River channel stability assessment under flow alteration: the Brda River case study (Poland)

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ABSTRACT

The processes of erosion, transport, and accumulation of river sediments are determined by the balance between the natural fluvial processes and the anthropic pressure. Evaluation of the degree of river channel stability is one of the ways to establish the pressure of human activity that could be directly reflected in the volume of eroded or accumulated sediments in a river. The research here proposed is focused on the last natural section of the Brda River (Poland), which represents a natural hotspot in a deeply anthropized fluvial system. To evaluate the human pressure on the natural river section, we developed a methodology that integrates hydrological and sedimentological studies as well as remotely sensed data. In particular, we applied: (i) the Indicators of Hydrologic Alteration (IHA) method, based on hydrological data; (ii) the erosion coefficient, based on suspended sediment balance; and (iii) spatial analyses of riverbed centerline migration of the Brda River in the section from Woziwoda to Płaskosz (northern Poland) to gain a comprehensive understanding of the fluvial dynamics in the area over a period of 60 years. A significant peculiarity of this research refers to the year 2001 when the operational regime of the Mylof Reservoir was changed from hydropeaking to run-of-river. The results obtained indicate a minor river regime transformation and sediment transport continuum disturbance. Finally, the link between the stability of the Brda riverbed, and the intensification of bank erosion (meandering) resulting from the balance of sediment supply, has been demonstrated. The results presented reflect the climate change trends (on the macro-scale) and human activity in the catchment (on the micro-scale) on the fluvial processes.

KEYWORDS

river stability; meandering river; sediment transport; the Indicators of Hydrologic Alteration (IHA); spatial analyses

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1. Introduction

Fluvial erosion is one of the most significant earth-modeling processes, shaping the earth's surface and creating landforms that can, directly or indirectly, impact human life (Brown et al. 2017). Fluvial geomorphology includes a wide set of landforms associated with erosion, transport, and accumulation of sediments. In general, erosive processes impact both the fluvial environment and the anthropic system. In particular, lateral erosion, as well as levee breach or meander cutoff, leads to the widening and the avulsion of the river channel within the valley (Leopold et al. 1992), causing problems connected to the sediment transport and deposition. The increase of sediments can lead to disruption of fish spawning in the gravel-bed rivers (Wood and Armitage 1997), habitat loss for species that depend on riverbank ecosystems (Florsheim et al. 2008), and interference with existing habitats, causing some species to be displaced (Poff and Zimmerman 2010). Fluvial erosion acts on both the river's bed (vertical incision) and the banks (lateral erosion). In the first case, bed erosion shapes the bottom of the river, as well as the fluvial landforms sited in the riverbed, e.g. point bars that can contribute to increasing the solid fluvial transport. On the contrary, bank erosion reshapes the river, sometimes causing the erosion of depositional landforms (e.g., flanks of fluvial islands) or causing fluvial avulsion processes (Ward et al. 2002). In general, the activity of a river can be derived from a multitemporal analysis of the channel path, occasionally indicating the activity of the erosive processes and their magnitude (Wohlfart et al. 2016; Monegaglia et al. 2018; Mandarino 2022; Bosino et al. 2024). The morphology of a river and its morphodynamics are guided by several factors like the hydrological conditions (Leopold et al. 1992), longitudinal channel slope (Montgomery and Buffington 1997), lithology (Słowik 2014), size of sediments present in the riverbed (Schuurman 2015), vegetation (Tal and Paola 2010) and anthropogenic factors (Graf 2006). Meandering channels are one of the most distinct river channel types that can be observed in lowland areas (Słowik 2013; Słowik et al. 2020; Oglęcki et al. 2021). Depending on the lithological nature, cohesion, and absorbency of the riverbank, water erosion mainly occurs during the floods causing sediment mobilization and erosion (Kleinhans et al. 2024) modifying the channel pathway. The water velocity acts on the intensity and nature of river erosion, depending on the slope, river channel shape and type, shear stress distribution, and water mass (Sylvester et al. 2019). It results in a simple dependence statement: the erosive power increases with the increase in water velocity (Leopold et al. 1992). In alluvial rivers, the type of water movement also affects the erosion process, where turbulent flow is considered highly energetic. Finally, the load and grain size of the transported sediment play a critical role in determining the intensity and type of the erosion process. Coarser sediments, such as gravel contribute more intense abrasion of the river channel and banks due to their kinetic energy, than finer sediments. The amount and grain size of the transported sediments depend in general on the catchment characteristics, e.g. geological structure (Konsoer et al. 2016), land use (Juez et al. 2018), vegetation cover (Larsen 1995), or degree of catchment transformation, e.g. presence of dams and reservoirs (Szatten et al. 2021). In meandering rivers, the sediments eroded from the riverbank are part of the sediment transport and can be partly accumulated on the opposite bank (point bar) due to the action of transverse thalweg (Sylvester et al. 2021). The constant increase of the radius of curvature leads to the cutoff of the meander pattern, shortening the river's course. The higher power of the water velocity above the cutoff point is conducive to bed erosion, which causes the bend to be blocked off from the main river. Over time, it is excluded from the river flow, becomes shallower, and an oxbow lake is formed (Shields and Abt 1989). On the other hand, the impact of humans on a fluvial system is well known to cause deep perturbations on river morphodynamics (e.g. Garzón and Alonso 2002; Walling 2006; Schuurman 2015).

Especially in the past century, most of the riverways that flowed in the alluvial plain were modified by humans for hydraulic purposes (dam construction), to protect villages and cities close by creating sometimes flood control polders, artificial riverbank protections, etc. (e.g. Habel 2013; Marren et al. 2014; Szatten et al. 2023). The impact of dam construction on floodplains as well as river morphodynamics is a worldwide phenomenon (e.g. Kingsford 2000; Marren et al. 2014; Liaghat et al. 2017). More in general, human interaction within rivers has meant that the natural conditions were replaced in large river portions. However, detecting and studying these sectors can be of fundamental importance to understand the original hydromorphological conditions of the river as well as to estimate the sources of sediments that can be directly correlated with the natural or anthropic erosion processes.

The main aim of the research is to assess the stability of the Brda riverbed on the section between Woziwoda and Płaskosz Villages, Kuyavian-Pomeranian Voivodeship, north-central Poland (Fig. 1), in relation to the catchment area's natural conditions as well as to human influence. The river transformation degree and the sediment transport dynamics were evaluated with hydrological, sedimentological, and spatial data. The research hypotheses assume that: (i) the Brda River water flow regime is transformed due to of human activity; (ii) the discharge alteration determines a change in suspended sediment transport dynamics having a direct response in channel meandering processes. The methodology proposed here, includes the long-term assessment of the mean annual variability of river discharge, the Suspended

Sediment Concentration (SSC) evaluation, its correlation with the hydrological alteration of the river (IHA method) in order to understand the hydrologic impact of human activities, the erosion coefficient (A) calculation in order to weight the erosion, transport and deposition processes, and finally, the multitemporal evaluation of the river sinuosity though dedicated Geographic Information System (GIS) analysis. Therefore, the study highlights that through modern GIS techniques and hydrological analysis, it is possible to derive information regarding channel stability in areas lacking long-term monitoring stations.

2. Material and methods

2.1 Study area

The Brda River is one of the largest lowland rivers in Poland, with a total length of 245 km and a total catchment area of 4,661 km^2 (Map of the Polish Hydrographic Division 2007). The river can be divided into three sections characterized by different environmental characteristics: (i) upper, mainly characterized by large lakes retention, (ii) middle, which preserves natural conditions and in which the study area is

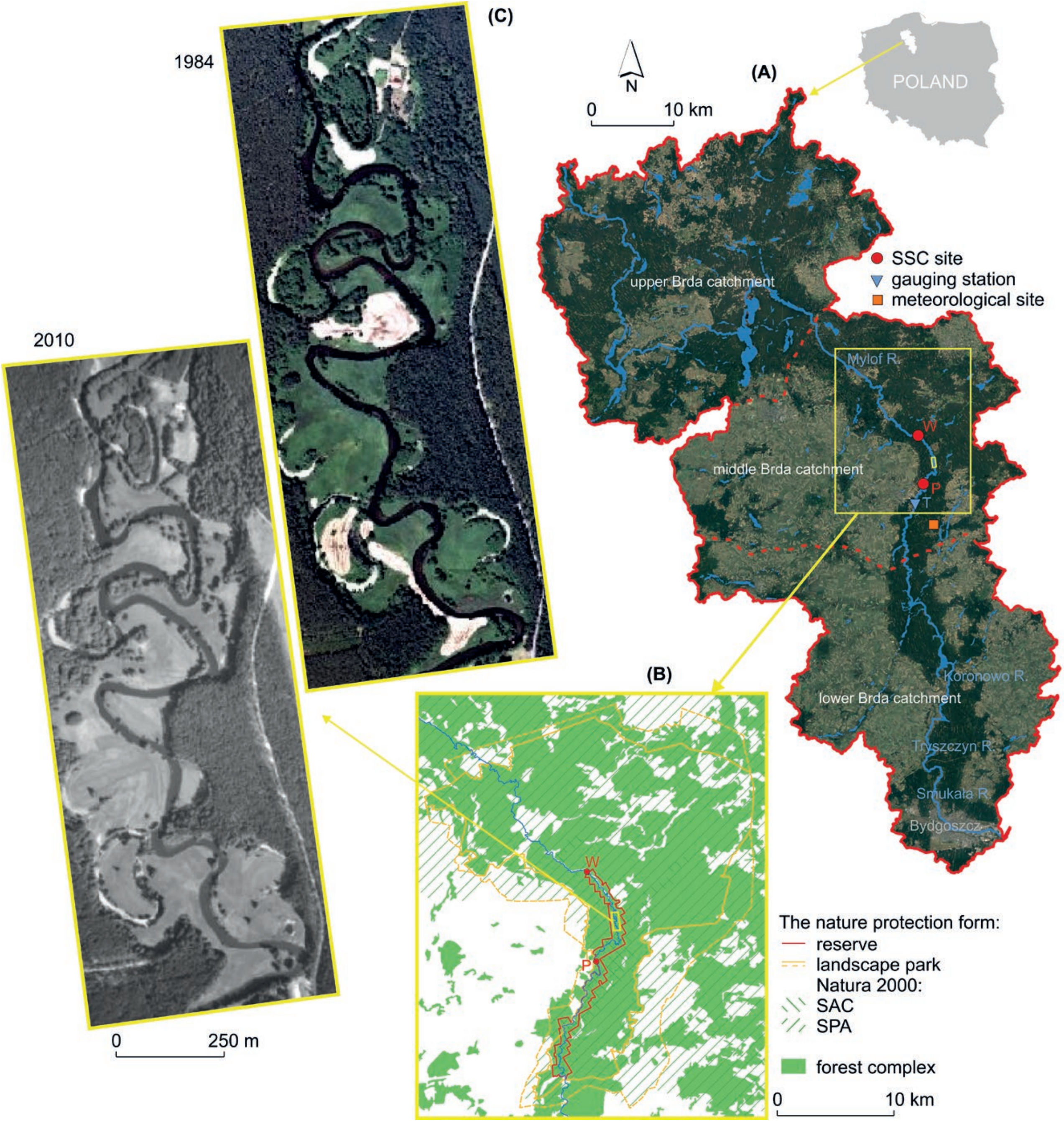

Fig. 1 Study area: (A) Land cover (Google satellite image) of the Brda catchment; (B) the nature protection form; (C) detailed study area in 1984 and 2010.

situated, and (iii) lower, which is highly modified by intense human activity (Fig. 1A).

In the upper part of the catchment, the Brda River flows through 16 natural lakes, which significantly stabilize its regime of water flow. The middle part of the Brda River catchment begins with the Great Brda Canal (104.2 km of the river course) and ends with the backwater of the Koronowo Reservoir (169.9 km of the river course). It is characterized by the dominance of forest cover quantifiable as about 60% of the entire catchment (Szatten and Habel 2020). In addition, this part of the river is characterized by the presence of the Mylof Reservoir which was created in 1848. The lower part of the catchment was already transformed in the 19th century by the construction of weirs and sluices for the mills and for timber rafting purposes (Szatten et al. 2021). Currently, the area is characterized by three artificial reservoirs: Lower Brda Cascade (Koronowo, Tryszczyn, Smukała), constructed in the 1960s (Szatten et al. 2018). In general, the Brda River is characterized by one of the lowest discharge variabilities among all Polish rivers (Choiński 1988).

The investigated study area covers a section of the Brda River enclosed between the villages of Woziwoda (140.8 km of the river course) and Płaskosz (159.0 km of the river course), where spatial analyses of channel meandering rate (section 2.3.3.) were performed for a part of the river near Gołąbek village with a length of 2.6 km (between 145.0 km and 147.6 km of the river course) (Fig. 1C). The river valley is made of fluvioglacial (outwash) sands and gravels, filled with Holocene peat sediments with a variable thickness from 1 to 2.5 m (Pikies 2009). The width of the river valley is about 400 m in the study area. In the research area, the riverbed has a uniform cross-sectional profile. It is deepest close to the concave bank, about 2.0–2.5 m at an average flow, and at the convex bank it is usually shallower – about 1 m. The average channel slope in the analyzed section is 0.23‰. This area is located on the ecotone border of two physic-geographical mesoregions, Tuchola Forest (in the north) and Brda River Valley (in the south) (Solon et al. 2018). In this sector Brda River has a meandric-shaped planimetric development and is sited in a large, densely forested complex of Bory Tucholskie. The most characteristic landforms of the area associated with the fluvial morphodynamics are the oxbow lakes, reactivated during high flow periods. The valley's edge is elevated above its bottom by about 10 m. Finally, the study area includes several nature protection forms, based on the Central Register of Nature Protection Forms provided in the web application (https://crfop.gdos.gov.pl), e.g. reserve – the Brda River Valley, Tuchola landscape park, the Special Areas of Conservation (SAC) – the Brda and Stążka Valley in Bory Tucholskie, and the Special Protection Areas (SPA) – Bory Tucholskie as part of the Natura 2000 protected area network (Fig. 1B).

The Mylof Reservoir operating regime changed in 2001. In our research, this date is considered as the threshold date for analysis because the hydropeaking operation regime (starts at the end of XIX Century, from the dam was commissioned) passed to the run-of-river operation implemented in 2001 (Fig. 2). Its introduction was related to the implementation of pro-ecological provisions of the Water Law Act (Water Law Act 2017). The first, hydropeaking operation regime resulted in a higher temporary increase in river flow downstream of the hydroelectric power plant than the second, run-of-river operational regime. This change is also observed throughout the entire Lower Brda cascade (Szatten et al. 2021).

2.2 Materials

The workflow adopted in this research is illustrated in Fig. 3.

2.2.1 Hydrological and climatological data

Hydrological data were daily values of discharge (Q, in $m^3 s^{-1}$) for the period 1981–2017 obtained from the

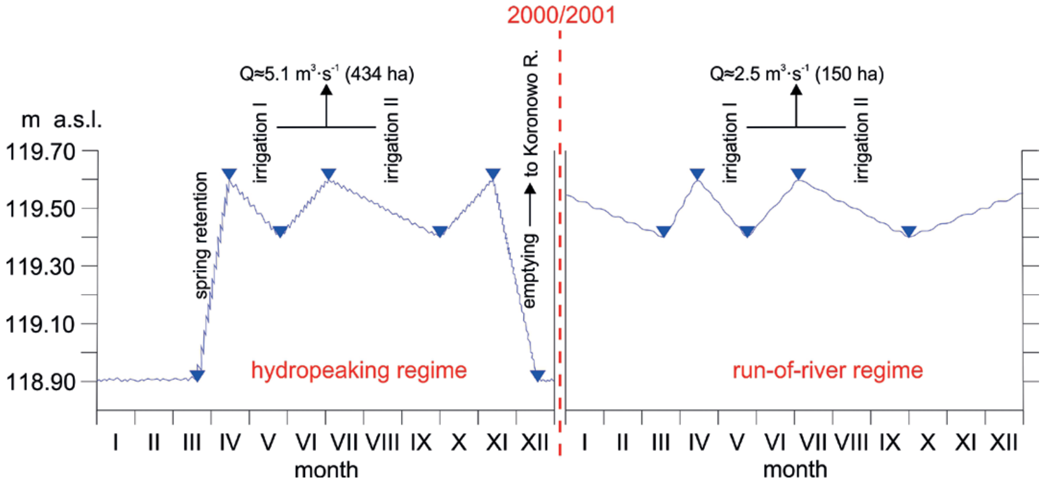

Fig. 2 The sketch of hydropeaking and run-of-river operational regime on Mylof Reservoir.

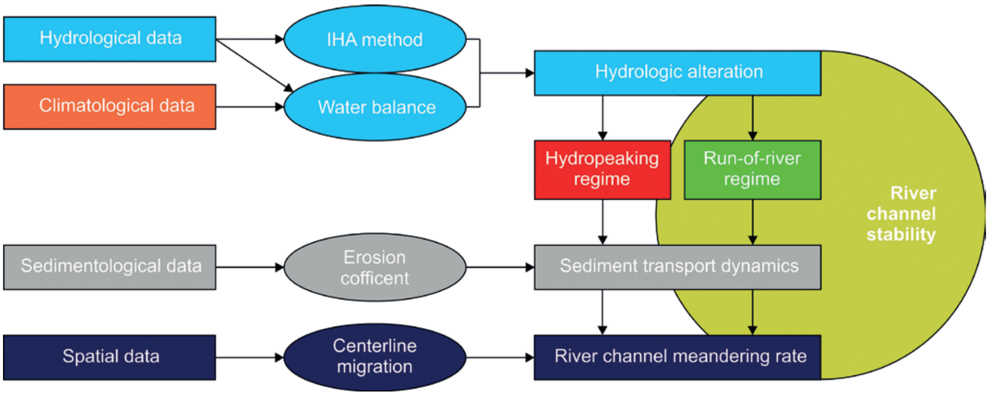

Fig. 3 General workflow of the Brda River Woziwoda-Płaskosz sub-catchment.

resources of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI). The Tuchola water gauging station (Fig. 1A) is located 159.1 km of the Brda River course, the closest to the study area, making it a reference station in determining the hydrological conditions for this part of the sub-catchment.

The annual sums of precipitation (in mm) were used from Płazowo meteorological station belonging to the IMWM-NRI for the years 1981–2017. The statistical significance of trends was tested using Student's t-test at a significance level of 0.05. Climatic data on annual precipitation anomalies were provided by the ERA5 Explorer web application (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview). The precipitation anomaly is understood as the difference (in %) between the annual precipitation (in mm) over the period 1981–2018, and the long-term average (reference period 1981–2010), using a combination of forecast models and data assimilation systems to "re-analyze" previous observations (Muñoz Sabater 2019). Based on the research by Okoniewska and Szumińska (2010), the water balance was supplemented with evaporation (E), calculating the catchment retention (ΔR) using the equation:

$$P - E - Q = \Delta R, \quad (1)$$

where: P is the annual sums of precipitation (in mm), E is annual evaporation (in mm) (Okoniewska and Szumińska 2010), Q is annual river flow (in mm), and ΔR is the catchment retention (in mm).

2.2.2 Sedimentological data

Sedimentological data are characterized by average monthly values of Suspended Sediment Concentration (SSC, in mg l^{-1}) from 1984 to 2011, obtained from the resources of the National Environmental Monitoring. The observation sites were located directly: (i) above the study area (Woziwoda, 140.8 km of the Brda River course) and (ii) below (Płaskosz, 159.0 km of the Brda River course) (Fig. 1). Due to the implementation of the provisions of the Water Framework Directive (2000) directly into the Environmental Monitoring Programme, monitoring was discontinued in the sites mentioned above after 2011. Their location within the Brda River water body from Bielska Struga to Hozjanna (code id 292551) (Map of the Polish Hydrographic Division 2007) prevented further monitoring in such a dense network of sites, which is the reason for the sedimentological data lack.

2.2.3 Spatial data

Spatial data included aerial photographs and an orthophotos map from the resources of the Head Office of Geodesy and Cartography, obtained using WMS services from the access point of the Spatial Information Infrastructure (geoportal.gov.pl). The data represented the ETRF2000-PL (EPSG:2180) metric coordinate system. Their detailed characteristics are presented in Tab. 1.

Tab. 1 Characteristics of spatial data.

No.	Data (Picture no.)	Centroid coordinates		Scale	Type	Q Tuchola $m^3 s^{-1}$
		X	Y			
1.	1984-08-23 (3139)	641094.42	430591.31	12 000	B/W	21.0
2.	1996-06-07 (0855)	640525.57	431808.39	26 000	RGB	16.3
3.	2004-07-30 (4729)	640538.80	431808.39	26 000	B/W	14.2
4.	2010-07-02 (0024)	641478.07	430961.72	48 000	RGB	12.9

Explanation: picture composition B/W – black/white, RGB – red-green-blue.

2.3 Methods

2.3.1 Hydrological transformation

To determine the hydrological boundary conditions affecting the fluvial processes in the research area, long-term trends of water discharge for the Tuchola water gauging station were derived starting from the method of integral curves described by Obodovskyi and Lukianets (2017). The input data were the annual characteristics of the discharge (Q_i), i.e. minimum (Q_{min}), maximum (Q_{max}), and average (Q_{av}) values, in the period 1981–2017. The long-term mean annual variability of river discharge was calculated using the equation:

$$k_i = \frac{Q_i}{Q_{av}} \rightarrow f_{(i)} = \sum(k_i - 1), (2)$$

where: k_i is the modular factor, Q_i is the value of the i-th term of the series, Q_{av} is the arithmetic mean, and $\sum(k_i - 1)$ is the sum of deviations.

The increase in the course of the curve (k_i) corresponds to the trend of increasing discharge, and conversely, when the curve decreases, a trend of decrease in discharge is observed.

Water balance (equation 1), and flow oscillation (equation 2) were verified using the distribution of annual precipitation anomaly – ERA5 model (Muñoz Sabater 2019), and together with the information about operational regime changes on Mylof Reservoir in 2001, was pointed out as boundary for further analyses.

The Indicators of Hydrologic Alteration (IHA), a method proposed by Richter et al. (1996), was utilized to assess the hydrologic impacts of human activities on the Brda River. IHA software (ver. 7.1.0) provided by The Nature Conservancy (Arlington, VA, U.S.) was employed for the calculations. The methodology included: (i) determination of input data for the periods 1984–2000, and 2001–2018, (ii) defining Non-Parametric Hydrological Statistics between time series, (iii) calculation of IHA values for 33 hydrological parameters described by Richter et al. (1996) and plotted in Fig. 4. According to Richter et al. (1996), they include 5 statistical groups: (i) the magnitude of monthly water conditions, (ii) the magnitude and duration of annual extreme water conditions, (iii) the timing of annual extreme water conditions, (iv) the frequency and duration of high and low pulses and (v) rate and frequency of water condition changes.

Classification of the discharge transformation for the 33 tested parameters was carried out based on the Range Variability Approach (RVA) criterion (Richter et al. 1997). The RVA uses the pre-development natural difference of IHA parameter values as a reference for defining the extent to which natural flow regimes have been altered and quantifies this alteration in a series of Hydrologic Alteration factors. According to the adopted method (Richter et al. 1998), the range $|RVA \leq 0.33|$ means low discharge transformation, the range $|0.34 \leq RVA \leq 0.67|$ is associated with moderate transformation, and finally, the range $|RVA \geq 0.68|$ corresponds to a large alteration.

2.3.2 Sedimentological analyses

The relation between discharge (Q) and SSC is one of the fundamental methods to determine the erosion-transport-accumulation conditions of the river catchment. This dependency is also used by Obodovskyi and Lukianets (2017) based on the erosion coefficient (A) definition, which is the antilogarithm of the value at the point of intersection with the Y-axis of the trend line from the distribution of dependencies $lg_{SSC} = f(lg_Q)$. The antilogarithm is a specific case of an exponential function, where the variable appears in the exponent (e.g., a^y). In the case of our data, a served (a) as the constant base (log10), while the exponent (y) varied (SSC or Q). Considering the availability of data described in subchapter 2.2.2, its value was determined for the Woziwoda (140.8 km of the Brda River course) and Płaskosz (159.0 km of the Brda River course) sites (Fig. 1) for the periods: 1984–2000, and 2001–2011. It is necessary to point out the weakness of our research here, because Q/SSC relationship is commonly modeled using a power function (Müller and Forstner 1968; Horowitz 2003), and lack of data made it impossible to use the best method to be expressed by hysteresis patterns (Gregory and Walling 1973) to describe this relationship. A value >7 of the A-coefficient (Obodovskyi and Lukianets 2017) is related to river channel instability, identified with intensive accumulation/sediment erosion processes. On the contrary, a low A coefficient value is characteristic of a stable riverbed. Also, based on monthly values SSC and Q was possible to calculate the Suspended Sediment Load (SSL) for the Woziwoda – Płaskosz sub-catchment from 1984 to 2010.

2.3.3 Multitemporal analysis

Spatial analyses were performed in QuantumGIS (ver. 3.22.13) and SAGA GIS (ver. 7.8.2) software (Conrad et al. 2015). The acquired aerial photographs and the orthophoto map, characterized in detail in subchapter 2.2.3, correspond to the metric spatial system ETRF2000-PL (EPSG: 2180). Using QGIS tools, the spatial extent of the Brda channel was digitized for 1984, 1996, 2004, and 2010. Then, the channel centerline was determined using the Geometric Attributes tool (Nyberg et al. 2015). The use of centerline in river planform change studies was proposed by Ikeda and Parker (1989). In the study area, 10 meanders were identified, and metric coordinates (Cx_iy_i) were assigned at characteristic points, enabling calculations of L_C – length of the river measured along the centerline, L_V – valley length, S – sinuosity index (Rust 1996) (equation 3), and MR – centerline migration rate, in m $year^{-1}$.

$$MR = \frac{L_C}{L_V}, (3)$$

The distances in the transects used to calculate the LC, LV, and MR indices were determined using equation 4:

$$C_{xiyi} = \sqrt{\left(x_i - x_{(i-1)}\right)^2 + \left(y_i - y_{(i-1)}\right)^2}, (4)$$

According to research by Rosgen (1994), values of sinuosity index (S) indicate straight (S < 1.1), wavy (1.1 ≤ S < 1.4), and meandering (S ≥ 1.4) channels. Additionally, the migration rate analysis included local morphometric valley conditions and erosion to the eroded (concave) bank or the point bar (convex) bank direction.

3. Results

3.1 Evaluation of hydrological alteration

The starting point for determining hydrological alteration in the Brda River was to describe the variability of water balance affecting the Brda River catchment. The analysis of annual precipitation (P), annual evaporation (E), catchment retention (ΔR) (Fig. 4A), and precipitation anomalies based on the ERA5 model

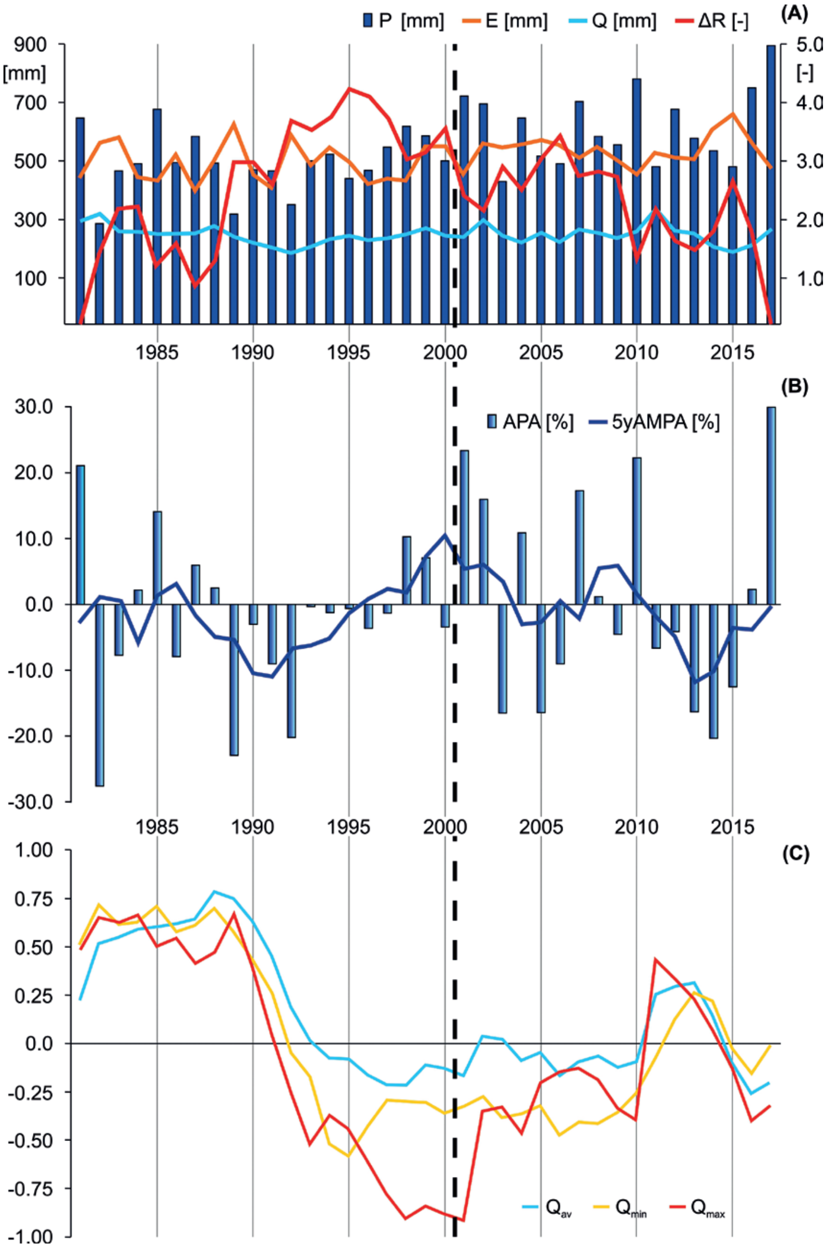

Fig. 4 The annual precipitation (P) at Płazowo site, annual sums of evaporation (E) (Okoniewska and Szumińska 2020), annual discharge (Q), and retention (ΔR) presented using the method of integral curves for the years 1981–2017 (A), the precipitation anomaly (APA) for each year in the 1981–2017 period as a percentage relative to the long-term reference period of 1981–2010 (B), and the long-term trend of water discharge for the Tuchola gauging station for $Q_{av.}$, Q_{max} and Q_{min} for the period 1981–2017 (C).

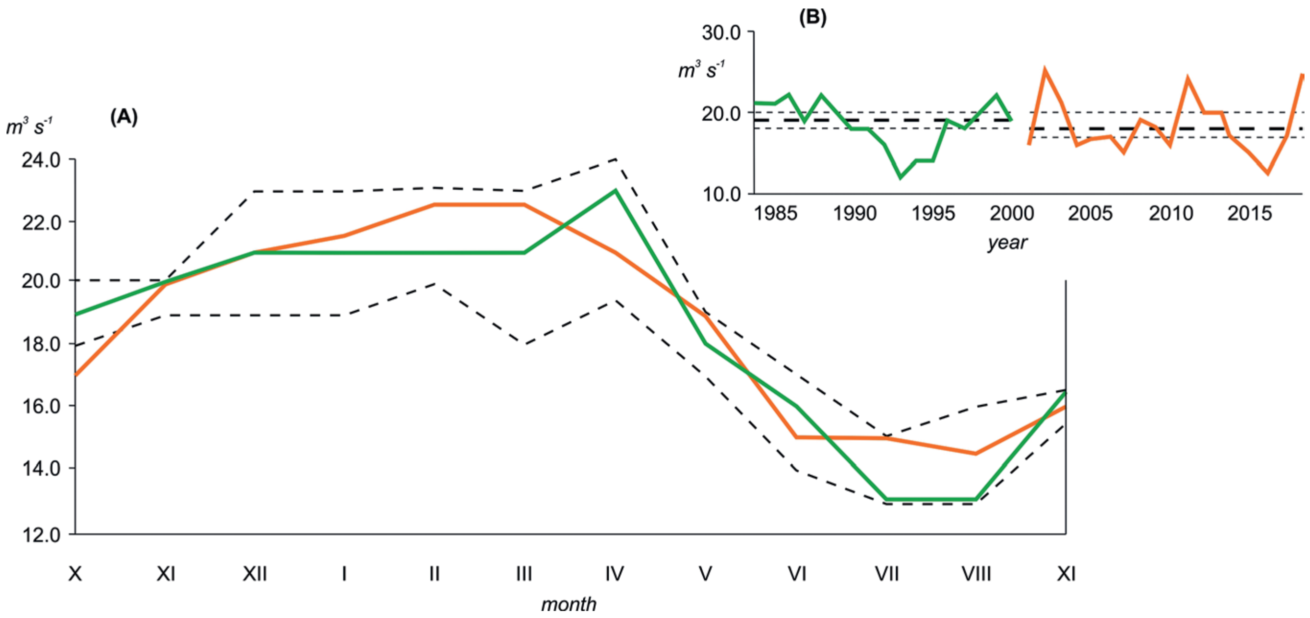

Fig. 5 Alteration of median monthly (A) and yearly (B) flows with RVA boundary (light blue area) for Tuchola gauging station in two analyzed periods (1984–2000 – green, and 2001–2018 – orange).

(Fig. 4B) in connection with the long-term trend of water discharge (Fig. 4C) enabled the determination of hydro-meteorological boundary conditions. Until the end of the 1980s, a stable trend of water discharge was observed, with a relatively stable precipitation component, and a decreasing trend of catchment retention (ΔR). The beginning of the 1990s was characterized by a reduction of atmospheric precipitation, and a strong negative precipitation anomaly, still a negative trend of retention (ΔR), which also resulted in a negative trend of water discharge. Then, a period of positive precipitation anomaly begins, which is reflected in a stabilization/slight increase in the trend of water discharge for Q_{av} and Q_{min}. However, the trend of water discharge for Q_{max} continues to decrease. Also, change in the ΔR trend is observed, indicating an increase in the retention of the catchment. The next change in the precipitation anomaly trend (Fig. 4B, from the year 2001), not clearly observed in annual precipitation (Fig. 4A) and the continued upward trend in retention (ΔR), results in an increasing direction of Q_{max} discharge trend, and a continuation of the positive trend of water discharge for Q_{av} and Q_{min}, which indicates the influence of different factors potentially including human activity, on the river regime. This indicator may be the change in the operational regime at the Mylof reservoir, allowing the indication of 2001 as the boundary year for IHA analyses. The following period (2010–2014) was characterized by positive precipitation anomalies and retetntion trend (ΔR) with negative trend of water discharge (Fig. 4). It is essential to point out that in the analysis of catchments with significant groundwater recharge and high surface retention, we observed a delay in the Q response to precipitation.

The Brda River is characterized by a typical lowland river regime, with higher discharge in the winter hydrological half-year (Fig. 5A). IHA research has shown that for October the Monthly Flow Alteration is outside of RVA boundaries, as 25th and 75th percentiles in the second period. Also, November, May, and July the Monthly Flows Alteration for the second period is very close to the RVA boundary. Moreover, for the two analyzed periods, it should be noted that the yearly flow below the RVA boundary occurred not only in the period of limited precipitation (1990s) with an average value 20.0 $m^3 s^{-1}$, but also in the second period (2001–2017) where the annual discharge values was 18.5 $m^3 s^{-1}$. In addition, variations significantly above and below the RVA boundaries (Fig. 5B).

In addition, considering the degree of flow transformation of the middle part of the Brda River catchment, IHA analyses indicated a significant discharge transformation in terms of individual groups of parameters. In the case of comparing the two periods (1984–2000 to 2001–2018), the greatest diversification of RVA can be noted in several parameters (Fig. 6): October Median Flows, 1-Day Minimum Flows, Date of Minimum Flows, Date of Maximum Flows, Low Pulse Count and High Pulse Count. The indicated parameters are consistent with the deviations of the water discharge trend shown in Fig. 4B.

In general, an increased dynamic in the changes of parameters is observed (Fig. 7). In the second period, the median value of 1-Day Minimum Flows outside of the RVA boundary is observed. Also, the median value of 1-Day Maximum Flows is higher in the second analyzed period. This proves the increase of extreme flow dynamics at the Tuchola gauging station. In the case

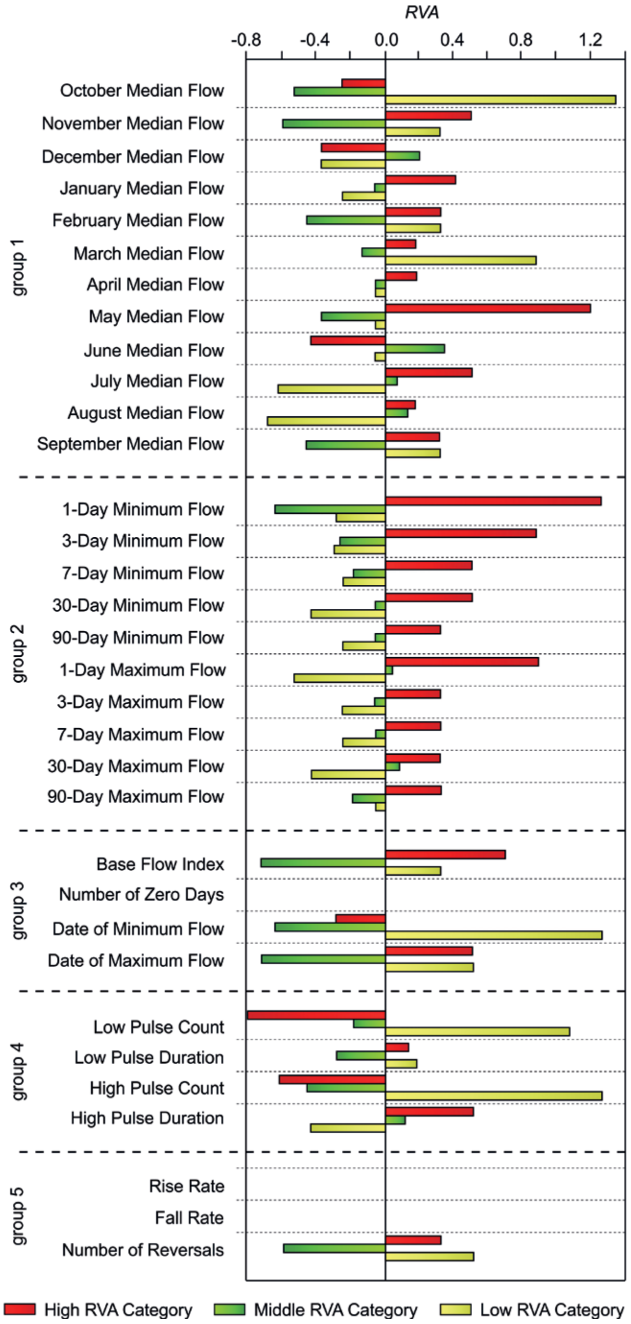

Fig. 6 Comparison of changes in the value of the greatest hydrologic alteration (HA) for 33 Indicators of Hydrologic Alteration (IHA) for the Tuchola gauging station using RVA target range between analyzed periods (1984–2000, and 2001–2018).

of the Date of Minimum Flow and Date of Maximum Flow, there was a significant acceleration (on median) from July 17 to June 30, and from February 22 to February 6, respectively. At the same time, in the second period, the median value of the above-mentioned indicators is below the lower RVA boundary. A similar situation is with the next two indicators. In the case of Low Pulse Count and High Pulse Count, there was a decrease in median values from 7 to 5 and from 8 to 6, respectively. At the same time, there is a clear tendency to decrease the dynamics of Pulse Count in the analyzed period. Changes in the dynamics of flows are also visible in the aspect of the Reversals indicator (Fig. 7).

3.2 Sedimentological response of hydrological alteration

The erosion coefficient (A) is related to the hydrological conditions and the dynamics of suspended sediment transport in the river and leads to information regarding the processes of erosion, transport, or deposition along a river. The analyzed section of the Brda River shows a high variability of sediment dynamics in time (Fig. 8). Generally, a decrease in the value of coefficient A on the Y-axis (Fig. 8) indicates a decline in SSC during the analyzed periods. However, for the period (1984–2000), a high A value for the Woziwoda site was observed, indicating the intensification of erosion processes and, thus, a decrease in the stability of the Brda riverbed. In this same period, Płaskosz site is characterized by a low A value, indicating high stability of the riverbed. The following period (2001–2018) is characterized by a decrease in the value of coefficient A, which indicates the high stability of the riverbed for all analyzed sites.

Sediment balance (SSL) confirms the assumptions of riverbed stability in the analyzed section of the Brda River. In the first period, both years with high positive and negative suspended sediment balances are observed, which confirms the thesis about the riverbed's instability. In the case of a positive balance, the erosion process predominated, and in the case of a negative balance, the accumulation of sediment predominated in the analyzed section of the Brda River. In the second period, mainly years with a relatively small positive sediment balance and years with stable conditions were observed (e.g. 2003, 2005, 2006, 2009) (Fig. 9).

3.3 Morphological response of hydrological alteration

The further step was assessing the river morphodynamics of the Brda River through the evaluation of the centerline in river planform change over time.

In the study area Brda River's meanders underwent typical spatial transformations, e.g. (i) extension (meander no. 6), or (ii) rotation (meander no. 4) (Fig. 10). Unfortunately, no case of neck erosion by chute was recorded in the analyzed period. However, on the analyzed orthophotomaps (Fig. 1) evidence of several meander cutoffs can be observed, now represented by oxbow lakes (Fig. 10).

In the analyzed period, most of the meanders are characterized by an increase in the sinuosity index (S) (Tab. 2). According to the criteria proposed by Rosgen (1994), out of the 10 analyzed meanders, 7 are characterized by an S value, which allows the classification of the channel as meandering. The highest value of the S index was recorded in meander no. 8

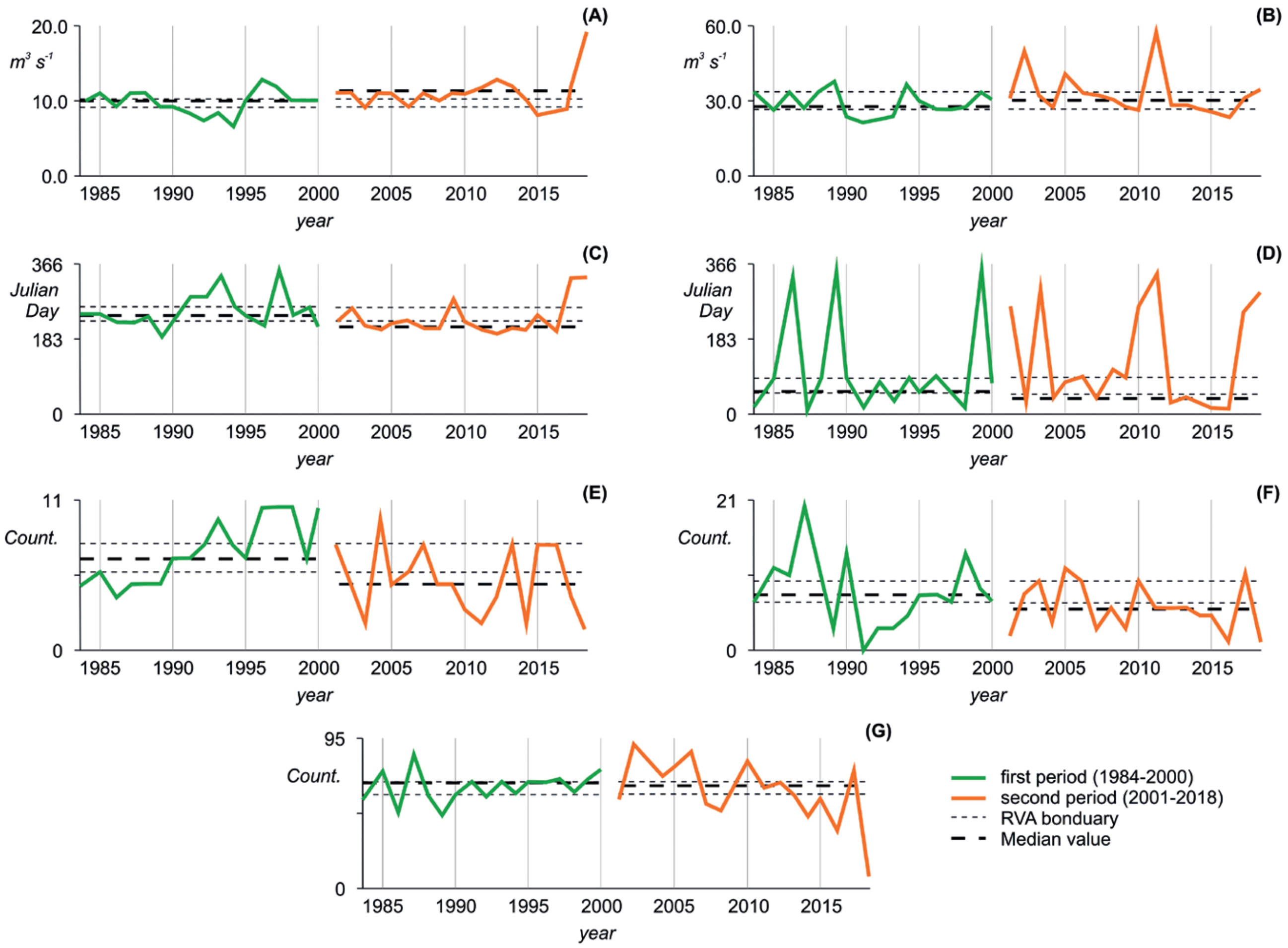

Fig. 7 Changes in medians of IHA selected indicators for the Tuchola gauging station in two analyzed periods (1984–2000, and 2001–2018): A – 1-Day Minimum Flows, B – 1-Day Maximum Flows, C – Date of Minimum Flow, D – Date of Maximum Flow, E – Low Pulse Count, F – High Pulse Count, G – Reversals (name of the indicators after Richter et al. (1996).

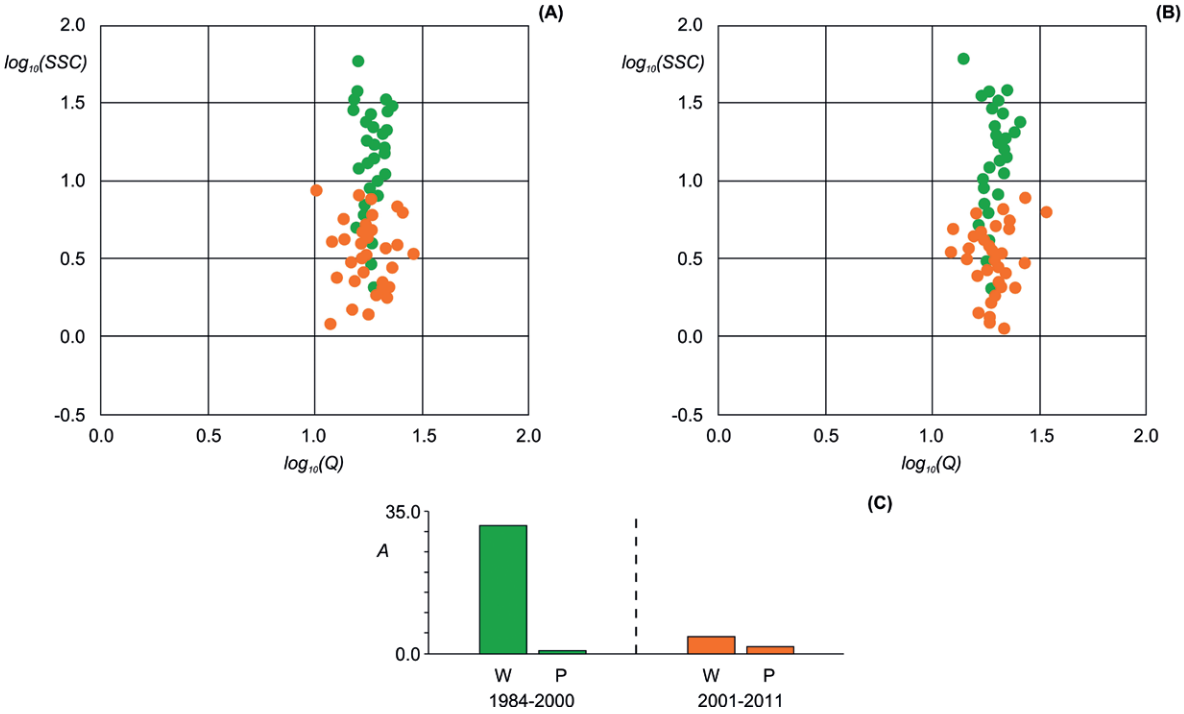

Fig. 8 The antilogarithm value of the erosion A-coefficient (C) for Woziwoda (a), and Płaskosz (b) in the analyzed periods: 1984–2000 (green), 2001–2011 (orange).

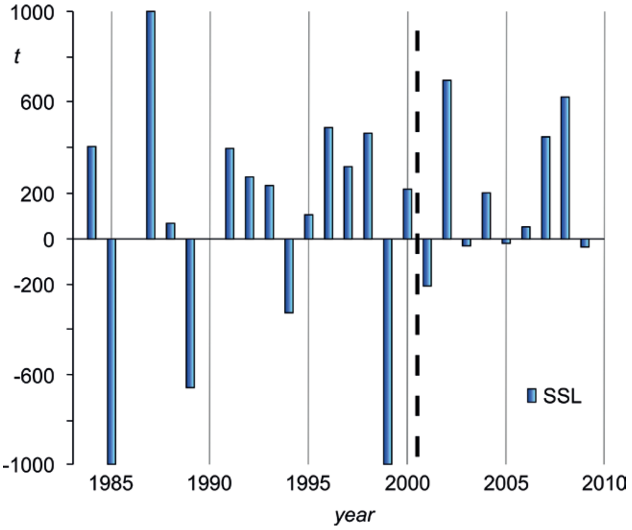

Fig. 9 Sedimentation balance (SSL) between Woziwoda and Płaskosz site (1984–2010).

Tab. 2 The sinuosity index (S) in the study area in analyzed years.

No.	1984	1996	2004	2010
1.	2.27	2.38 (+)	2.34 (–)	2.27 (–)
2.	1.26	1.31 (+)	1.36 (+)	1.37 (+)
3.	1.80	1.85 (+)	1.74 (–)	1.90 (+)
4.	1.73	1.60 (–)	1.69 (+)	1.72 (+)
5.	1.19	1.21 (+)	1.16 (–)	1.18 (+)
6.	2.25	2.38 (+)	2.38	2.41 (+)
7.	1.54	1.56 (+)	1.56	1.51 (–)
8.	7.93	8.85 (+)	9.01 (+)	9.00 (–)
9.	1.40	1.37 (–)	1.38 (+)	1.36 (–)
10.	2.06	2.25 (+)	2.11 (–)	2.20 (+)

Explanations: 1–10 meanders as Fig. 10; S index: wavy (1.1 ≤ S < 1.4) – black, and meandering (S ≥ 1.4) – red; +/– extension/cutoff year to year.

(S ≈ 9.00). The year-on-year change in the S index value indicates that the highest channel migration occurred in the years 1996, and 2010 (Tab. 2). This indicates substantial channel dynamics in the studied section of the Brda River. Based on the above-described criteria (Rosgen 1994), the remaining parts of the Brda riverbed (meanders no. 2, 5, 9) correspond to the wavy river channel type.

In addition, the centerline of the river channel migration rate varies, reaching a maximum of 1.0 m year^{-1} (Fig. 11). It should be noted that the migration of the channel centerline occurs due to bank erosion phenomena that shape the morphology of both the convex and concave parts of the meander. In most cases, bank erosion was observed (Fig. 11 – red color), indicating higher migration rates. It should be noted that two meanders (no. 4 and 8) covering the section of the river with the oxbow lake cutoff before 1984 (Fig. 10) were characterized by channel migration and rectification of the channel path. In the case of the other analyzed meanders, the thalweg shifted according to the fluvial processes using a change in the course of the channel. Mainly, the change in the orientation

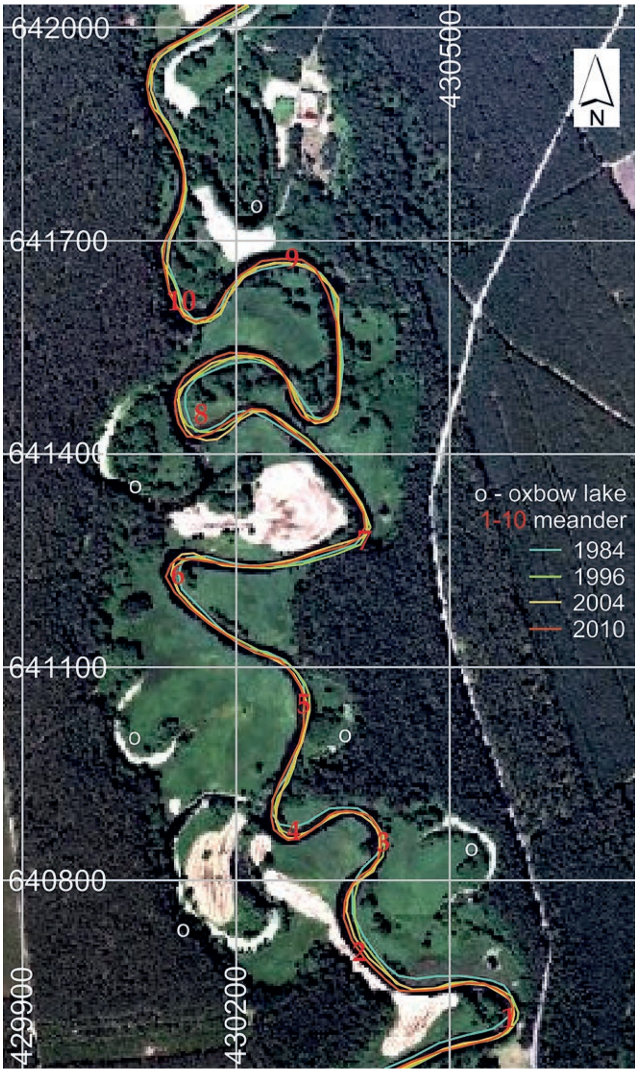

Fig. 10 Spatio-temporal changes of the Brda River centerline in the period 1984–2010 (1–10 analyzed meanders).

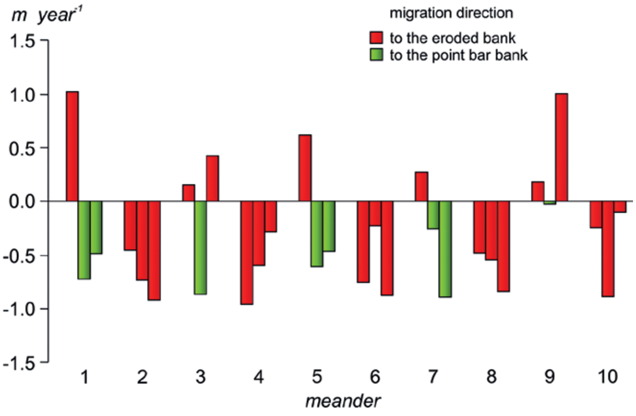

Fig. 11 The centerline of river migration rate (MR); Explanations: 1–10 meanders as Fig. 10; data bars in sequence 1984–1996, 1996–2004, and 2004–2010.

of the eroded bank in the period 1984–1996 (Fig. 11) can be observed in six (no. 1, 3, 5, 7, 9) studied meanders. It is worth noting that this concerns meanders located closer to the eastern edge of the valley. This situation may be caused by (i) the river reaching the edge of the valley, which may result in more difficult erosion, or (ii) the presence of bank vegetation. The latter has an important impact on the rate of meander migration rates (Micheli et al. 2004). Based on the qualitative analysis of trees vegetation conducted on aerial photographs and orthophotos map (Fig. 1, Tab. 1) it is noted that for meanders 1, 3, 7, and 10 it could have influenced the erosion resistance, which confirms the above thesis.

4. Discussion

Considering the significant transformation of river catchments as a result of human activity (Belletti et al. 2020), the continuity of sediment supply from source areas to coastal areas at the end of the system is disturbed (Walling 2006). The sediment continuum of the Brda River is heavily disturbed mainly due to the construction of artificial reservoirs (Szatten and Habel 2020; Szatten et al. 2021) that dramatically change the natural flow condition in the river. Today, the studied section of the river is characterized by the lowest pressure of human activity from all the Brda sub-catchments due to a lack of significant inflows (Map of the Polish Hydrographic Division 2007), point sources of pollution (Szatten and Habel 2020), presence of Bory Tucholskie forests (CLC 2018), and the presence of numerous nature protection restrictions (subchapter 2.1). In addition, it can be assumed that sediment dynamics is a derivative of natural channel processes in the studied sub-catchment, under the influence of geomorphological as well as external hydrological conditions partly connected to human activities (Marren et al. 2014).

The discharge differentiation of the Brda River is relatively small and relates to the lithological homogeneity of the bedrock that forms the catchment – outwash sands and gravels (Pikies 2009) and with the presence of a large number of lakes in the fluvial system (Choiński 1988). The above mentioned natural catchment characteristics result in a large retention capacity of the catchment and the long circulation time of water. The Brda River is characterized by a typical lowland river regime, with higher flows in spring and lower flows in summer (Fig. 5). The river flow indicators commonly established in the literature (Knighton 1998; Ward and Robinson 2000; Leopold et al. 1992; Montgomery and Buffington 1997; Słowik 2014; Schuurman 2015) are influenced by a combination of natural and anthropogenic factors: (I) climatic factors (e.g. precipitation, evapotranspiration, evaporation, seasonal variation as extreme events), (II) catchment characteristics (e.g. topography, soil type, land use, and vegetation change), (III) geological and geomorphological factors, and (IV) human activities (e.g. agricultural, urbanization, water management). The authors decided to select for the current research the parameters that were subject to the highest dynamics: factor I – precipitation, evaporation, and catchment retention, factor II – land use change, factor III – meandering dynamics related to SSC, and factor IV – change on operational system of Mylof Reservoir. The rest of the indicators were impossible to investigate due to lack of data or small variability of the indicator over time.

In the period 1981–2017, the river was significantly influenced by the precipitation component (factor I), which confirms the negative trend of water discharge in the early 1990s (Fig. 4). The observed drought was the result of fluctuations in the climatic factor. It was related to the recorded drought in Poland, e.g. in 1991, 1992, and 1994 (Somorowska, 2016). Also, it is essential to notice the time-delayed response of catchments such as the Brda River to rainfall, caused by a wide presence of forested areas (Szatten and Habel 2020) and lakes (Choiński 1988) resulting in significant water losses to evapotranspiration, especially in the summer half-year, when low water flow dominated (Fig. 5A). Furthermore, it is worth to note that in the research of Okoniewska and Szumińska (2010) a statistically significant increase in the evaporation trend in North-Western Poland was shown. Their data allowed to calculate water balance (equation 1) in the 1981–2017 period showing (i) general dominance of negative values of the retention factor (ΔR) which led to reduction of water resources in the catchment, and (ii) changes in the ΔR trend in 1995 from negative to positive, reflected in the increase of Q_{max}. However, in the long-term analyses (Fig. 4) considering the above-mentioned time-delayed response, a combination of limited precipitation supply and negative value of the water balance component – ΔR (Fig. 4A) with the occurrence of decreasing trend of water discharge (Fig. 4C) was observed, which partially links the influence of the climatic factors with the discharge.

However, the variation of the RVA category of the IHA (Fig. 6) in the second investigated period indicated pressures of human activity on the hydrological conditions. Comparing the two analyzed periods between 1984–2000 and 2001–2017, the dynamics of extreme flows on Tuchola gauging station were increasing. IHA analyses showed that particular indicators: October Median Flows, 1-Day Minimum Flows, Date of Minimum Flows, Date of Maximum Flows, Low Pulse Count, and High Pulse Count affected the largest diversity of IHA indicators (Fig. 7). The change in river regime (factor IV) is associated with the functioning of the Mylof reservoir, located above the study area, which is consistent with the results of research on other reservoirs, including Li et al. (2011), Habel (2013), Gierszewski et al. (2020), and (Szatten and Habel 2020).

Between 1990 and 2018, land use changes (factor II) in the entire Brda River catchment included a 1.8% increase in artificial surfaces and a 1.3% rise in forested and semi-natural areas, accompanied by a 2.1% decline in intensive agricultural land (Szatten and Habel 2020). These changes reflect moderate shifts primarily driven by agricultural extensification, afforestation, and urbanization processes within the catchment area.

The dynamics of hydrological conditions are directly reflected in the suspended sediment transport (factor III). In general, there was a trend of a decrease in the SSC over time (Fig. 8). It is due to the reduction in the supply from point pollution sources (Szatten and Habel 2020), which is consistent with the trend observed in Poland (Marszalewski and Piasecki 2014). We include here the reduction of point sources of water pollution related e.g. to industry, and treatment plants, and represented by the SSC indicator as per Water Framework Directive (2000) regulations. A decrease in the SSC between the studied sites was noted (Fig. 8), indicating that the section of the river between Woziwoda and Płaskosz has a generally accumulative character expressed by the surveyed suspended sediments. However, the erosion coefficient A for the Woziwoda site in the first studied period (1984–2000) assumed high values (Fig. 8) indicating that the above described hydrological transformations determined the increased channel instability. This hydrological transformation can be related to the hydropeaking operational regime at the Mylof Reservoir (factor IV). In this period, the intensive erosion/accumulation processes dominated the Brda riverbed in different parts of the river. In the second analyzed period (2001–2017), both observed sites were characterized by an increase in channel stability (Fig. 8). In general, above the study area was the sediment source supply area, which then was accumulated in the analysis section of the Brda River (Fig. 9).

The spatial analyses showed that the Brda River channel in the studied section was characterized by intensive centerline dynamics (factor III) (Fig. 10), as lowland river conditions. Studies show varying rates of increase of sinuosity index (S) in different river systems, e.g. Bolivian Amazon – increasing S from 1.4 to 3.6 between 1988 and 2010 (Monegaglia and Tubino 2019), increasing S from 0.95 to 3.25 between 1984 and 2014 (Ahmed et al. 2019). The highest dynamics were observed for the periods 1996-2010 (Tab. 2), when there was a strong migration of the river channel centerline, increasing the sinuosity index, and leading to the extension of the meanders (Fig. 10). It should be noted that the increase in the dynamics of channel migration refers to the above-described increase in the dynamics of extreme (minimum and maximum) flows, described by IHA results (Fig. 7). Abad and Garcia (2007) showed that hydrodynamics is the primary influential meandering factor. As stated by Allen (1997), during low water levels the eroded bank can be affected by water runoff, and during high water levels the riverbank can be washed by the river flow providing sediments to the fluvial system. These processes can be related to higher SSC on the Woziwoda site in the first analyzed period (Fig. 8).

The “butterfly effect” described by Meakin et al. (1996) makes the meandering river system difficult to predict in time and space. On the one hand, the meandering process is related to unstable conditions of the river catchment scale. On the other hand, the meandering process has also a stable character. The fully developed meanders of the Woziwoda-Płaskosz study area have similar characteristics of analyzed parameters, e.g. wavelength, amplitude, and meander belt width; their values are around the quasi-equilibrium

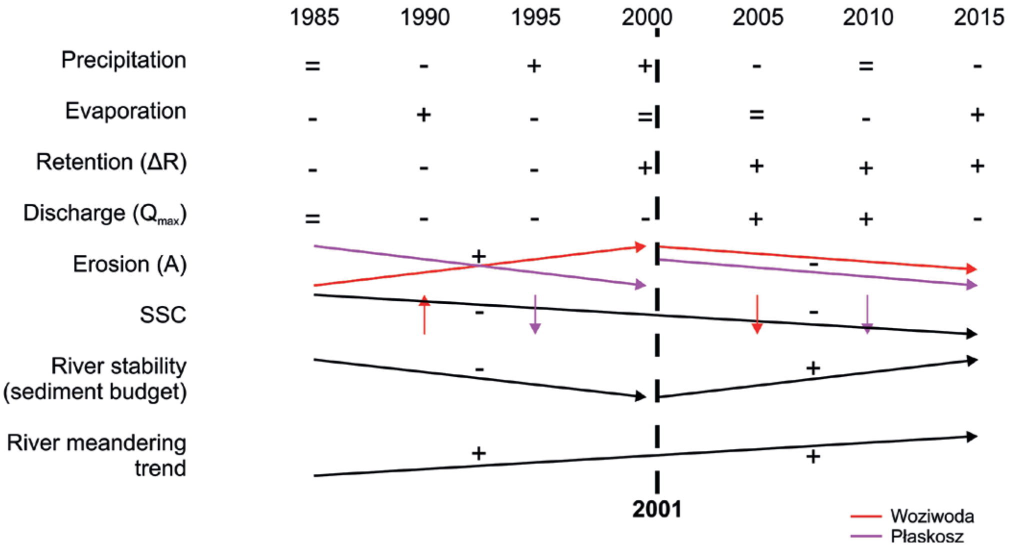

Fig. 12 Processes over time; Explanations: + ↑ increasing trend, – ↓ decreasing trend; = no trend/stability, Q_{max} – maximum discharge, A – erosion coefficient, SSC – Suspended Sediment Concentration.

state described by Xu et al. (2011), and showed stable conditions, especially in the second analyzed period. The analysis made it possible to determine the spatio-temporal source of sediment supply in the section of the river between Woziwoda and Płaskosz, which determines the sediment continuum in the middle section of the Brda catchment (Fig. 12).

5. Conclusions

This study has analyzed changes in discharge, precipitation, evaporation, catchment retention, sediment balance, and centerline migration in the Brda River caused by a combination of natural processes and human activities. Results showed that hydrological and sedimentological conditions of the sub-catchment are variable in time and space. The conducted research revealed that long-term trends of water discharge reflect the dependence between precipitation supply and evaporation components, considering the natural characteristics of the catchment (lithology, topography, etc.) constantly under the impact of negative retention capacity (ΔR). In addition, a time-delayed response of catchments is caused by a large percentage of forested areas and lakes which results in significant water losses to evaporation. In fact, our studies confirmed general rainfall-discharge trends, as exemplified by the low river flows caused by a prolonged drought observed in Poland in the 1990s. However, the greatest impact on the river flow regime on the studied section of Brda River was the change in the functioning of the Mylof Reservoir, from hydropeaking to run-of-river in 2001. Furthermore, if from one side a reduction in the sediment transport due to accumulation processes was detected, from the other side an increase of the flowing water energy, due to "hungry water" processes, was observed and related to the increase in meandering trend. The transformed river regime of the Brda River also influenced the channel meandering processes, directly related to extreme (minimum and maximum) flows. The supply of sediment to the Brda River fluvial system occurs prevalently after low water levels when material from eroded banks is washed (by runoff processes) or subjected to mass movement (down slopes under the force of gravity) into the river. As a result of water regime changes, the balance of suspended sediment of the river was disturbed in the analyzed section, decreasing the SCC values recorded in the analysis sites, with a positive SSL indicating sediment accumulation in the Płaskosz site. Worth to note, that in our research SSC does not include a detailed composition of the solids (e.g. organic part, phyto- and zooplankton). However, it will be possible to fill the gaps in our study in the future, giving a comprehensive picture of the supply sources in the catchment scale. Summarizing, our results contain valuable information that can be used to manage channel stability in areas lacking long-term monitoring stations, indicating water-sediment-land management direction at the catchment scale. The main novelty of this study is the integrated picture of fluvial processes describing long-term changes influenced by human activities from a regional perspective.

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