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Estimation of Long-Term Suspended Sediment Yield from a Small Agricultural Catchment

Adam Krajewski[1*], Kazimierz Banasik[1,2], Leszek Hejduk[1]

[1] Department of Water Engineering and Applied Geology, Warsaw University of Life Sciences, Nowoursynowska 159, 02-776 Warsaw, Poland

[2] Institute of Technology and Life Sciences – National Research Institute, Falenty, Poland

* Corresponding author's e-mail: adam_krajewski1@sggw.edu.pl

ABSTRACT

Predicting and estimating sediment yield from the catchment is crucial for the effective management of water resources and controlling soil erosion. Universal Soil Loss Equations (USLE) and their modifications have been appreciated and commonly applied among many methods. The idea of this work is to use the ESDAC database (a web platform hosting a series of pan-European and global datasets on soil erosion) to build the modified form of the USLE for the Zagożdzonka catchment, a small agricultural area located in central Poland. The calculated sediment yield is compared with the one determined based on the reservoir survey. The conducted analyses show that the average annual suspended sediment yield from the study catchment estimated using the MUSLE equation accounts for 201 Mg and is close to that determined based on the reservoir survey, i.e., 248 Mg. However, MUSLE, with the initially proposed parameters, will overpredict sediment transport at the study site. The ESDAC database may support local studies concerning soil erosion and sediment transport. The research is helpful for policymakers, planners, and engineers.

Keywords: MUSLE, sediment transport, agricultural catchment, reservoir siltation.

INTRODUCTION

Suspended sediment (SS) is a fine material carried in the river channel without contact with the bed. Sediment transport has global and local effects on ecosystems, the economy, and people's lives. Deltas, which are considered biodiversity hotspots, can exist only where rivers discharge enough sand and mud (Giosan et al 2014). However, excessive amounts of sediment affect the intensity of reservoir sedimentation and can damage hydraulic structures (Gonzalez Rodriguez et al. 2023; Liu et al. 2023). Also, other contaminants, such as heavy metals or radionuclides as well as microplastic may be carried along with the sediment (Eyrolle et al. 2020, Zeng and Yang 2020 Krajewski et al. 2022). Maximum sediment yields are associated with the area of China, West America, and the Mediterranean, while the lowest is with the low relief regions, i.e., northern Eurasia (Walling and Webb 1996). Therefore, predicting and estimating sediment yield from the catchment is crucial for effectively managing water resources and controlling soil erosion (Ciupa and Suligowski 2022). However, small catchments are often overlooked in large-area studies, which do not consider details on local topography or land management (Mitchell et al. 2001; Brański and Banasik 1993; Panagos et al. 2015). Transferring results from a regional to a local scale may lead to erroneous estimation of sediment yield and further to inadequate sediment control practices.

Among many applied methods, Universal Soil Loss Equations, USLE (Wischmeier and Smith 1978), and its further modifications are the basis for many studies (de Vente and Poesen 2005; Borelli et al. 2021). In its simplest form, USLE requires data on rainfall erosivity, catchment topography, land cover, and soil types. It allows calculations on a different time and space scale depending on the variant. For instance, Banasik et al. (2021) applied the classic USLE method to analyze the long-term intensity of reservoir siltation in relationship to environmental changes, while Barteni et al. (2021) used a modified form of the equation (MUSLE) to predict future response of a small alpine catchment to single heavy rainfall. Other authors attempt to improve the method by introducing new parameters or their new interpretations (Tsige et al. 2022, Shi et al. 2022).

ESDAC is an online web platform hosting a series of pan-European and global datasets, maps, and soil-related documents (Panagos et al. 2022). Among others, it contains the information on soil loss at 100 m resolution for the EU estimated using Revised USLE (RUSLE) and the values of individual parameters of the soil loss equation (Panagos et al. 2015). These partial data provide the opportunity for new analyses. Therefore, an attempt was made to determine whether the data from such a large-scale (EU) study can be used for local analyses (several dozen km^2).

This work sought to develop a MUSLE model utilizing the ESDAC database, apply it for SS modeling, and compare the obtained results with field measurements (reservoir survey). The objectives of this paper were twofold: a) to assess the applicability of the ESDAC database in case of small, local study sites and b) to estimate the long-term sediment yield from an agricultural catchment based on flow data.

MATERIALS AND METHODS

Study area and data

This research concerned the area of the Zagożdżonka River catchment (central Poland), which is a left tributary of the Vistula (Figure 1). The study site has been under hydro-meteorological monitoring at the Warsaw University of Life Sciences since 1962. The field investigations in this area were initiated due to the growing water needs of a local chemical factory. Over the years, the scope of research has expanded and now concerns climate change, flood prediction, soil erosion, sediment transport, and reservoir sedimentation (Banasik et al. 2001, 2016; Krajewski et al. 2019, 2021; Banasik et al. 2021). The catchment area at Płachty gauge station amounts to 82.4 km^2. Forests cover more than half (56%) of the study area. Arable land accounts for 29% and meadows for about 10%. The rest are wetlands and residential areas (Krajewski et al., 2021). Most soils can be identified as porous and sandy (light loamy sands: 56% or loamy sands: 32%). The relief is typical for a lowland site; the slope of the main channel ranges from 2‰ up to 3.5‰. The methodology for collecting field data is based on the guidelines of the national hydro-meteorological service (IMGW 2022). The discharge is calculated based on the continuous record of the water stage and a rating curve. Suspended sediment transport is estimated based on flow data and samples (mixture of water and sediment) taken directly from the stream.

The climate in this part of Poland is continental. Average annual precipitation amounts to 614 mm, while runoff is 105 mm. The annual air temperature is 8.4°C. From the analysis of long-term data series, it is also known that water resources are decreasing in the investigated area. There is a downward trend in annual runoff (-0.9 mm/year) and an increase in air temperature (0.04°C/year) starting from 1960 (Krajewski et al. 2019; Hejduk et al. 2019). Downstream of the Płachty gauge station there is located a reservoir called Górny Pond. It was constructed in 1976 to secure the water needs of a factory. Nowadays, it only has a recreational function. The reservoir has a volume of 215,000 m^3 and an area of 13.3 ha. A regular survey was conducted (every ten years on average) to analyze the changes in depth and volume of the Górny Pond (Banasik et al. 2012; Banasik et al. 2021). Over 40 years, the annual volume loss has been estimated at 1000 m^3. The trap efficiency calculated based on comparing SS loads inflowing to and outflowing from the reservoir during a flood event is 86%.

Suspended sediment yield estimation based on flow data

The total suspended sediment yield in the investigated period is assumed to be the sum of sediment load discharged during flood events and in a non-flood period:

$$Y = Y_F + Y_{NF} \tag{1}$$

where: Y – total suspended sediment yield (Mg) estimated based on flow data, Y_F – suspended sediment yield for flood events in the investigated period (Mg), Y_{NF} – suspended sediment yield during non-flood period (Mg).

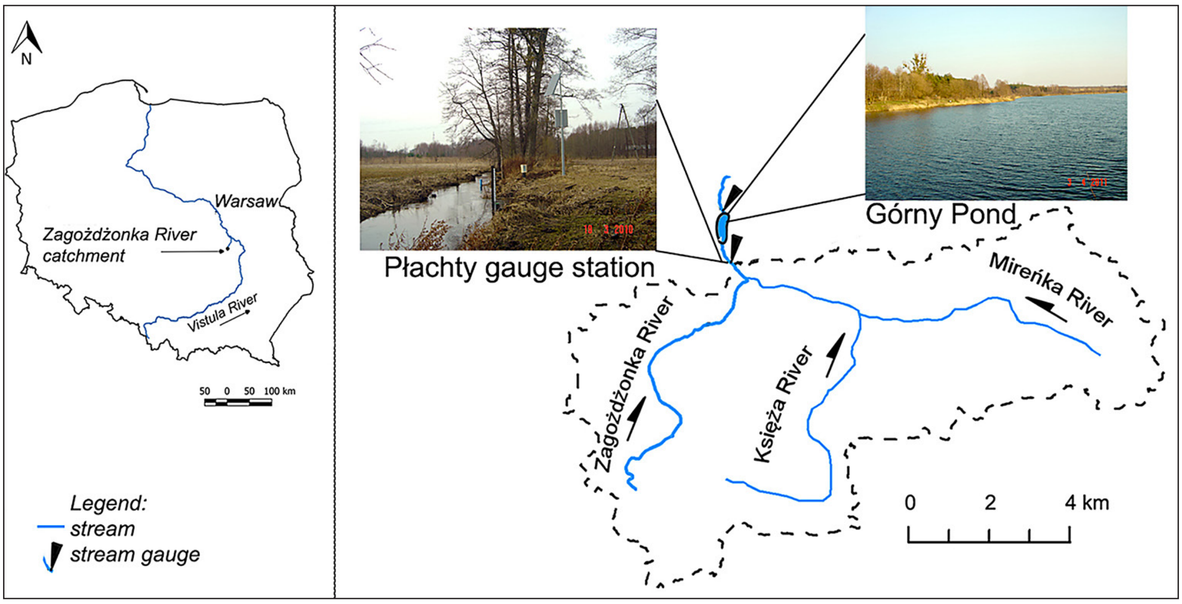

Figure 1. Locality map of Zagożdżonka River catchment

For a single flood event sediment transport is calculated according to MUSLE method (Williams 1975):

$$y_i = \alpha \cdot KLSCP(V \cdot Q_{max})^{\beta} \quad (2)$$

where: y_i – suspended sediment yield for i-th flood, Σy_i (Mg), α, β – MUSLE coefficients (-), K – soil erodibility (Mg/ha/[(MJ/ha)(mm/h)]), LS – topographic factor (-), C – cover factor (-), P – support practice factor (-), V – flood volume (m^3), Q_{max} – peak flow (m^3/s).

Flood volume and peak flow (V, Q_{max}) were estimated based on daily discharge data. The parameters of the soil loss equation (K, LS, C, P) were determined for the catchment based on the ESDAC database (2021). It contains high-quality, accessible data on the spatial variability of the USLE parameters for the area of the European Union (excluding urban areas). MUSLE coefficients (α, β) were optimized using the least squares method. This was possible as the sediment loads were known (measured) for ten flood events.

In non-flood period, sediment load was established as a product of daily discharge and average (constant) sediment concentration:

$$y_{NF} = 0.0864 \cdot c_d \cdot Q_d \quad (3)$$

where: y_{NF} – daily suspended sediment yield for non-flood period, Σy_{NF} (Mg), c_d – average, daily SS concentration, constant, c_d= 3 g/m^3, Q_d – daily discharge m^3/s.

Suspended sediment yield estimation based on acoustic depth measurements

On the basis of acoustic depth measurements of the Górny Pond (located downstream of Płachty gauge station), it is known that the average annual (2010–2020) volume of sediment deposits equals 710 m^3 (Banasik et al. 2021). The same research estimates the bed load input to the reservoir at 496 m^3. Therefore, knowing the trap efficiency of the reservoirs (86%) and the density of deposits (1 Mg/ m^3), the inflow of suspended sediment may be calculated from the following equation:

$$Y_R = \frac{1}{TE}(V \; - V_{BS})\rho \quad (4)$$

where: Y_R – total suspended sediment yield (Mg), TE – trap efficiency of the reservoir (%), V – total volume of deposits (m^3), V_{BS} – volume of bed load sediment (m^3), ρ – density of deposits (Mg/m^3).

RESULTS

Over 2015–2021, ten runoff–suspended sediment events were recorded. This data was further used to build a MUSLE model. Figure 2 presents the investigated floods. Among the listed, event no. 5 is the largest in peak flow, i.e., 2.3 m^3/s, and suspended sediment transport, i.e., 29.8 Mg, lasted six days. For all events, the first flush effect may also observed, i.e., rapid increase in SS concentration and occurrence of its peak value

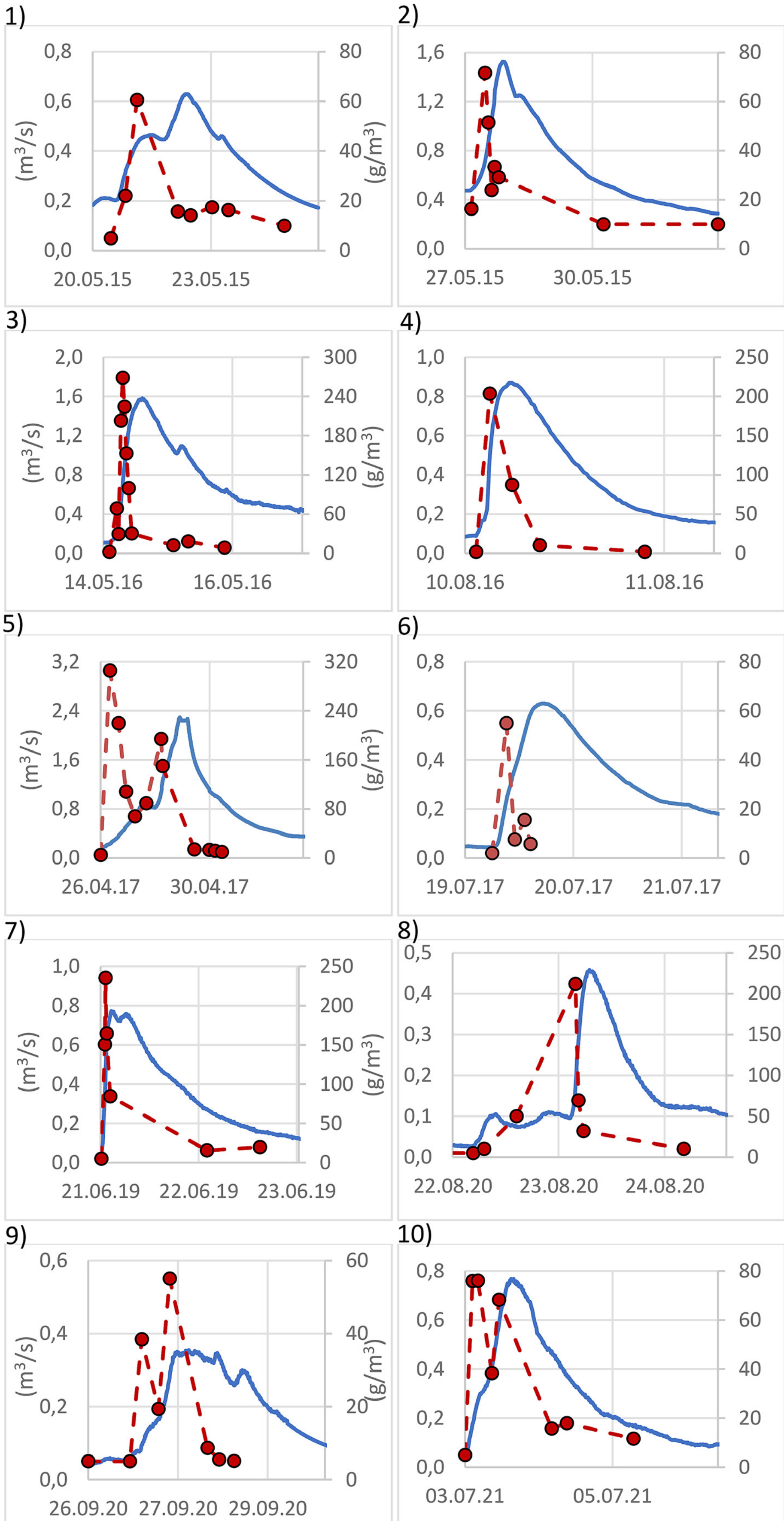

Figure 2. Flood events measured at the Płachty gauge station; solid line is discharge (m^3/s), dashed line with dots is SS concentration (g/m^3)

before peak flow. The USLE equation parameters (KLSCP) were averaged over the catchment area using digital maps from the ESDAC database (2021). In the case of the investigated catchment, there is an additional set of the exact parameters determined based on local topographic and soil maps (Table 1). By comparing these two sets, the authors would like to assess the usefulness and applicability of the global set (ESDAC database) for the case of local study sites. As one can note, these two are relatively consistent. The most remarkable difference occurs for the land cover factor, C. According to Banasik et al. (2021), values have decreased over the last 40 years from 0.077 to 0.047.

Other coefficients of the equation (α, β) were developed based on recorded rainfall – runoff – suspended sediment events (see Figure 2 for details) by applying the least squares approach. Figure 3 presents the relation between flood characteristics (volume, peak flow) and SS yield for the catchment of Zagożdżonka River. It should be noted that the horizontal axis is logarithmic. Estimated MUSLE parameters are $2.56 \cdot 10^{-4}$ and 1.17 for α and β, while the result of multiplying KLSCP equals $7.79 \cdot 10^{-3}$. This equation was used in further analyses.

Daily discharge data were used to select flood events for each hydrological year between 2010-2020 (corresponding to acoustic depth measurements of the reservoir). Simultaneously, a set of data for non-flood periods was created. In the case of flood events, the MUSLE equation was applied, and for the non-flood period, Equation 3 was used. Figure 4 presents measured discharges and calculated SS load, for example, year i.e., 2011. The sediment loads discharged during flood events were divided by the duration of the flood event. Thus, each bar of the graph represents the daily SS load. In 2011, there were 19 flood events, while the non-flood period lasted for 227 days. The total SS yield was 317 Mg. However, seven most significant floods accounted for almost 90% of this load. It can be stated that the sediment load is significantly higher during flood events. Over 2010–2020, the annual sediment transport varies widely from 19 to 699 Mg (Table 2). The average

Table 1. Parameters of the USLE for the Zagożdżonka catchment

Symbol	Parameters value acc. to:	
	ESDAC (2023), own elaboration	Local topographic and soil maps, as presented by Banasik et al. (2021)
K	0.265	0.247
LS	0.312	0.396
C	0.102	0.077–0.047*
P	0.924	0.90
KLSCP	$7.79 \cdot 10^{-3}$	$6.78\ 10^{-3}$–$4.14 \cdot 10^{-3}$

Note: *depending on the period, from 1980 up to 2020.

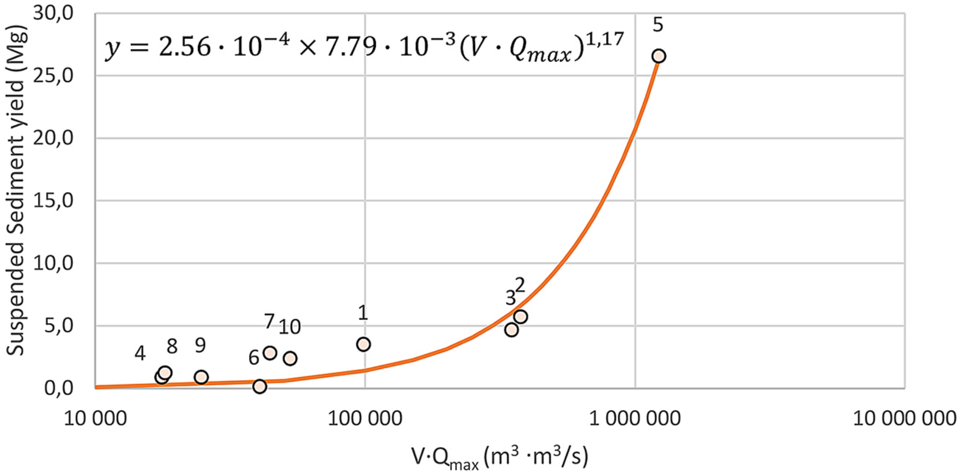

Figure 3. MUSLE equation – estimated relation for the Zagożdżonka river at the Płachty gauge station. Numbers correspond to the recorded events

load is 201 Mg. In dry years with only few flood events (2012, 2016, 2020), the intensity of sediment transport decreases. For periods rich in water, with a lot of rainfall (2010, 2011, 2013), the SS discharge exceeds the mean value.

By solving Equation 4, the average suspended sediment yield has been estimated based on the reservoir survey. It equals 248 Mg. This is also 19% higher than the previously determined value (based on flow data) of 201 Mg.

DISCUSSION

MUSLE equation is a quick and straightforward method for calculating SS yield during a single flood event. In this work, it was used to determine the long-term sediment discharge from the small agricultural catchment. The difficulty in method application is the need to specify the parameters of the equations. This issue has been partially solved by Panagos et al. (2015), who prepared digital maps of soil erosion for the EU.

For the study site, the most significant differences were noted in the case of the cover factor, C. The one established based on the ESDAC database (0.102) was twice higher than Banasik et al. (2021) developed. This may be due to the land use changes in the Zagożdżonka catchment. In the last 20 years, the amount of arable land decreased by more than 10%; at the same time, an increase in the forest cover was observed (Krajewski et al. 2021). The ESDAC database was prepared on the basis of Corine Land Cover maps from 1990, 2000, and 2006 (Panagos et al. 2015). The cover coefficients given by Banasik et al. (2021)

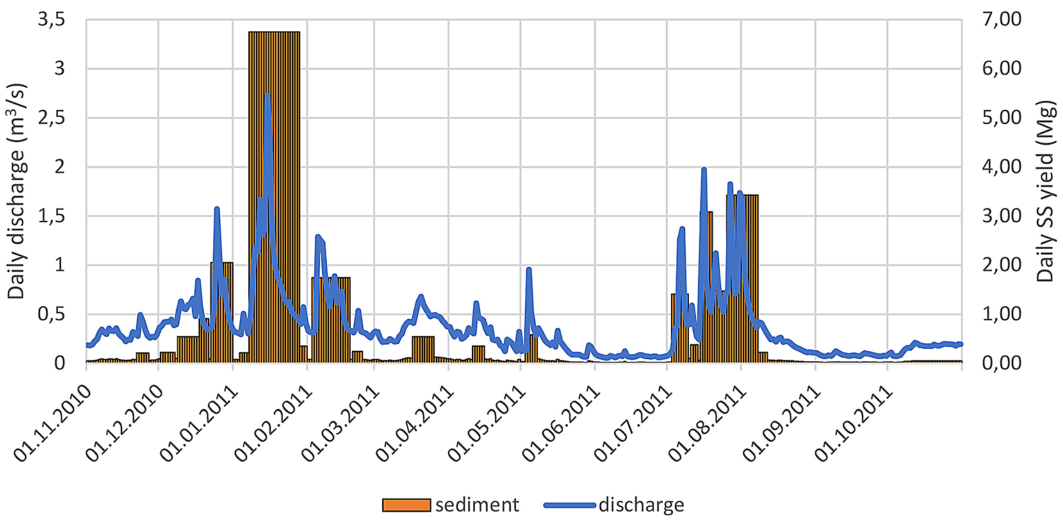

Figure 4. Daily discharge and sediment yield for Zagożdżonka at Płachty in 2011

Table 2. Estimated SS sediment loads at Płachty in the period 2010–2020

Year	SS load (Mg) estimated based on flow data			Total SS load (Mg) calculated based on reservoir deposits
	For flood period	For non-flood period	Total	
2010	683	16	699	248
2011	305	11	317	
2012	7	12	19	
2013	522	12	534	
2014	75	12	87	
2015	55	11	65	
2016	20	14	34	
2017	128	12	141	
2018	60	12	72	
2019 (up to June 2020)	16	22	38	
Average	187	14	201	

changed from 0.077 up to 0.047 in the years 1980 -2020. It is possible that the difference in the C parameter results from the validity of source data in different periods. Thus, it can be supposed that in the regions where intensive land cover changes take place, i.e., suburban areas, it may be necessary to additionally verify the C parameter, if it was established based on the ESDAC database.

The following two parameters for the MUSLE are α and β. Their first values proposed by Williams (1975), were 11.8 and 0.56 and concerned the territory of the USA. However, adapting the same values in a different region and under different climatic conditions may lead to errors in estimating the sediment load. Madeyski and Banasik (1989) were among the first ones, who tried to adapt the MUSLE to the local conditions of southern Poland. For 78 storm events from five small Carpathian catchments, they obtained parameters α and β, amounting to $5.42 \cdot 10^{-4}$ and 1.02, very close to those found for Zagożdżonka. In the case of study catchmen,t MUSLE with the originally proposed parameters will overpredict sediment transport. Thus, for the region of central Poland and in the absence of measurement data, it will be appropriate to use the optimized, above-mentioned parameters.

The equation developed for the Zagożdżonka catchment based on field data. For ten flood events, measured and calculated sediment loads are comparable, i.e. in total they equal 49.1 and 42.3 Mg, respectively. However, the established method seems applicable to the products of peak flow and volume up to $1.2 \cdot 10^6$ $m^3/s \cdot m^3$. After exceeding this threshold, the shape of the curve is more uncertain and thus the real intensity of sediment transport may be also different than predicted. In the analyzed period, two large floods (greater than a 10-year flood, $Q_{10\%} = 8.2$ m^3/s) occur with peak flows of 9.9 m^3/s in 2010 and 9.3 m^3/s in 2013. They have a significant impact on the sediment output in these two years.

Average annual suspended sediment yields estimated based on acoustic depth measurements (248 Mg) and discharge data (201 Mg) can be considered as similar. Assuming the sediment density is 1 Mg/m^3, these two loads correspond respectively to 0.12% and 0.09% of the total volume of the Górny Pond. Such an approximation is sufficient to determine the insensitivity of siltation and reservoir lifetime. The conducted analysis confirms that most of the sediment load is transported during the few floods that occur during the year. Similar findings on the impact of extreme events on sediment transport have also been made by Larson et al. (1997) and Porto and Callegari (2019). This trend is not maintained for dry periods (2012, 2016, 2019). On average, SS yield during non-flood events accounts for about 7% of the total load discharged from the catchment. However, in dry years, with a low number and magnitude of floods, it may even be more than half. Therefore, it should not be overlooked when estimating the total yield.

This work confirmed the usefulness of the data contained in the ESDAC database for local studies. This also creates opportunities for further local scale analyses on the erosivity of individual storms or modeling sediment graphs during single flood events. The research may contribute to preparing water management or sediment control plans and, therefore, is also helpful for policymakers, planners and engineers.

CONCLUSIONS

In this study, long-term suspended sediment yield has been estimated based on the discharge data and verified with the use of acoustic depth measurements of the reservoir. On the basis of the conducted research, the following conclusions have been drawn. Average annual suspended sediment yield from the Zagożdżonka catchment at Płachty estimated with the use of MUSLE equation, accounts for 201 Mg. This result is similar to the one determined on the basis of the reservoir survey, i.e., 248 Mg. MUSLE with the originally proposed parameters will overpredict the sediment transport in the study site. In the case of lowland catchments located in central Poland, it is recommended to use the parameters estimated in this work i.e., $\alpha = 2.56 \cdot 10^{-4}$ and $\beta = 1.17$. The ESDAC database may be used as a source of information for local studies concerning soil erosion and sediment transport, however, in the case of the areas where changes in land use are observed, additional verification of the land cover parameter is recommended.

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