studied catchment consists of agriculturally useful land of the Carpathian Foothills (Punzet 1971). Thus the introduction of agriculture in these areas could not have significantly altered the water balance and influx of weathering material into the studied river channel.

An analysis of fluvial processes occurring in the mouth section of the Soła between the 15th and 19th centuries requires an assessment of changes in the studied region's climate, water balance, and vegetation cover in the Pleistocene. The effects of cooling in the Pleistocene continue to affect these processes today – their legacy is still tangible (Klimek 1979). In addition, the geographic environment in the study area was affected by the Little Ice Age whose effects exacerbated the impacts of environmental changes caused by the Pleistocene glaciation. Researchers vary in their estimation of the duration of the Little Ice Age, but generally agree that it lasted between 300 and 500 years, ending in the second half of the 19th century (Lamb 1977; Porter 1986). The last several decades of the 19th century were characterized first and foremost by extreme weather phenomena including low temperatures and snowfall in high mountain areas even in summer – as well as by strong downpours and fast-moving thunderstorms. Air temperature conditions have shifted the upper tree line and the species composition of forests. Weathering types have also changed as a result. As a consequence, precipitation-driven and snowmelt-driven runoff patterns have changed as well. Rapidly changing temperatures characterized by frequent freeze and thaw cycles and intense snowfall and rainfall events exacerbated mechanical weathering in the study area. Cooling effects shifted the upper tree line downward, revealing significant areas without tree cover. Research by M. Ralska-Jasiewiczowa (1972) and L. Starkel (1968) has shown that the upper tree line in the Soła catchment used to reach elevations between 400 and 600 m a.s.l., and the catchment as a whole was only 10% to 30% forested. Intense precipitation led to much stronger surface runoff, producing a greater influx of rock material to river channels and higher discharge in general. In effect, rapid influx of coarse products of mechanical weathering led to their aggradation and exceedance of the river's bedload transport capacity. The aforesaid environmental processes served as the main driver of the evolution of the Soła River in the direction of a braided channel, which functioned at the beginning of the studied period. The formation of braided channels is the result of two key factors – changes in discharge due to increased surface runoff driven by a lowering tree line or deforestation driven by human impact as well as changes in material influx featuring more gravel-type versus silt and dust-type material. L.B. Leopold and

M.G. Wolman (1957) examined threshold values for channel gradient and channel-forming discharge whose exceedance may trigger a change in river channel type. The study found that in natural conditions braided channels are characterized by a larger gradient than that of meandering channels, thus the former are associated with higher discharge driven by extreme weather phenomena occurring during the Little Ice Age.

On the other hand, S.A. Schumm (1968) was able to show that the shape of the river channel is associated directly with the quantity of bedload and the nature of the given bedload. River transporting small quantities of suspended bedload are single-current-type, narrow, and deep. Rivers transporting a lot of bedload (larger grain size) tend to be multi-current-type, wide, and shallow. In addition, in this case, the influx of coarse-grained weathering material was also driven by ambient climate conditions.

HUMAN IMPACT IN THE SOŁA DRAINAGE BASIN IN THE 18TH AND 19TH CENTURIES

In addition to natural factors, fluvial processes in the Soła river valley were strongly affected by human impact in the form of almost complete deforestation of the Foreland and lower elevations of hillslopes in the Beskidy Range. The abovementioned changes were associated with a time period when forested areas were treated as a source of timber to be used in various economic endeavors, and in some cases timber was also sourced for wartime military purposes. According to J. Miklaszewski (1928) the forest cover of the region of Galicia decreased approximately 2.5% between the years 1815–1824 and 1878–1880, from a value of 28.2% to 25.7%.

These areas were cleared for crop cultivation (Klimek 1987; Święchowicz et al. 2021). Research work by E. Gil and J. Słupik (1972) indicates that changes in land use on Carpathian hillslopes led to an increased intensity of flooding in the area and increased bedload in rivers. One effect of this consisted of changes in river channels including that of the Soła, which became more natural due to an increase in the surface area of braided reaches of river (Keller ed. 1899).

The construction of hydrotechnical structures in a valley or in a river channel leads most often to rapid and substantial changes in fluvial patterns. Both natural factors and regulation works helped shape the channels of Carpathian rivers in the 19th century. Earthen and wooden dams (in German: die Klause/der Floßsee) were built in Beskidy area forests in the 19th century to help drive logs downriver. When abruptly lowered the dams would make it possible to float logs in the downriver direction (Łajczak 2005; Sowiński 2013).

Log driving occurred more efficiently at high water stages. In the 1870s log driving down the Soła River declined due to the construction of a railroad across the upstream part of the Soła catchment. These logs were often used to build railroad ties (Keller ed. 1899). In most cases only single structures were built in the Soła valley and included weirs, groins, levees, and riverbank reinforcements constructed by local governments and landowners.

Roads running along the river were also reinforced, as were the bases of road and railroad bridges. The introduction of these structures helped generate local increases in river flow rates and in effect increased debris transport rates. The transported matter usually became deposited in the form of bars downstream of the eroded river section (Keller ed. 1899). The one exception in this case consisted of river structures situated on property owned by the Archduke of the Habsburg Empire – these were found in the upstream part of the Soła and its tributaries. The said structures were carefully built of stone – mostly dams and weirs – and held back river water at high water stages. They were equipped with sluices and stone-lined canals allowing for the release of water in the course of major floods. Weirs and simple riverbank reinforcements were also built in the downstream section of the Soła – mainly in the vicinity of the towns of Kęty and Oświęcim. These structures would become damaged or completely destroyed in the course of even midsize flood events. In some cases these hydrotechnical structures were moved to other locations following destructive flood events (Keller ed. 1899).

Water management documents indicate that log driving was an important part of the Soła region's economy in the 19th century. This practice was employed most often at medium and high water stages. The logs were then floated as far as Oświęcim. The Directors of the Archduke's Land Holdings in Żywiec had a concession for log driving to supply iron smelters near the towns of Sporysz and Węgierska Górka. This business produced a significant impact on the Soła river channel. Log driving was quite difficult in the Żywiec Basin, the Foothills, and Oświęcim Basin, where the Soła divides into a number of branches. The anastomosing or braided river channel forced log drivers to identify the proper Soła river channel following every major flood event (Figs. 4–9). Its riverbanks were reinforced with rock debris and built upwards with sand and loam. The structures were surrounded by willow and wicker, while lateral channel spurs were separated from the main channel with dikes (Keller ed. 1899).

THE SOŁA CHANNEL IN THE CARPATHIAN FORELAND IN THE LATE 18TH AND 19TH CENTURIES

The Soła river channel pattern found in the Carpathian foreland, as seen in the late 18th century, can be observed on Austrian military maps produced by F. von Mieg in the years 1779–1783 (Sheet 9, Column 2, Section 4 and Sheet 9, Column 3, Section 10) (Originalaufnahmskarte… 1779–1783). A fragment of this map is shown in Figure 2. Two distinct reaches may be observed in the channel section from Kęty to the point of confluence with the much bigger Vistula River. The first follows an anastomosing pattern and ends before the city of Oświęcim near Stary Staw Lake. The second reach follows a strongly meandering pattern and ends at the point of confluence with the Vistula. The width of the Soła between the town of Kęty and the Vistula River ranged from 40 to 60 meters. On the other hand, the Soła river follows multiple channels along the section from Kęty to Stary Staw – this section includes large islands that used to be part of the alluvial plain. The width of this zone ranged from 500 to 600 meters. The sinuosity of the river at this point equaled 1.41 (Fig. 2, Table 1). The second reach running from the city of Oświęcim to Stary Staw to the Vistula River followed a typical meandering flow pattern with a channel sinuosity value of 2.07 (Fig. 2, Table 1).

B. Woskowicz-Ślęzak (2013) considers this to be a braided channel, although at one point she states that the studied channel follows a multi-channel-type pattern also known as anabranching. He makes this observation for the Kęty region based on 15th and 16th century maps. This section of river channel was very sinuous with a sinuosity value of 2.59 and four channels. It is our view that the studied channel represents an anastomosing river channel (Teisseyre 1991) or a high-energy multi-channel (Rinaldi et al. 2016). The second reach running from Oświęcim to Stary Staw to the Vistula River had a meandering channel with a channel sinuosity value of 2.07 (Fig. 2, Table 1).

K. Witkowski (2017) investigated the Skawa channel and argues that the presence of very large mid-channel bars and islands in this river channel in the 19th century suggests the existence of a multi-channel system. He further makes the argument that very large mid-channel landforms are shown on maps of the Soła River. In his view one cannot rule out the existence of multi-channel systems in the Western Carpathians in the 19th century. A similar view is held by J. Czaja (2017) who states that the Little Vistula had some reaches in the early 19th century featuring meandering and anastomosing flow. A. Teisseyre (1991) notes that anastomosing river systems were quite common in basins in the Sudety Mountains and in their foothills as late as the early 20th century when they were purposefully destroyed in the process of river regulation. Remnants of these systems can be observed at select

Table 1.

Parameters of the Soła channel in the section from Kęty to the point of confluence of the Soła and Vistula rivers in the period 1779–1783 and 1861–1862

Soła section:	Kęty - Oświęcim		Oświęcim – estuary to the Vistula	
Period of study / Parameters of the channel	years			
	1779–1783	1861–1862	1779–1783	1861–1862
Length (km)	25.1	21.0	8.0	5.5
Width (m)	40–60	140–180*	40–60	90–140*
Length of the valley (km)	17.8	17.8	8.0	5.5
Curvature (P)	1.41	1.18	2.07	1.42
Number of lateral channels	19	20	–	2
Lentgth of lateral channels (km)	16.0	14.8	–	4.2

* width during full channel volume fill.

locations. Maps from the late 18th century do suggest that the Soła River had an anastomosing system at the time.

The studied river channel was examined for the second half of the 19th century on the basis of a map at the scale of approx. 1:28,800 (Militäraufnahme... 1861–1862). The Soła river channel changed substantially across the Carpathian Foreland in the second half of the 19th century (Fig. 3). Its channel evolved from a meandering and anastomosing type to a braided type in the section from Porąbka to downstream of the city of Oświęcim compared with the situation at the end of the 18th century.

The anastomosing zone reaching 750 meters in width became transformed into a channel with multiple threads (Militäraufnahme ... 1861–1862). The new channel was as much as 700 meters wide. In its bankfull state the Soła River followed a channel characterized by low sinuosity (P = 1.18) (Table 1). Its wide bed featured numerous bank attached bars and mid-channel bars – up to 600 meters long and 250 meters wide (Fig. 3). The greatest degree of river channel braiding was observed between Kęty and Bielany (Fig. 3). The river channel became about 25.6% shorter between the late 18th century and late 19th century due to changes in the course of the Soła River observed in the Carpathian Foreland (Table 1). To summarize, the channel of the Soła River became a typical braided channel in the second half of the 19th century, with the exception of the reach just prior to the point of confluence with the Vistula River (Fig. 3). This reach also became braided-type about 1875. This channel pattern survived until the end of the 19th century when river regulation works began on the river and the first section to be regulated was the one near the city of Oświęcim.

CHANGES IN THE SOŁA CHANNEL PATTERN NEAR OŚWIĘCIM IN 1812 AND 1814

The first of the analyzed maps was created in 1812 or also one year before one of the greatest floods ever recorded on the Vistula River and its tributaries in the 19th century (Fig. 2). The main Soła channel had a length of about 3.48 km and a width up to about 70 or 80 meters. The length of its lateral channels was about 4.2 km with a width of 20 to 40 meters. The examined map also shows the location, size, and shape of levees and dikes as well as cross sections of the Soła channel (Fig. 4). The section of the channel characterized by anastomosing patterns became increasingly braided and single-channeled (Figs. 4, 5). A system of longitudinal and transverse dikes and weirs directed water flow in the Soła towards the left bank, as the right bank was filled with built-up areas of the city of Oświęcim.

One of the main roads from the city ran in the northern direction via a bridge on the Soła River. Longitudinal and transverse dikes were constructed on the left and right bank of the river to protect the abutments of the bridge. A manmade, reinforced canal about 0.7 km long was built along the left bank of the Soła, about 200 to 250 m from the edge of the river channel. It was most likely used to drain agricultural areas. The map uses colors to show different types of land use. Purple-brown is used to show arable land, green indicates meadows and pastureland, gray is used for woodland and shrub areas, and light yellow denotes sand bars and sand-gravel bars. The authors of the map marked the course of the Soła River and checked the depth of the middle of the river every several hundred meters. The average depth of the bankfull Soła ranged from 0.2 to 0.5 meters, while maximum depths ranged from 1.5 to 2.2 meters (Table 2). The authors also collected data for four cross sections of the main river channel in the area of well-established bars.

A map of the Soła valley from 1814 shows the river network following a major flood event in August of 1813 that significantly altered the entire system of river channels, green areas, and bars. The flood destroyed all hydrotechnical structures and a bridge over the Soła River (Fig. 5). The main channel of the Soła was about 3.39 km long and 70 to 80 meters wide. The average depth of the bankfull river was about 1.0 meter, while the maximum depth was 1.92 meters. The length of lateral channels was about 2.22 km (excluding dry channels), with a width of 20 to 40 meters.

The map shows the main current of the river and its depth as well as data for four channel cross sections for a reach about 0.8 km long. A drainage canal operational in 1812 was washed over and widened by a flood wave, while bank reinforcements were destroyed (Fig. 5). The map in question also shows a new hydrotechnical structure – one not observed in 1812 (Fig. 5).

Table 2.
Parameters of the Soła channel in the Oświęcim area in the years 1812–1875

Parameters of the channels \ Years		1812–1814		1822–1833		1864–1875	
		1812	1814	1822	1833	1864	1875
Main channel	Length (km)	3.48	3.39	3.08	3.41	2.59	2.99
	Width (m)	40–80	50–110	30–80	30–90	25–50	20–55
	Depth (m)	0.66–2.21	0.63–1.92	–	0.63–2.05*	0.32–1.89	0.79–3.32
	Curvature (P)	1.21	1.18	1.17	1.32	1.22	1.46
Lateral channels	Length (km)	4.21	2.23	2.97	6.57	0.63	2.66
	Width (m)	20–40	5–20	10–25	5–30	15–30	10–25
	Depth (cm)	16–205	79–111	–	24–190	–	47–71
	Number of channels	12	5	7	13	3	14
Sandbanks & landslides	Number	18	11	9	16	7	16
	Size (m) (length–width)	400–80	200–100	200–40	300–100	115–25	400–120
	Height above the water table (cm)	100	50	–	150	–	–

* excluding the artificially deepened channel section (depth up to 5.70 m)

This is a side channel about 1.0 km long and found parallel to the right bank of the Soła River. The map also features the location and size of dikes, weirs, levees, and cross sections of the Soła River (Fig. 5). The river's multithread channel became increasingly single-channel, but with multiple currents. Two main determinants of this state included a major flood event and human impact in the form of river regulation.

CHANGES IN THE SOŁA CHANNEL SYSTEM NEAR OŚWIĘCIM IN 1822 AND 1833

Changes in the Soła river channel pattern, as seen on maps from 1822 and 1833, illustrate shifts in fluvial processes occurring in the studied valley. These changes were due to flooding in 1813 that almost completely destroyed the hydrotechnical structures present in the entire Soła valley. It may be argued that the floods returned the valley to its natural runoff formation state consisting of erosion, debris transport and finally deposition. The result was an increase in the size of the migration zone and revived water flow in a number of river channels. The studied river rapidly adapted to these new conditions and shifted its flow channel in the direction of braided-type.

The map from 1822 shows that a number of groins and transverse dikes remained after the flood along the right bank of the Soła. The mapmakers did not mark a flow channel in the main channel of the Soła. They also did not analyze any cross sections. The map from 1822 does provide a plan for the regulation of the Soła – the red line on the map (Fig. 6). The main channel of the Soła has a length of about 3.08 km, which is the same length as that of its side channels. The main channel is 40 to 50 meters wide, while the side channels are 20 to 50 meters wide. On the other hand, the water mill canal became shortened to just 0.67 km along the studied section of the main river (Fig. 6, Table 2).

A map produced in 1833 provides a more detailed cartography of the study area, along with hydrotechnical structures. The number of longitudinal and transverse embankments, spurs, and dikes significantly increased. Three longitudinal profiles of the studied river were examined and the depth of water in wet channels was noted along with the depth of dry channels. The relationship between the depth of dry river channels was noted with respect to minimum water levels in wet channels (Fig. 7). The minimum average depth of dry channels was found to be 0.85 meters. Dry channels were suspended over the main river channel at a height of 0.16 to 1.07 meters. The authors of the plan once again returned to determining the main river channel and its major tributaries. Approximately every 200 meters, the depth of the river in the channel was also measured. Analyzing the depth distribution in the Soła riverbed, a segment of the river with a length of about 200 meters was identified, where the depths in the water-filled channel ranged from 3.20 to 5.70 meters.

These almost incredible depth values were associated with the presence of dikes running across the river channel (Fig. 7). The dikes were constructed in a way such that the free flow zone along the left bank of the river was only 1 to 2 meters wide. The water flow above the dikes became halted, while the downstream reach became much deeper and narrower thanks to the strong water current that also removed sandy and gravelly river sediments. The depth in the remaining sections analyzed ranged from a minimum of 0.10 m to a maximum of 0.90 m. The main channel of the Soła River was 3.41 km long and 40 to 50 meters wide, while its side channels were 6.57 km long and 20 to 50 meters wide. The studied water mill canal was 0.66 km long and its location pattern had not changed (Fig. 7, Table 2).

CHANGES IN THE SOŁA CHANNEL PATTERN NEAR OŚWIĘCIM IN 1864 AND 1875

Significant differences may be observed when comparing maps of the Soła river channel pattern in the years 1864 and 1875 in relation to that in 1822 and 1833. The bed of the river became 400 meters narrower, and the number and length of channels both significantly declined. This was clearly due to major changes in fluvial processes affecting the river. The Great Flood of 1813 was followed by years of rebuilding of key weirs, groins, levees, transverse dikes, and bank reinforcements. These efforts then produced significant changes in erosion, transport, and accumulation conditions. The weakening of these processes can be inferred from the types of main hydrotechnical structures built in the riverbed. The Soła river channel became mostly single-channel and multi-current. Logging and log driving in the upstream part of the catchment also contributed to this situation, which affected the channel as far as Oświęcim (Keller ed. 1899).

The studied map from 1864 shows the main channel of the Soła as having a length of 2.59 km and a width of 40 to 60 m. The length of its side channels equaled 0.63 km with a width of 20 to 40 m. The water mill canal, in operation since 1814, became more than twice as long – 1.4 km in length (Fig. 8). The map also shows depths and widths at 10 locations along the main Soła channel. The average depth ranged from 0.3 to 0.8 m, while maximum depth ranged from 1.5 to 1.9 m (Table 2).

The Soła channel pattern found on the map from 1875 is clearly different from that on the map from 1864. The river channel is narrower, and its migration zone is also much more narrow. The channel pattern was strongly affected by a major flood on the Soła in July of 1867. The main river channel now featured expansive bars 150 to 400 m long and 70 meters wide, on average (Fig. 9). New side channels also had formed featuring multiple branching sites. The main channel of the Soła was 2.99 km long and its width was 40 to 60 m. Average depths ranged from 0.8 to 1.0 m, while maximum depths ranged from 2.8 to 3.32 m. Side channels were 3.46 km long and 20 to 40 m wide. It is important to note that all of these changes occurred within the river bed of the Soła. The main river channel changed its location at the point of confluence with the water mill canal, which shortened it to 0.98 km (Figs. 8, 9). Over the course of a few decades (1812 to 1875) the channel of the Soła River near the town of Oświęcim became narrower, from a width of 70 to 80 m to a width of 40 to 60 m (Figs. 4 to 9). This outcome was the product of both natural environmental conditions and impactful human activity across the catchment in general and in the studied river channel itself.

DISCUSSION

The present-day channel of the Soła river in the vicinity of its confluence with the Vistula River is the product of multiple physical changes over the centuries. Changes in the course, shape, and type of the channel were triggered by varying physiographic conditions including catchment land use and frequency of major flood events. However, the main driver of change in this river channel over the last 300 years has been human impact. The Soła river channel changed from an anastomosing channel in the 19th century to a single-pathway braided channel. Subsequent stages included a gradual reduction in the width of the channel, increasing depth, and the formation of multiple threads along the single-channel Soła River.

Prior to the 19th century the predominant river channel type in large Carpathian valleys was the braided river type, with meandering at lower elevations, and even locally anastomosing patterns (Galarowski, Klimek 1991; Woskowicz-Ślęzak 2013; Witkowski 2015; Krzemień, Gorczyca 2021b). Similar changes, as those in the lower Soła channel, were noted for the lower Skawa channel by K. Witkowski (2015) who was able to show that a single braided channel functions in the naturally-evolving valley. On the other hand an anastomosing channel has formed near the point of confluence of the Skawa and Vistula rivers on the flatlands of the Oświęcim Basin. The direct cause of this change in the Soła river channel pattern was river regulation, occurring at variable intervals since the late 18th century. Dikes, weirs, watermill channels, and locally embankments were built along the river. As shown in the paper the channel type and pattern changed following each high water stage.

Similar results were obtained by researchers examining changes in the course of the Little Vistula River and its tributaries in the western part of the Oświęcim Basin (Czaja et al. 1993; Czaja 2010; Czaja 2017; Czaja, Rahmonov 2017). They used archived maps and historical records to show that sections of the anastomosing channel were subject to both natural and anthropogenic changes. Their study shows that in 1736 the floodwaters of the Vistula River entered a watermill channel during a key flood event in the headwater part of the Vistula catchment and established a new river flow pattern. The main channel of the Vistula was shortened from 7.2 km to 5.5 km, while the distance between the old channel and new channel ranged from 0.5 to 1.0 km.

Studies on braiding in the Carpathian tributaries of the Vistula were also conducted by H. Hajdukiewicz and B. Wyżga (2013) as well as B. Wyżga et al. (2013). They write that the cause of river braiding in this case was a substantial influx of debris to river channels driven by slope deforestation in the 19th century and the accompanying increase in the amount of precipitation during the Little Ice Age. H. Hajdukiewicz and B. Wyżga (2013) used an old Austrian military map (scale: 1:25,000) to show that the maximum number of threads in river channels ranged from 3 to 5 in the second half of the 19th century, while the average width of major Carpathian river channels ranged from 52.5 m to 92.9 m, and maximum width was found to be between 3.5 and 6.2 times greater than the minimum width.

In addition, the above study also notes the fact that changes in the Soła channel type along with similar changes in other Carpathian river channels was associated with the effects of changed flood dynamics caused by river regulation and reduced debris influx from catchments. The study goes on to state that the condition of river channels in the study area at the beginning of the 19th century was not natural and was driven by intense human impact throughout the catchment including deforestation and the introduction of potato farming. We agree with this assessment of the situation. At the same time the study provides serious arguments in favor of the continued maintenance of this non-natural state of river channels (Hajdukiewicz, Wyżga 2013). The said channels are characterized by high capacity at high discharge as well as increased channel capacity relative to straight, regulated river channels.

Research work designed to determine changes in gravel-bed river channels during the post-regulation era in the late 20th century was performed also by E. Gorczyca et al. (2020) who studied the Raba River. The said catchment and the Soła catchment examined in this study are characterized by a similar set of environmental and economic features. While E. Gorczyca et al. (2020) focus on present-day evolution of the said river channel, they also describe its evolution in the 19th century. The authors note that the Raba had a braided channel at the time. The study discussed the intensification of local agriculture and the construction of dirt roads as a key factor in channel evolution, leading to the influx of coarse and fine clastic material to the said river channel. In later years the evolution of the Raba river channel was characterized by the introduction of riverside embankments, levees, and various dikes.

The research was conducted not only in mountainous areas and foothill areas but also across lowland areas. An example of this is a study by P. Słowik (2013) in the Obra river catchment in western Poland who used ground-penetrating radar to determine channel characteristics present before the introduction of river regulation in the studied area. Research has shown that the Obra River had many characteristics of a single-channel, meandering watercourse in the Holocene, which the author calls a "natural state." The Obra began to adopt an anastomosing channel form in the early 19th century. It was a meandering channel where the main river channel was divided by an array of sandbars and islets that would change shape after every larger flood event. While the author does not examine the various causes of changes in the Obra river channel, it may be presumed that they were similar to those that affected Carpathian river channels. These included deforestation, expansion of agricultural areas, and increased dirt road construction.

At the same time the process of multi-channel watercourse formation was not due to some collection of local factors. Human impact was first and foremost the driving force behind this process. Likewise, the introduction of hydrotechnical structures in catchments was the cause of the evolution of river channels into straightened, single-channel systems regardless of the geographic location of a catchment. This rule applied to all the studied cases.

CONCLUSION

The functioning of the Soła river channel situated in the Carpathian foreland in the south of Poland from the late 18th century to late 19th century reflects natural conditions and human impact across its catchment area, and especially in the channel itself. The main changes introduced in this river channel were driven primarily by man. Historical data show that increasing rates of change in the examined channel were driven by the practice of large-scale deforestation (a 2.5% decrease in forest cover in the years 1815–1880) in the upstream part of the catchment, log driving as well as river regulation works.

The use of historical maps made it possible to track changes in the Soła channel over the course of many decades. These maps and other sources of data in the literature show that anastomosing channels used to function in the downstream sections of the Little Vistula, Soła, and Skawa rivers. The same was true of river channels in the midmountain basins in the Sudety Range in what is now southwestern Poland. Anastomosing river channels disappeared gradually over time due to initially local river regulation and subsequently the regulation of entire channel sections. Only the Skawa channel continued to feature some anastomosing reaches. The availability of good historical maps, although at varying scales, made it possible to assess the studied channel for time periods in the past characterized by a significant degree of human impact across the catchment and in the channel itself. The natural and manmade conditions described in the present paper for the studied river channel do not have any present-day equivalents in this particular study area.

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