

Article

Analysis of Long-Term Geomorphological Processes in Carpathian Riverbeds Affected by Bridges

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Abstract

Riverbed dynamics and erosion processes remain an important research issue, particularly under increasing anthropogenic pressure on river systems. This study investigates long-term channel changes and bed-incision processes in selected Carpathian rivers—the Skawa, Raba, and Dunajec—with particular emphasis on bridge-affected reaches. The analysis combined hydrological and geomorphological data with one-dimensional MIKE 11 hydraulic modelling to assess local changes in flow parameters and indicators of erosion potential under Q1% flow conditions. In the analysed cross-sections, riverbed lowering ranged from 1.0 to more than 3.5 m over the observation period, confirming the occurrence of long-term channel degradation. The results indicate that this process was primarily related to historical gravel extraction and channel regulation, whereas bridges mainly modified local hydraulic conditions. In the vicinity of bridge structures, flow velocity increased to as much as 7.31 m/s, and local changes in water surface elevation reached 0.90 m, indicating increased susceptibility to local scour near piers and abutments. The modelling also showed marked local increases in bed shear stress. At the same time, the results do not support the conclusion that bridges are the primary cause of systemic erosion at the scale of entire river reaches. This research contributes to sustainable development because it provides the knowledge needed for better management of rivers and bridge infrastructure in a way that is environmentally, socially, and economically safe: it shows that long-term riverbed degradation results mainly from earlier anthropogenic transformations, such as aggregate extraction and river regulation, while bridges primarily alter local flow conditions and may increase the risk of erosion around piers and abutments.

Keywords: geomorphological processes; bridges; numerical modelling; MIKE 11; sustainable development; Carpathian rivers



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1. Introduction

River channel dynamics and erosion processes remain among the key issues in contemporary fluvial geomorphology, particularly under conditions of increasing anthropogenic pressure on river systems. Morphological changes in river channels are difficult to interpret because they result from the complex interplay of flow conditions, sediment transport, channel geometry, and the structure of bed material. Advances in research methods, including the use of ground-penetrating radar supported by other measurement techniques,

have enabled more precise recognition of changes in channel architecture, their dynamics, and their potential causes [1]. Under conditions not strongly affected by human activity, a river channel tends to move toward hydrodynamic equilibrium by adjusting its geometry to the acting flow forces, hydraulic resistance, and sediment availability [2,3]. In practice, however, many contemporary mountain rivers function under persistently disturbed equilibrium conditions, and one of the main causes of channel deepening is anthropogenic transformation, especially gravel extraction and channel regulation [4].

Bed erosion has been observed in many rivers worldwide, regardless of their geographical or climatic setting, with particularly strong intensification during the twentieth century [5,6]. This process may be triggered by a single factor disturbing hydrodynamic equilibrium, but more often it results from the combined action of several factors. The most important mechanisms leading to channel incision include gravel extraction from the riverbed [7–11], interruption of sediment continuity by dam reservoirs [9,12,13], improperly designed or executed channel regulation works [14–18], and land-use changes in the catchment, including increased forest cover that reduces sediment supply to the channel [19,20]. In most cases, bed erosion develops as a consequence of the combined effects of reduced sediment availability and increased transport capacity of the flow [21–27].

Similar processes have also been documented in the rivers of the Polish Carpathians [28–32]. Their magnitude and rate were shaped by a combination of socio-economic transformations that have taken place since the late nineteenth century. High population density and the predominance of agriculture in the Upper Vistula valleys encouraged regulation works aimed at reducing flood hazard [33]. As a result, many channel reaches were shortened, straightened, and hydraulically adjusted, which increased flow energy and sediment transport capacity [34–38]. In the second half of the twentieth century, an additional factor limiting sediment supply was the reduction in cultivated land and the increase in forest cover, particularly in the mountainous part of the Carpathians [39–41]. At the same time, rapid urbanization and industrialization in southern Poland after World War II significantly increased the demand for aggregates, and river channels and valley floors became the easiest and cheapest source of these materials [42–44]. Consequently, many Carpathian rivers experienced persistent bed degradation of a long-term, system-scale character.

The consequences of bed incision are numerous and affect not only channel morphology itself, but also infrastructure and valley-floor environments. The most important effects include undermining of river training structures and bridge foundations, exposure of water intakes, drainage of alluvial aquifers, drying of agricultural soils in valley bottoms, increased bank height and slope instability, reduced lateral connectivity between the channel and the floodplain, and deterioration of hydromorphological conditions for aquatic organisms [6,32,45–52]. For this reason, identifying the course and rate of erosional processes is essential for assessing channel stability and predicting future changes. In many previous studies, the extent of erosion has been determined from changes in channel bed elevation relative to the initial bed level [24,53,54]. However, under long-term channel adjustment, a more reliable picture of degradation may also be obtained from the analysis of annual minimum water levels, which reflect persistent lowering of the bed [28,29,55].

Channel stability is particularly important in the vicinity of bridge structures. One of the most serious threats to bridge safety is local scour around piers and abutments, especially during floods and high-flow events [56]. This process results from complex interactions among turbulent flow, local vortex systems, and sediment transport, and therefore has a distinctly three-dimensional character [57–60]. Previous studies have shown that scour depth and extent depend on flow characteristics, the degree of channel constriction in the bridge zone, inlet and outlet conditions, and the type of bed material [57–60]. It has also been emphasized that long-term bed degradation at the reach scale may further

increase the vulnerability of bridge foundations to damage [61]. This means that threats to bridge structures should not be considered solely in terms of local scour, but also within the broader context of long-term morphological channel adjustments.

Although numerous studies have examined local scour at bridge supports and others have addressed long-term riverbed degradation, there is still a lack of research linking these two scales of analysis, particularly in Carpathian rivers. Existing studies usually focus either on the point-scale assessment of scour hazard at a specific structure or on the regional description of channel changes, without clearly relating long-term, system-scale bed degradation to the local hydraulic influence of bridge structures. This research gap is especially evident in mountain and foothill rivers, where the effects of historical channel regulation, gravel extraction, and contemporary technical infrastructure overlap.

The aim of this study was therefore to determine the long-term trends of bed-level change in selected Carpathian rivers and to assess to what extent bridge structures modify local hydraulic conditions that may promote erosion. The analysis covered selected reaches of the Skawa, Raba, and Dunajec rivers. The study was based on hydrological and geomorphological data, an analysis of changes in annual minimum water levels and bed elevations, and hydraulic modelling using MIKE 11. It was assumed that long-term channel degradation primarily reflects historical anthropogenic transformations at the catchment and channel scale, whereas bridges mainly act as local modifiers of flow hydraulics, potentially creating zones of increased scour risk around piers and abutments. In this framework, the hydraulic model was used not to directly reproduce a three-dimensional scour hole, but to assess changes in flow parameters and indicators of erosion potential within bridge cross-sections.

The connection between the two analytical scales adopted in this study is interpreted as mechanistic rather than fully morphodynamic. Long-term bed degradation defines the background morphological condition of a given reach, progressively lowering the channel bed and increasing the exposure and vulnerability of bridge foundations, whereas the bridge itself acts as a local hydraulic modifier that may concentrate flow, alter water levels, and increase flow velocity and bed shear stress during high flows. Accordingly, the hydraulic model was used not to reproduce a three-dimensional scour hole directly, but to identify where bridge-induced changes in hydraulic parameters may locally amplify erosion potential within a channel already affected by long-term degradation. Thus, the study links reach-scale degradation trends with bridge-scale hydraulic effects through a two-scale interpretative framework rather than through a fully coupled simulation of bed evolution.

2. The Study Area

The study focused on selected bridge structures located on three Carpathian tributaries of the Vistula River: the Skawa, Raba, and Dunajec Rivers (Figure 1). The study sites were selected to include bridges situated in different parts of the analysed river courses, which made it possible to compare channel changes in mountain, foothill, and lower-river reaches. Differences in catchment size and morphological conditions were also taken into account, as these factors may influence both the course of erosional processes and the local effect of bridge structures on flow hydraulics.

The source area of the Skawa River is located in the Żywiec Beskids, below the Szytkowicka Pass. The river flows through the Makowski Beskids and, in its middle and lower course, through foothill areas and the Vistula valley, before joining the Vistula River at river kilometre 22.7. The catchment area of the Skawa River is 1160 km². Three research profiles located in different parts of the river course were included in the analysis. The Sucha Beskidzka profile is situated at river kilometre 45.7, and the staff gauge is mounted

on the road bridge along the Sucha Beskidzka–Maków Podhalański route. The Wadowice profile is located at river kilometre 21.2, while the gauge is situated 75 m downstream of the bridge on the Wadowice–Kalwaria Zebrzydowska route (Figure 2). The third profile, Zator, is located at river kilometre 4.8, and the staff gauge is mounted on the road bridge along the Zator–Skawina route. This arrangement of sites makes it possible to analyse the influence of bridge structures in the upper, middle, and lower course of the river.

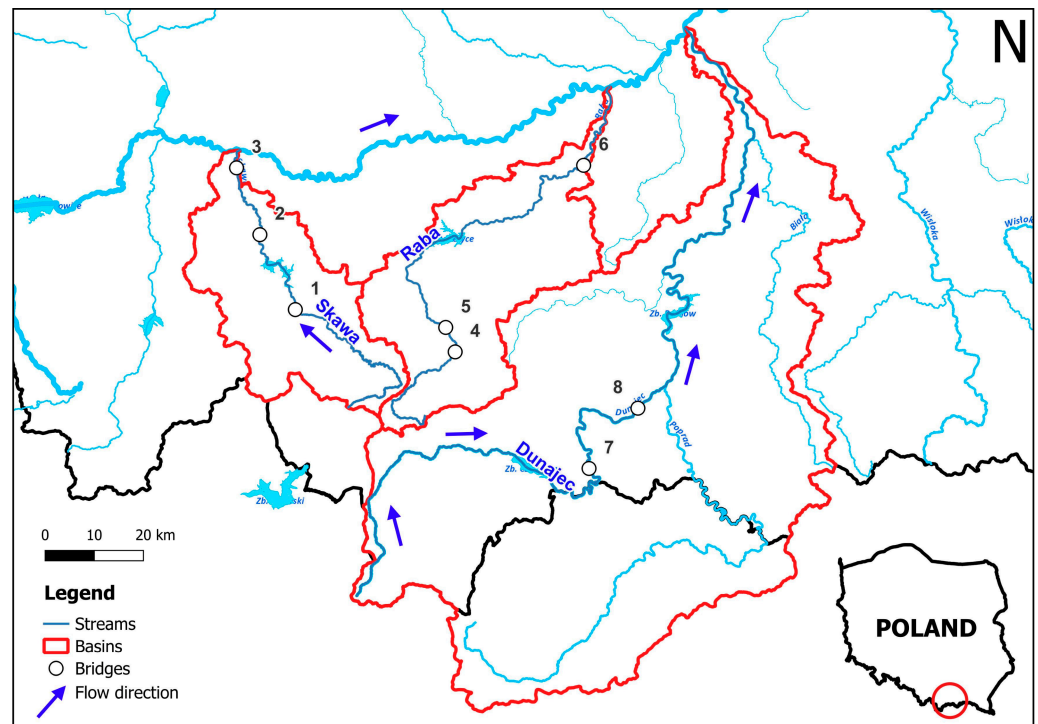


Figure 1. Location of the study area (bridges in: 1—Sucha Beskidzka, 2—Wadowice, 3—Zator, 4—Mszana Dolna, 5—Kasinka Mała, 6—Proszówki, 7—Krościenko, 8—Gołkowice).

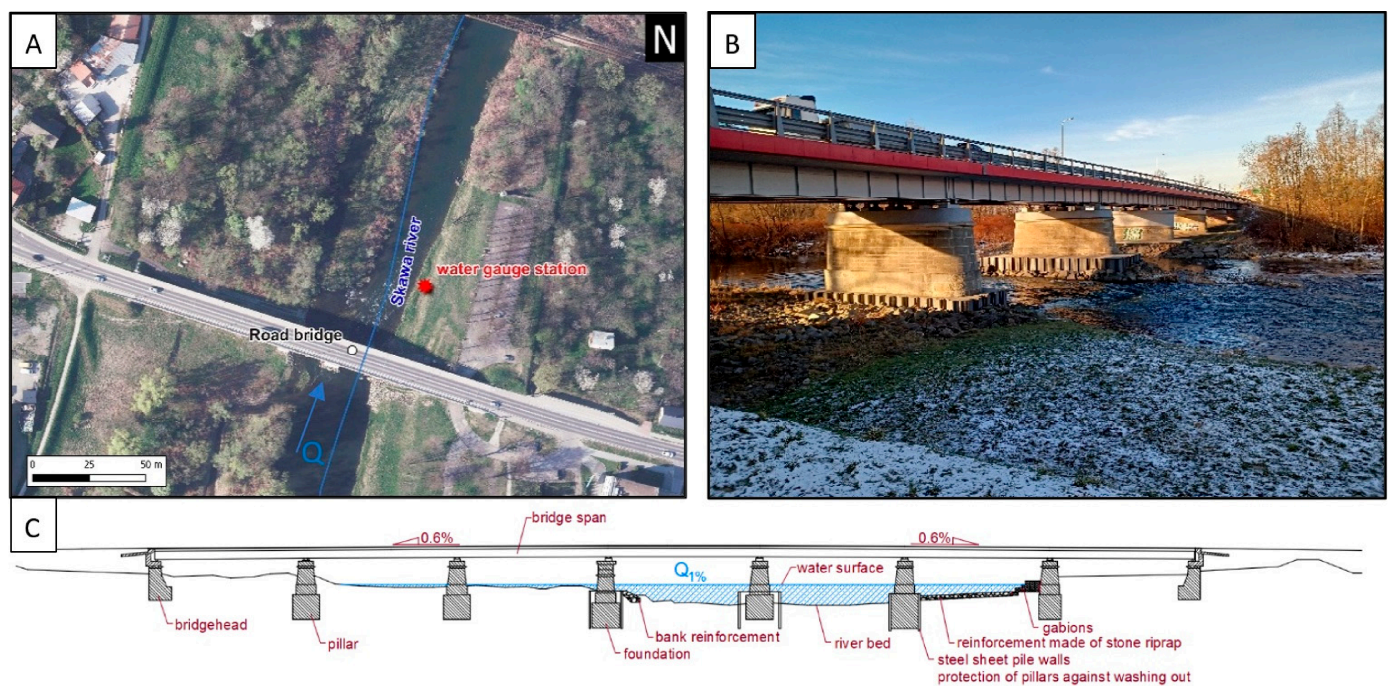


Figure 2. Bridge over the Skawa River in Wadowice: (A) top view, (B) photograph, (C) cross-section scheme.

The source area of the Raba River is located in the Gorce Mountains, after which the river flows through the Western Beskids, the Western Beskid Foothills, and the western part of the Sandomierz Basin. In its lower course, the Raba flows through the Vistula Plain and joins the Vistula River near Uście Solne at river kilometre 134.7. The catchment area of the Raba River is 1537.1 km². Three research profiles were selected along this river. The Mszana Dolna profile is located at river kilometre 102.7, 15 m upstream of the railway bridge on the Mszana Dolna–Rabka route. The Kasinka Mała profile is situated at river kilometre 95.9, and the gauge is located 100 m downstream of the bridge on the Mszana Dolna–Lubień route. Both sites represent the upper course of the Raba River. The third profile, Proszówki, is located in the lower course of the river, at river kilometre 21.7, 200 m downstream of the bridge on the Bochnia–Kraków route. This selection of sites allows a comparison of channel changes and hydraulic conditions in reaches occupying different positions along the river longitudinal profile.

The Dunajec River is formed by the confluence of the Czarny Dunajec and Biały Dunajec in Nowy Targ, at river kilometre 199.2. Between river kilometres 171.0 and 154.0, the Dunajec forms the border between Poland and Slovakia. It then flows through the Orawa–Nowy Targ Basin, passes south of the Gorce Mountains, cuts through the Pieniny Mountains, the Beskid Sądecki, the Sądecka Basin, the Rożnów Foothills, and the Vistula Plain, and finally joins the Vistula River near Opatowiec. The catchment area of the Dunajec River is 6804.0 km². Two profiles located in the upper course of the river were included in the study. The Krościenko profile is situated at river kilometre 149.2, at the road bridge on the Krościenko–Szczawnica route. The second profile, Gołkowice, is located at the road bridge on the Nowy Sącz–Szczawnica route, at river kilometre 119.0. In both cases, the gauges were located in the immediate vicinity of the bridge structures.

The selected profiles represent diverse morphological settings and different positions within the river system. Therefore, their comparison is not intended as a simple one-to-one assessment of the magnitude of change between rivers, but rather as a basis for identifying common trends in channel degradation and evaluating the extent to which bridge structures modify local hydraulic conditions under different fluvial settings.

3. Materials and Methods

Annual minimum water levels obtained from the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) were used to analyse long-term channel changes. The longest observation series (1900–2022) were available for the Krościenko profile on the Dunajec River, Proszówki on the Raba River, and Wadowice on the Skawa River. For the remaining sites, the data series were shorter or contained gaps due to missing measurements, particularly in Gołkowice on the Dunajec and in Sucha Beskidzka and Zator on the Skawa.

The intensity of erosional changes was assessed based on the assumption proposed by Punzet [62], according to which the course of annual minimum water levels over a multi-year period reflects the position of the channel bed, and changes in these water levels correspond to changes in bed elevation over time [63,64]. The long-term series of annual minimum water levels in the analysed profiles were divided into time intervals within which bed-level changes were described using the following function:

$$H_i(T) = H_{av}(T) + \varepsilon \quad (1)$$

where

ε —random component (residual component, called remainder),

$H_{av}(T)$ —regression function expressed as a linear function:

$$H_{av}(T) = E(H|T) = \alpha T + \beta \quad (2)$$

where

T —observation year,

α —erosion or accumulation intensity indicator, cm per year,

β —constant, cm.

The parameter α represents the average annual rate of bed lowering or aggradation within a given time interval. The parameters α and β were estimated using the least squares method. Equations (1) and (2) were applied only within the time intervals defined for a given profile.

All changes in staff gauge zero levels and any relocations of gauging stations were taken into account in the calculations. Based on observed bed-level changes in these cross-sections, the average annual rate of bed lowering was calculated and compared with the coefficient α in the function $H_i(T)$. Owing to the limited reliability of some historical cross-sections, this type of verification could only be carried out for selected sites.

Flood events were also analysed in the studied rivers, with particular attention paid to their influence on channel processes in the vicinity of bridge structures. Data on flood waves, peak discharges, and their basic hydrological characteristics were obtained from IMGW-PIB. This part of the analysis focused mainly on flows with peak values ranging from Q50% to Q1% (from 2- and 100-year flood), because changes in river cross-section geometry may also occur during more frequent flows than in the 1% event, provided that critical shear stresses for sediment transport are exceeded [65]. At the same time, extreme flows may lead to rapid morphological changes that are particularly important for the stability of bridge piers [66].

For the hydraulic analyses, one-dimensional models developed in the MIKE 11 system by DHI as part of the National Protection System programme were used. These models were provided by the Regional Water Management Authority in Kraków. For each hydraulic model, a corresponding reference hydrological model was developed in the HEC-HMS 4.7 software for the respective catchment. The hydrological models were calibrated using data from gauging stations. Flow increments along the analysed river reaches were represented according to the size of partial catchments and inflows from tributaries. On this basis, the inflow conditions for the hydraulic models were defined. The bridge geometry used in the present study was taken from the source hydraulic models supplied by the Authority. According to the methodology applied in the preparation of these models, the geometric input data included geodetic surveys of channel cross-sections at bridge locations together with measurements of structural elements, including abutments and piers.

All MIKE 11 calculations were performed under unsteady-flow conditions, with boundary conditions specified in the form of hydrographs rather than as a fixed steady discharge. Consequently, the Q1% value used in this study should be understood as the peak discharge of a hypothetical design flood wave with an exceedance probability of 1%, applied as a uniform comparative scenario for all analysed bridges, and not as a single constant flow. This approach is consistent both with the documentation of the source models and with the methodology of hydraulic modelling used for flood hazard maps, in which boundary conditions may be defined as discharge or water-level hydrographs.

For each model, calibration was carried out using data from the 2010 flood, whereas verification was based on the 2014 flood. The procedure involved comparison of observed and simulated hydrographs and the following goodness-of-fit measures reported in the source model documentation: the correlation coefficient, the special correlation coefficient, the total square error, peak stage error, peak discharge error, peak timing shift, and flood-

wave volume error. According to the source documentation, the quality of fit for the analysed rivers and gauging stations was classified as good, very good, or excellent.

In the present study, MIKE 11 was used to assess local changes in hydraulic conditions in bridge reaches rather than to directly reproduce the three-dimensional scour hole developing around bridge supports. A one-dimensional model makes it possible to evaluate changes in basic flow parameters in bridge cross-sections, such as water surface elevation, mean flow velocity, and bed shear stress, which were treated here as indicators of erosion potential. The analysis was therefore limited to three computational cross-sections for each structure: upstream of the bridge, at the bridge axis, and downstream of the bridge. Thus, the model was used to evaluate hydraulic indicators in bridge cross-sections, not to reconstruct the three-dimensional geometry of local scour holes.

Because the analysed bridges are located in different parts of the catchments and represent different hydrological settings, a common flow scenario was adopted to allow comparison of their effects. A flow with an exceedance probability of 1% (Q1%) was selected, in accordance with engineering practice traditionally applied in bridge design [67]. In the present study, however, the role of Q1% was primarily comparative: it served to assess how bridges modify local flow hydraulics and scour hazard under high-flow conditions, rather than to explain the long-term bed degradation itself, which was mainly associated with historical gravel extraction, channel regulation, and other anthropogenic transformations.

The computational core of the MIKE 11 model is the hydrodynamic module, which solves the one-dimensional Saint-Venant equations [68]. The continuity equation is expressed as:

$$\frac{\partial Q}{\partial x} + \frac{\partial(A + A_0)}{\partial t} - q = 0 \quad (3)$$

and the momentum equation is as follows [68]:

$$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2 / A)}{\partial x} + gA \left(\frac{\partial H}{\partial x} + S_f + S_e \right) + L = 0 \quad (4)$$

where

Q —discharge ($\text{m}^3 \cdot \text{s}^{-1}$);

H —water level (m);

A —active cross-sectional area (m^2);

A_0 —inactive cross-sectional area of flow (m^2);

x —distance (m);

t —time (s);

q —lateral inflow or outflow per unit length ($\text{m}^3 \cdot \text{s}^{-1}$);

β —momentum coefficient for velocity distribution (-);

g —gravitational acceleration ($\text{m} \cdot \text{s}^{-2}$);

S_f —slope of channel or floodplain friction (-);

S_e —slope of elongation—shortening (-);

L —effect of lateral flow momentum (m).

The value of the friction slope S_f is calculated using Manning's equation for steady flow [69]:

$$S_f = \frac{n^2 |Q| Q}{A^2 R^{4/3}} \quad (5)$$

where

n —Manning's roughness coefficient (-);

R —hydraulic radius (m).

The solution to Saint-Venant's mathematical equations uses an advanced scheme of entangled finite differences developed by Abbott and Ionescu [70]. The equations are solved using an iterative method.

Bed shear stress was calculated using the following formula [71]:

$$\tau = \rho g \frac{V^2}{n^2 h^{1/3}} \quad (6)$$

where

ρ —density of the fluid ($\text{kg}\cdot\text{m}^{-3}$);

g —acceleration due to gravity ($\text{m}\cdot\text{s}^{-2}$);

n —Manning's roughness coefficient (-);

h —water depth (m);

V —flow velocity ($\text{m}\cdot\text{s}^{-1}$).

The construction of the one-dimensional hydraulic model included the schematization of the river network, the introduction of cross-sections, the definition of hydrodynamic parameters, the incorporation of engineering structures, the establishment of boundary conditions, and finally model calibration, verification, and computation [72,73]. Flow resistance between water and the underlying surface, both in the main channel and on floodplains, was represented by roughness coefficients, which constitute the key hydraulic parameters of the model. The presence of engineering structures such as bridges, culverts, weirs, and footbridges affects local flow conditions by modifying the flow geometry, hydraulic radius, and backwater conditions [73,74]. For the geodetic cross-sections, a distributed roughness approach was applied, meaning that each reach between two geodetic surveys was assigned an individual Manning coefficient. The initial values were determined on the basis of land-cover codes assigned in the field by surveyors and land-cover information from the BDOT10k database and were subsequently verified during model calibration. The final Manning roughness coefficient is shown in Table 1.

Table 1. The values of the Manning coefficient adopted for numerical modeling.

Research Object	Upstream	Bridge Cross-Section	Downstream
Sucha Beskidzka	0.080	0.033	0.080
Wadowice	0.060	0.040	0.060
Zator	0.080	0.040	0.080
Mszana Dolna	0.100	0.040	0.100
Kasinka Mała	0.100	0.040	0.100
Proszówki	0.100	0.040	0.100
Krościenko	0.020	0.020	0.035
Gołkowice	0.038	0.038	0.038

The incorporation of bridge structures into the hydraulic model required the generation of three cross-sections for each structure: at the bridge location and at reference sections located upstream and downstream at a distance corresponding to the structure width. The analysed bridge structures were not modelled using alternative, dedicated bridge equations, but by means of a combination of the culvert and weir elements available in MIKE 11. In this approach, the culvert element represents flow through the bridge opening, including pressure flow, whereas the weir element represents overtopping flow above the structure. The total discharge through the bridge section was therefore calculated as the sum of flows through both elements. Individual spans were introduced separately, so the effect of bridge piers was accounted for indirectly through the subdivision into spans and through the inclusion of local losses at the inlet and outlet, as well as losses related to free-surface

flow, friction resistance, and internal turbulence. In this modelling scheme, MIKE 11 does not allow direct geometric implementation of piers. In the model, bridge geometry was represented as a system of hydraulic structures describing flow beneath the bridge and, where relevant, overtopping flow above the structure [73]. This modelling framework made it possible to evaluate the extent to which the presence of a bridge modifies local hydraulic parameters and may enhance erosion processes.

4. Results

Annual minimum water levels from the eight gauging sites reveal a widespread tendency toward channel-bed lowering. However, the timing, rate, and persistence of this process varied substantially among rivers and among individual reaches. None of the sites followed a simple monotonic trajectory. Instead, incision was commonly interrupted by short phases of aggradation or relative stabilisation, showing that channel adjustment resulted from the combined influence of human interventions and natural disturbances rather than from a single basin-wide trend. Across the study area, the most important controls appear to have been historical sediment extraction, channel regulation and narrowing, grade-control structures, and recurrent flood events that redistribute bed material. Because several gauging profiles are located upstream or downstream of the analysed bridges rather than exactly within bridge cross-sections, the historical water-level series should be interpreted primarily as indicators of reach-scale bed evolution. In contrast, the hydraulic models describe the local bridge effect under site-specific Q1% flows.

4.1. Long-Term Channel-Bed Changes Inferred from Annual Minimum Water Levels

The Skawa (Figure 3, Table 2) sites illustrate three different modes of adjustment. Sucha Beskidzka records a moderate early incision, followed by a prolonged depositional phase, and then renewed instability. Between 1901 and 1960, the bed lowered by about 0.93 m at roughly $1.3 \text{ cm} \cdot \text{yr}^{-1}$, probably in connection with sediment extraction for local construction. Although the observation gap in 1961–1970 prevents precise reconstruction, the series's structure suggests that degradation may have continued during that interval. From 1971 to 2000, however, the signal shifted toward accumulation, especially after 1980, which is consistent with channel widening along the Osielec–Sucha Beskidzka reach. Since 2001, alternating erosion and accumulation have been observed again, but the overall trend still points to a slight lowering. Wadowice represents a much more dynamic and unstable reach. Early incision in 1905–1949 was followed by a short bed-level rise of about 0.4 m in 1947–1949. Then, after a short 5-year accumulation period, there was rapid degradation during 1955–1970, which was intensified by both sediment extraction and repeated floods. The following decade brought temporary aggradation, but in 1980–1994, bed lowering accelerated sharply. Currently, since 2013, a slow aggradation of sediment has been observed, making Wadowice the most variable Skawa station in the long-term record. Zator, in turn, documents a long erosional history that later shifted toward stabilisation. Strong degradation occurred from the interwar period until about 1980 and is plausibly linked to industrial-scale gravel extraction carried out between 1918 and 1970. After the weir was built in 1975, the trajectory changed markedly: from 1984 onward, the channel became broadly stable, with only a slight aggradational tendency despite later flood events. Taken together, the Skawa profiles show that long-term bed evolution depended less on the mere presence of bridge structures than on reach-scale changes in sediment supply and longitudinal control.

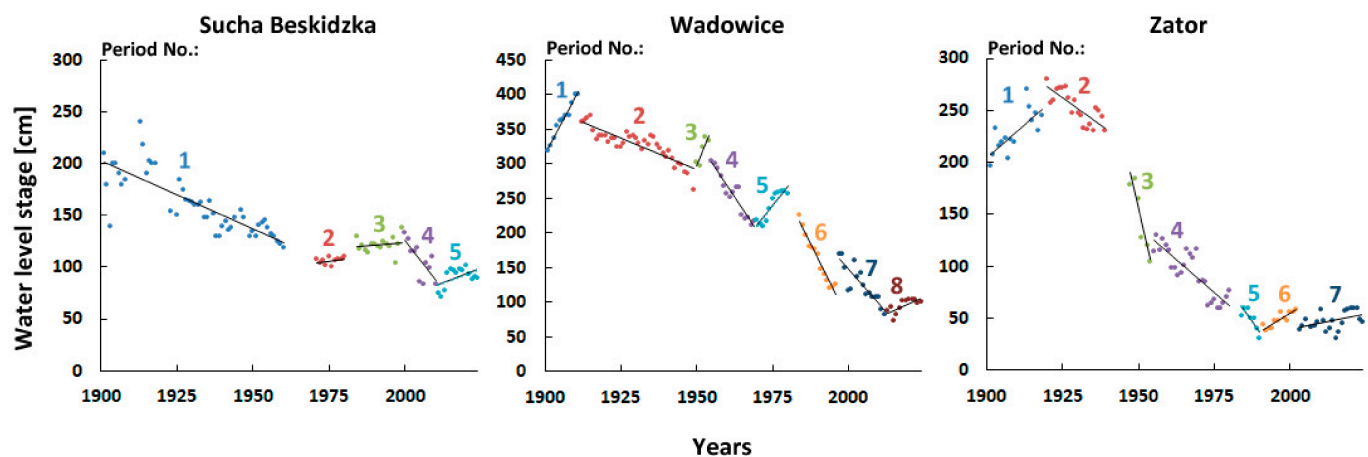


Figure 3. Annual minimum water levels indicating erosion and accumulation processes in the Skawa River.

Table 2. Variability of the Skawa River bed position along with regradation formulas.

Period No. *	Time Frame	Equation of the Riverbed Position	R ² Coefficient	Bed Level Change [cm·yr ^{−1}]	Bed Level Change (Start – End) [cm]
SUCHA BESKIDZKA					
1	1901–1960	$H = -1.31T + 2687.6$	0.67	−1.3	−91
	1961–1970	No data			
2	1971–1980	$H = 0.37T + 624.0$	0.11	+0.4	+2
	1981–1983	No data			
3	1984–1999	$H = 0.25T - 376.5$	0.03	+0.3	+8
4	2000–2010	$H = -3.85T + 7817.0$	0.55	−3.8	−50
5	2011–2024	$H = 1.12T - 2162.1$	0.25	1.1	+14
WADOWICE					
1	1901–1911	$H = 8.13T - 15145.0$	0.96	+8.1	+81
2	1912–1949	$H = -1.83T + 3860.5$	0.76	−1.8	−97
3	1950–1954	$H = 10.6T - 20372.0$	0.79	+10.6	+71
4	1955–1969	$H = -6.57T + 13149.0$	0.90	−6.6	−88
5	1970–1980	$H = 5.76T + 11144.0$	0.82	+5.8	+38
	1981–1983	No data			
6	1984–1996	$H = -8.84T + 17746.0$	0.95	−8.8	−100
7	1997–2012	$H = -4.88T + 9906.0$	0.75	−4.9	−88
8	2013–2024	$H = 1.97T - 3885.0$	0.50	+2.0	+13
ZATOR					
1	1901–1918	$H = 2.54T - 4628.8$	0.54	+2.5	+48
2	1920–1939	$H = -2.09T + 4285.9$	0.62	−2.1	−49
	1940–1946	No data			
3	1947–1954	$H = -12T + 23555.0$	0.86	−12.0	−74
4	1955–1980	$H = -2.53T + 5076.6$	0.73	−2.5	−38
	1981–1983	No data			

Table 2. *Cont.*

Period No. *	Time Frame	Equation of the Riverbed Position	R ² Coefficient	Bed Level Change [cm·yr ^{−1}]	Bed Level Change (Start – End) [cm]
5	1984–1990	$H = -4.14T + 8280.7$	0.69	−4.1	−22
6	1991–2002	$H = 1.68T + 3316.2$	0.76	+1.7	+14
7	2003–2024	$H = 0.58T - 1129.1$	0.20	+0.6	+7

where H—water surface elevation [cm], T—time [year], *—The period and regression equation are correlated with the data shown in the graph (Figure 3).

The Raba profiles (Figure 4, Table 3) are equally heterogeneous, but they most clearly express persistent post-1970 incision. Mszana Dolna differs from the other sites in that aggradation dominated until 1969; only later did the reach enter a prolonged erosional phase. From 1970 to 1999, and again from 2000 to 2013, bed lowering remained intense, while repeated floods likely supported bed-material transport and sustained incision. Although the rate decreased after 2014, the cumulative lowering was sufficient to leave the downstream water intake approximately 1.5 m above the present bed. The sediment accumulation recorded in 2024 may suggest a deceleration of erosion; however, a definitive assessment of this phenomenon requires further monitoring. Kasinka Mała shows the strongest recent erosion continuity. Bed lowering dominated already in 1967–1973, then accelerated around 1973/1974, when the channel dropped by about 0.46 m, probably in relation to the 1972 and 1974 floods. Another abrupt lowering of about 0.66 m occurred in 1998–2003. Following a period of intense erosion that ended in 2011, a phase of slight material deposition was observed. However, since 2016, erosive processes have once again resumed. Proszówki records the clearest legacy of human modification. After a weak early phase of incision, the reach underwent sustained degradation in 1921–1981, most likely driven by channel gravel extraction, frequent floods, and engineering works that deepened the channel and reduced the bed width to about 25 m. Later changes were stepwise rather than continuous: a stable phase in 1982–1991 was followed by a sudden lowering around 1991/1992, which was related to the regulation of the riverbed. After 1998, there was relative stabilization, but in 2008/2009 there was a drastic lowering of the riverbed caused by the passage of a flood wave. These three sites therefore suggest that the Raba has been especially sensitive to the interaction between flood disturbance and inherited channel modifications, with bridges operating within a preconditioned, often already degrading fluvial system.

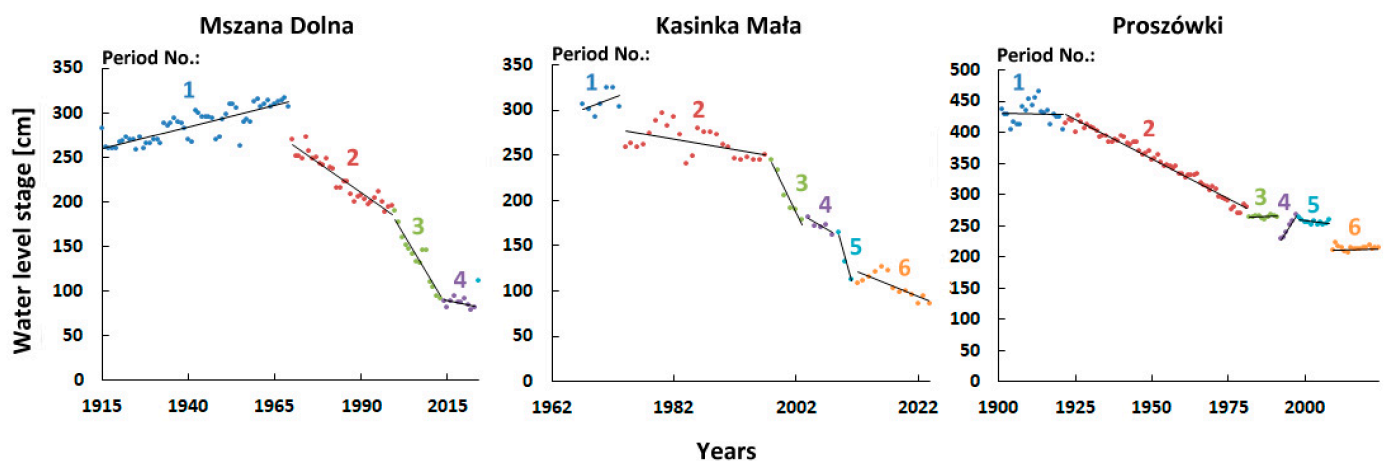


Figure 4. Annual minimum water levels indicating erosion and accumulation processes in the Raba River.

Table 3. Variability of the Raba River bed position along with regradation formulas.

Period No. *	Time Frame	Equation of the Riverbed Position	R ² Coefficient	Bed Level Change [cm·yr ^{−1}]	Bed Level Change (Start – End) [cm]
MSZANA DOLNA					
1	1915–1969	$H = 0.96T - 1577.3$	0.68	+1.0	+24
2	1970–1999	$H = -2.66T + 5499.7$	0.88	−2.7	−74
3	2000–2013	$H = -6.55T + 13292.0$	0.88	−6.6	−99
4	2013–2023	$H = -0.68T + 1469.1$	0.20	−0.7	−7
KASINKA MAŁA					
1	1967–1973	$H = 2.54T - 4686.8$	0.20	+2.5	−3
2	1974–1997	$H = -1.16T + 2578.4$	0.25	−1.2	−8
3	1998–2003	$H = -13.60T + 27414.0$	0.92	−13.6	−66
4	2004–2008	$H = -3.90T + 7995.2$	0.74	−3.9	−20
5	2009–2011	$H = -25.5T + 51391.0$	0.98	−25.5	−51
6	2012–2024	$H = -2.71T + 5571.6$	0.62	−2.71	−23
PROSZÓWKI					
1	1901–1920	$H = +0.34T - 212.6$	0.02	+0.3	−13
2	1921–1981	$H = -2.49T + 5214.1$	0.97	−2.5	+124
3	1982–1991	$H = 0.15T - 24.7$	0.04	+0.2	0
4	1992–1997	$H = 8T - 15710.0$	0.97	+8.0	+38
5	1998–2008	$H = -0.55T + 1348.6$	0.21	−0.5	−4
6	2024–2009	$H = 0.014T + 184.0$	0.01	0.0	+3

where H—water surface elevation [cm], T—time [year], *—The period and regression equation are correlated with the data shown in the graph (Figure 4).

The Dunajec sites (Figure 5, Table 4) combine long-term incision with clearer episodes of later stabilisation or flood-related reversal. Krościenko underwent intense erosion in 1900–1921, then remained relatively stable in 1922–1965, before a distinct lowering of about 0.86 m occurred in 1966–1974. The source data associate this episode not only with natural channel processes but also with river training works downstream of the gauge, where bilateral channel lining likely concentrated flow and intensified erosion; the large floods of 1970 and 1972 probably amplified this response. After 1975, the bed became relatively stable. Gołkowice shows a longer but more moderate erosional history. The bed lowered in 1910–1931 and again, more slowly, in 1931–1960; renewed incision continued in 1975–2014. In total, during the period 1900–2014 the riverbed lowered by almost 1 m. Floods occurred on average every few years during 1972–2014 and repeatedly destabilised the channel. After the 2014 flood, the reach aggraded by about 0.3 m, but erosion resumed again from 2015 onward. In geomorphic terms, both Dunajec reaches appear strongly flood-sensitive. However, they also demonstrate that channel response depended on local regulatory legacies and on whether high flows reinforced incision or temporarily restored sediment storage.

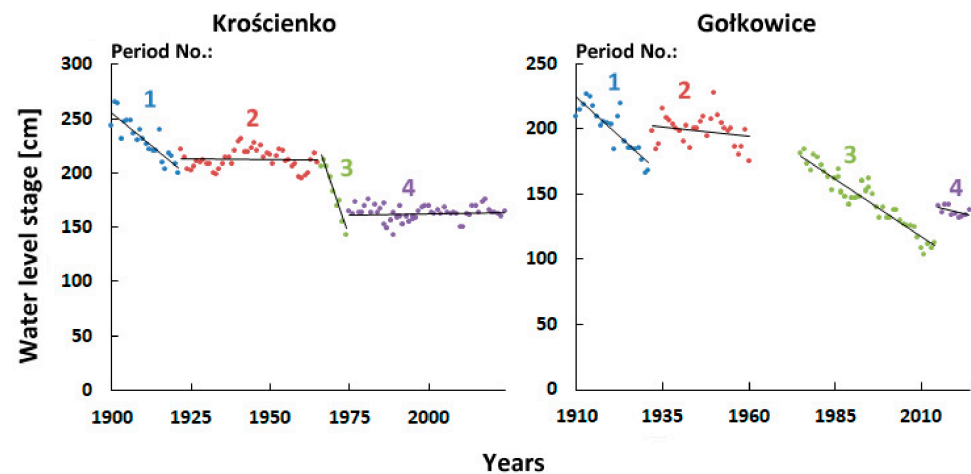


Figure 5. Annual minimum water levels indicating erosion and accumulation processes in the Dunajec River.

Table 4. Variability of the Dunajec River bed position along with regradation formulas.

Period No. *	Time Frame	Equation of the Riverbed Position *	R ² Coefficient	Bed Level Change [cm·yr ^{−1}]	Bed Level Change (Start – End) [cm]
KROŚCIENKO					
1	1900–1921	$H = -2.42T + 4859.5$	0.76	−2.4	−43
2	1922–1965	$H = -0.02T + 251.9$	0.01	0.0	−12
3	1966–1974	$H = -8.55T + 17026.0$	0.93	−8.6	−63
4	1975–2024	$H = 0.05T + 67.7$	0.01	+0.1	0
GOLKOWICE					
1	1910–1931	$H = -2.43T + 4868.0$	0.74	−2.4	−42
2	1932–1960	$H = -0.28T + 743.3$	0.04	−0.3	−28
	1961–1974	No data			
3	1975–2014	$H = -1.77T + 3673.4$	0.88	−1.8	−68
4	2015–2024	$H = -0.70T + 1544.2$	0.31	−0.7	−3

where H—water surface elevation [cm], T—time [year], *—The period and regression equation are correlated with the data shown in the graph (Figure 5).

Viewed together, the historical records do not support a single, shared chronological sequence across all reaches. Instead, they point to four recurrent modes of behaviour: (1) prolonged incision later followed by stabilisation, as in Zator and Krościenko; (2) early or temporary aggradation replaced by later degradation, as in Mszana Dolna; (3) continued or stepwise incision with only short interruptions, as in Kasinka Mała and Proszówki; and (4) highly oscillatory behaviour, as in Wadowice and, to a lesser extent, Sucha Beskidzka and Gołkowice. This variability is geomorphologically significant because it indicates that bridge reaches are embedded within channel systems with distinct adjustment histories. The same local hydraulic disturbance may therefore act differently depending on whether the host reach is already stabilised, still degrading, or prone to alternating erosion and deposition.

4.2. Hydraulic Response of Bridge Reaches Under Q1% Flow

Hydraulic modelling shows that bridge effects were predominantly local, but the intensity of that local signal differed strongly among sites. The weakest response occurred at Sucha Beskidzka and Proszówki, a moderate response at Mszana Dolna, Krościenko,

and Gołkowice, and the strongest response at Wadowice, Zator, and Kasinka Mała. The key point is that bridges rarely altered downstream conditions over long distances; instead, they mainly produced local backwater, local flow concentration along the bridge axis, and, in some cases, higher shear stress in selected cross-sections (Table 5).

Table 5. Changes in hydrodynamic parameters in the area of bridges.

River	Site	Group	ΔWSE Upstream [m]	ΔWSE Down- stream [m]	ΔV Upstream [m·s ^{−1}]	ΔV at Bridge [m·s ^{−1}]	ΔV Down- stream [m·s ^{−1}]	$\Delta \tau$ Upstream [Pa]	$\Delta \tau$ Down- stream [Pa]
Skawa	Sucha Beskidzka	W	0.00	+0.03	−0.02	+0.84	0.00	−2	0
	Wadowice	S	+0.90	0.00	−0.79	+2.95	−0.03	−15	+646
	Zator	S	+0.04	+0.17	+1.15	+5.67	+1.14	+241	+235
Raba	Mszana Dolna	M	−0.38	0.00	0.00	+0.90	+0.42	+105	0
	Kasinka Mała	S	−0.76	−0.01	0.00	+3.03	+0.61	+254	0
	Proszówki	W	−0.04	+0.01	0.00	+0.64	+0.03	+1	0
Dunajec	Krościenko	M	+0.66	+0.10	−0.54	+1.90	0.00	0	0
	Gołkowice	M	+0.55	0.00	−0.59	+1.56	0.00	−34	0

where group: W—weak interaction, M—medium interaction, S—strong interaction. hydrodynamic parameters: ΔWSE —difference in water surface elevation [m a.s.l.], ΔV —velocity difference [m·s^{−1}], $\Delta \tau$ —shear stress difference [Pa].

The weakest bridge effect was recorded at Sucha Beskidzka and Proszówki. In Sucha Beskidzka, the bridge and no-bridge scenarios produced identical water surface elevation at the upstream cross-section (329.15 m a.s.l.) and only a 0.03 m difference downstream (329.25 m a.s.l. without the bridge and 329.28 m a.s.l. with the bridge). Bed shear stress was nearly the same in both scenarios, and velocity differences did not exceed 0.02 m·s^{−1} in the river channel. However, in the bridge section, the water velocity increased from 1.64 m·s^{−1} to 2.48 m·s^{−1}. In Proszówki, backwater was also negligible, shear-stress changes were very small, and the only clearer response was a local increase in velocity along the bridge axis, from 1.57 to 2.21 m·s^{−1}, while downstream conditions remained essentially unchanged. These two reaches, therefore, represent cases in which the present bridge geometry does not substantially alter hydraulic conditions beyond the immediate vicinity of the structure. This is especially informative in Proszówki, where long-term channel degradation is pronounced despite a weak current bridge signal, implying that historical incision there cannot be attributed primarily to the bridge itself.

A second group comprises Mszana Dolna, Krościenko, and Gołkowice, where the bridge effect is evident but remains spatially limited. In Mszana Dolna, the bridge caused a drop in the water level above the bridge (from 399.15 m a.s.l. to 398.77 m a.s.l.) and an increase in velocity in the bridge zone (from 1.09 m·s^{−1} to 1.99 m·s^{−1}) and below (from 1.04 m·s^{−1} to 1.46 m·s^{−1}). It produced higher upstream shear stress (from 112 Pa to 217 Pa), whereas downstream shear stress remained almost unchanged. Krościenko also showed a clear backwater in the bridge cross-section (from 418.82 m a.s.l. to 419.48 m a.s.l.), but downstream water-level differences did not exceed 0.10 m. Shear stress remained essentially unchanged, while flow velocity increased only along the bridge axis (from 3.07 m·s^{−1} to 4.97 m·s^{−1}) and decreased upstream (from 3.01 m·s^{−1} to 2.47 m·s^{−1}), indicating redistribution of flow rather than a strong downstream erosive signal. Gołkowice behaved similarly: the structure caused a local water-level rise from 317.47 m a.s.l. to 318.02 m a.s.l. The increase in the water level above the bridge resulted in a reduction in velocity from 3.36 m·s^{−1} to 2.77 m·s^{−1}. There is an increase in velocity (from 3.46 m·s^{−1} to 5.02 m·s^{−1}) along the bridge axis, and the left downstream water level and velocity are effectively unchanged. In both Dunajec sites, therefore, the bridge primarily reorganises the local flow

field within the bridge cross-section without producing a distinct downstream hydraulic effect. Geomorphically, this pattern suggests that the bridges may focus local scour during high flows. However, they do not by themselves account for the longer-term evolution documented in the gauge series.

The strongest hydraulic response occurred at Wadowice, Zator, and Kasinka Mała, although the nature of that response differed among them. In Wadowice, the bridge produced a distinct local backwater effect (from 257.45 m a.s.l. to 258.35 m a.s.l.) and a major concentration of flow along the bridge axis, where velocity rose from $1.80 \text{ m}\cdot\text{s}^{-1}$ to $4.75 \text{ m}\cdot\text{s}^{-1}$. However, the downstream water level is unchanged. However, the water level downstream remained unchanged and the velocity was also almost unchanged, but it increased the shear stress significantly (from 27 Pa to 668 Pa). The significant increase in shear stress is a consequence of the narrowing of the bridge's active opening by the piers located in the riverbed. Consequently, the water above the bridge accumulates, increasing the hydraulic gradient and concentrating energy losses due to the narrowing of the bridge opening. Wadowice clearly represents a site where the bridge strongly modifies local hydraulics. Zator shows the clearest combination of higher velocity and higher shear stress in several cross-sections. The bridge slightly increased the water level at the bridge section and by 0.17 m downstream, while also raising velocity upstream (from $1.60 \text{ m}\cdot\text{s}^{-1}$ to $2.75 \text{ m}\cdot\text{s}^{-1}$), along the bridge axis (from $1.64 \text{ m}\cdot\text{s}^{-1}$ to $7.31 \text{ m}\cdot\text{s}^{-1}$), and downstream (from $1.72 \text{ m}\cdot\text{s}^{-1}$ to $2.86 \text{ m}\cdot\text{s}^{-1}$). Shear stress likewise increased markedly both upstream (from 112 Pa to 350 Pa) and downstream (from 128 Pa to 362 Pa). Kasinka Mała also shows a strong bridge signal, evidenced by increased upstream shear stress (from 161 Pa to 415 Pa) and higher velocity along the bridge axis (from $1.47 \text{ m}\cdot\text{s}^{-1}$ to $4.50 \text{ m}\cdot\text{s}^{-1}$) and downstream (from $1.33 \text{ m}\cdot\text{s}^{-1}$ to $1.94 \text{ m}\cdot\text{s}^{-1}$). In geomorphic terms, these three sites represent the highest local scour potential among the analysed bridges.

The comparison between historical channel change and present hydraulic modelling is particularly important. A strong local bridge effect does not necessarily correspond to the strongest long-term bed degradation, and vice versa. Proszówki is the clearest example of a mismatch: it records substantial historical incision despite a weak present hydraulic bridge signal. Zator provides another instructive contrast: the bridge currently enhances local erosive power, but the long-term bed trajectory was dominated first by industrial gravel extraction and later by stabilisation following the weir's construction. Krościenko and Gołkowice show local bridge-induced reorganisation of flow without major downstream hydraulic consequences, while their historical records point to the importance of channel training and repeated floods. Kasinka Mała is almost the opposite case, where a strong local bridge effect operates within a reach that is already actively degrading, suggesting that bridge-related scour may amplify an ongoing geomorphic tendency. Overall, the combined evidence indicates that bridges should be treated as local modifiers of erosion hazard, superimposed on broader reach-scale channel trajectories, rather than as the sole or principal cause of century-scale riverbed lowering.

5. Discussion

An analysis of long-term changes in bed elevation in the investigated profiles shows that, despite periods of local aggradation, the dominant trend in all of the analysed rivers was long-term channel-bed lowering. The magnitude of this process varied spatially. In the Skawa River, bed lowering reached approximately 1.5 m at the Sucha Beskidzka profile, approximately 3.5 m at the Wadowice profile, and over 2.3 m at the Zator profile. In the Raba River, bed lowering reached approximately 2.4 m at the Mszana Dolna and Kasinka Mała profiles, and more than 2.5 m at the Proszówki profile. In the case of the Dunajec, the riverbed depression ranged from 0.9 to 1.0 m both on the Krościenko and Gołkowice

profiles. These values indicate that the Carpathian rivers investigated here were affected by long-term, system-scale channel degradation, rather than only by local, short-term episodes of morphological change.

The chronology and scale of these transformations suggest that the main causes of long-term bed lowering should be sought primarily in anthropogenic alterations of channels and catchments, such as in-channel sediment extraction, river regulation, channel narrowing and straightening, and changes in sediment transport conditions during flood events. At the same time, the evolution of these rivers cannot be explained solely by historical engineering works, because ongoing land-use and climate changes may also modify the magnitude and timing of sediment delivery from slopes, tributaries, and valley-floor storage to the main channel. In the Polish Carpathians, reforestation and abandonment of cultivated land may reduce hillslope erosion and attenuate runoff in some sub-catchments, thereby lowering sediment supply to the channel and reinforcing sediment-starved conditions in already incised reaches [41,75,76]. Conversely, projected increases in precipitation, especially during winter and spring, together with warmer winters and reduced snow cover, may enhance runoff, remobilise previously stored sediment, and shift the seasonal pattern of sediment delivery to the channel network [75,76]. This means that changes in transport intensity and changes in sediment availability should be considered jointly: where supply decreases, the same flow may act on a channel with lower bed-material replenishment, whereas periods of increased runoff may temporarily reactivate transport of stored sediment. In this context, bridge structures cannot be regarded as the primary cause of historical bed degradation. Their role is different: they act mainly as local modifiers of flow hydraulics, which may superimpose on an already existing degradation trend and locally increase the risk of scour around piers and abutments.

A particularly well-documented example is provided by the Raba. Historical analyses indicate that channel incision in this river was initiated by river-control works and reduced bed-material supply associated with basin-management change and later intensified by gravel extraction and modified flood flows. More recent data for the upper Raba above the Dobczyce reservoir, and for Raba sub-basins more generally, shows that precipitation change exerts the strongest positive effect on sediment loads, whereas temperature increase and land-use change alone tend to reduce them slightly; progressive forest expansion at the expense of agricultural land may therefore noticeably lower sediment delivery, especially in the upper basin, while in the lower, more agricultural part this compensating effect is weaker [75,76]. However, this mechanism is limited in winter, when warmer conditions, reduced snow and frost cover, and a shift from snowfall to rainfall may enhance runoff-induced soil erosion and increase sediment transfer despite afforestation. Thus, in the Raba catchment, future channel response may increasingly reflect the interaction between long-term sediment starvation and more seasonal and episodic transport pulses, although the magnitude of these changes remains sensitive to the adopted climate dataset and modelling assumptions [31,34,75–77].

A similar interaction between catchment-scale change and channel response can be inferred for the Skawa. Historical analyses of the lower Skawa indicate that channelisation, embankment construction, gravel mining, and, later, the reduction in bed-load continuity by the Świnna Poreba dam were the dominant controls on the transformation of formerly multi-thread reaches into a narrower, regulated channel. At the same time, forest cover in the Skawa catchment increased from 25.5% in 1860 to 46.8% in 2013, suggesting reduced agricultural pressure and potentially lower diffuse sediment supply from slopes; however, this effect should be treated as secondary to direct channel engineering and in-channel sediment extraction. From a climatic and hydrological perspective, the Skawa sub-basin shows a significant decrease in streamflow despite no clear trend in annual precipitation,

and much of the analysed period was characterised by meteorological drought. This suggests that future sediment delivery in the Skawa may depend less on annual precipitation totals alone than on changes in runoff seasonality, the persistence of low-flow periods, and the episodic remobilisation of stored sediments during high-flow events [78,79].

An analogous interaction of channel engineering, land-use change, and hydroclimatic variability can also be identified for the Dunajec, particularly in the reach from the Pieniny Gorge to Tarnów. Twentieth-century analyses show that the gorge section between Szczawnica and Zabrzeż/Tylmanowa remained comparatively stable because valley confinement and bedrock exposures limited lateral adjustment and incision, whereas downstream alluvial reaches toward Nowy Sącz, Zgłobice, and Żabno underwent much stronger narrowing and bed lowering in response to channelisation, gravel mining, and progressive sediment starvation. In the middle course, renewed channelisation reduced average low-flow width by about 20% and produced up to ~2 m of incision, while in the lower course, incision reached 3.1 m at Żabno and 3.4 m at Zgłobice [38]. This sediment deficit was strengthened by catchment-scale land-use changes: in the montane part of the Dunajec basin forest cover increased from 26% to 42% and arable land declined from 45% to 17% between 1931 and 2000 [38], and in the upper Dunajec basin agricultural land decreased by about 20% between 1980 and 2010 [80], with the largest declines affecting arable land and part of the former agricultural area undergoing grassing-over or self-afforestation [81]. At the same time, recent climatic change did not simply alter mean annual totals, but shifted the seasonal structure of water input, with decreases in December, June, and August and increases in March, May, and September, together with reduced repeatability of precipitation and discharge [82]; below the Czorsztyn-Sromowce Wyżne complex, dam operation additionally increased the regularity and laminarity of flow dynamics at Sromowce Wyżne and Krościenko [83]. These changes may be expected to modify both the timing and pathways of sediment transfer. In the downstream Dunajec, this is expressed not only by incision, but also by rapid fine-grained deposition in abandoned side channels and inter-groyne basins, indicating that channel regulation simultaneously accelerated in-channel transport and redirected part of the load onto confined floodplain surfaces [84].

This distinction is crucial for the interpretation of the modelling results. The hydraulic analysis was carried out for a Q1% flow, which in this study served as a standardized comparative scenario for all bridge structures. This made it possible to assess how bridges modify local flow parameters under high-flow conditions, but it does not mean that the Q1% flow itself explains long-term bed lowering of several metres. Long-term channel degradation results from the cumulative effect of multiple factors operating over decades, whereas the hydraulic model shows where a bridge may locally intensify erosion potential.

In the Skawa River, the influence of bridges on hydraulic conditions varied between profiles. At Sucha Beskidzka, the bridge had little effect on water level, flow velocity, or bed shear stress, suggesting a minor role in local flow modification. In contrast, at Wadowice and Zator, the bridges produced more distinct hydraulic changes. In Wadowice, a local backwater effect and flow acceleration along the bridge axis were observed. High shear stress values result from the presence of bridge piers in the riverbed, which significantly narrows the active cross-section, increasing the hydraulic gradient and concentrating energy losses. At Zator, the bridge increased both velocity and bed shear stress, indicating a stronger local impact and a possible contribution to scour development, although not as the main cause of long-term bed lowering.

In the Raba River, bridge effects were also spatially variable. At Mszana Dolna, the bridge caused slight upstream backwater and increased velocity and bed shear stress, while its downstream influence was limited. At Kasinka Mała, hydraulic changes were more pronounced, especially near the bridge axis and upstream section, where higher velocity

and shear stress suggest increased erosion potential. At Proszówki, the bridge had only a minor effect on water level and bed shear stress, with clearer changes limited mainly to flow velocity near the structure. These results show that bridge impacts depend strongly on local channel geometry, bridge characteristics, and flow conditions.

In the Dunajec River, at Krościenko and Gołkowice, bridges mainly altered flow velocity and water level close to the bridge axis. Upstream deceleration and acceleration through the bridge opening were observed, reflecting local flow contraction. However, downstream changes in bed shear stress were small, indicating that bridge influence in this river was mostly local and short-range.

These results are consistent with the literature on local scour at bridge structures. Studies by Hong and Abid [57], Chiew [70], Ettema [71], Suriya et al. [85], and Jabbar Jamel [86] indicate that bridges and their supports may locally disturb flow structure, cause flow concentration, increase turbulence, and promote scour around piers and abutments. Aulia [74] additionally showed that morphological changes in the bed and banks near bridges may affect not only the channel itself but also slope stability and infrastructure safety. Research conducted on the Rönne River [87] further confirmed that local flow conditions near bridges and bends may favour the development of deep erosion zones. Our results are consistent with this line of research but extend it by adding a regional and long-term perspective. Unlike studies focused on individual structures and local scour, the present study combines the analysis of historical bed degradation with an assessment of local hydraulic changes in bridge zones.

One important conclusion from the analyses is that comparing bridges located in different parts of river courses requires caution. The investigated structures are situated under different morphological and hydrological conditions: some are located in upper reaches, whereas others are in lower reaches characterized by different catchment sizes, cross-sectional geometry, regulation history, and sediment-transport regimes. Therefore, the results should not be treated as a simple ranking of the “most hazardous” bridges, but rather as evidence of different variants of local bridge influence on flow hydraulics under diverse fluvial settings.

The interpretation of the results should also take methodological limitations into account. This caution also applies to future-oriented interpretations of sediment delivery, because recent scenario-based studies for the Raba catchment have shown that the magnitude and seasonal pattern of projected sediment loads may vary depending on the adopted climate dataset, reference period, and model ensemble [77]. The MIKE 11 model applied in this study is a one-dimensional model, which means that it is well suited for assessing changes in water level, mean flow velocity, and indicator values of bed shear stress in a cross-section, but it does not directly reproduce the three-dimensional vortex structures responsible for the development of local scour holes around bridge supports. Consequently, the results should be interpreted as indicating zones of increased erosion potential, rather than as an exact representation of local scour geometry around piers. Additional uncertainty arises from the use of annual minimum water levels as an indirect indicator of bed-level change, the unequal length of observation series, and the limited reliability of some archival cross-sections.

From a practical point of view, the results indicate the need for a two-track approach to erosion-risk management. On the one hand, it is necessary to identify and limit long-term bed degradation processes at the scale of entire river reaches, especially where sediment extraction or strong river-training works occurred historically. This reach-scale perspective should be complemented by monitoring of catchment-scale changes in land use, forest cover, winter precipitation, and snow conditions, because these factors may alter sediment delivery to channels and, consequently, the availability of bed material in bridge

reaches [41,75–82]. On the other hand, local hydraulic assessment in bridge zones is also necessary, including monitoring of the bed, foundations, and changes in flow conditions during flood events. As emphasized by Pagliara et al. [88] and Kazemian et al. [89], modern monitoring methods, including acoustic sonar and structural vibration analysis, may provide important support in identifying scour hazards and reducing the risk of bridge damage.

These findings also clarify how the results can be used in sustainability-oriented river and infrastructure management. First, climate-resilient design of bridge infrastructure in incised Carpathian rivers should not be based only on the present design discharge and local pier hydraulics. It should also include the historical bed-level trajectory and the expected future sediment budget of the reach. In a degrading channel, even a structurally safe bridge may gradually lose hydraulic and geomorphic safety margins as the bed is lowered, flood velocities increase, foundation exposure becomes more probable, and lateral connectivity with the floodplain is reduced. Adaptation should therefore combine conventional scour protection with periodic surveys of bed elevation, post-flood inspections, and, where feasible, measures that restore sediment continuity or reduce flow concentration rather than merely armouring the channel. Such an approach is particularly relevant under changing precipitation, snowmelt, and land-use conditions in the Carpathians, because future risk may depend as much on episodic sediment pulses and sediment deficits as on the magnitude of individual flood peaks [41,75–82].

Second, the results have implications for sustainable sediment-management policy in Poland and the EU, where river-basin planning, flood-risk reduction, infrastructure safety, and ecological-status objectives need to be coordinated. Treating bridges as the main explanation for riverbed lowering would lead to narrowly local engineering responses, whereas the evidence indicates that policy should prioritise reach-scale sediment budgets, limits on extraction from channels and valley floors, assessment of the cumulative effects of river training, and cooperation between infrastructure managers, water authorities, and environmental agencies. In incised reaches, sediment should be treated not only as a hazard to be removed, but also as a resource supporting channel stability, flood-plain connectivity, groundwater levels, and aquatic habitats. This is important for balancing flood-protection objectives with hydromorphological integrity: excessive channel straightening and hard bank protection may increase conveyance locally, but can deepen incision, simplify habitat structure, and transfer erosion risk downstream [6,32,45–52]. Conversely, restoration measures that increase roughness, reconnect floodplain surfaces, or support gravel replenishment may improve ecological conditions, but they must be de-signed so that they do not create unacceptable local risk to bridges and settlements. The results therefore support a multi-criteria management framework in which bridge safety, flood protection, sediment continuity, and ecological status are assessed together. For the investigated rivers, the most sustainable strategy is not to choose between infrastructure protection and geomorphic integrity, but to identify where local structural protection is necessary and where reach-scale measures can reduce the underlying degradation trend.

In summary, the analyses show that bridges are not the main cause of long-term degradation of the investigated channels, but depending on local conditions they may significantly modify flow hydraulics and create zones of increased local erosion risk. The most important conclusion is therefore not simply that bridges have an effect, but that this effect must be properly interpreted within the broader context of pre-existing, system-scale channel degradation. Only such an approach makes it possible to correctly assess the hazard to bridge infrastructure and to formulate appropriate conclusions for design, monitoring, and river management.

The results should therefore be interpreted as evidence of interacting controls operating at different temporal and spatial scales. The long-term analysis shows whether a bridge is situated in a reach already affected by persistent bed lowering, whereas the hydraulic modelling indicates whether the structure locally amplifies flow contraction, velocity, water-level changes, or bed shear stress under a standardized high-flow scenario. Where both components coincide, the susceptibility of the bridge zone to local scour should be regarded as particularly high—not because the bridge is the primary cause of reach-scale incision, but because it superimposes local hydraulic forcing on a channel already undergoing long-term degradation. Conversely, where the hydraulic effect of the bridge is small, the observed bed lowering should be attributed mainly to broader reach-scale drivers rather than to the structure itself. Such an integrated approach is better suited than isolated local interventions to reconcile flood protection with the long-term ecological and geomorphic integrity of river corridors.

6. Conclusions

The analyses carried out confirm that, in all investigated profiles along the Skawa, Raba, and Dunajec rivers, the dominant trend was long-term channel-bed lowering, with the magnitude of this process ranging from approximately 1.0 m to more than 3.5 m over the analysed observation periods. The chronology and extent of these changes indicate that the principal causes of channel degradation were primarily historical sediment extraction, channel regulation, and recurrent flood events, rather than the presence of bridges as such. This means that the investigated Carpathian rivers have undergone long-term, system-scale transformations associated with anthropogenic disturbance of channel equilibrium.

The hydraulic analysis performed for the Q1% flow, adopted as a standardized comparative scenario, showed that bridges may locally modify flow conditions, causing changes in water level, flow velocity, and bed shear stress in bridge cross-sections and in their immediate vicinity. However, the magnitude of this impact was strongly spatially differentiated. In some locations, the influence of the structures was clear, especially along the bridge axis and in directly adjacent cross-sections, whereas in others it remained small or marginal. These results indicate that bridges are not the main cause of channel-bed degradation at the scale of entire river reaches, but they may create local zones of increased erosion and scour risk near piers and abutments. Accordingly, erosion hazard at bridge sites should be assessed jointly from the long-term degradation trajectory of the river reach and the local hydraulic response of the bridge cross-section, because only the combination of these two components captures the actual susceptibility of bridge zones to scour and foundation exposure.

The obtained results should be interpreted with due consideration of methodological limitations. As a one-dimensional model, MIKE 11 allows the assessment of changes in basic hydraulic parameters and the identification of zones with increased erosion potential, but it does not directly reproduce the three-dimensional processes of local scour around bridge supports. This means that the presented results should be treated as an indicator-based assessment of hydraulic hazard, rather than as an exact representation of local scour geometry. This applies particularly to extreme values, which require cautious interpretation and, in selected cases, additional verification.

From a practical point of view, the findings indicate the need for a two-track approach to erosion-risk management. On the one hand, it is necessary to limit and monitor channel degradation processes at the scale of entire river reaches, especially in areas where sediment extraction or intensive river training works were carried out in the past. On the other hand, local assessment of hydraulic conditions in bridge zones is also required, including monitoring of the channel bed, foundations, and changes in flow conditions during flood events. Consequently, the influence of bridges should already be taken into account at the

stage of design, modernization, and operation of bridge structures, together with regular assessment of channel stability in their vicinity.

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