



New sediment continuum measurements in the Brda River (Poland): the results of the functioning of the 50-year Koronowo dam

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Abstract

Purpose As documented by multiple studies, the construction of artificial reservoirs influences fluvial processes. The hydrographic barrier causes a water regime change, and the effects are evident in the accumulation of sediment in the reservoir as well as the intensification of the erosion process below the dam due to the lack of sediments for transport in the river. Moreover, the use of lateral canals on the reservoirs causes additional transformations of the river system, excluding the river part below the dam from the natural system of the catchment area. This research aimed to determine the impact of the creation and functioning of the Koronowo Reservoir dam on the Brda River and its lateral canal on the continuum of sediment transport, with particular emphasis on suspended sediment.

Methods The research was based on analysing the available hydrological data and the measurements of suspended sediment concentration during the water flushing maintenance works into the Brda River channel. In addition, a set of morphometric indices obtained through dedicated terrain analysis were necessary to understand the area's morphodynamics and sediment sources. The suspended sediment concentration (SSC), suspended sediment volume concentration (SVC), and Sauter mean diameter (SMD) data were measured by a LISST-25X, and spatial data were obtained through the System for Automated Geoscientific Analyses (SAGA GIS) software.

Results and conclusion The results were combined with the Connectivity Index evaluation as well as field surveys and made it possible to identify new sources of material supply to the Brda catchment below the dam, thus identifying a disturbance in the sediment transport continuum in the catchment area. Research is a critical element in sustainable sediment management in the catchment, using a controlled sediment flushing operation and identifying local new sources of sediment supply.

Keywords Sediment continuum · Suspended sediment transport · Artificial reservoir · Fluvial processes · LISST-25X · Connectivity Index

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1 Introduction

The functioning of the river system is a balance between the natural environmental characteristics of a catchment and human pressure. This system may undergo rapid transformations due to exogenous factors, e.g. a catastrophic Vajont landslide generated a wave below a dam in the Piave Valley, Italy (Barla and Paronuzzi 2013) as slowly evolving due to natural processes. On the other hand, human activities connected to water reorganisation and land use change can intensify soil erosion and sediment distribution processes in the catchment. Moreover, an increased supply of sediment to rivers may result, among others, from changes in the land use of the entire catchment (Saito et al. 2001), increased

deforestation (Cebecauer and Hofierka 2008), increase in the surface of concrete areas (Ciupa 2009), mining (Doretto et al. 2016), and pollution supply (Uemaa et al. 2005). At the same time, on the spatial and temporal scale, the sediment supply balance reflects the morphological transformations of the river channel (Turowski et al. 2010).

The most significant transformation of the fluvial system is the construction of a dam that crosses the entire width of the river valley. The intensification of dam construction in the world occurred in the twentieth century when over 45 thousand of this type of construction were built (WCD 2000). The most common functions of reservoirs are irrigation, energy production, drinking water supply, and flood control (ICOLD 2007). According to the research of Grill et al. (2019), only 37% of rivers longer than 1000 km are free-flowing. On the other hand, Li et al. (2011) state that over 50% of the world's large rivers have lost their hydromorphological and ecological continuity, which is crucial from the point of view of the requirements of Directive 2000/60/EC (2000) and the current trends in environmental policy aimed at the balance between the state of the environment and human needs (Reyjol et al. 2014). The problem of the lack of sediments lack below dams, and the associated increase of fluvial erosion processes is common and identified in different parts of the world, for example downstream from the Włocławek Dam in the Vistula River (Poland) (Habel 2013; Babiński et al. 2014), Kaniv Dam in the Dnieper River (Ukraine) (Gierszewski et al. 2020; Szmańda et al. 2021), Black Bute Dam in the Stony Creek (CA, USA) (Kondolf 1997), and the dams in the Yangtze River (China) (Li et al. 2011) and Drava River (Hungary) (Słowik et al. 2018).

Most research on the dam–environment transformation relationship focused on the effects on the fluvial continuum (Vannote et al. 1980; Van Rijn 1984), erosion below the dams (Kondolf 1997; Yang et al. 2011; Habel 2013; Babiński et al. 2014; Słowik et al. 2018), sediments trapping, which reduces reservoir capacity (Walling and Fang 2003; Klaver et al. 2007), changes on water regime (Zhang et al. 2015; Gierszewski et al. 2020; Szmańda et al. 2021), the circulation of nutrients (Matysik et al. 2020), riverine habitats (Lenders et al. 2006; Cattaneo et al. 2021), reduce biodiversity (Pelicice et al. 2015), decrease nutrients matter deposition below (Nilsson and Berggren 2000), and reduction of sediment supply to coastal areas (Vörösmarty et al. 1997; Syvitski and Milliman 2007; Hu et al. 2009; Giosan et al. 2014). In addition, based on a series of studies, it was highlighted that the dams completely stopped bedload sediment transport (e.g. Babiński 1994).

Therefore, to understand the hydrodynamics and potential sources of sediments in the area, our research focused on measuring the suspended sediment below the dam through laser diffraction instruments. The assessment of suspended

sediments plays a key role in the hydrogeological behaviour of the river below the dam as well it is fundamental for the biological component of the river. In order to avoid negative effects on river flow, treatments are applied for artificial replenishment of sediments below the dam (Kondolf and Matthews 1993; Rollet et al. 2008) to minimise the damaging impact of the so-called ‘water hungry’ effect (Kondolf 1997). In addition, in our case, interventional flushing of water from the dam is executed two times per year and is aimed at flushing the sediments accumulated in the reservoir (McCartney et al. 2001; Chen et al. 2012) or, as in the case of the research area, cleaning the river channel below the dam from accumulated material. The Koronowski Reservoir (Fig. 1) represents a unique example of how superficial hydrography can be modified, affecting fluvial morphodynamics. The hydropower plant (HPP) associated with the Koronowski Reservoir is not directly located on the dam (on the main course of the Brda River), but the water is supplied through a lateral canal. As a result, a 10 km section of the river is excluded from the circulation of the fluvial system.

Empirical methods with remote sensing techniques or specific field surveys can determine the sediment transport dynamics in the catchment and its sources. In the case of the first type, water turbidity measurement data are necessary to be collected with the use of traditional techniques (Wren et al. 2000) or widely used optical methods (Williams 1989; Czuba et al. 2015; Haun et al. 2015; Felix et al. 2016; Guerrero et al. 2017). In the case of the second group, the determination of catchment erosion susceptibility is commonly used by remote sensing techniques, e.g. the Erosion Potential Method (EPM) (Amiri 2010), the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997), or the Maximum Entropy Model (Brzezińska et al. 2021). Finally, a dedicated field survey can be adapted to precisely map punctually or spatially distributed sources of sediments, represented by landslides and soil erosion processes highly connected with the drainage system (La Licata et al. 2023). The sediment Connectivity Index (IC) can be derived to evaluate the areas prone to be sources or sinking of sediments and to detect the areas potentially connected to the river system where geomorphological processes act as sources of sediments (Borselli et al. 2008).

Therefore, the main objective of the research is to determine the impact of the creation and functioning of an artificial reservoir with a lateral canal (Fig. 1) on the continuity of sediment transport, with particular emphasis on suspended sediment for the last 50 years. The novelty of our research is the application of a multi-factor analysis in order to evaluate the impact of hydrological and geomorphological factors, influenced by human activities, on the fluvial processes in a section of the river completely excluded from the regular water circulation due to the presence of a dam. Currently, an essential scientific reason for research to optimise the management of sediment in dammed catchments is required

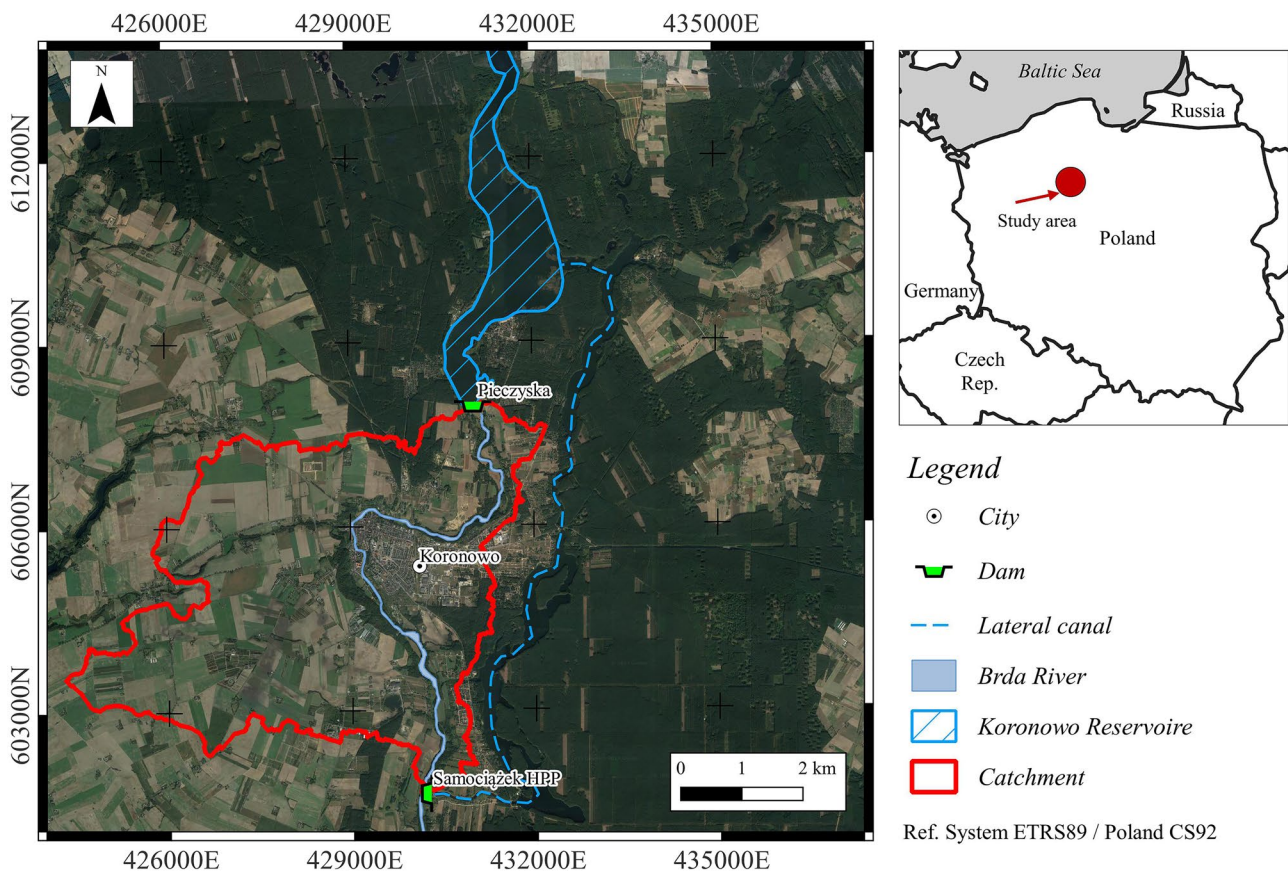


Fig. 1 Main anthropic elements and hydrological assets in the study area

from climate change (Pińskwar et al. 2019), human activity increasing (Syvitski and Kettner 2011), and implementation of the sustainable policy revitalisation of degraded and changed aquatic ecosystems (Simons et al. 2001). Most of the research was conducted on the river sections directly below the dam. Our research is unique due to the functioning of the lateral canal; thus, it concerns a river section out of the fluvial system for over 50 years. The study area is characterised by an earth dam in the village of Pieczyska, which acts as a sediment barrier (Fig. 1). The following data were used to understand the hydromorphological dynamic in the area: (a) hydrological data, (b) sedimentological data, and (c) spatial and geomorphological data collected in the area below the Koronowski Reservoir dam. The tested research hypotheses included the following: (i) the creation of the dam caused an irreversible change in the Brda River regime; (ii) there is a disturbance in the sediment transport continuum, change of the source of sediment supply from the allochthonous/total catchment area of the Brda River to local sources/sub-catchment, and (iii) flushing of the river channel has a local character without impact on the Lower Brda Cascade (LBC) reservoir. The applied methods indicate quantitative (hydrological and sedimentological

analyses) and qualitative (spatial analyses and IC) changes in sediment transport and field survey in the catchment area. The studies carried out are essential for water and sediment management in the catchment and long-term observation of environmental pressures.

2 Material and methods

2.1 Study area

The study area is located in the Brda River catchment, the left tributary of the Vistula River in the northwest part of Poland (Fig. 2). The catchment area is 4661 km², and its length is 245 km (Map of the Polish Hydrographic Division 2007). The average annual Brda River discharge is 18.9 m³ s⁻¹ measured in Tuchola (36.9 km North to the dam) and 26.2 m³ s⁻¹ recorded at the Smukala gauging station (28.9 km South to the dam) (Szatten et al. 2021) (Fig. 2). Considering the river regime of the catchment area above the study area, the Brda River's river–lake system is functioning (Szatten et al. 2021). However, as demonstrated by Choiński (1988), the Brda River has one of the lowest values of the

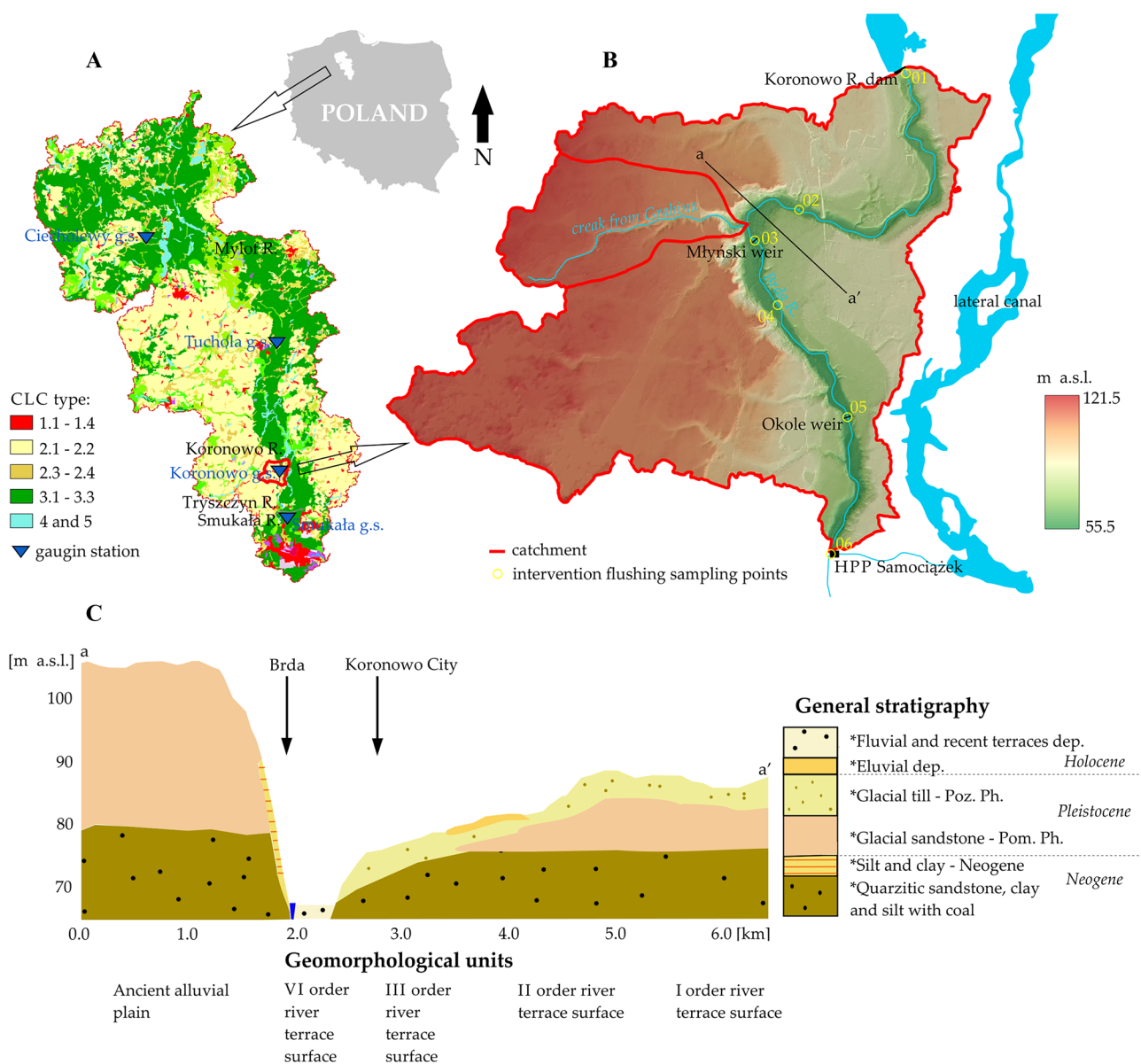


Fig. 2 Study area: **A** Corine Land Cover (2018) of Brda River catchment, CLC type as Heymann et al. (1994); **B** DEM of Brda River between Pieczyska dam and HPP in Samociązek; **C** Main geomorphological units drawn starting from the original map of Listkowska (1985)

flow diversification index among Polish rivers. It is due to the low landscape variability, the large thickness of sandy Quaternary deposits, the presence of 16 lakes in the upper part of the catchment area (Szatten et al. 2018), and the high rate of afforestation of the catchment area (Jutrowska 2007). The average annual sum of precipitation in 1971–2000 in the Brda catchment area is approximately 550 mm year⁻¹ (Lorenc 2005).

According to the physical and geographic regionalisation of Kondracki (2000), the Brda catchment is located in the Brda Valley area, and it borders the Krajna Lake District area from the west and the Świecie Upland area from the

east. The geomorphological evolution of the Brda Valley is related to the Cenozoic evolution of the area. In particular, on the top of the old Neogenic deposits, a wide set of Quaternary deposits accumulated during the youngest phases of the Pleistocene Pomeranian as well as the Poznan glaciations (Marks 2005) can be found (Fig. 2). These deposits are mainly represented by sandy and silty layers as well as till deposits. Moreover, from the available geological map of the area (Listkowska 1985) as well as from field evidence, the valley is covered with sandy fluvioglacial sediments, surrounded by glacial uplands made of clays separated by different-grained sands (Galon 1953). Finally, a set of river

terrace deposits is associated with the Brda River. South to the Koronowski reservoir, it is possible to observe the post-glaciation incision of the Brda River, which has shaped four orders of river terraces morphologically well visible in the field.

Nowadays, the river terrace scarps are forested; however, field evidence of instability, e.g. rotational landslides scarp and associated landslides bodies, can be observed (Fig. 3). Due to the homogenous and highly permeable texture of the deposits that compose and mantle the river terraces, and considering the vegetation that grows in the area, soil erosion evidence like rill interrill or gully erosion can be sporadically mapped. However, the geomorphological setting of the area allows high connectivity between different orders of river terraces and the Brda River, allowing landslides occurrences and sediment mobilisations. In addition, due to morphological evidence like a small fluvial fan, the second-order drainage can bring sediments into the main river. Based on the Corine Land Cover (CLC) database, Szatten and Habel (2020) found that forests and intensively agricultural areas dominate the Brda catchment, covering 46.9% and 36.6% of its area, respectively. The other classes of coverage occupy smaller and not significant areas. Another characteristic feature is the change in the dominant type of land cover with the increase of the catchment area in the longitudinal profile; thus, the forest area decreases, and the agricultural and anthropogenic areas increase, moving south. Regarding the characteristics of the aquatic elements present in the area, it is possible to observe a deep human intervention with the natural hydrological asset of the river. A wide set of anthropogenic landforms like dams, reservoirs, artificial channel waterways, and riverbank protecting elements can be mapped. However, the reservoir and the HPP are the main impacting elements of the area, causing sediment transport interruption. Evaluating the water discharge of the Brda River from the Koronowski reservoir to the Samociążek HPP, the small amount of water present is mainly due to the local terrace spring that inflows into the Brda, guided by the water gradient forced by the altitude of the lateral canal.

Overall, the Brda River is strongly hydrotechnically modified for the production of hydroelectricity. In fact, in the area, there are four artificial reservoirs: Mylof—capacity of 16.2 million m³ (Biuro 2015); Koronowo—with a capacity of 81.0 million m³ (Szatten et al. 2018); and Tryszczyn and Smukała—overall capacity of 3.2 million m³ (Biuro 2014) (Fig. 2). The last three reservoirs consist of the LBC, which performs energy, flood protection, and recreation functions. The estuary section of the river in Bydgoszcz has also undergone intense hydrotechnical transformations for centuries—mills, weirs, and locks (Szatten 2015).

Detailed hydrological and sedimentological studies and spatial analyses concerned the catchment area of 29.38 km² (Map of the Polish Hydrographic Division 2007) (Fig. 2).

The dam, created in 1961 (Ambrożewski 2011) damming waters of Brda River to a height of 15 m, up to the ordinate of 81.5 m above sea level—normal damming level (NDL) (Szatten 2015). An additional 10 m hydraulic gradient was obtained by directing the water southwards through a 10 km long lateral canal, profit by the bottom of the glacial channel of the Lipkusz-Białe lakes, to the HPP (Fig. 2). The total capacity of turbines is 26 MW, which enables annual electricity production of 40,841 GWh. This way, the Brda River between the dam in Pieczyska (49.1 km Brda) and the hydropower plant in Samociążek (39.1 km Brda) was eliminated from the fluvial system. The water in the river channel comes from the seepage of water through the dam made of sand, seepage of groundwater from the upper lateral canal, and small tributaries from the Krajna Upland (Pietrucień, 1967). Two hydrotechnical structures counteract its outflow: the Młyński weir on 44.9 km of the Brda River's course and the Okole weir on 42.0 km of the Brda River's course (Fig. 2).

2.2 Materials and methods

The workflow adopted in this study is illustrated in Fig. 4.

2.2.1 Intervention discharge of water from the dam of the Koronowski Reservoir

The hydrological data were collected from different sources depending on the period of interest: (i) archival data (Pietrucień, 1967) between 1925 and 1934; (ii) daily discharges (in m³ s⁻¹) obtained from the public database of the Institute of Meteorology and Water Management—National Research Institute for the years 1951–1960; (iii) water stages (in m) and discharge (in m³ s⁻¹) observed by the authors at selected sites during the river channel flushing and sedimentological observations (Fig. 2) between 1961 and 2022.

Twice a year, the intervention of water discharges from the Koronowski Reservoir to the Brda River channel is carried out with the purpose of cleaning the Brda River channel of accumulated sediments in the section between the dam in Pieczyska and the HPP in Samociążek (Fig. 2). Research was carried out during the intervention discharge of water from Koronowski Reservoir dam on June 17, 2014, and November 11, 2022. The interval between the measurement series resulted from the availability of the LISST-25X device. Hydrological observations and water sampling were carried out on the day of flushing by the bottom gate from the Koronowski Reservoir dam, which included initial conditions (5:30–6:00, Q = 0.0 m³ s⁻¹), flushing operation (lasted only 2 h, i.e. 6:00–7:00, Q = 15.0 m³ s⁻¹; and 7:00–8:00, Q = 10 m³ s⁻¹), and stabilising conditions (8:00–16:30, Q = 0.0 m³ s⁻¹). During this time, detailed observations were carried out on six measurement

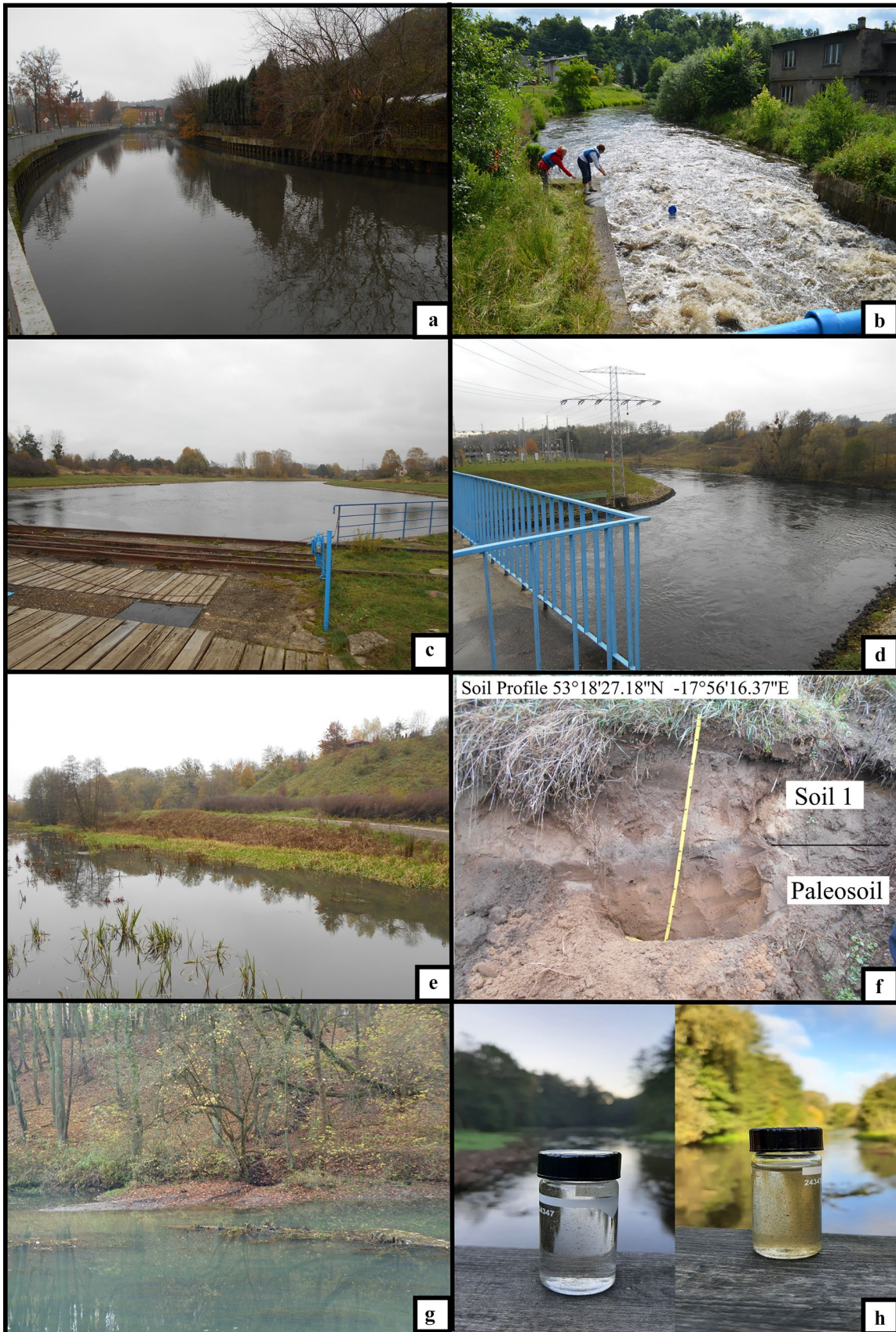


Fig. 3 Principal geomorphological and geological evidence of the study area: **a** Artificial channel (Brda River) south of Koronowo. **b** Flushing operation in 2014 at station 03 reported in Fig. 2. **c** End of lateral canal in Samociążek. **d** Confluence of the below the HPP in Samociążek with the Brda River. **e** River terrace and natural banks of Brda. **f** Soil profile in the glacial Pleistocene sandstones with evidence of reduction levels and paleosol. **g** Alluvial fan triggered by small gully processes on litter and topsoil. **h** Turbidity of water of the Brda River before and while flushing in 2022

profiles in 2014 and one site in 2022 (Fig. 2), whose locations resulted from the previously conducted field reconnaissance. At each site, observations of the water stage were carried out with a measurement frequency of 15 min, using geodetic water gauges with an accuracy of 0.01 m, by the PL-KRON86-NH altitude system. At the same time in 2014, one-litre bottles of water samples were taken for laboratory determinations of suspended sediment concentration (SSC, in mg l^{-1}) every 15 min using a slowly filling bathometer (Wren et al. 2000). Laboratory determinations of SSC used the commonly used filtration method using paper filters with a porosity of $0.45 \mu\text{m}$ and a subsequent drying procedure (Polska Norma 2007).

In addition, the discharge observations were carried out in the selected sites using an acoustic current meter (OTT GmbH C20). It was possible to calculate the transported suspended sediment load (SSL, in g s^{-1}) with the following formula:

$$SSL = SSC \times Q \quad (1)$$

where *SSC* is suspended sediment concentration, in mg l^{-1} , and *Q* is discharge in $\text{m}^3 \text{s}^{-1}$.

As part of observing changes in the morphology of the Brda River bottom, in the stretch below the dam, due to water flushing, a comparison of the river depth before and after its cleaning was made. Measurements were carried out based on a network of 42 cross-sections of the Brda River over a length of 3.3 km (Fig. 2: Sect. 03–05). The GPS RTK/DGPS Trimble R8 measuring device was used, enabling the measurement accuracy in real-time via the GSM (RTK) network: horizontal $\pm 10 \text{ mm RMS}$ and vertical $\pm 18 \text{ mm RMS}$. Measurements were carried out accurately to the ASG-EUPOS network, using the RTK method (Prawo Geodezyjne i Kartograficzne 1989) in the 1992 State Geodetic Coordinate System (PUWG92). The collected data made it possible to calculate the thickness of sediments accumulated or eroded due to the intervention water discharge.

2.2.2 New sources of suspended sediments–SVC and SMD measurements

The determination of suspended sediment sources of the fluvial system of the Brda River catchment was possible

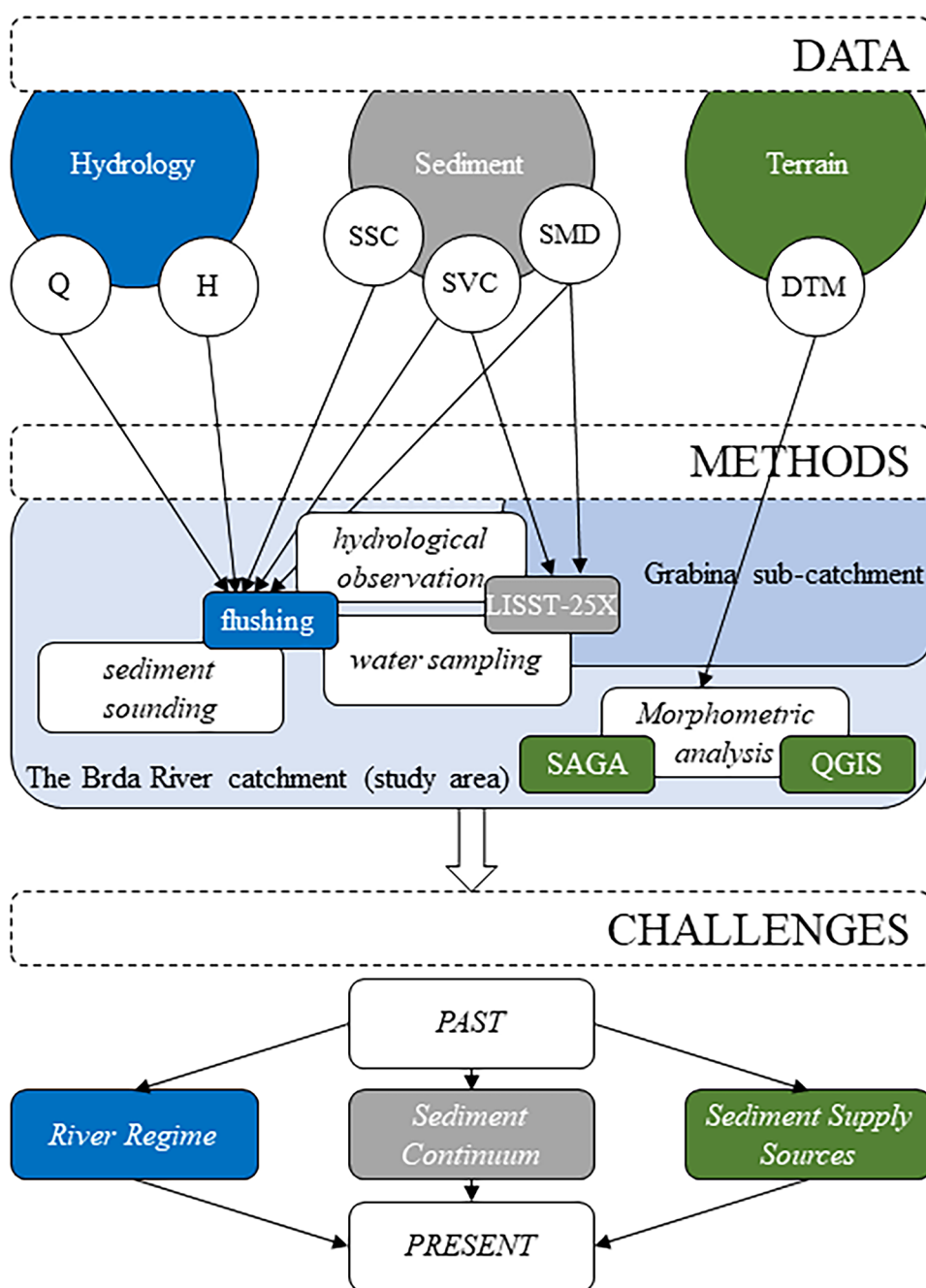
using water turbidity measurement carried out using the Laser In Situ Scattering Transmissometer LISST-25X device (Sequoia 2008). The observations were carried out in 2020 on the largest tributary of the Brda River in the study area during an intense rainfall (Fig. 2) and in 2022 on the measurement profile (Fig. 2, site no. 4) while flushing operation. The rainfall intensity recorded during the observation period was 10.3 mm h^{-1} . The analysed creek from Grabina Hill has a length of 3.3 km and a catchment area of 3.55 km^2 (Fig. 2). It represents a typical agricultural catchment in a moraine plateau area. Flow rate observations were carried out using an acoustic current meter (OTT GmbH C20). The measurements of SVC and SMD are based on the Lorenz-Mie scattering of low-angle laser light sources (Sequoia 2008). It allowed us to estimate the Suspended Sediment Volume Concentration (SVC, in ml l^{-1}) in two variants: (a) for the full-range (0.1 and 1000 mg l^{-1} with a resolution of 0.025%, for an optical length of 2.5 cm) and (b) for a sub-range of suspension grains with a diameter larger than $63 \mu\text{m}$. Besides, measurements using the LISST-25X device allowed the Sauter mean diameter (SMD, in μm) to be determined in two variants: (a) for the full-range (2.5 and $500 \mu\text{m}$ with a resolution of $1 \mu\text{m}$) and (b) for a sub-range of suspension grains with a diameter range between 63 and $500 \mu\text{m}$. In the case of sediment concentration, the Lorenz-Mie theory of light scattering showed that collimated laser light illuminating grain particles would scatter most of its energy at specified angles, e.g. small grains scatter energy at larger angles and conversely. The LISST-25X mathematically inverts the scattering to determine the sample's size distribution and concentration of suspended sediment grains (Filippa et al. 2011).

2.2.3 Spatial analyses

The spatial data was obtained from Poland's Head Office of Geodesy and Cartography resources. The base material was a Digital Terrain Model (DTM) with a horizontal resolution of $1 \text{ m} \times 1 \text{ m}$ and a vertical resolution of 0.15 m in the form of ASCII XYZ GRID files in the metric coordinate system 1992.

Morphometric analyses were performed using SAGA v.2.3.2 software (Conrad et al. 2015). Base DEM was converted to a 1×1 cell size GRID format file. In the next step, GRID was transformed hydrologically using the Fill Sinks formula proposed by Planchon and Darboux (2002). The final raster allowed the determination of selected physical characteristics of the catchment area by the modules and the source indicated in Table 1. Basic and enhanced terrain analysis was performed on the DEM, and in particular, the parameter of slope, aspect, LS-factor, terrain roughness index (TRI), topographic wetness index (TWI), stream power index (SPI), geomorphon and morphometric protection index were derived.

Fig. 4 General workflow of Brda River sub-catchment research



Furthermore, the Connectivity Index (IC) was calculated by adapting the procedure specified by Borselli et al. (2008) for the open-source SAGA and QGIS. The DEM represents the input parameters of the model, as well as the Cover manage – C-factor. The latest indicates the effect of vegetation cover and management on soil erosion. Moreover, it represents an important factor in evaluating the ability of vegetation canopy and ground covers to resist soil erosion, and its value is between 0 and 1 (Wang et al. 2016). Due to the absence of high-detail data, the value of the C-factor was assigned following the methodology suggested by Tosic et al.

(2011). In the first step, the land-use type was derived from the available cOoRdination and iNformation on the Environment (CORINE) Land Cover (CLC) database (2018). Subsequently, the C-factor values have been assigned to all the occurring land-use types (Table 2) according to the average values cited in the literature (e.g. Tosic et al. 2011; Li et al. 2013; Wang et al. 2016). Lastly, as input data, a shape representing the urban and road areas was created. The final map representing the IC was fundamental to understanding the spatial relation between sediment sources and their availability in the Brda River. Finally, two spots of geomorphological

Table 1 Characteristics of spatial indicators determined for the Brda catchment with the use of SAGA software

No.	Indicator	Description	Reference
1	Slope	Terrain steepness	Zevenbergen and Thorne (1987)
2	Aspect	Exposition of the slope	Zevenbergen and Thorne (1987)
3	LS-factor (LSF)	Based in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978)	Moore et al. (1991)
4	Terrain roughness index (TRI)	A Quantify the topographic heterogeneity	Riley et al. (1999)
5	Topographic wetness index (TWI)	A potential generation of runoff	Boehner et al. (2002)
6	Stream power index (SPI)	Erosive power of flowing water	Moore et al. (1991)
7	Geomorphons	Divide the DEM according to morphological criteria	Jasiewicz and Stepinski (2013)
8	Valley depth	Difference between the elevation and an interpolated ridge level	Conrad et al. (2015)

maps (Listkowska 1988; Wiczonek and Stoiński 2009) were realised through field survey and Google Earth images (2020) to better understand the active processes and to map the potential sources of sediments correlated with the IC.

3 Results

3.1 Water dynamics in the Brda River

In the period before the Koronowski Reservoir construction in 1961, the discharge in the Brda River represented the natural regime of the lowland river with a predominance of runoff in the winter half-year (Fig. 5). The discharges followed a seasonality trend and were maximum in the winter and spring months, and the lowest for the end of the summer. The dam's construction and the direction of the entire flow of water to the lateral canal completely changed the water regime on the 10 km section of the Brda River below the dam. There was a significant reduction of the recorded discharges to the level of about $2.0 \text{ m}^3 \text{ s}^{-1}$ and the equalisation

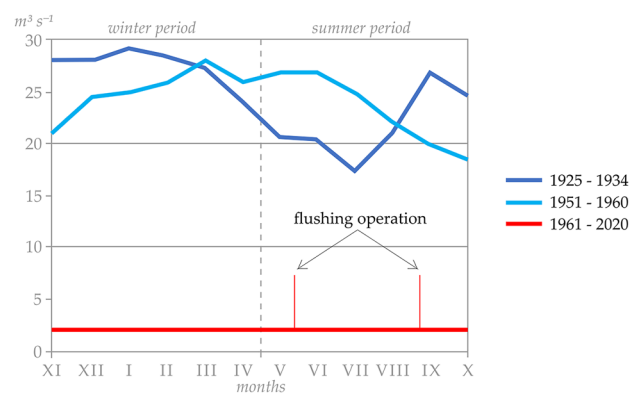
of the hydrograph during the year (Fig. 5), completely changing the water regime in the study area. Intervention water discharges from the Pieczyska dam twice a year, causing incidental discharge in the Brda River in Koronowo at a level of about $7 \text{ m}^3 \text{ s}^{-1}$ (Fig. 5).

The intervention discharge of water to the Brda River in 2014 using the bottom gate at the Pieczyska dam (Fig. 2 – 01) lasted 120 min. Water was flushing during the operation regime: in the first hour of $15 \text{ m}^3 \text{ s}^{-1}$ and during the second hour of $10 \text{ m}^3 \text{ s}^{-1}$. Each time such a large discharge of water causes an increase in the water level in the outlet channel of more than 1.0 m. After the flushing, the water in the outlet channel dropped to the original level quickly.

A different course of water stage characterised the artificial wave at each observed site (Fig. 6). The water reached the second measuring station (Fig. 2 – 02) at a speed of 3.69 km h^{-1} , covering a distance of 4 km in 65 min. The water elevation during the culmination discharge increased by 0.75 m (Fig. 6). The next measuring station was located on the Młyński weir (Fig. 2 – 03), through which water was controlled. The wave reached the speed of 2.88 km h^{-1} , with the culminating discharge at 9:10. At 11:10, the water discharge was equalised, which meant the end of the flushing of

Table 2 The CLC 2018 code (Heymann et al. 1994) and corresponding C-factor

Land use CODE	Description	C-factor
111	Continuous and discontinuous urban fabric	0
112		
121	Industrial or commercial units	0
211	Non-irrigated arable land	0.1
231	Pastures	0.08
242	Complex cultivation patterns	0.05
243	Land principally occupied by agriculture, with significant areas of natural vegetation	0.06
311	Broad-leaved forest	0.004
312	Coniferous forest	0.004
512	Water bodies	0

**Fig. 5** Average monthly discharges at the Koronowo water gauging station

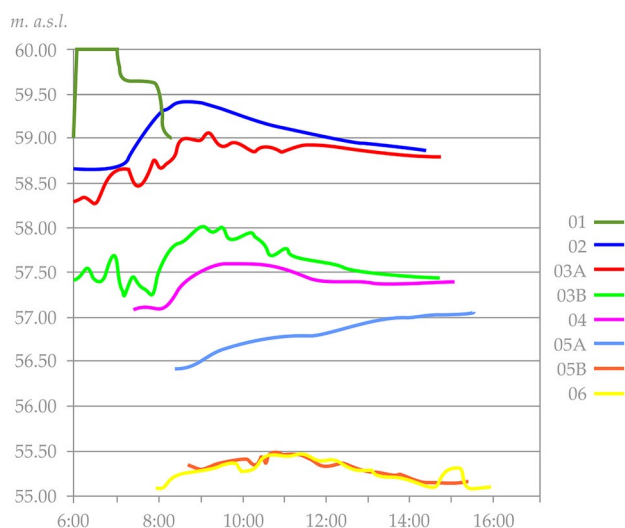


Fig. 6 Propagation of the water stages in the longitudinal profile of the Brda River while flushing in 2014

this section of the river. On the following site—Kozi Mostek (Fig. 2 – 04), before the flood wave reached, the ordinate of the waters oscillated within the range of 57.08–57.10 m above sea level (Fig. 6). Small fluctuations resulted from modifying the water discharge through the Młyński weir. During the culmination of discharge, the ordinate of the water increased to 57.61 m above sea level, and the measured discharge was $9.8 \text{ m}^3 \text{ s}^{-1}$. The speed of the flood wave decreased to 1.07 km h^{-1} . From 12:15, the water level in the trough stabilised (Fig. 6). At the Okole weir site (Fig. 2 – 05), the initial ordinate of the water table was 56.47 m above sea level, and during the culmination of the discharge, it increased by 0.30 m (10:30). At 11:40, the staff of the HPP closed part of the gates on the weir, which resulted in water damming above the weir to the maximum elevation of 57.04 m above sea level (14:50). In the section where the waters of the Brda connect with the waters outflowing of the HPP in Samociążek (Fig. 2 – 06), the water level in the river was under the influence of the HPP operation—daily fluctuations in discharge from $2 \text{ m}^3 \text{ s}^{-1}$ to about $40 \text{ m}^3 \text{ s}^{-1}$. The discharge of the artificial wave on this section of the river was not clearly recorded in the hydrograph (Fig. 6).

3.2 Flushing of the sediments

The suspended sediment concentration (SSC) on the day of flushing, before the opening of the bottom gate at the Pieczyska dam (Fig. 2 – 01), was $5.0\text{--}9.0 \text{ mg l}^{-1}$. At 6:00, in the first moments of increasing the water discharge, there was a rapid increase in the SSC to the level of 308.0 mg l^{-1} (Fig. 7). Such a high value comes from the material accumulated in the area of the bottom gate, resuspended by the high energy discharge of water, and from river channel below

the dam. The instantaneous suspended sediment load (SSL) was 4.62 kg s^{-1} . Subsequently, the SSC in the water outflow from the bottom gate decreased and stabilised at 10.0 mg l^{-1} , with a tendency to decrease slowly despite a discharge of about $10.0 \text{ m}^3 \text{ s}^{-1}$. After the discharge of water from the reservoir was stopped, another increase in the turbidity of the waters was noticed, which could have resulted from the fact that the outflow of clean waters from the reservoir to the Brda River was limited.

Before the arrival of the artificial wave at the measuring station above Koronowo (Fig. 2 – 02), the SSC fluctuated at a low level of $\sim 3.0 \text{ mg l}^{-1}$ (Fig. 7). The turbidity started to increase with the rise of the water stage, reaching the maximum value of 343.0 mg l^{-1} at 8:00, 2 h after opening the bottom gate. Even though the water ordinate was increased for another 40 min, the values of SSC began to decrease systematically, reaching 128.0 mg l^{-1} at the time of the peak of the flushing wave. After that, they continued to decline to a level of about 10 mg l^{-1} , recorded at 10:30. Comparing the determined values of the SSC with the first station (Fig. 2 – 01), a significant increase in concentrations is noticeable.

The site on Młyński weir (Fig. 2 – 03) is characterised by a high diversification of the SSC course during the Brda River's flushing. From the beginning of the flushing, they were characterised by high concentrations of suspended sediment (Fig. 7). This fact resulted from the resuspension of fine-grained sediments accumulated in the Brda River channel, which was caused by the operational work of the weir before flushing. SSC ranged from 129.0 to 469.0 mg l^{-1} . The increase in turbidity from the level of about $130.0\text{--}140.0 \text{ mg l}^{-1}$, related to the beginning of the wave, starts at 8:00. After 30 min, it reached the maximum value of 509.0 mg l^{-1} . From that moment, the SSC began to decrease systematically. At 11:10, when the intervention into the water level in the weir was ended, the SSC dropped to 20.0 mg l^{-1} . After an hour, they stabilised at a level below 7.0 mg l^{-1} . The values of the observed SSC at the Młyński weir (Fig. 2 – 03), compared to the previous site (Fig. 2 – 02), indicate the resuspension of bottom sediments and their transition to fluvial transport (Fig. 7).

Before the wave, high SSC (147.0 mg l^{-1}) was recorded at the Kozi Mostek site (Fig. 7 – 04), which resulted from the delivery of suspended sediments as a result of sequential water discharges at the Młyński weir (Fig. 7 – 03). Maximum turbidity was recorded 35 min after the start of the water level rise and 20 min before the peak discharge – 374.0 mg l^{-1} (Fig. 7). After the discharge stabilises, the SSC fluctuates between 4.0 and 8.0 mg l^{-1} .

In addition, Fig. 7 shows the dynamics of suspended sediment transport on the Okole weir (Fig. 2 – 05), including its small size compared to the previous sites. During the systematic rise of the upper water level, which lasts until 10:30, the values of SSC oscillate at a low level. The water

reaching the Brda River caused an increase in the capacity of the Okole weir reservoir after its previous emptying. At the same time, there was an increased accumulation of suspended sediment in the Okole weir reservoir. In the time from 10:30 to 11:40, when the upper water level stabilises, there is an increase in water turbidity. The maximum damming, which can be obtained with the open gates, causes the water to flow through the Okole weir (Fig. 6 – 05) reservoir unimpeded. Suspended sediment no longer accumulates to such a large extent but is transported along with the flushing wave along the Brda River. Along with the closure of some of the weir gates (11:40), the turbidity of the waters rapidly decreases to the level of 10.0 mg l^{-1} . However, the flushing wave still reached the Okole weir reservoir (Fig. 6 – 05), causing an increase in the elevation of the upper water level. For the second time, an increase in SSC value in the Brda riverbed waters was recorded. A maximum SSC of 36.0 mg l^{-1} was recorded at 12:20. After complete stabilisation of the upper water ordinance, the SSC ranged from 6.0 to 8.0 mg l^{-1} (Fig. 7 – 05).

The course of SSC at the site located on the lower water of the Samociążek HPP (Fig. 7 – 06) during flushing depended to a greater extent on the operation of HPP than on the water supply through the Brda River. Hence, the load supplied through the Brda River trough was strongly diluted (the water outflowing from the reservoir through the HPP has SSC ranging from 4.0 to 8.0 mg l^{-1}). The maximum SSC on the HPP Samociążek site was 30.0 mg l^{-1} (Fig. 7 – 06).

3.3 Sediment balance in the longitudinal profile of Brda River

The soundings of the bottom ordinates and sediment thickness in the cross-section profiles were carried out immediately before and after the flushing of the Brda River, making it possible to determine the range of distinct zones: erosion (redeposition), transport, and sediment accumulation (Fig. 8).

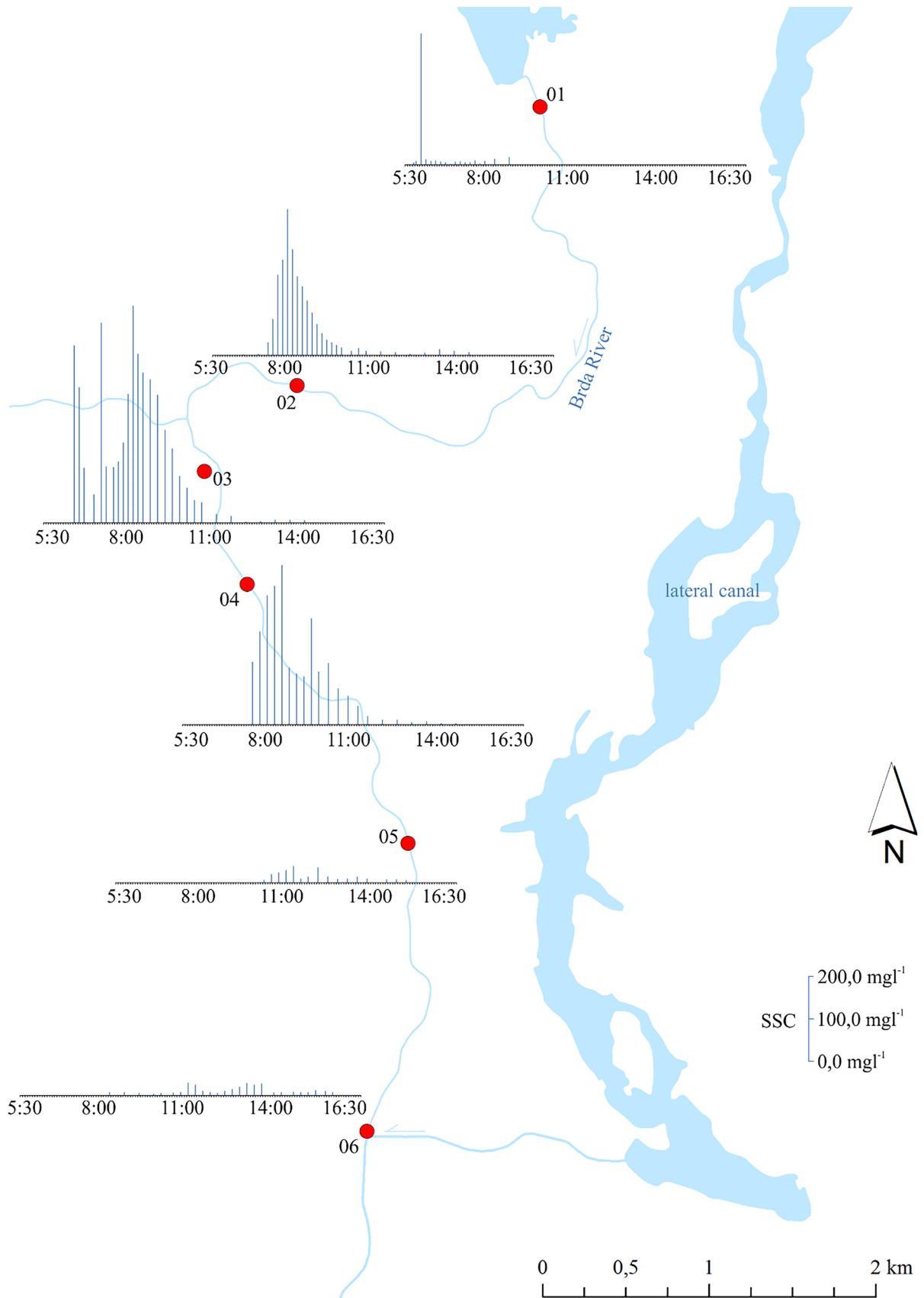
After the flushing, the first section (A), i.e. from the Młyński weir (Fig. 2 – 03) to Kozi Mostek (Fig. 2 – 04), is characterised by a significant loss of sediments. The maximum sediment thickness before flushing was here, on average, about 1.0 m. After flushing, the Brda riverbed was almost devoid of fine-grained bottom sediments. The average maximum thickness of sediments decreased to the level of about 0.4 m. The next section (B) is also characterised by reduced sediment thickness after flushing. However, their loss is no longer as large as in the case of the first part. With the end of this part (B), the area of erosive activity of waters flushed from the dam in Pieczyska ends. On the other hand, section (C) is characterised by a similar thickness of bottom sediments compared to the measurements carried out before the channel cleaning. It is a sediment transport zone. A significant increase in sediment thickness characterises

the next part (D). They were accumulated in the Okole weir reservoir. However, not the entire reservoir was characterised by an increase in the amount of sediment material. The zone closest to the weir was characterised by a decrease in the maximum sediment thickness, which was the basis for its separation as a separate area (E) of an erosive character. This loss is probably caused by the operation of the water discharge from the upper water reservoir of the Okole weir (Fig. 2 – 05)—the drop of 0.5 m of the water layer in about 3.5 h on the day preceding flushing. The last section F, also of an erosive character, was separated downstream from the Okole weir (Fig. 2 – 05). The discharge of water on the day preceding flushing and the passing of part of the wave on the day of flushing resulted in reduced sediment thickness.

The field measurements were the basis for calculating the estimated capacity in the Okole weir reservoir (area 0.45 ha). With the damming water level of about 57.0 m a.s.l., the reservoir capacity (V_0) before flushing was about 27.4 thousand m^3 , and the volume of accumulated sediment in it is about 14.1 thousand m^3 . After flushing, the reservoir was filled with sediments, its capacity (V_1) decreased to about 25.3 thousand m^3 (7.5%), and the volume of accumulated sediments increased to about 16.1 thousand m^3 (12.7%).

3.4 New sources of sediments

Determination of the sedimentological, morphometric, and physical characteristics of the Brda catchment area between the Pieczyska dam and the Samociążek HPP made it possible to detect the sources of sediments that cause the sediment transport in Brda River while normal conditions (excluding flushing operation) and define potential new sources of sediment supply (including flushing of the channel). Field observations were integrated with DTM analysis to map the evidence and the areas prone to be eroded by running water or affected by mass movements. The principal geomorphological element that shaped the study area is the Brda River which has incised four orders of river terraces creating the typical morphology of lowland areas. From the DTM analysis (Fig. 9), the morphometric indices were extrapolated, showing particular aspects not observable directly in the field. The slope value range between 0 and 24%, showing the highest value on the fluvial erosion scarps (Fig. 9a); the aspect is heterogeneous due to the morphological setting of the area. In fact, the area is averaging as flat with two different west and east facing slopes represented by the fluvial erosion scarps (Fig. 9b). LSF values oscillate in the range from 0 to 3. The maximum values are characteristic of the edge zone of the Brda valley and the estuary sections of creeks flowing from the plateau (Fig. 9c). The TRI shows a similar spatial distribution and ranges from 0 to 0.16, highlighting a topographic differentiation and shows potential sources of sediment supply (Fig. 9d). Moreover,



◀**Fig. 7** Suspended sediment concentration (SSC, in mg l^{-1}) during the intervention water discharge from the Koronowski Reservoir in the longitudinal profile of the Brda against the background of the LBC in 2014 (Map of Polish Hydrographic Division 2007)

another important indicator, the TWI, shows areas with a high potential for saturated surface runoff, which can be identified with the possibility of outflowing sediments from concave terrain forms. Its values oscillate in the range of 1 and 13, highlighting how running water can affect several parts of the Brda scarp as well as interesting slope features like landslides (Brda valley, smaller creeks, and depressions in the upland area) (Fig. 9e).

The SPI ranges between 0 and 20 and indicates a linear system of areas that generate and transport sediment in the studied catchment, correlated with the runoff lines (Fig. 9f). To support the DEM observation, a morphometrical classification of the landscaper was done through the geomorphons derivative. This shows the main geomorphological classes of the area (Fig. 9g), highlighting the river terraces, slopes, and main drainage. Finally, the valley depth showed an altitude of the territory between 0 and 20 m up to the Brda River.

Hydrological studies and spatial analysis indicate that after the Brda River watercourse modification due to the Pieczyska dam's construction, the discharge and sediment transport capacity were dramatically changed. The small creek from Grabina (Fig. 2) flowing from the upland area below the dam constitutes the primary, but not the unique, sediment supply source to the Brda River's fluvial system. The observations carried out in Gabina Creek during 2020 (Fig. 10) using LISST-25X showed that a significant supply of suspended sediment to the Brda River takes place in the event of heavy rainfall. Before rainfall, the full-range SVC values in the investigated creek were about 0.2 ml l^{-1} , and the discharge was about $0.1 \text{ m}^3 \text{ s}^{-1}$. At the time of the beginning of the precipitation, the observed maximum full-range SVC peaks fluctuated in the range of $18\text{--}21 \text{ ml l}^{-1}$, and the maximum concentration was observed about 20 min after the occurrence of the precipitation. The maximum recorded discharge was $0.52 \text{ m}^3 \text{ s}^{-1}$. Then, a slight decrease in the concentration of suspended sediments in the creek was observed; however, the maximum peaks still reached about 14 ml l^{-1} . A similar trend was observed for sub-range SVC. However, concentrations were recorded at a lower level (Fig. 10). The opposite is the case with full-range and sub-range SMD, the transport of which is inversely proportional to the discharge in the creek. The largest particles in both ranges were supplied in the initial phase of precipitation/runoff from the catchment. Their maximum dimensions reached $13 \mu\text{m}$ and $68 \mu\text{m}$, respectively, for full-range and sub-range SMD. Then, the noted SMD values in both ranges decreased significantly (Fig. 10).

Verification of the suspended sediment supply sources as a result of the flushing of the Brda riverbed was obtained during field research in 2022 with the use of LISST-25X. It has been shown that the dynamics of suspended sediment transport in 2022 will take a similar course to 2014, which indicates that the process is repeatable. Both the water levels (H) and the turbidity (SSC/FNU) assume maximums at similar times (Fig. 11). In addition, detailed measurements made it possible to identify the sources of suspended sediment supply. The observed increase of the Brda River to the bank full of water stage ($H \approx 58.40 \text{ m a.s.l.}$) results in the transport of suspended sediment silt fraction ($\text{SMD} < 25 \mu\text{m}$) accumulated in the riverbed in the period from the last flushing. At the same time, a systematic increase in the values of SVC and FNU was recorded (Fig. 11). A further increase in the water level ($H \approx 58.60 \text{ m a.s.l.}$) resulted in a decrease in the SVC and FNU values, which indicates the depletion of material in the riverbed. However, a strong increase in SMD was observed (max. $\approx 65 \mu\text{m}$) due to the flooding of the floodplain and the initiation of suspended sediment fine sand fraction. Then, the extinction phase is observed, where the energy of flowing water decreases, resulting in a decrease in all observed parameters (Fig. 11).

However, the processes that act on the Brda fluvial erosion scarps and the vertical and secondary horizontal incision of the Brda itself contribute to the sediment apport in the fluvial system. From the field observation, several gravitative and fluvial and runoff processes can be observed and mapped on the fluvial erosion scarps of the Brda River. The calculated Connectivity Index helps to detect the areas prone to be sources or sinks of sediments. Moreover, the IC highlights also how a specific landform (i.e. landslide or fan) can be highly connected to the main river, becoming a source of sediments (Fig. 12). Finally, two geomorphological sketches were realised following the Italian guidelines for the geomorphological mapping (Campobasso et al. 2021) through field survey and Google Earth images. The maps highlighted a territory deeply influenced by fluvial, slope, and human processes. As shown in Fig. 12, the correspondence between IC and the geomorphological process is evident. The geomorphological maps can validate the derived connectivity index highlighting the morphodynamics of the area.

4 Discussion

As specified by several authors, the creation of artificial reservoir influence on fluvial processes and the knowledge of the cause-effect relationship of human activities is fundamental in sustainable sediment management of the catchment. The role of reservoirs in sediment trapping transported from the catchment area is indisputable (Van Rijn 1984; Walling and Fang 2003; Klaver et al. 2007; Habel 2013). The

decrease in water flow causes sediment accumulation, especially in the backwater area and close to the dam. Previous studies of the analysed Koronowski Reservoir also showed sediment accumulation in the reservoir (Szatten and Habel 2020), reducing capacity in 54 years by 6.2% (Szatten et al. 2018). However, the reservoir-sediment balance excluded the study area—the Brda River in the section from the dam in Pieczyska to the HPP in Samociążek (Fig. 1). At the same time, research indicates a change in the water regime below the water stages (Zhang et al. 2015; Gierszewski et al. 2020; Szmańda et al. 2021). The most frequently defined effect of reservoir functioning was the reduction of the minimum and maximum discharges (Magilligan and Nislow 2005; Wang et al. 2006; Pyron and Neumann 2008; Zhang et al. 2014). In the case of the study area, the water regime change was extreme due to the construction of the dam (Fig. 5). Directing the main water outflow through a 10 km long lateral canal to the HPP completely excluded the studied part of the Brda River from the fluvial system. The natural regime of the lowland river with a predominance of runoff in the winter half-year was replaced by artificial management controlled by the operation of two weirs. As indicated above, the water supply takes place from seepage of water through a dam built of sand, seepage of groundwater from the direction of the lateral canal located above, and small tributaries from the area of the Kraina Upland (Pietrucień 1967). The discharge during the year was equalised to about $2.0 \text{ m}^3 \text{ s}^{-1}$.

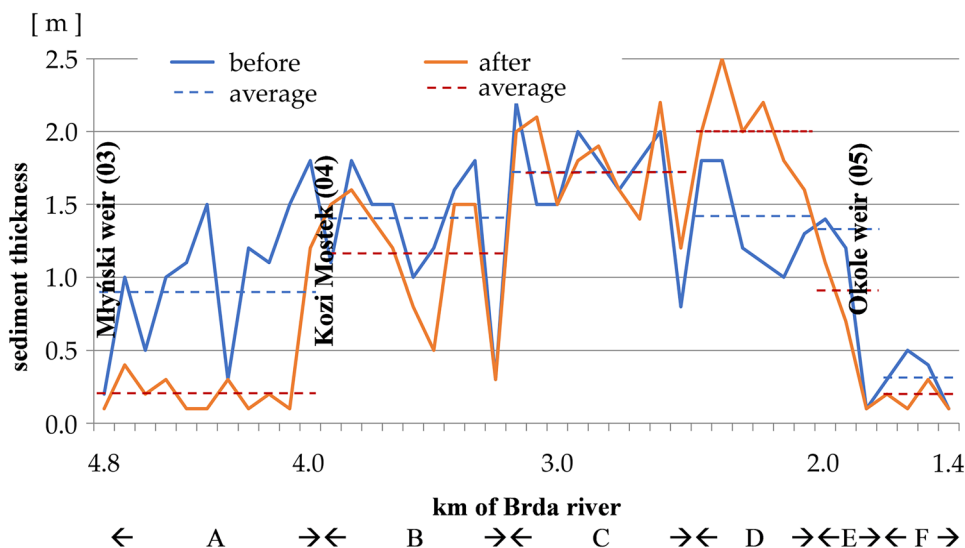
Significant changes in the discharge in the Brda River occur only at the time of the intervention flushing from the Koronowski Reservoir, which takes place twice a year (Fig. 5). The artificial wave with a maximum amplitude ranging from about 1.0 m directly below the dam to about 0.3 m is aimed at cleaning the river bed from accumulated sediment (Fig. 6). Controlled sediment flushing operation,

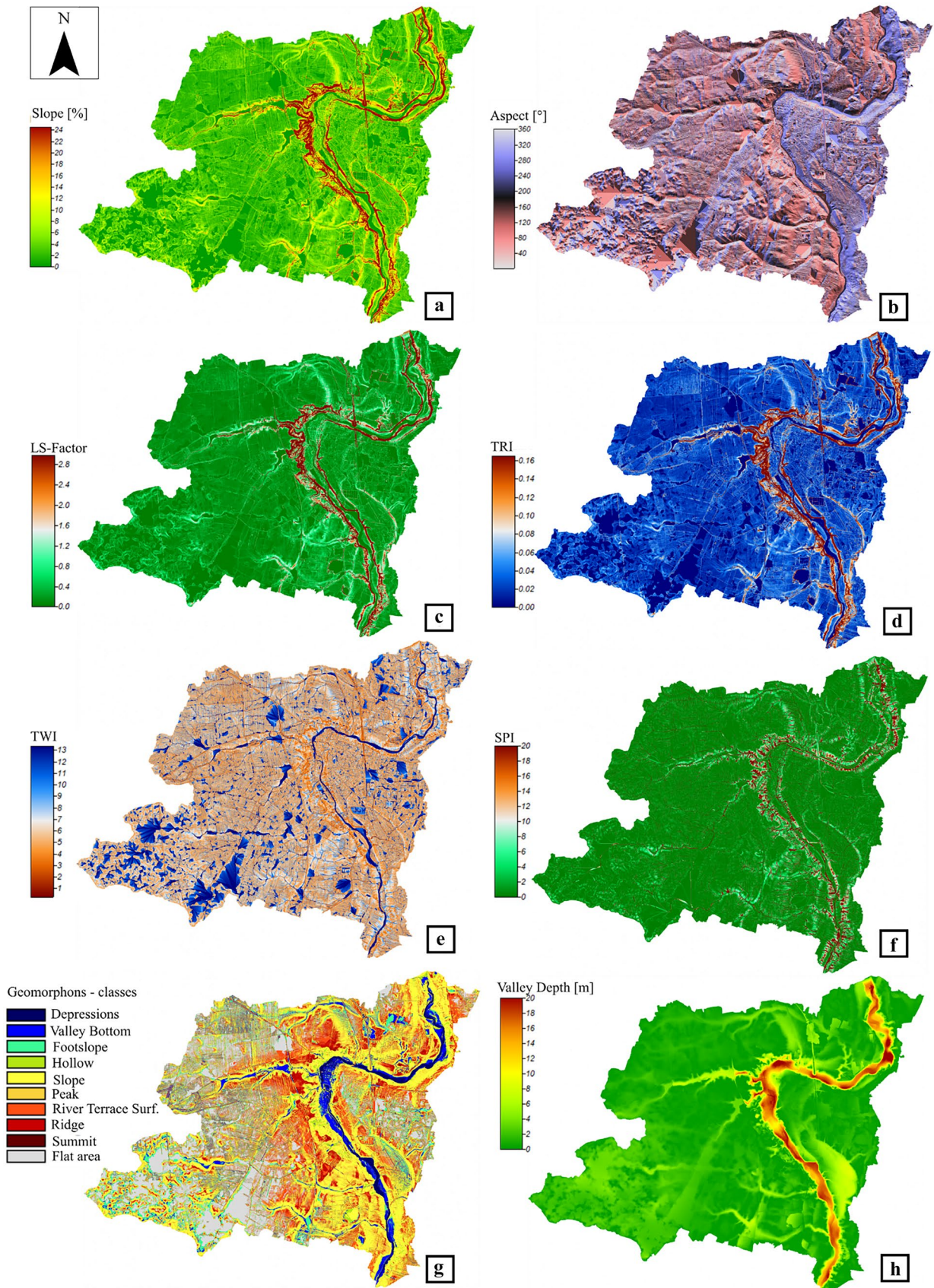
Fig. 9 Spatial image of morphometric and physical characteristics of the study area catchment, **a** slope, **b** aspect, **c** LS-factor, **d** terrain roughness index (TRI), **e** topographic wetness index (TWI), **f** stream power index (SPI), **g** Geomorphons, and **h** valley depth

as the most commonly used sediment management system in the world below the water stages (Espa et al. 2019; Morris 2020), enables the phenomenon described by Kondolf (1997) as ‘hungry water’ to occur in this section of the river. It is not observed in the remaining period, i.e. almost the entire year except for 2 days. It is a different situation from any water stage in the world that is not cascaded. The intensification of erosion processes below the water stages has been demonstrated by numerous studies, including Kondolf (1997), Yang et al. (2011), Habel (2013), Babiński et al. (2014), Słowik et al. (2018), and Gierszewski et al. (2020).

As a result of the intervention of water discharge from the Koronowski Reservoir, there is a temporary increase in the intensity of sediment transport in the studied section of the Brda River. Nevertheless, taking into account the archival data of the discharge (Fig. 5) with lower energy than the average state before the dam was built. Below the dam (Fig. 2 – 01), only a temporary increase in the turbidity of the waters was observed (Fig. 7), which resulted from the activation of the accumulated material in the area of the bottom gate of the Koronowski Reservoir. Relatively low SSC values resulting from the typically lacustrine nature of the reservoir (Szatten 2016a, b) serve as an energy factor during channel flushing. During the 2-h flushing, the SSL in the first measurement profile (Fig. 2 – 01) amounted to about 3.4 tonnes, while already in the first 10 min, water transported 81% of the SSL (about 2.8 tonnes). At the following sites in the longitudinal profile (Fig. 2 – 02–04), a systematic increase in suspended sediment concentration in the Brda waters was observed (Fig. 7).

Fig. 8 The thickness of sediments in the longitudinal profile of the Brda River below Pieczyska dam immediately before and after the flushing in June 2014





Research by Lepage et al. (2020) showed that SSC while flushing operations were, on average, 6–8 times higher than during flood events the upper Rhône River. The SSL in the profile (Fig. 2 – 04) increased to the level of about 15.9 t. As the research showed, it was a river part of intense erosion and sediment transport (Fig. 8). A hysteresis effect was observed between the discharge/water stage in the river channel and the SSC, related to the supply and/or depletion of material for transport in the riverbed (Froehlich 1982; Williams 1989; Kostrzewski et al. 1994). The normal loop (Fig. 11) indicates that the maximum concentration of the transported material is ahead of the maximum water stage (discharge) in the river channel. On this basis, it can be concluded that the suspended sediment supply has an autochthonous source—the erosion of

the Brda riverbed due to high-energy water discharge without sediment. There is ‘a hungry water’ effect described by Kondolf (1997). Also, the observed increase in SMD to fine sand fraction results from the transport of suspended sediment eroded from the floodplain area (Fig. 11), pointing out new supply sources.

The SSC at the site closing the studied section of the Brda River (Fig. 2 – 06) depended to a greater extent on the operation of the HPP than on the supply of sediment from the Brda riverbed while flushing. The SSL at the 06 site (Fig. 2) decreased to the level of about 3.7 tonnes. The load delivered through the Brda River was strongly diluted, which indicates the proper management of the flushing process, limiting the negative impact on the river below. The problem of proper

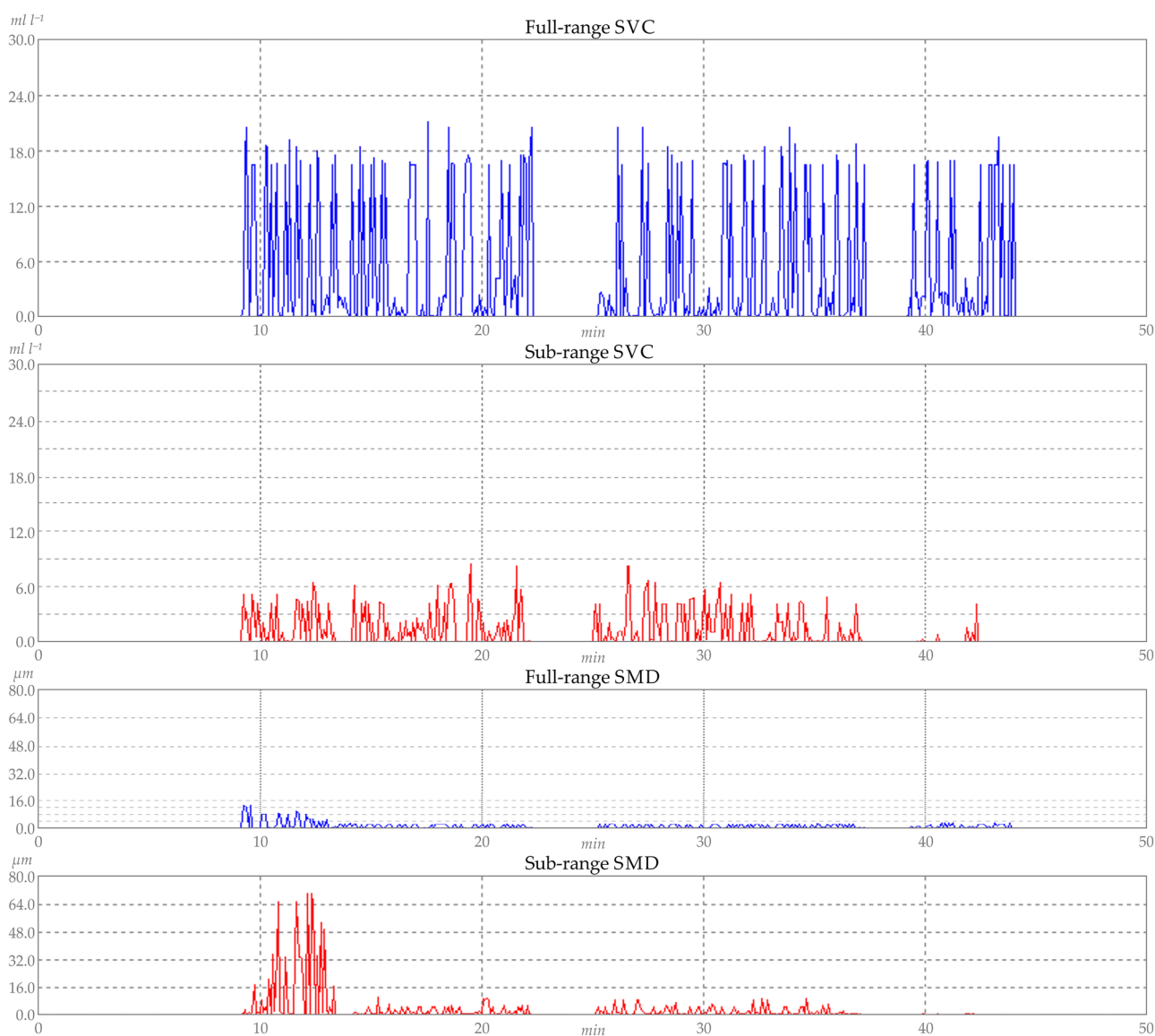


Fig. 10 Suspended sediment supply from Grabina sub-catchment in the heavy rain event in 2020: full-range and sub-range for SVC and SMD

sediment management due to reservoir flushing was also presented in research by Espa et al. (2019) and Doretto et al. (2019). Therefore, based on the course of the turbidity in the longitudinal profile, it can be concluded that the Okole weir reservoir (Fig. 2 – 05) is of decisive importance in the process of accumulation of suspended sediment supplied with the waters of the Brda as a result of its interventional flushing. The research showed that it was a river section of intensive accumulation (Fig. 8), and the observed maximum impact range of water and sediment discharge is limited to the 10 km long river section between the Pieczyska dam and the Okole weir. The sediment source is the Brda riverbed, which becomes heavily silted due to the supply of sediment and the lack of discharge. On the other hand, the reservoir of the Okole weir is mostly silted.

The results of morphometric and physical analyses of the catchment also confirmed the local nature of the sediment supply. The investigated indicators enabling the determination of the denudation capacity of the Brda catchment area (LSF, TRI, IC) showed that the edge zones, in particular, the deeply indented Brda River valley, but also smaller tributaries (Fig. 12), have the possibility of active supply of sediment to the fluvial system. Moreover, in observing Fig. 12, the landforms associated to the Brda slopes may act as a source

of sediments. In fact, both the landslides and the alluvial fan are eroded by fluvial processes and are also interested by runoff processes and incised by gullies erosion, which causes a longitudinal slope erosion making sediments available in the fluvial system. IC maps were used by Martini et al. (2022) to represent the areas for potential connection to stream network, considered a useful tool for structural sediment connectivity. As shown by the studies of Moore and Wilson (1992) and Bianchini et al. (2016), terrain analysis is fundamental to understanding the investigated area's morphodynamics. High values of the LSF index, with the large incision of the river valley relief, define potential sediment supply areas as a consequence high erosive power of the surface runoff. Also, the spatial distribution of the TWI and SPI indicators shows the possibility of erosion and transport of sediment from the catchment area (Fig. 9). High TWI values indicate areas with high flow accumulation, usually wet sites (Sørensen et al. 2006). When the possibility of sediment supply from the Brda catchment is excluded—no discharge due to the dam operation (Fig. 5), these are potential new sediment sources. They can be activated in the event of landslide movements (Zabuski et al. 2014), the above-described interventional flushing of the river channel (Fig. 11), or the occurrence of extreme precipitation (Fig. 10).

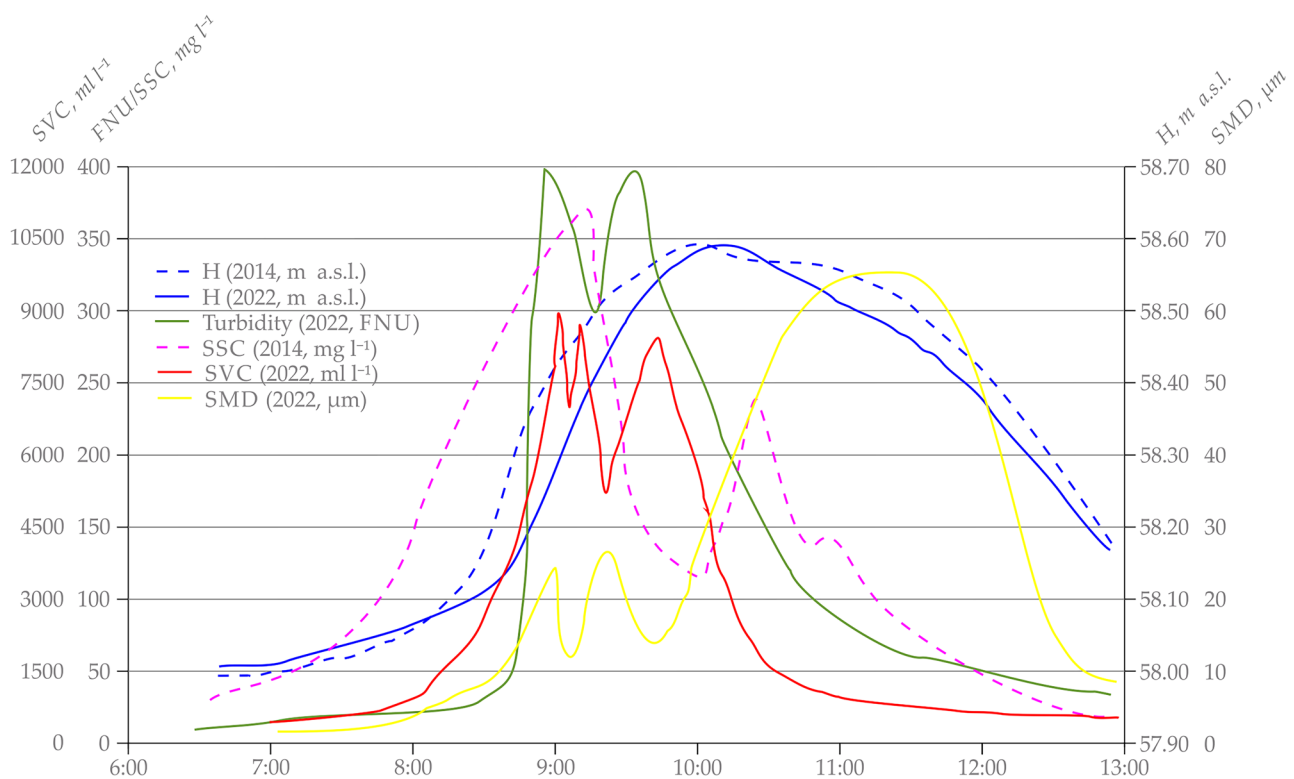


Fig. 11 The suspended sediment transport characteristics while flushing operation on site no 4 in 2021: H, water level; FNU, turbidity; SSC, suspended sediment concentration; SVC, suspended sediment volume concentration; SMD, Sauter mean diameter

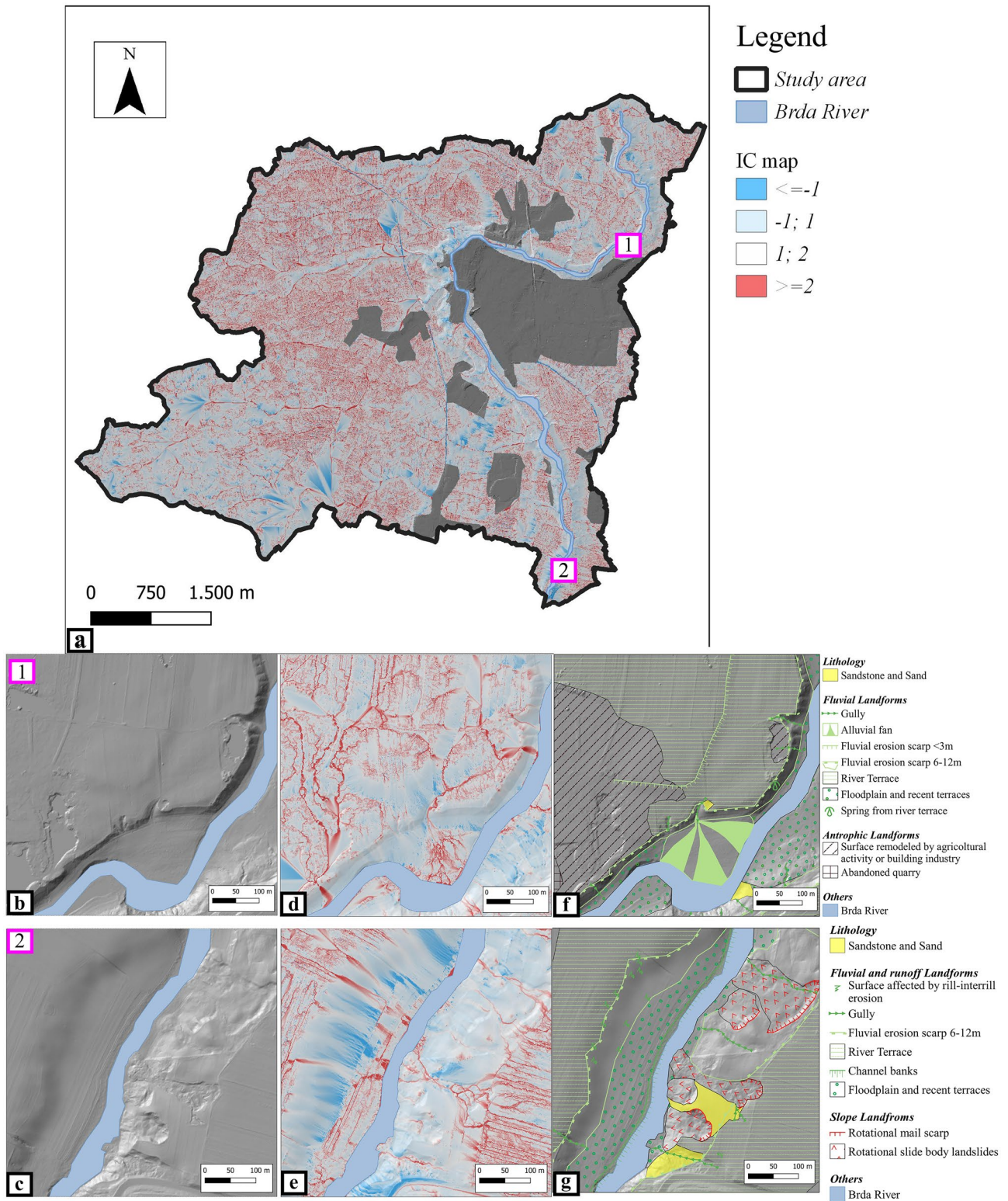


Fig. 12 a IC map with two focus. b and c Analytical hillshading. d and e Focus of IC. f and g Geomorphological maps (based on DTM, the Head Office of Geodesy and Cartography in Poland)

The transport of suspended sediments takes place in the pulse mode, resulting from hysteresis (Walling 1977; Williams 1989) and waves, related to an immediate water supply to the river, identified with the flood wave on the river (Chalov et al. 2015). The observed values of SVC and SMD (Fig. 10) are relatively high, considering the possibilities of water outflow through the studied creek. It proves the importance of the local source of suspended sediment supply for the Brda River, transported during precipitation. The observed maximum SVC (Fig. 10) in the investigated creek to the Brda River is recorded with a delay to the start of precipitation. Thus, the building of the catchment affects the dynamics of suspended sediment transport. It aligns with the results observed by Bosino et al. (2022), who measured the SVC and SMD of drained sediments in a small basin. At the same time, larger suspended sediment particles are recorded in the initial transport stage (Fig. 10), related to the decreasing transport capacity during the precipitation event.

To summarise, the course of fluvial processes in the catchment area with dammed water, especially in the section of the river completely excluded from the natural river outflow, is an excellent example of the human impact on the environment. The conducted sediment continuum studies on the example of the Brda River below the Koronowski Reservoir, using the methods described above, enable the implementation of controlled sediment flushing operation and management of the sediment supply from new sources, aiming at reducing the human pressure on the environment.

5 Conclusions

Based on the results of conducted studies on the functioning Koronowski Reservoir with its lateral canal on the suspended sediment transport continuum of the Brda River catchment below the dam, the following conclusions were drawn:

1. The creation of the Koronowski Reservoir in 1961 caused an irreversible change in the Brda River regime on the section from the dam to the HPP in Samociążek.
2. Flushing the riverbed due to an emergency water discharge from the dam, aimed at clearing the river channel of accumulated sediment, causes a temporary transport of sediments—especially suspended sediment. However, the conducted research shows a local nature of flushing without affecting the below LBC reservoirs.
3. Our priority and synthetic studies, using the LISST-25X device, allow us to define the change in the source of sediment supply to the Brda catchment area. From allochthonous area—identified with the processes of erosion/transport/redeposition of sediments from the total Brda River catchment to local sources—limited only to the

area of the sub-catchment area of approximately 29.38 km². New sediment supply sources are mainly material from bottom erosion of river channels (vertical incision process) and floodplain areas. The conducted research has also shown that relatively small creeks, combined with the active processes on the Brda slope, can supply the river channel with sediment as a result of a supply caused as a result of intense precipitation.

4. Thus, the sediment transport continuum in the Brda catchment area was disturbed because the river section in Koronowo was excluded from the natural circulation of sediments in the catchment area due to hydrotechnical transformations. This situation applies to each of the artificial reservoirs with lateral canals that enable the outflowing of the water.
5. Below the dams, a key element in sediment management is controlled sediment flushing operation, aimed at flushing the accumulated sediment in a way that does not affect the quality of the aquatic environment below. It results from environmental, legislative, and technical as well as social requirements—taking into account public participation in environmental awareness.

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Declarations

Competing interests The authors declare no competing interests.

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