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Contemporary suspended sediment yield of Caucasus mountains

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Abstract. Processes linked to climate change and intensified anthropogenic pressure influence the environment, the hydrology and by extent the denudation processes in the Caucasus mountain belt. Quantitative assessments of sediment fluxes and their temporal evolution in this mountain region are required for various environmental and engineering purposes, including the planning and maintenance of water reservoirs and other structures. In this paper, we present a first analysis of the hitherto largest suspended sediment yield (*SSY*) database for the Caucasus region, comprising data from 198 catchments (>4000 catchment-years of observations). We present an overview of the existing contemporary *SSY* data from gauging stations observations. Based on these data and different models, we propose preliminary maps of the spatial patterns of *SSY* and denudation rates in the Caucasus region.

1 Introduction

Denudation rates in the mountains are controlled by both endogenic and exogenic factors. Endogenic factors include the degree of tectonic uplift and seismic activity and are typically considered to be the dominant driving force of denudation rates in tectonically active mountain ranges (e.g. Malamud et al., 2004; Montgomery and Brandon, 2002). Nonetheless, also exogenic factors play a crucial role. These include climatic conditions and vegetation cover (e.g. Syvitski and Milliman, 2007). They are especially key factors to understand temporal trends in sediment fluxes and denudation rates at contemporary time scales.

The Caucasus mountains are a highly tectonically and seismically active region, resulting most probably in high long-term denudation rates. At the same time, patterns and trends of climate and vegetation cover likely also exert significant control on suspended sediment yields (*SSY*, [$\mathrm{t\,km^{-2}\,yr^{-1}}$]) at annual to decadal timescales. Disentangling the role of tectonic and geomorphic controls *SSY* from the role of climate and land cover is a central challenge (e.g. Syvitski and Milliman, 2007; Vanmaercke et al., 2015). This is not only of fundamental scientific importance but also of great relevance from a catchment and water resources management perspective (e.g. for the construction and maintenance of water reservoirs). This challenge is especially pertinent in the light of ongoing climate change and increasing anthropogenic pressure (including land use/land cover changes).

A key obstacle in addressing this research challenge is the availability of sufficient and reliable *SSY* observations in order to statistically discern the relative importance of its different driving factors (e.g. Vanmaercke et al., 2011, 2015). Here we aim to help addressing this gap by quantitatively assessing the spatial patterns of contemporary *SSY* in the Caucasus region, based on a large dataset of gauging stations observations from mid the 1920 to 2015.

2 Materials and methods

A large number of studies focussed on compiling and understanding patterns of *SSY* at regional to global scales. Several of these also consider (parts of) the Caucasus region (Dedkov and Moszherin, 1984, 1992; Jaoshvili, 2002; Milliman and Syvitski, 1992; Vanmaercke et al., 2011). We developed a comprehensive database of contemporary *SSY* observations for the Caucasus mountains by integrating these existing datasets and complementing them with hydrological observations at gauging stations in the Russian Federation (State Water Cadastre; https://gmvo.skniivh.ru/, last access: 19 June 2019) as well as *SSY* observations for specific catchments reported by individual studies (Abduev, 2015; Eyubova, 2015; Khmeleva et al., 2000; Magritskii, 2011).

Given that these observations were derived from different sources, also the reliability of the resulting *SSY* varies. This reliability depends on the measuring procedure and especially the sampling frequency (e.g. Moatar et al., 2006). However, also the length of the *SSY* observation periods is an essential factor. Vanmaercke et al. (2012) showed that uncertainties on average *SSY* values based on a short measuring period (1–5 years) due to inter-annual variations in sediment yield are typically at least as large as the uncertainty relating to the measuring period. Moreover, such average *SSY* values are relatively more likely to underestimate the actual average *SSY* (Vanmaercke et al., 2012). Given these concerns, we only considered catchment *SSY* values from direct gauging station (*GS*) observations with a measuring period (*MP*) of at least 10 years.

In total, our Caucasus database comprised *SSY* observations for 198 catchments. An overview of the data is given in Table 1, while the temporal coverage of the database is shown in Fig. 1. The sum of all *MP*s yields a total of 4011 catchment-years of observations. However, for several entries from Dedkov and Moszherin (1984) start and end date was unknown. We assumed a value of 10 years for such entries. With respect to catchment sizes, 17 *GS*s have a catchment area $<100\,\mathrm{km}^2$, 101 *GS*s have a catchment area between 100 and $1000\,\mathrm{km}^2$, 64 between 1000 and $10\,000\,\mathrm{km}^2$, and 16 have a catchment area $>10\,000\,\mathrm{km}^2$ (see Fig. 2).

Overall, SSY values ranged between 3.6 and $4100\,\mathrm{t\,km^{-2}\,yr^{-1}}$, with an average value of $442\,\mathrm{t\,km^{-2}\,yr^{-1}}$ and a median of $197\,\mathrm{t\,km^{-2}\,yr^{-1}}$. Two catchments in our database had an exceptionally low *SSY* value (respectively 3.6 and $3.9\,\mathrm{t\,km^{-2}\,yr^{-1}}$). These two catchments were located in the submontane zone of Azerbaijan and Armenia. Given that these *SSY* are clearly lower than what can be expected for this kind of environments (e.g. Vanmaercke et al., 2011) and the reliability of these observations could be questioned, these two observations were not considered for further analyses. According to a Shapiro-Wilks test, the SSY observations are log-normally distributed. All further analyses were therefore conducted on the $\log_{10}$ of the *SSY*.

In order to visualize and better understand the patterns of *SSY* in the Caucasus, we used several methods to spatially interpolate $\log_{10}$ (*SSY*). These included Ordinary Kriging (*OK*), Co-Kriging with an elevation as a co-variable (*CK-h*) and Co-Kriging with a Mean Local Relief as a co-variable (*CK-mlr*), *k*-nearest neighbors (*KNN*) and *k*-nearest neighbors with a co-variable (*KKN-h, KKN-mlr*). *OK*, *CK*, *CK-h* and *CK-mlr* were performed with the R package *automap* (Hiemstra et al., 2009), *KNN*, *KKN-h*, and *KKN-mlr* with the

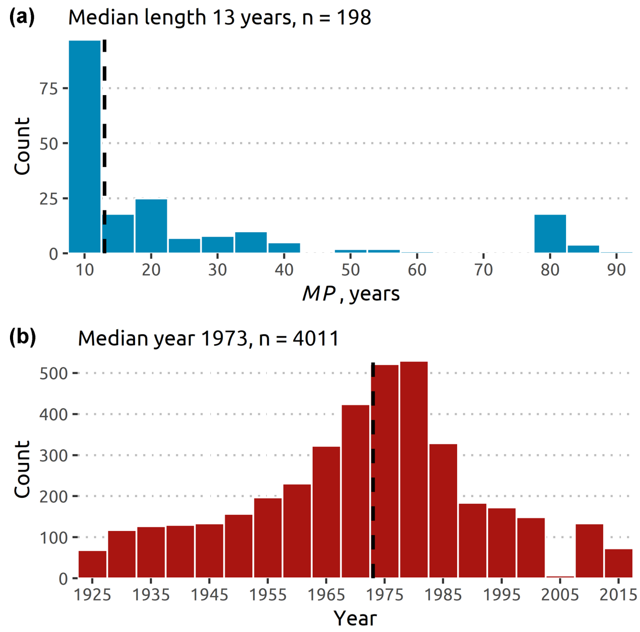

Figure 1. Temporal coverage of the Caucasus *SSY* database. A: distribution of the measuring periods for which gauging station *SSY* observations are available. B: amount of catchment-year *SSY* data available per 5-year period.

R package *kknn* (Schliep and Hechenbichler, 2016). Elevation (H, [m]) and Mean Local Relief (*MLR*, [m]) were chosen as an auxiliary variables due to their expected correlation with *SSY* (Ahnert, 1970; Milliman and Syvitski, 1992; Montgomery and Brandon, 2002). Elevation data was accessed with the *elevatr* package (Hollister and Tarak Shah, 2017) in *R*. *MLR* was calculated as a difference between maximum and minimum H within a 10 km buffer as it was suggested by Montgomery and Brandon (2002). We randomly split our database into two datasets: one for training and one for validation (Table 2).

The performance of these interpolations was assessed based on the root mean square error (*RMSE*), the mean error (*ME*), the Nash–Sutcliffe efficiency (*NSE*; (Nash and Sutcliffe, 1970), the coefficient of determination (R^2) and Spearman's coefficient of correlation (r).

To assess the total sediment load of the Caucasus, the sediment export of a catchment (*SSL*, $\mathrm{t\,km^{-2}\,yr^{-1}}$) was calculated as:

$$SSL = SSY \cdot A, \tag{1}$$

with: A – the catchment area [km^2]. If there were several *GS* at one river we considered the most downstream station (with the largest catchment area) for calculating *SSL*. For the ungauged basins we made estimate based on our interpolation. We calculate an average *SSY* for every ungauged basin draining to the exit of our study area and multiply this with the size of the basin in order to have an estimate of the *SSL*. To

Table 1. SSY database overview (with outliers).

Country	Number of catchments (catchment – years)	Data sources
Abhazia (part of Georgia)	6 (54)	Khmeleva et. al. (2000), Dedkov and Mozherin (1984)
Armenia	25 (NA)	Dedkov and Mozherin (1984)
Azerbaijan	54 (466)	State water cadastre; Eyubova (2015), Abduev (2015)
Georgia	22 (NA)	Dedkov and Mozherin (1984)
Russia	91 (3491)	Magritskii (2011); State water cadastre;
TOTAL	198 (4011)	
		https://gmvo.skniivh.ru/ (last access: 19 June 2019)

NA: not available.

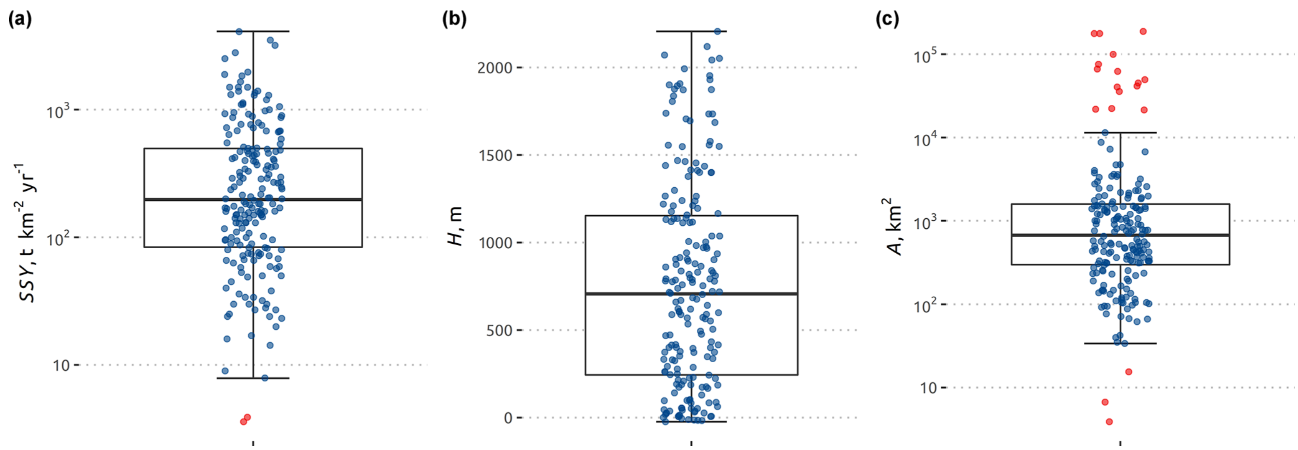

Figure 2. Distribution of *SSY* observations in our database **(a)** and boxplots of elevations of the gauging stations **(b)** and their catchment areas **(c)**.

define basin borders for the ungauged watersheds we used HydroBasins level 5 (Lehner and Grill, 2013).

3 Results

The results of the six interpolation methods (*OK*, *CK-h*, *CK-mlr*, *KNN*, *KNN-h*, *KNN-mlr*) are shown in Table 3. Overall, these results show that observed *SSY* values are strongly spatially correlated. As such, about 70 % of the observed spatial variation in *SSY* can be estimated based on a spatial extrapolation of observations from other *GS*. This is shown by both the *KNN* and *OK* approach. Adding the considered co-variable (elevation or Mean Local Relief) slightly improves the prediction quality, but also significantly changes the simulated spatial pattern of *SSY*. The *CK* approach shows the best training results in terms of *NSE*, R^2 and *r* values but clearly performs worse in terms of validation. The *KNN-h* approach shows the smallest difference between training and validation metrics: both *NSE* and R^2 are above average. Moreover, *KNN-h* has the best results for validation. We, therefore, considered *KNN-h* as the optimal approach to assess the spatial variation of *SSY* in the Caucasus region. Figure 3 illustrates the simulated spatial distribution of *SSY* and elevation.

Overall, mean *SSY* values are higher in the northern part of the Caucasus (504 t km^{-2} yr^{-1}) are higher than for the southern part (396 t km^{-2} yr^{-1}). The difference is significant and not related to differences in altitude (Fig. 3). Furthermore, *SSY* values are very low (< 50 t km^{-2} yr^{-1}) in most of Armenia and Azerbaijan, especially in the highland steppic zone. On the other hand, the highest values of *SSY* (> 1000 t km^{-2} yr^{-1}) are observed in the Dagestan steppes (eastern part of the Caucasus). Furthermore, *SSY* values are significantly higher in the high mountain belt of the central part of Caucasus. This is likely due to the presence of glaciers and the sparse vegetated cover in these headwater catchments.

We estimated that the total measured suspended sediment load (*SSL*) from rivers draining the Caucasus Mountains is about 98 Mt yr^{-1}. This value is based on direct measurements from 196 *GS*, which covers 61 % of the total area of

Table 2. Ranges and characteristics of the observed suspended sediment yields and the generated training and validation datasets (without outliers).

	Number of catchments	SSY_{min}, $t\,km^{-2}\,yr^{-1}$	SSY_{max}, $t\,km^{-2}\,yr^{-1}$	SSY_{mean}, $t\,km^{-2}\,yr^{-1}$	SSY_{med}, $t\,km^{-2}\,yr^{-1}$	SD
Train	156	7.9	4100	470	204	660
Validation	40	17	1650	354	164	400
TOTAL dataset	196	7.9	4100	446	200	620

Table 3. Performance measures of the different tested interpolation methods (see text for further details).

Model	Type	RMSE	ME	NSE	R^2	r
KNN	Train	0.31	0.0055	0.7	0.69	0.84
	Validation	0.27	−0.033	0.7	0.7	0.87
OK	Train	0.24	0.00056	0.81	0.81	0.91
	Validation	0.27	−0.046	0.69	0.68	0.86
KNN-h	Train	0.3	−0.0076	0.71	0.7	0.85
	Validation	0.26	−0.013	0.72	0.71	0.84
CK-h	Train	0.24	−0.0002	0.82	0.82	0.91
	Validation	0.27	−0.046	0.7	0.69	0.84
KNN-mlr	Train	0.3	0.00036	0.72	0.71	0.86
	Validation	0.29	−0.068	0.65	0.66	0.83
CK-mlr	Train	0.23	−0.0008	0.83	0.83	0.92
	Validation	0.28	−0.05	0.68	0.67	0.86

the study area. *SSL* of the ungauged part of the Caucasus is $50\,Mt\,yr^{-1}$ (based on the *KNN-h* interpolation).

4 Discussion

The *SSY* database presented in this article is the hitherto largest in its kind. Overall, *SSY* estimates for Caucasus rivers remain relatively scarcely reported in scientific literature. Overall, the average *SSY* of our database ($446\,t\,km^{-2}\,yr^{-1}$) corresponds very well to the average *SSY* reported for catchments in Alpine zones in Europe ($451\,t\,km^{-2}\,yr^{-1}$; Vanmaercke et al., 2011).

We also compared our findings with earlier estimates of denudation rates in the Caucasus. One of the first assessment was made by Gabrielyan (1971), who reported a mean annual denudation rate of Caucasus of $0.2\,mm\,yr^{-1}$. Mozzherin and Sharifullin (2015) estimated that mean annual denudation rates in the Caucasus range between 0.005 and $2.32\,mm\,yr^{-1}$. They calculated denudation rates (h_c, [$mm\,yr^{-1}$]) using the following formula:

$$h_c = \frac{SSY}{2.65} \cdot 10^{-3}, \quad (2)$$

To compare the results of our database with these previous findings, we converted our *SSY* values to h_c using the same equation. As such, the mean denudation rate for the Caucasus region based on our database is $0.17\,mm\,yr^{-1}$ with a maximum h_c of $1.55\,mm\,yr^{-1}$. As indicated by Fig. 4, the spatial patterns of our database correspond relatively well with those estimated by Mozzherin and Sharifullin (2015). The main difference between their and our estimates occurs in the center of the Caucasus (Georgia). The density of *GS* is scarce in this region and, as such uncertainties are especially important in this part of the study area. Areas having a relatively low denudation rate (e.g. $h_c < 0.1\,mm\,yr^{-1}$) agree well for both approaches. However, areas with a high h_c ($> 0.25\,mm\,yr^{-1}$) occupy 31 % of the study region according to our assessment and only 18 % according to (Mozzherin and Sharifullin, 2015). These differences are likely attributable to different measuring periods, differences in interpolation methods, as well as the larger amount of observations used in our study. As such, we believe that our assessment provides a refinement of the earlier estimated spatial patterns of *SSY* for the Caucasus region. Nonetheless, further improvement remains possible. As a next step, we aim to include additional relevant variables (e.g. relating to land cover, climatic conditions, lithology and soil characteristics, topography, tectonics and seismicity) in our assessment of *SSY*. This may not only improve our understanding of spatial and temporal patterns of *SSY* but will also help in disentangling the relative impor-

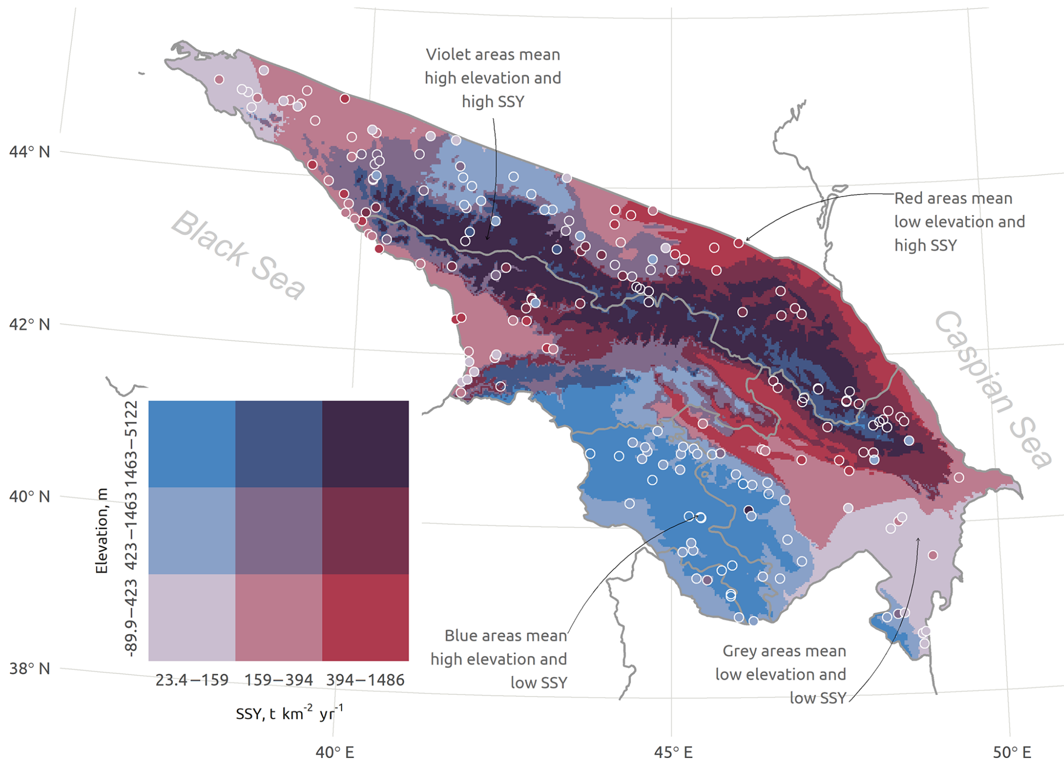

Figure 3. Elevation (H, m a.s.l.) and average annual Suspended Sediment Yields (SSY, $\mathrm{t\,km^{-2}\,yr^{-1}}$) as estimated based on our SSY database.

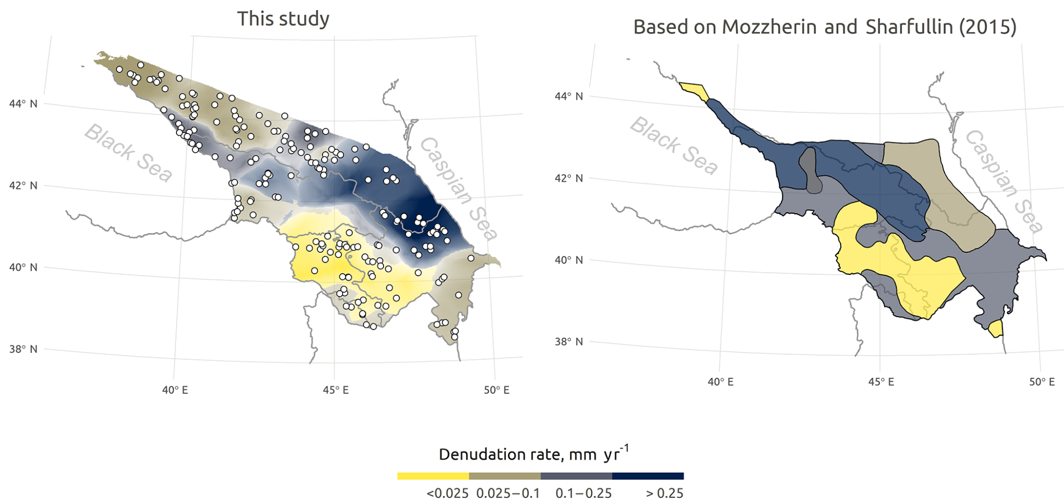

Figure 4. Spatial patterns of estimated average denudation rates for the Caucasus ($\mathrm{mm\,yr^{-1}}$) and comparison with the estimates of Mozzherin and Sharifullin (2015).

tance of endogenic and exogenic drivers of catchment-wide denudation.

5 Conclusions

In this paper, we presented the hitherto largest SSY database for the Caucasus region as well as some first explorative analyses of the spatial patterns of SSY. We found that Caucasus SSY values are similar in range and average to those of catchments in European alpine climatic zones. Observed SSY values are strongly correlated in space, allowing a reasonable assessment of spatial patterns of SSY based on a geographical interpolation of GS observations. Adding information on elevation further improved the accuracy of our simulations. This methodological approach in combination with the hitherto largest *SSY* dataset allowed to make an updated assessment of spatial patterns of *SSY* in the Caucasus (Fig. 3).

Data availability. Reproducible R code is available at the GitHub repository (https://github.com/atsyplenkov/caucasus-sediment-yield) (Tsyplenkov et al., 2019). Contact Anatoly Tsyplenkov (atsyplenkov@gmail.com) for more information.

Author contributions. VG, AT conceived and designed the research; AT performed the experiments and analyzed the data; AT, VG and MV wrote and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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