



Sediment load variability in response to climate and land use changes in a Carpathian catchment (Raba River, Poland)

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Abstract

Purpose This study analyzes the variability of sediment loads under variant climate change and land use scenarios in a Carpathian catchment with a dam reservoir. The areas with the highest share of sediment loads are tracked to establish possible indications for future catchment management plans.

Materials and methods Analyses were performed for the Raba River catchment (Poland, Carpathian Mountains) with use of the Macromodel DNS/SWAT. The RCP 4.5 climate forecast predictions (2021–2050 and 2071–2100), downscaled for the area of Poland, and land use predictions from the DYNA-Clue model for the Carpathian area, were taken into consideration. A total of seven scenarios were created, accounting for precipitation (P1 and P2), temperature (T1 and T2), land use (LU) changes, and combined effects (COMB1 and COMB2).

Results and discussion The average load delivered to the dam reservoir was estimated as 2.43 Gg y⁻¹, and its seasonal/yearly variability was followed by local meteorological phenomena. Among the tested factors, precipitation change, in terms of total amount and intensity, exerted the most impact on sediment loads causing their increase. Temperature and land use changes resulted in a slight decrease. Combined scenarios implied that changes of the catchment area use, such as increase of forest cover, can noticeably reduce sediment loads delivered into a dam reservoir.

Conclusions The performed simulations revealed the importance of incorporating variant scenarios for catchment management plans, development of land use mitigation measures (erosion), and operational procedures for the dam reservoir. Particular attention should be paid to warmer winters with heavy rainfalls and temperatures above zero, which together with a lack of plant vegetation result in elevated annual sediment loads reaching the dam reservoir. Further changes must be mitigated by anti-erosion investments.

Keywords Carpathian catchment · Climate change · Land use change · Sediment loads · Dam reservoir

1 Introduction

Climate change impact at the catchment scale has been studied intensely over the last 20 years. Multiple

publications have reported alterations in flow characteristic, flood event frequency, and snow cover extent (Bussi et al. 2016; Hattermann et al. 2017). Moreover, these alterations are further amplified by shifts in the land use induced by temperature and precipitation changes (Wang et al. 2016; Bussi et al. 2017) or resulting from socio-economic reasons (Grecequet et al. 2017). Since these shifts of water and runoff cycles can severely disturb natural processes like weathering and erosion, changes in sediment fluxes can also be expected (Simonneaux et al. 2015; Yang et al. 2015). Assessment of sediment quantities delivered from a catchment is particularly important for regions that are highly vulnerable to erosion, e.g., mountainous areas with high slopes, and/or intensive and frequent rainfalls. Also, sediment continuity in a majority of these catchments has been obstructed by anthropogenic factors, e.g., alterations to channel morphology, or construction of dams and reservoirs (Apitz 2012;

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Ahilan et al. 2018). Especially, in the latter case, estimations of the sediment accumulation rate and remaining reservoir capacity are of a crucial significance (Alighalehbabakhani et al. 2017). Current studies related to sediment quantity estimations under climate change scenarios generally predict an increase of sediment loads under an upward trend of average precipitation due to intensification of soil erosion (Lu et al. 2013; Darby et al. 2015; Zhou et al. 2017; Giardino et al. 2018; Barrera Crespo et al. 2019). However, the response in individual catchments can vary due to possible changes in vegetation cover, as a result of water balance changes, reducing erosion in the area. The response of catchment models to temperature changes is even more complex, naturally displaying either an increase or a decrease in sediment loads (Bussi et al. 2016). Since temperature shifts can affect catchment water balance through various local phenomena, e.g., early snowmelt, droughts/rainfall occurrence, and distribution of vegetation cover, their impact on sediment loads seems to be strongly related to catchment geographical settings (Jentsch and Beierkuhnlein 2008; Ricci et al. 2018; Shrestha and Wang 2018). Therefore, to produce reliable predictions, modeling efforts should incorporate results of downscaled climate predictions, account for regional trends in land use change, and analyze them simultaneously (Bussi et al. 2016).

The main goal of the study was to analyze the variability of sediment loads under variant climate change and land use scenarios in a Carpathian catchment with a dam reservoir. The Raba River (southern Poland) has been selected as the study venue, since its catchment represents the most typical conditions for this region. The upper part of this river flows through a mountainous area with a considerable number of agricultural fields. Also, the river features a drinking water dam reservoir, accumulating sediments delivered from the upper part of the catchment. The sediment load variability was tested with use of the Macromodel DNS/SWAT (Discharge-Nutrient-Sea/Soil Water Assessment Tool) under the RCP4.5 climate change predictions, downscaled for the Polish area (Mezghani et al. 2017). To account for local land use changes, the results from the DYNA-Clue (Dynamic Conversion of Land Use and its Effects) model for the area of interest were taken into consideration (Price et al. 2017). Besides tracking the effects of individual precipitation, temperature, and land use changes, the goal of the study was to observe the impact of the combined changes on the sediment loads. Delimitation of the sub-catchments with the highest portion of sediment loads delivered to the reservoir was tracked to establish possible indications for future catchment management plans.

2 Materials and methods

2.1 Research area

The Raba River (131.9 km) flows from the Carpathian belt of the Gorce Mountains (source—780 m a.s.l.) to the Vistula River (outlet—180 m a.s.l.), and constitutes its right-side tributary (Fig. 1). This river features a dam reservoir (Dobczyce) at 60.1 km, which is the main source for drinking water of approximately half a million people (Mazurkiewicz-Boron 2016; Operacz 2017). The Raba River catchment (1537.1 km²) has a pronounced dual character, a mountainous part located upstream from the reservoir, and a sub-montane following the downstream reach of the river. These parts are very different in terms of terrain slope, soil type, and land use. The upper part of the basin is characterized by high slopes, forested areas, and loamy soils, while the lower part is covered mainly by loess and the land use is dominated by agriculture. The mountainous nature of the upper part of the Raba River catchment manifests with a fast reaction to precipitation, due to its high slope gradients and relatively low soil permeability. The river features very large amplitudes of water levels and flows, with maximum values recorded in the snow melt period, and early summer long-lasting rainfall events. The following sediment load variability was analyzed for the Myślenice calculation profile (Fig. 1) which encompasses the upper part of the Raba River catchment, and constitutes the last water gauge/monitoring point upstream from the reservoir. Selection of this calculation profile allowed us for the first time to simulate the effects of climate change in the Polish Carpathians on the sediment load delivered to the dam reservoir.

2.2 Macromodel DNS/SWAT

The spatio-temporal variability of the sediment loads for the Raba River catchment was analyzed with use of the Macromodel DNS/SWAT which was developed at the Institute of Meteorology and Water Management—National Research Institute (Instytut Meteorologii i Gospodarki Wodnej—Państwowy Instytut Badawczy—IMGW-PIB), and described previously (Ostojki 2012; Wilk et al. 2017, 2018a, b; Szalinska and Wilk 2018; Szalińska et al. 2018). Briefly, the developed Macromodel provides a platform where the SWAT module (Arnold et al. 2012; Abbaspour et al. 2015) is integrated with other models (e.g., hydrological and meteorological), and in-situ and/or remote catchment data. The SWAT module itself has been recognized by the Nexus Tool Platforms (Mannschätz et al. 2016) as the best available hydrological model, based on its easy accessibility, wide application possibilities, and numerous publications which can support current and new users. In the current research, the

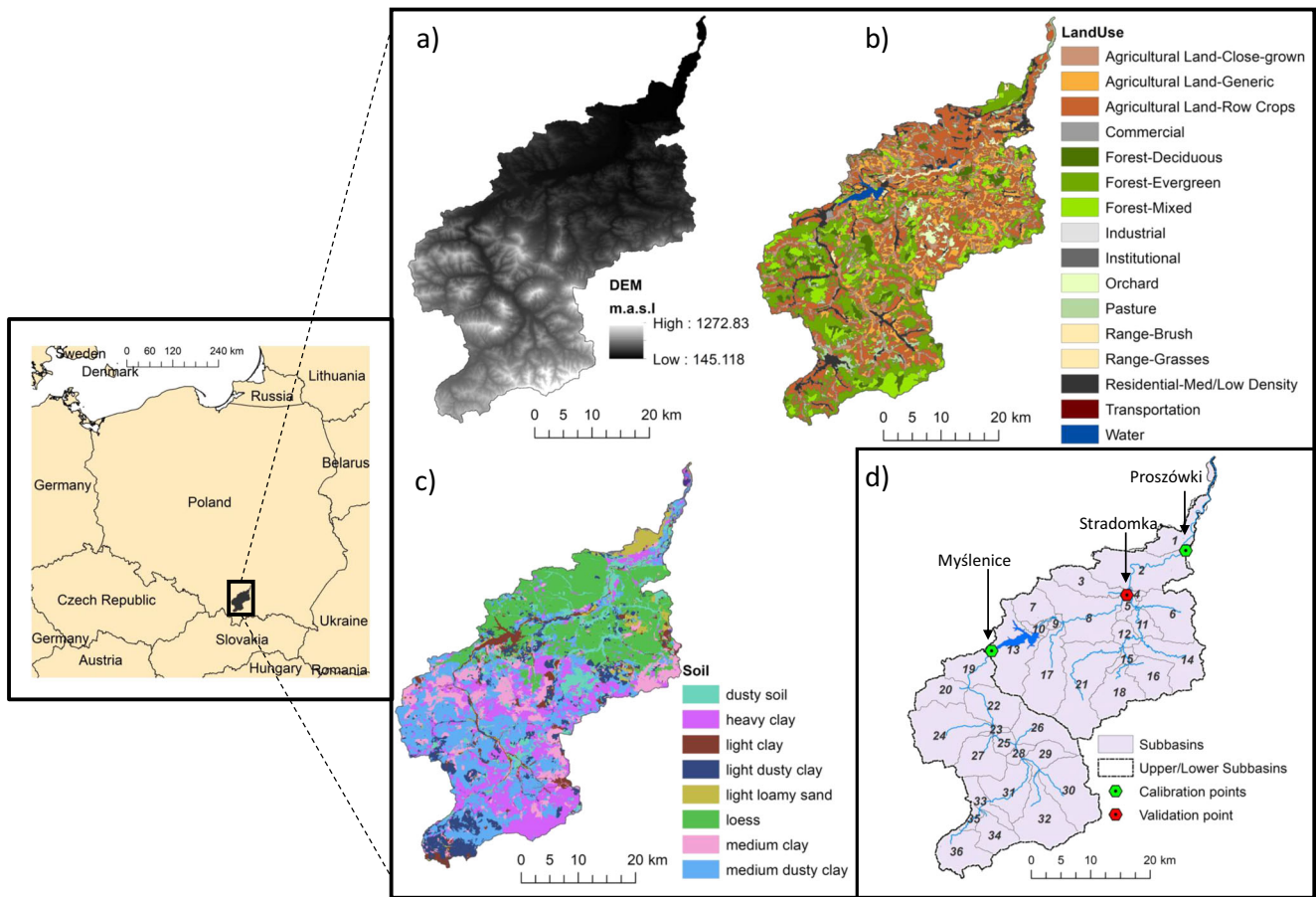


Fig. 1 Location of the Raba River catchment with maps of **a**) slope, **b**) land use, **c**) soil type, and **d**) calculation profiles of Myślenice and Proszówki

SWAT model version 2012 has been used. The Macromodel DNS/SWAT is characterized by a high flexibility and facilitates analyses and illustration of relationships between input and output variables.

Moreover, this Macromodel allows creation of variant scenarios, and investigation of effects caused by the change of one or several parameters in a time perspective. To create the Raba River catchment model the following data have been used:

- map of Poland hydrographical divisions, scale of 1:10,000 (source: IMGW-PIB, resolution: 5 m);
- digital elevation model (DEM), scale of 1:20,000 (source: IMGW-PIB, resolution: 10 m);
- soil map—detailed data on soil types (Table S1, Electronic Supplementary Material—ESM), scale of 1:5000 (source: Institute of Soil Science and Plant Cultivation, resolution 2.5 m);
- land use map—based on Corine Land Cover (CLC 2012), and agrotechnical data from the Local Data Bank (source: Copernicus Programme, resolution 20 m) and;
- meteorological data (1992–2016, e.g., precipitation and temperature) for 75 stations located directly in the catchment, and within 20 km from its borders (source: IMGW-PIB).

To facilitate detailed spatial analysis of the sediment load sources, the studied catchment has been divided into 50 sub-catchments, based on the surface water bodies (SWB) division. To accommodate some modeling needs (large urban areas, dam reservoir, and in-situ tests) selected sub-catchments were modified according to the location of computational profiles.

The SWAT model offers four methods to simulate sediment transport (i.e., Bagnold, Kodoatie, Molinas, and Wu and Yang sand and gravel method). In the current study, the Kodoatie method was chosen because it allows us to analyze sediment load by individual fractions. Moreover, it is considered to be particularly effective for suspended and small sediment particles. This method has been described as an optimized sediment transport equation, using non-linear optimization and field data for different river sediment particle sizes (Kodoatie 2000; Ayaseh et al. 2019).

$$conc_{sed, ch, mx} = \left(\frac{a * v_{ch}^b * y^c * S^d}{Q_{in}} \right) * \left(\frac{W + W_{btm}}{2} \right)$$

Where: $conc_{sed, ch, mx}$ is the maximum sediment concentration ($t\ m^{-3}$); v_{ch} is mean flow velocity ($m\ s^{-1}$); y is mean flow depth (m); S is energy slope ($m\ m^{-1}$); Q_{in} is water entering the

reach (m^3); a , b , c , and d are regression coefficients for different bed materials; W is channel width at the water level (m); and W_{btm} is bottom width of the channel (m).

2.3 Sensitivity analysis, calibration, and validation of the model

The SWAT-CUP (calibration and uncertainty program, Fukunaga et al. 2015) and its SUFI-2 algorithm were employed to perform sensitivity, calibration, and uncertainty analyses of the model runs (Kumar et al. 2017). Sensitivity of parameters was determined with use of a multiple regression model, which regresses the Latin hypercube-generated parameters against an objective function based on defined values for calibrated variables (Abbaspour et al. 2015). Sensitivity analysis results for parameters of flow and sediment are listed in Table S2 (On-line Supplementary Material).

Model calibration and validation were performed with use of the flow data obtained from the IMGW-PIB, and total suspended sediment concentrations from the state monitoring system (Polish Inspectorate of Environmental Protection). Due to the fact that the state monitoring frequency is relatively low (12 times per year), the LOAD ESTimator program (LOADEST) (<https://water.usgs.gov/software/loadest/>) was used to assist in the development of the regression model for reliable estimation of constituent load (calibration). Explanatory variables within the regression model included functions of streamflow, decimal time, and additional user-specified data variables. The formulated regression model then was used to estimate loads over a user-specified time interval (estimation). Mean load estimates, standard errors, and 95% confidence intervals were developed on a monthly and seasonal basis (Krishnan et al. 2018; Lee et al. 2018). Due to the dual character of the Raba River catchment, the calibration process was performed for the two parts of the catchment separately. For the upper part, the catchment calibration was performed in the calculation profile of Myślenice, while the profile of Proszówki was selected for the lower part (Fig. 1d). The results obtained for both profiles were used to calibrate and verify the model.

Validation of the model was performed for the Stradomka River, which is a right-bank tributary of the Raba River and is also subjected to suspended sediment state monitoring measurements. To assess fitness of the model to the monitoring results, four statistical measures, coefficient of determination (R^2), the Nash–Sutcliffe model efficiency coefficient (NSE), percentage of bias (PBIAS), and Kling-Gupta efficiency (KGE) have been used (Patil and Stieglitz 2015; Xing et al. 2018; Da Silva et al. 2018; Libera and Sankarasubramanian 2018). The obtained calibration and validation results for individual statistical measures and time periods are presented in Table S3 and Fig. S1 (On-line Supplementary Material).

2.4 Modeling scenarios

To discuss climate and land use change impact for the sediment load, several variant scenarios have been created for the study area. Their reference point is the baseline scenario (0), which is a simulation of the Raba River model that passed the calibration procedure. To account for the predicted climate changes (precipitation and temperature) for two future time horizons (2021–2050 and 2071–2100) based on RCP4.5, the results of the dynamical downscaling for the area of Poland were taken into consideration (Mezghani et al. 2017; Climateimpact 2019). Accordingly, two precipitation (P1 and P2) and two temperature (T1 and T2) scenarios have been created (Table 1).

The land use scenario (LU) has been based on the results of the FORECOM project (<http://www.gis.geo.uj.edu.pl/FORECOM/index.html>) implemented to improve understanding of past, present, and future forest cover changes in the Swiss Alps and the Polish Carpathians in the context of climate changes. The LU scenario implemented in the current study was based on the DYNA-Clue model for the two Carpathian localities (Szczawnica and Niedźwiedz) for the future time horizon of 2060 (Price et al. 2017). This scenario assumed an increase of forested areas by 16%, and an increase of urban areas by 6%, at the expense of areas used for agriculture. In the SWAT model, land use is one of the pivotal elements for catchment division into the hydrologic response units (HRU), which are the basis of the model's structure and subsequent simulations. The HRUs are defined by lumping similar land use, soil, and slope, and they are not spatially distributed. Therefore, land use changes for the LU scenario were applied using a dedicated function (land use update). This function allowed for dynamic changes during simulation imitating the surface changes for individual types of land use (Marhaento et al. 2017). To assess combined effects of all forecasted changes, final scenarios for the near (COMB1 = P1 + T1 + LU) and far future (COMB2 = P2 + T2 + LU) have been created.

3 Results

Results of the Macromodel DNS/SWAT enabled the sediment load analysis in the Myślenice calculation profile located directly upstream from the Dobczyce Reservoir. The average annual sediment load flowing into the reservoir has been estimated at 2.43 Gg y^{-1} for the baseline scenario (0) (Table 2). Analysis of the temporal variabilities for this load revealed statistically significant differences among season averages ($n = 25$, ANOVA, $p < 0.05$), with the lowest average load share detected in autumn (19%). For the remaining seasons, the average loads constituted 26% of the total values during

Table 1 Median changes (RCP4.5) of precipitation (%) and temperature (°C) for the Myślenice calculation profile for the adopted climate and land use scenarios

		P1 2021–2050	P2 2071–2100	T1 2021–2050	T2 2071–2100
Winter	(Dec–Feb)	9.5	16.74	1.1	2.29
Spring	(Mar–May)	8	15.89	0.84	1.83
Summer	(Jun–Aug)	2.63	1.21	1.01	1.68
Autumn	(Sep–Nov)	2.11	4.25	0.95	1.88

the spring and summer months, and 29% in the winter. For all seasons, a statistically significant relationship between sediment load and precipitation has been detected ($p < 0.02$), with R values ranging from 0.66 to 0.79 for spring, summer, and autumn, and equal to 0.48 for winter. The variability of seasonal loads (Fig. 2) reflects local meteorological phenomena, e.g., occurrences of a snow melt in the winter months of 1993, and 2003 (45% of total load), or occurrence/intensity of precipitation during the summer of 2005 (up to 47% of the total load). Also, the impact of wet/dry years is clearly visible in the temporal sediment load distribution. For instance, 1996, considered as one of the driest years in the analyzed period, noticeably impacted the sediment load at the calculation profile, especially in the winter. In turn, the flood of 2010 contributed to a rapid increase of the sediment load, compared to 2009. In May 2009, 0.1 Gg of sediment, on average, passed through the calculation profile, while in May 2010, this value rose to approximately 1 Gg.

Application of precipitation and temperature scenarios provided an opportunity to assess possible impact of future climate changes on reservoir siltation, which is an issue of key impact since the analyzed catchment is located in an area very prone to erosion. If we assume a hypothetical situation that the future climate will only cause an increase of average annual rainfall level, then such a

change will increase the sediment load flowing into the reservoir by over 8% for the near future scenario (P1), and by over 20% for the far future (P2). Even more pronounced differences in the precipitation impact can be observed when the sediment load has been split seasonally. A similar increase of the winter and spring average values has been detected for the near future scenario (P1, approx. 10%), while the predicted far future change (P2) distinguished the spring load change with an increase by 35% (0.2 Gg per season). Also, the highest variability of the average loads for this season should be observed, with a 5–95 percentile range of 0.77–1.56 Gg. As for the summer and autumn periods, changes of the average sediment loads did not exceed 8% (P2). If only temperature changes occur separately in the future, we could expect a decrease of the annual average sediment loads by approx. 6% for the T1 scenarios, and 3% for the T2 scenario. The decreasing pattern for temperature was detected for all seasons, except for the T2 scenario in winter where the sediment load increased by 6%. The largest sediment load reduction in the range of 11–13% (for T1 and T2, respectively) occurred in spring. In the remaining seasons, sediment load reduction remained under 5%. The land use scenario (LU), resulting in a decrease of the area used for agricultural purposes by 22%, reduced the average

Table 2 Yearly ($Gg\ y^{-1}$) and seasonal ($Gg\ season^{-1}$) average sediment loads for the Myślenice calculation profile under climate and land use change scenarios within the 5–95 percentile range

Scenario		0	P1	P2	T1	T2	LU	COMB1	COMB2
Time horizon		1992–2016	2021–2050	2071–2100	2021–2050	2071–2100	–2060	2021–2050	2071–2100
Year	Mean	2.43	2.63	2.90	2.29	2.35	2.30	2.39	2.72
	Perc. 5–95	1.42–3.96	1.60–3.91	1.80–4.64	1.45–3.80	1.37–4.10	1.34–3.70	1.56–3.90	1.59–4.37
Winter	Mean	0.71	0.78	0.88	0.67	0.75	0.65	0.66	0.87
	Perc. 5–95	0.31–0.85	0.35–0.89	0.40–1.01	0.32–1.08	0.37–1.14	0.30–0.79	0.36–0.93	0.44–1.43
Spring	Mean	0.63	0.70	0.85	0.56	0.55	0.58	0.63	0.73
	Perc. 5–95	0.53–1.21	0.66–1.20	0.77–1.56	0.47–1.10	0.50–1.18	0.51–1.15	0.55–1.20	0.62–1.45
Summer	Mean	0.63	0.67	0.68	0.62	0.62	0.62	0.65	0.65
	Perc. 5–95	0.24–1.32	0.27–1.27	0.28–1.36	0.21–1.34	0.19–1.57	0.23–1.27	0.23–1.42	0.22–1.45
Autumn	Mean	0.45	0.47	0.48	0.43	0.43	0.44	0.45	0.46
	Perc. 5–95	0.22–0.90	0.23–0.95	0.24–0.94	0.21–0.87	0.21–0.87	0.22–0.87	0.22–0.88	0.23–0.93

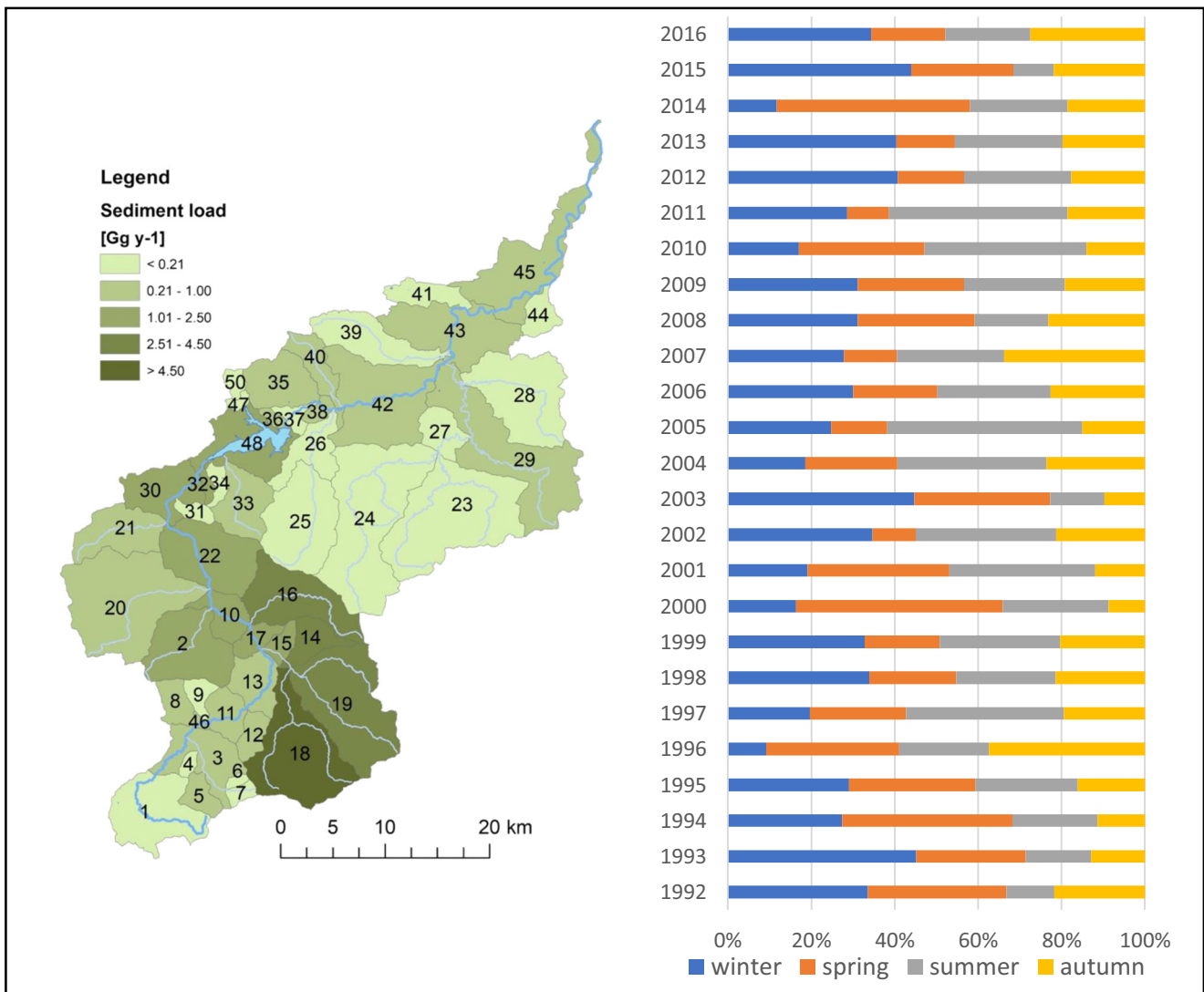


Fig. 2 Sub-catchment sediment loads and seasonal sediment pattern for the Raba River baseline scenario for the Myślenice calculation profile

yearly sediment load by approximately 5%. Seasonal differences for LU were uniform for winter and spring (approx. 8%) and for summer and autumn (approx. 2%).

However, since the predicted changes most probably will occur simultaneously in the catchment, the cumulative effect of the scenarios should be taken into consideration. Therefore, by combining corresponding scenarios for the adopted time horizons (P1 + T1 + LU, and P2 + T2 + LU), two combined scenarios have been created (COMB1 and COMB2). The near future predictions (COMB1) resulted only in a slight decrease of the yearly average load in the calculation profile by 2%. A similar trend was followed by the seasonal average loads, with the exception for the summer period, when an approx. 3% increase was observed. For the far future scenario (COMB2), a sediment load increase for the yearly and seasonal average values was detected, from 2% for the autumn period, up to 23% in the winter months.

Despite the fact that the study focused on the sediment load delivered into the dam reservoir, the other computational profiles located in the catchment have been also investigated. Since most of the Carpathian catchments are subjected to intense erosional processes, planning of the mitigation action must be effective and very precise. The use of the Macromodel DNS/SWAT enabled spatial analysis of the sediment load sources distributed in all Raba River sub-catchments (Fig. 2). The baseline scenario for the Raba River revealed sub-catchments with the highest sediment load, exceeding 2.5 Gg y^{-1} . All of them (Nos. 18, 19, 14, and 16) are located in the upper part of the catchment and are characterized by large averages slopes (28.5%, 22.6%, 18.7%, and 20.9%, respectively), and intensive precipitation (approx. 1400 mm y^{-1}). Particularly interesting is sub-catchment No. 18, releasing over 4.5 Gg y^{-1} of sediment, which has slopes of the highest elevation peak in this region (Turbacz, 1310 m a.s.l.).

4 Discussion

Estimation of sediment loads released from catchments has a long tradition and is crucial for various ecological and technical perspectives, especially in catchments heavily affected by anthropogenic activity (Fox et al. 2016; Walling 2017). Currently, such estimations are generally performed with use of modeling tools, enabling them to provide fairly accurate predictions, and to delineate areas contributing the most to the total sediment load (Liu et al. 2015; Nguyen et al. 2019). The sediment load variability has been investigated for the Myślenice profile localized in the direct vicinity of the river outlet to the dam reservoir (Dobczyce). Since this reservoir is supplied mostly by the Raba River (approx. 90% of total inflow), this profile can be considered as representative of the sediment loads delivered from the upper part of the catchment. According to the baseline scenario (0), based on a quarter century observation (1992–2016), 2.43 Gg y⁻¹ of sediment on average passes through this calculation profile, and this value remains in concordance to the results of other studies (Drzewiecki and Mularz 2008). The range of the sediment loads in this profile is very broad (1.42–3.96 Gg y⁻¹) and generally follows the occurrence of dry (1992–1996) and wet (2005, 2010, and 2014) years (Fig. 3). Moreover, an impact of precipitation regimes can be tracked from the

Macromodel results. The two highest sediment loads were recorded in 2005 and 2010 (3.9 and 3.1 Gg y⁻¹, respectively), which were the years with exceptional rainfall. The total yearly sum of precipitation reached over 1275 mm in 2005, while in 2010, which was the year that had the biggest floods in Poland, surpassed 1800 mm. The lowest sediment load was detected in 1993 (1.31 Gg), when the total rainfall remained under 1000 mm. In August 2014, the occurrence of short-term but very heavy rainfalls (with average hourly intensity above 40 mm h⁻¹) in the analyzed area (Bryndal et al. 2017) was responsible for a significant sediment load increase, reaching up to 0.8 Gg m⁻¹ (Fig. 3).

Analysis of the temporal patterns revealed winter as the most important sediment delivery season. Although this period (December–February) is not abundant with precipitation, the occurrence of atypical high rainfall events have been observed in this area during the winter months, during so-called anomalously wet seasons (AWS) (Cebulska and Twardosz 2014). Also, a decrease of snowfall and an early snow melt have to be considered very important factors increasing total loads during winter seasons in this region (Stryker et al. 2018). Available meteorological data (source: IMGW-PIB) clearly show a gradual shortening of periods with air temperatures below 0 °C and snow cover. These phenomena combined with lack of vegetation cover could largely enhanced soil particle

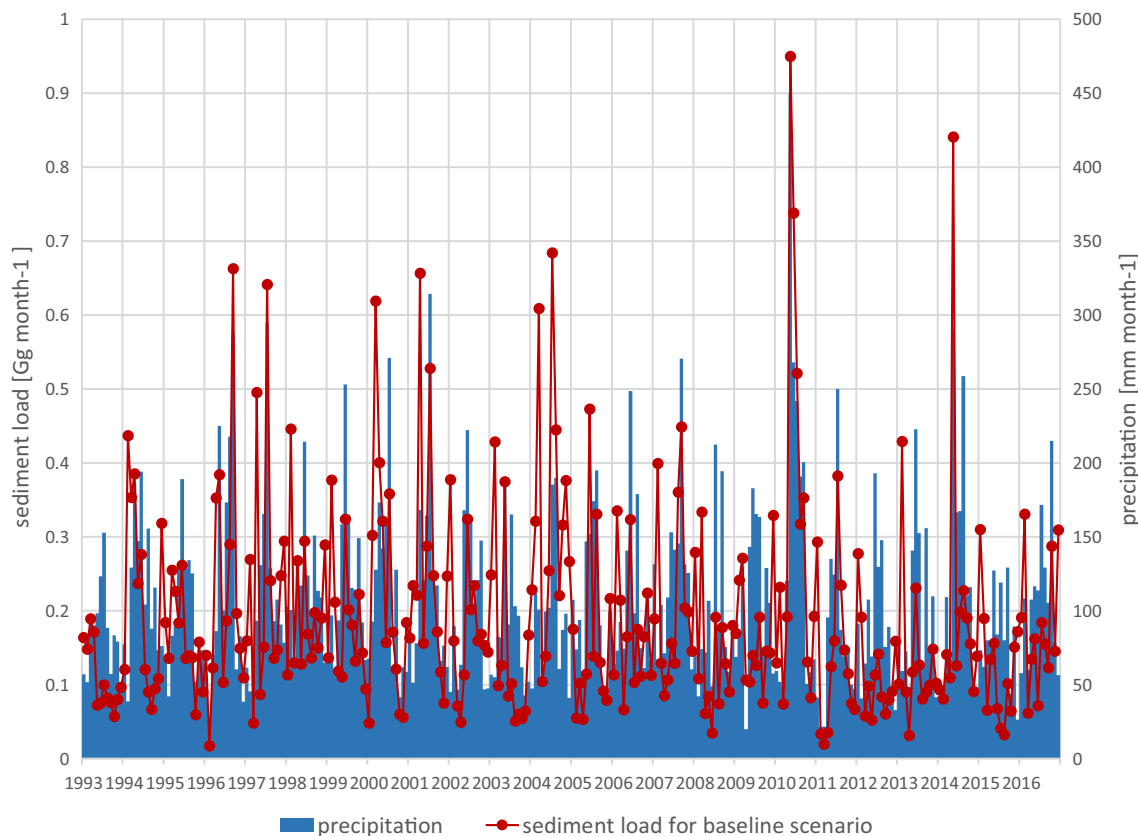


Fig. 3 Temporal distribution (1992–2016) of sediment loads (Gg month⁻¹) with respect to precipitation (mm month⁻¹) for the Myślenice calculation profile

transport from the catchment to the receiving water body. The lowest sediment loads were generally detected during autumn (September–November), which is typically considered as dry and as a low flow season for the Carpathian watercourses (Jokiel and Tomalski 2017).

The relationship between sediment load and precipitation is even more visible when climate changes are being discussed. This is particularly important for this catchment area since the precipitation pattern in the Carpathian region already differs from the values adopted for the rest of the country, exceeding the Polish average value (600 mm) by 60–150%. The increased values of precipitation imposed on the baseline Raba River model (0) under the adopted climate scenarios (P1 and P2) resulted in a further increment of the sediment loads by almost 0.20 Gg y^{-1} in the near and 0.48 Gg y^{-1} in the far future simulations. Since the forecasted precipitation changes clearly amplify the seasonal variability (Table 1), even bigger sediment loads could be introduced to the reservoir during the winter and spring periods.

Nonetheless, the opposite decreasing trend of sediment loads should be considered when temperature and land use changes are taken into consideration. The local temperature growth predictions, estimated on average at 1°C for the near and at 2°C for the far future simulations for this area, are considerably lower than the values adopted in similar studies (Tasser et al. 2017; Zhou et al. 2017). The modeling results revealed a considerable drop of sediment load between 0 and T1 scenarios (approx. 0.14 Gg y^{-1} on average), however, the increased temperature growth by 1°C (T2) produced a relatively low change of 0.08 Gg y^{-1} (Table 2). To elucidate this issue, several additional variant scenarios were run to simulate a gradual change of temperature (Fig. 4).

The obtained results suggest that the initial temperature change by 0.25°C in the Macromodel DNS/SWAT already

resulted in a sudden decrease of yearly average sediment load (approx. 0.1 Gg y^{-1}). This initial drop of sediment load is most likely caused by the SWAT model specificity and its sensitivity to even small changes of the variant parameters. Although a plethora of studies have reported a temperature impact on sediment loads (Bussi et al. 2016; Ahilan et al. 2018), such results have never been reported before, which suggests that this issue must be further investigated. The following values, up to the temperature rise of 2°C (T2), showed only slight variability, in the range of 3–6% of the T0.25 sediment load value. This load stabilization phenomena suggests that the forecasted temperature changes below 2°C have an insignificant influence on the sediment load in the analyzed profile, while the subsequent increase of temperature (T2.5–T4) will cause a tangible decrease of sediment loads in the catchment. Temperature rise is supposed to change evapotranspiration and extend the vegetation season, and thus retain plant cover thereby decreasing overall rainfall erosion for longer periods (Routschek et al. 2014). However, this may also cause water depletion in the catchment (Lu et al. 2013) and induce faster snowmelt, which can hypothetically result in higher erosion (Zhou et al. 2017). Therefore, it is strongly recommended that modeling studies should focus on different geographical settings of the studied catchments.

The Macromodel DNS/SWAT also revealed sub-catchments particularly prone to sediment release (Fig. 2). Generally, the Raba River catchment is strongly exposed to erosional processes, controlled mainly by land slope, soil characteristics, and land use. The upper part of the studied area features very high slopes (average of 23%), and despite predominant forest land cover (50% of the upper Raba River catchment), is highly prone to sediment release. Moreover, the sub-catchments with elevated sediment load proportions (Nos. 18, 19, 14, and 16; Fig. 2) are abundant within agricultural

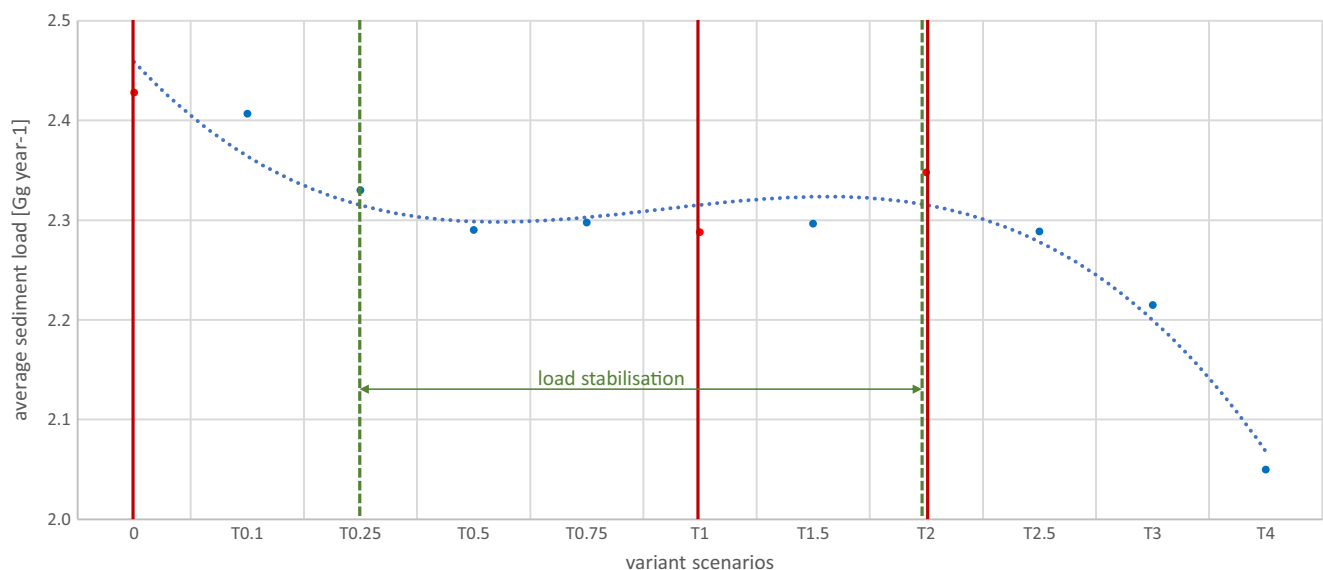


Fig. 4 Variability of sediment loads (Gg y^{-1}) for the Myślenice calculation profile for temperature change scenarios (T0.1–T4)

lands (40%), with fields located on the lower slopes. The lower part of the catchment (downstream from the reservoir) is mainly used for agricultural purposes (63% of the area of the lower Raba River catchment). Therefore, its soil erodibility factor is generally higher than in the upper part (dominant USLE-k factor for the lower Raba River catchment—0.2, for the upper part—0.14), however, the significantly lower slope angles (average of 12%) result in a lower intensity of erosion.

As for the predicted land use and land cover changes, refrainment from agricultural activities in the mountainous regions and gradual reforestation of the abandoned areas has already been observed in some regions (Price et al. 2017; Tasser et al. 2017). Moreover, due to socio-economic changes, areas used for agriculture are gradually being transformed and used for non-agricultural purposes, including residential, construction, or service facilities (Verburg et al. 2008; Bucała-Hrabia 2017a, b; SzwaGrzyk et al. 2018). Such changes may have contradictory impacts on the formation of runoff, and therefore for the sediment delivery from the catchment. Concurrently, the forest expansion attenuates runoff (e.g., due to retention increase), while urbanization increases it (e.g., due to the increase of impermeable areas) (Tellman et al. 2015). However, given the extent of the predicted changes (decrease of areas used for agriculture by 16%), the general outcome of the adopted land use scenario (LU) will result in a decrease of the sediment loads by approximately 0.16 Gg y^{-1} on average.

As presented above, changes of individual climate and land use parameters can result in opposing sediment load trends. Therefore, superimposed precipitation, temperature, and land use predictions are taken into consideration. The combined near future (2021–2050) predictions for the upper Raba River catchment (COMB1) exhibited a decrease of sediment load introduced into the reservoir (by approx. 0.13 Gg y^{-1}). This result stems from the predicted land use changes mitigating soil erosion, and therefore, decreasing sediment delivery (Routschek et al. 2014). The far future scenario (2071–2100, COMB2) will possibly bring an increase of sediment delivery by 0.29 Gg y^{-1} on average. This increase can be attributed to a high percentage of precipitation increase predicted in the winter and spring months for this time horizon.

5 Conclusions

For the first time, a detailed modeling study of the impact of changes in climate and land use on sediment loads has been undertaken for a Carpathian catchment. The total loads estimated for the profile representing sediment delivery to the dam reservoir exhibited seasonal/annual variability related to the occurrence of local meteorological phenomena. These predictions of sediment accumulation rate and remaining

reservoir capacity are particularly important for reservoir management in the context of sedimentation mitigation planning. The near (2021–2050) and far (2071–2100) future climate change predictions revealed a strong direct correlation of the sediment loads with precipitation increase. However, the aforementioned temperature impact requires particular attention, and further studies on this relationship with sediment loads must be carried out. Since the temperature change by 1–2 °C resulted in sediment loads decrease by about 5%, a temperature change above 2 °C caused a decrease in the range of 16%.

In the combined future scenarios, land use exerted the highest impact on sediment loads, which indicates that proper mitigation measures for erosion must be planned for this catchment. However, the question is whether it can be assumed that land use changes, especially enlargement of forest cover, can effectively stop the negative effects of climate changes in mountainous areas affected by water erosion. Regarding this issue, an interesting observation has been made in conjunction with the combined scenarios. For the COMB1 scenario, sediment loads changed by 2% which indicates that the effects of precipitation, temperature, and land use change balance each other, which is a key conclusion for reservoir management. This indicates that reservoirs located in a mountainous region will be refractory to some extent in the near future to the effects of climate change in the context of sediment load. In the long-term predictions (COMB2), a large increase of sediment load caused by rainfall increase will no longer be offset by a sediment load decrease resulting from the temperature and land use changes. Therefore, anti-erosion actions should be planned for in the future and their cost implemented in the perspective management plans. In a mountainous catchment, afforestation is considered as one of the most effective techniques preventing erosion (Buendia et al. 2016; Kim et al. 2017). Currently, a policy promoting afforestation is pursued both in Poland and throughout the EU. This is especially beneficial for farmers with poorer land quality in regions with severe climatic conditions, such as these in the Raba River catchment. In such cases, farmers who decide to pursue afforestation of their land can benefit from special subsidies. If these activities are continued, it can be expected that the forecasted growth of the forest area forms the LU scenario and will remain realistic. However, it is also important to remember that forest age plays an important factor in protection of soils from erosion. Soil in agricultural areas freshly transformed into forest has higher susceptibility to erosion compared to old forest areas (Yesilonis et al. 2016). It is also important to remember that not only the magnitude of sediment load is important for dam reservoirs but also the analysis of individual sediment size fractions that flow into the reservoir. It is mainly smaller fractions (i.e., clay and silt) that transport the largest amount of pollution such as heavy metals or biogenic compounds. It is these fractions that dominate the

upper Raba River catchment, constantly posing a threat to the quality of water in the reservoir, and possibly to the people that use this water source for drinking purposes.

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