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Agricultural intensification vs climate change: What drives long-term changes of sediment load?

Shengping Wang[1,2,3*], Peter Strauss[2], Carmen Krammer[2], Elmar Schmaltz[2], Borbala Szeles[3,4], Günter Blöschl[3,4]

1. *College of Hydraulic and Hydro-Power Engineering, North China Electric Power University, Beijing, 102206, P.R.China*
2. *Institute for Land and Water Management Research, Federal Agency for Water Management, A-3252 Petzenkirchen, Austria*
3. *Institute of Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Vienna, Austria*
4. *Vienna Doctoral Programme on Water Resource Systems*

***Corresponding author**: Shengping Wang

Email: wangshp418@126.com; Shengping_Wang@ncepu.edu.cn

Abstract: Climate change and agricultural intensification are expected to increase soil erosion and sediment production from arable land in many regions. However, so far, most studies have been based on short-term monitoring and/or modeling, making it difficult to assess their reliability in terms of long-term changes. We present the results from a unique data set consisting of measurements of sediment loads from a 60ha catchment (the HOAL Petzenkirchen in Austria) over a time window spanning 72 years. Specifically, we compare Period I (1946-1954) and Period II (2002-2017) by fitting sediment rating curves for the growth and dormant seasons for each of the periods. The results suggest a significant increase in sediment yield from Period I to Period II with an average of 11.6±10.8 ton·yr^{-1} to 63.6±84.0 ton·yr^{-1}. The sediment

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flux changed mainly due to a shift of the sediment rating curves (SRC), given that the annual streamflow varied little between the periods (5.6 $l{\cdot}s^{-1}$ and 7.6 $l{\cdot}s^{-1}$, respectively, on average). The slopes of the log regression lines of the SRC for the growing season and the dormant season of Period I were 16.72 and 4.9, respectively, whilst they were 5.38 and 1.17 for Period II, respectively. Climate change, considered in terms of rainfall erosivity, was not responsible for this shift, given that erosivity decreased by 30.4% from the dormant season of Period I to that of Period II, and no significant difference was found between the growing seasons of Periods I and II. However, the sediment flux changes can be explained by changes in crop type and parcel structure. During low and median streamflow conditions (*i.e.* $Q < Q_{20\%}$), land consolidation in Period II (*i.e.* theparcel effect) did not exert an apparent influence on sediment production. Whilst with increasing stream flow ($Q > Q_{20\%}$), parcel structure played an increasingly role in sediment yield contribution, and leading to a dominant role due to enhanced sediment connectivity in the landscape at extremely high flow conditions (*i.e.* $Q > Q_{2\%}$). The increase in cropland in Period II at the expense of grassland had an unfavourable effect on sediment flux, independent of streamflow, with declining relevance as flow increased. We conclude that both land cover change and land consolidation should be accounted for simultaneously when assessing sediment flux changes. Especially during extremely high flow conditions, land consolidation substantially alters sediment fluxes, which is most relevant for long-term sediment loads and land degradation. Increased attention to improving parcel structure is therefore needed in climate adaptation and agricultural catchment management.

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Keywords: **Sediment regime; Land use/cover change; Parcel structure; Climate change; Agricultural catchment**

Introduction

Soil erosion is a risk of worldwide importance because of its environmental and economic consequences (García-Ruiz, 2010; Prosdocimi et al., 2016). Climate change, land use/cover changes and other anthropogenic activities are commonly considered potential agents driving variation of soil erosion rates (Nearing et al., 2004; Jean-Baptiste et al., 2015; Zhang et al., 2021). The impacts of future climate projections or recently observed climate change on soil erosion have been explored in a number of studies (Nearing et al., 2004; Zhang and Nearing., 2005; Mullan, 2013; Jean-Baptiste et al., 2015; Palazon and Navas, 2016; Mullan et al., 2019). Changes in land use or land cover have also been widely investigated, using either experimental observations or modelling approaches at various scales (e.g. Korkanç et al., 2018; Silva et al., 2017; Bochet et al., 2006; Karvonen et al., 1999; Ozsahin et al., 2018; Nampak et al., 2018; Li et al., 2019; Perović et al., 2018). Additionally, the relative contributions of climate change and land use/cover change have been increasingly investigated in recent years as both agents usually exert their influence on soil erosion simultaneously. In a review on anthropogenic and climatic impacts on Holocene sediment dynamics of the Western Mediterranean basin (Bellin et al., 2013), the impacts of climatic and anthropogenic activities on sediment dynamic were found to interact with each other during moist climatic periods, whilst the enhanced sediment load was found only closely associated with enhanced aridity during dry climatic periods, independent of the intensity and type of human activities. By using field investigation combined with modeling, Zhang et al. (2021) quantitatively evaluated the contribution of climate change, land use, and silt trap dams to sediment reduction of a typical Loess watershed over 1987-2016, with contribution values being 29%, 40%, and 31%, respectively. Sun et al. (2020) quantified the contribution of climate change and land-use change to sediment reduction of a Loess watershed over 1997 to 2016, in which both engineering measures and land-use change accounted for 62% and 23 - 42% of sediment reduction, respectively, the rest being explained by climate change. Management practices generated a higher impact on soil erosion at the plot scale than climate change (Scholz et al., 2008). Also, livestock grazing accelerated soil erosion more than climate change in Qinghai-Tibet Plateau (Li et al., 2019).

The previous findings provide valuable information for implementing water and soil conservation measures and improving agricultural productivities (Nampak et al., 2018; Li et al., 2019). However, the role of landscape structure changes has so far not received much attention, even though land-use policies such as land consolidation have been changing agricultural practices to a large extent since the beginning of agricultural industrialization after 1945 (e.g. Moravcová et al., 2017; Devaty et al., 2019) and in particular in countries where the industrialization of agriculture is relatively recent (Bouma et al., 1998; Moravcova et al., 2017; Zhang et al., 2021). Landscape structures usually influence erosion due to the boundary effects between

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land uses and land units (parcels) that differ in water and sediment trapping capacity (Baudry and Merriam, 1988; Merriam, 1990; Takken et al., 1999; Phillips et al., 2011). Van Oost et al. (2000) and Devaty et al. (2019) evaluated the role of landscape structure by accounting for its spatial connectivity using modelling approaches and found that landscape structure is an essential factor when assessing the risk of soil erosion affected by land-use changes. Both studies emphasized the potential impacts of parcel structure changes on sediment production through altering hydrological and sediment connectivity. However, both authors relied on models, making connectivity assumptions in their studies. Instead of focusing on the spatial connectivity, others (e.g. Bakker et al., 2008; Sharma et al., 2011; Chevigny et al., 2014;Wang et al., 2021; Tang et al., 2021; Madarász et al., 2021) evaluated the effect of terrain, soil properties, lithology, management practices and other processes associated with landscape and/or land structure changes and highlighted their impact on sediment production. It has also been shown that the impact of landscape structure on erosion is more heterogeneous when different crops are grown, and the underlying lithology, soil properties and topography show substantial spatial variability across the catchment (David et al.,2014; Cantreul et al., 2020).

Even though numerous studies have addressed the effect of climate change and land management on soil erosion and sediment production, most studies have been based on short-term monitoring and/or modeling, which makes it difficult to assess their reliability in terms of long-term changes that are the most relevant from a practical perspective. This paper aims at evaluating the relative roles of climate change, land

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use and land cover changes (LUCC) and change of land structure on sediment production. We present the results from a unique data set consisting of measurements of sediment loads from a small agricultural catchment over a time window spanning 72 years. The catchment is the 66 ha Hydrological Open Air Laboratory (HOAL) Petzenkirchen (Blöschl et al., 2016), which, in addition to being exposed to climate change, has experienced a significant change in land use and land cover as well as parcel structure for erosion control during the past decades. Both discharge and sediment yield have been monitored in the HOAL catchment since the 1940s. This provides an opportunity for disentangling the impact of parcel structure and land use/land cover change, and the impact of climate change based on long-term measurements. Specifically, we aim at i) exploring how the sediment regime has changed between the periods of 1946-1954 and 2002-2017; ii) analyzing whether climate change or land-use changes (or both) were responsible for any change in sediment regime; and iii) identifying the relevance of land structure change (i.e. land consolidation) on erosion control compared to that of a change in land use or cover.

2. Methods

2.1 Catchment characteristics

The HOAL catchment is situated in Lower Austria's alpine forelands (48°9' N, 15°9' E) with elevations ranging from 268 m to 323 m a.s.l. and a size of 66 ha. The climate of the catchment belongs to the temperate, continental climate zone (Dfb) according to Köppen-Geiger (Kottek et al., 2006), with a mean annual precipitation of 746 mm (1946 - 2006), 62% of the rain falling between May and October. The mean daily air

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temperature is 8.8°C (1946-2006), and the dominant land use is arable land, accounting for, on average, 82% of the catchment over the past few years. Typical crops include winter wheat, corn and barley. Deciduous trees grow along the creek (6%), 10% of the area is grassland, and 2% is paved. The subsurface of the catchment consists of tertiary marine sediments. Soils are classified into five types: calcic cambisols, vertic cambisols, gleyic cambisols, planosols and gleysols (IUSS Working Group WRB, 2015).

2.2 Data availability

Both streamflow discharge (*Q*, l/s) and sediment concentration (*C*, mg/l) have been measured at the catchment outlet since the 1940s. Data records from 1946-1954 (Period I) and 2002 to 2017 (Period II) were available for this analysis. Due to technological advances, the data was measured with different methods. In Period I, discharge was registered at 10 min resolution by a Thompson weir and a paper chart recorder, while in Period II, it was registered at 5 min resolution by an H-Flume and a pressure transducer. Sediment concentrations were measured manually every 3-4 days in Period I, whilst an automatic method plus additional manual sampling was applied in Period II. Daily precipitation and 5-min rainfall intensities were available for both periods, but for Period I, 5-min rainfall intensities were only available during the vegetation period.

We used parcel-based land use data from 1946 to 1949 and 2007 to 2012, representing Period I and Period II land use, respectively. Land use categories were agricultural land, including crop type, grassland, forest, roads and settlements. We defined a parcel

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as a continuous area of land with a single crop type. Parcel boundaries were specified according to the cadastral map and aerial photographs. In Period II, these boundaries were also visually inspected. Figure 1 depicts the geographic catchment location, and parcel structure and land use for a specific year in each period.

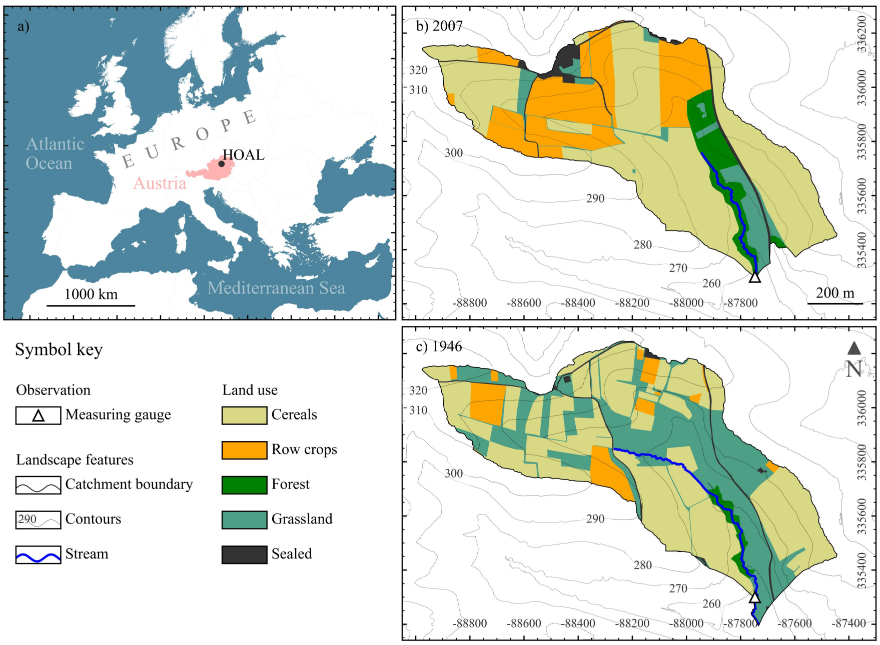

Figure 1 Geographical location of the HOAL catchment in Petzenkirchen in Austria and Europe and Parcel structure and land use in the HOAL catchment for 1947 (a) and 2007 (b). The black hatched area in b) represents a difference in catchment size due to the relocation of the stream gauge in Period II. Coordinates as EPSG: 31256 – MGI / Austria GK East (meters).

2.3 Data analysis

2.3.1 Changes in rainfall erosivity and flow regime

The effect of rainfall on erosion was quantified by the R-factor of the Revised Universal Soil Loss Equation (RUSLE), which is defined as the product of kinetic

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energy of a rainfall event and its maximum 30-min intensity, using the rainfall erosivity tool RIST (USDA-Staff, 2019) according to

$$EI_{30} = \sum_{i=1}^{m} E_i \cdot I_{30,i} \qquad (1)$$

where EI_{30} is the Annual R-factor ($N{\cdot}h^{-1}{\cdot}yr^{-1}$) calculated as the sum of single event R-factors, E_i is the total kinetic energy for a single event ($kJ{\cdot}m^{-2}$), I_{30} is the maximum rainfall intensity in 30 minutes within a single event *i* ($mm{\cdot}h^{-1}$), and *m* is the number of events per year.

We assumed erosivity density *ED* (*i.e.* EI_{30} divided by event precipitation) to be a particularly relevant climatic indicator of the soil erosion process and catchment sediment yield. We, therefore, tested whether the means of the monthly erosivity density (*ED*) are significantly different between Period I and Period II by using a t-test. Due to the absence of rainfall intensity measurements, we could not calculate *ED* for the months of the dormant season (November to March) of Period I. For this case, we calculated *ED* from a relationship between EI_{30} and monthly rainfall of Period II, assuming that the relationship was sufficiently temporally invariant over the investigated periods. Erosivity is very low during the dormant season (Figure 3a); thus, the error arising from the use of this relationship is expected to be small.

We also compared daily flow duration curves to understand whether hydrological regime change has influenced flow transporting capacity and sediment regime variation. Following the definitions of Smakhtin (2001), we compared low flow ($Q_{70\%}$), high flow ($Q_{10\%}$) and median flow rate ($Q_{50\%}$) quantiles for the two periods.

2.3.2 Sediment regime analysis

Sediment regimes were mainly analyzed using sediment rating curves (SRC). Following a common approach (Asselman, 2000; Warrick and Rubin, 2007; Sheridan et al., 2011; Vaughan et al., 2017; Khaledian et al., 2017), the SRCs were assumed to follow a power-law function, which was fitted by least squares regression:

$$C = a \cdot Q^{b} \qquad (2)$$

where C is sediment concentration ($mg \cdot l^{-1}$), Q is discharge ($l \cdot s^{-1}$), and a and b are dimensionless regression coefficients. The coefficient a is usually associated with easily transported intensively weathered materials and may vary over seven orders of magnitude (Syvitski et al., 2000). The parameter b represents the capacity of the stream to erode and transport sediment, reflecting how sediment concentration is non-linearly related to streamflow (Sheridan et al., 2011; Fan et al., 2012). It typically varies from 0.5 to 1.5 and rarely exceeds 2. Sometimes b is also regarded as a measure of the quantity of new sediment sources available (Vanmaercke et al., 2010; Guzman et al., 2013).

Considering that data records were registered with different resolutions for Periods I and II (See section 2.2), for the sake of consistency, we used monthly averages, as conducted in the other studies (Syvitski and Alcott,1995; Sheridan et al., 2011; Hu et al., 2011), to construct SRC. We assumed that monthly averages could reflect a varied hydrological and/or sediment response to seasonally prevailing weather characteristics such as dry periods or convective storms (Sheridan et al., 2011).

We chose arithmetic means of the observations to represent the monthly Q and C values. These monthly averages were pooled together and then grouped into growing

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season of Period I (Period I_G), dormant season of Period I (Period I_D), growing season of Period II (Period II_G), and dormant season of Period II (Period II_D), respectively. For each of these four periods, we fitted SRC.

We analyzed the fitted SRC by two strategies to evaluate whether and how the sediment regime changed between these periods. Besides directly comparing the slope of the four seasonal SRC, we also fitted SRC by season and year and plotted the regression coefficients *a* against their corresponding *b* to evaluate a possible sediment regime shift during Periods I and II. Thomas (1988) suggested that this technique could exclude the interference of different sampling practices with the estimated sediment regime.

It is suggested that for the years (or catchments) with similar means of log-Q and log-C, SRC would usually pass through one common point O (Thomas, 1988; Syvitski et al.,2000; Desilets et al., 2007; Sheridan et al., 2011). This common point O (Figure 2a) is usually interpreted to reflect time invariant catchment characteristics, such as relief, drainage area, and drainage density, while the variation of the slope of SRCs (Figure 2a) is interpreted to reflect temporally dynamic characteristics, such as average or maximum discharge and sediment availability (Asselman, 2000). The coefficients *a* of the SRCs having a common point are usually inversely linearly related with *b* as well (Thomas, 1988, Syvitski et al., 2000 and Desilets et al., 2007). This provides a means for testing whether periods (or catchments) have similar sediment transporting regimes by plotting coefficient *a* against *b* (Figure 2b). That is to say, thatthe points plotted on the same line (A, B, C) in Figure 2b are representative

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of periods (or catchments) having similar sediment transport regimes. Points A of Figure 2b (upper-left-side) usually exhibit steeper rating curves than points C (lower-right side). For different lines in Figure 2b, the lower ones represent situations with most of the annual sediment load transported at relatively low flow discharge, and the higher ones represent situations with suspended sediment mainly transported at high streamflow. Thus, it is possible to reveal changes in sediment transport regimes. Compared to a direct evaluation of rating curves, relating coefficient *a* to exponent *b* is more conductive to revealing the temporal evolution of the sediment regime (Syvitski et al., 2000; Desilets et al., 2007).

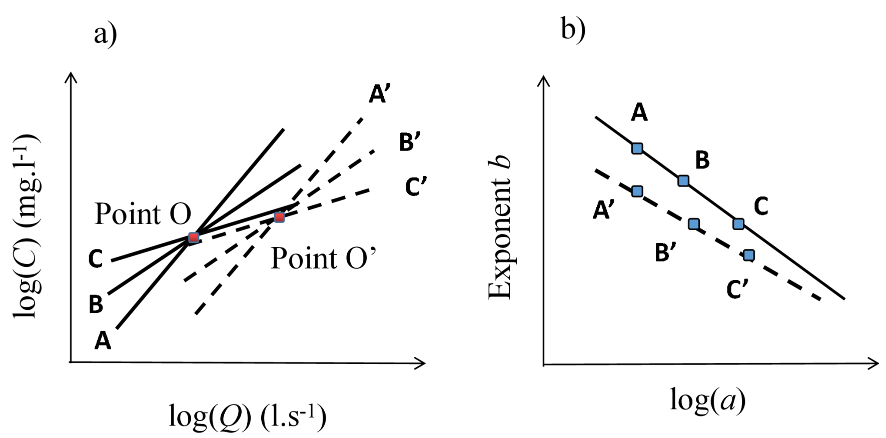

Figure 2 Schematic showing a) how sediment rating curves (SRC) may rotate around a common point and b) how exponents *b* of the SRC relate to coefficients *a*. Lines A, B and C on the left are SRC of different periods (e.g. years) sharing a similar common point O. Once sediment regimes shift due to the changes in catchment characteristics (change in drainage density, drainage area, and topography…..) the common point O would change to point O', and the linear relationship between *a* and *b* of the SRC would exhibit a shift as well. The schematic is based on $\log C = \log a + b \cdot \log Q$ (Equation 2).

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To account for uncertainties of the fitted SRC during each period, we additionally established theoretical sediment rating curves (tSRC); i) for each period (*i.e.* Period I_G, Period I_D, Period II_G, and Period II_D), we carried out random sampling of $log\ a$ (n=500, package "sample" in RStudio), assuming that the samples of the coefficient of log a follow normal distributions (Figure 4), which was proved with a Kolmogorov-Smirnov test of normality (mean = 1.02, SD = 2.01, n=44); ii) given the set of the sampled 500 values of log a, we generated a set of values$b$according to the previously established linear relationship between log a and b; iii) given a set of specified Q values, we derived 500 tSRC for each period, corresponding to the paired log a and b samples; iv) using these tSRC we calculated the 50 percentile, 5 percentile, and 95 percentile for each period to reveal uncertainties of the sediment rating curves.

The tSRC of the periods were also used to quantify the effect of land consolidation, *i.e.* change of parcels structure and sizes (Parcel_effect) versus the effect of land use and land cover changes (LUCC_effect).Since vegetation usually plays a minor role in the dormant season due to the absence of a dense vegetation cover on arable land and little erosive rainfall (Madsen et al., 2014; Kundzewicz, 2012; Salesa and Cerda, 2020; Hou et al., 2020), landscape structure in the dormant season was considered a critically important factor affecting runoff production and sediment production (Sharma et al.,2011; Devátý et al., 2019). Therefore, we hypothesized that the total change in sediment yield (Total effect) resulted from land cover change

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(LUCC_effect), land structure change (Parcel_effect) and climate change (Climate_effect). The effects of land cover and land structure change could be quantitatively separated according to the seasonal differences in tSRC after determining the climate change effect. Specifically, we assume that the shift of sediment regime from Period I_D to Period II_G is representative of the Total_effect (Equation 3), and the shift in sediment regime between Period I_D and Period II_D is mainly due to land consolidation (Parcel_effect) (Equation 4). Thus, the LUCC effect could be estimated according to Equation (5) if the Climate_effect was insignificant (section 3.1). The contributions of Parcel_effect and LUCC_effect to the Total_effect were estimated according to Equations (6) and (7), respectively.

$$\text{Total\_effect} = tSRC_{50\%}(\text{Period II\_G}) - tSRC_{50\%}(\text{Period I\_D}) \qquad (3)$$

$$\text{Parcel\_effect} = tSRC_{50\%}(\text{Period II\_D}) - tSRC_{50\%}(\text{Period I\_D}) \qquad (4)$$

$$\text{LUCC\_effect} = \text{Total\_effect} - \text{Parcel\_effect} - \text{Climate\_effect} \qquad (5)$$

$$\text{Parcel\_effect}\ (\%) = \frac{\text{Parcel\_effect}}{\text{Total\_effect}} \times 100 \qquad (6)$$

$$\text{LUCC\_effect}\ (\%) = \frac{\text{LUCC\_effect}}{\text{Total\_effect}} \times 100 \qquad (7)$$

3. Results

3.1 Changes in climate and flow regime

Because climate is commonly found responsible for hydrological change (e.g., Kelly et al., 2016; Wang et al., 2020), we compared erosivity density (*ED*) and monthly

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precipitation (P) of the two periods to examine whether climate affected the variation of sediment regime in the catchment. The mean monthly *EDs* in the growing season were 2.37 ± 1.38 and 1.84 ± 0.86 ($N{\cdot}h^{-1}{\cdot}yr^{-1}{\cdot}mm^{-1}$) (standard deviation between years), respectively, which was not significantly different ($p>0.05$) between the first and second period (Figure 3a). In contrast, mean monthly *ED* in the dormant seasons showed a significant ($p<0.05$) decrease from the first to the second period (0.66 ± 0.21 and 0.42 ± 0.11 ($N{\cdot}h^{-1}{\cdot}yr^{-1}{\cdot}mm^{-1}$), respectively. No significant difference was found between the first and second periods for the mean monthly P in dormant or growing season (Figure 3b). The mean monthly *P* in Period I was 50 ± 33 and 76 ± 54 mm for the dormant and growing season, and 53 ± 29 mm and 79 ± 47 mm in Period II. The decrease in *ED* during the dormant season of Period II and the insignificant change in monthly P suggest that climate change between Period I and II was not responsible for an increased sediment availability (see section 3.3).

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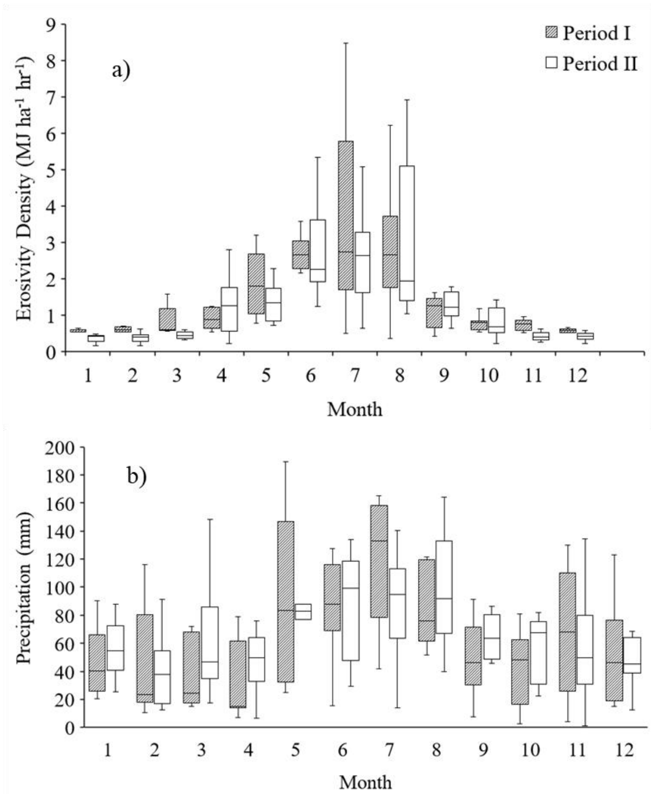

Figure 3 Distribution of a) monthly mean erosivity density and b) monthly precipitation for Periods I and II.

Daily flow duration curves for both periods are displayed in Figure 4. Generally, daily streamflow in Period I was higher than that of Period II. The $Q_{70\%}$ low flow of the two periods was 2.3 and 1.9 $l{\cdot}s^{-1}$, the $Q_{50\%}$ median flow was 3.1 and 2.7 $l{\cdot}s^{-1}$, and the $Q_{10\%}$ high flow was 7.3 and 6.5 $l.s^{-1}$, respectively. The decreased flow regime of Period II, probably in part due to increased evapotranspiration over the past decades (Duethmann and Blöschl, 2018), suggests a smaller streamflow transport capacity and indicates that it was not responsible for the increased sediment transport in Period II (see section 3.3).

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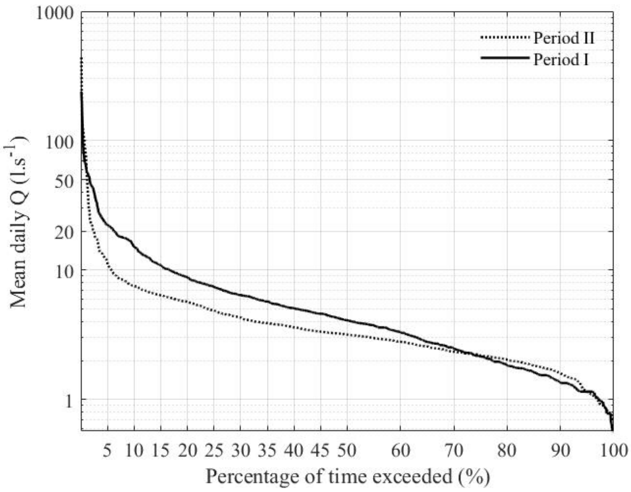

Figure 4 Mean daily flow duration curve for Periods I and II.

3.2 Change in land use and land organization

Table 1 shows how land use changed between the two periods. During Period I, cropland and grassland accounted for 73% to 82% and 14% to 22% of the area. However, due to agricultural intensification, cropland increased to around 82% in Period II, at the expense of a decreasing share of grassland. Forest, including sparse forest, accounted for 1.8% area during Period I but increased considerably until Period II to around 11%. Within the land use class of arable land, a substantial change from crops with low risk to cause soil erosion to crops with a high soil loss potential appeared. This was particularly true for maize. In addition, the diversity of crops decreased considerably (Table 2). This shift to agricultural uniformity is likely to affect also land structure effects.

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Besides the change in land use, the parcel structure of the catchment also changed (Table 1). This change was related to a land consolidation plan issued in 1955 in Austria (Devátý et al., 2019) and a massive trend to agricultural industrialization that evolved after 1945. During Period I, arable land was fragmented across many small parcels, with a mean parcel size between 0.5 - 0.6 ha and a parcel density (number of parcels per ha area) between 1.7 - 2.0 ha^{-1} in different years. In Period II, these values increased considerably to mean parcel sizes between 1.7 - 2.7 ha and parcel densities between 0.3 - 0.6 ha^{-1}. Similarly, the mean parcel size and parcel density of grassland during Period I were 0.13 - 0.17 ha and 5.2 - 7.2 ha^{-1}. It had changed to 1.06 ha and 0.9 ha^{-1} in Period II.

Table 1 Parcel and land use statistics for Periods I and II. Land use for the years 1946 to 1949 represents Period I, land use for the years 2007 to 2012 represents Period II; N is the number of parcels for a given land use, density is the number of parcels per ha, mean size represents the mean area of parcels with a particular land use.

	Parcel Structure							
Land use	**Period I**				**Period II**			
	N	**Density ($1\cdot ha^{-1}$)**	**Mean size (ha)**	**Area (%)**	**N**	**Density ($1\cdot ha^{-1}$)**	**Mean size (ha)**	**Area (%)**
Arable land	70-111*	1.7-2.0	0.5-0.6	73-82	21-33	0.3-0.6	1.7-2.7	81-82
Grassland	70-81	5.2-7.2	0.1-0.2	14-22	6	0.9	1.1	3-4
Forest	1	-	1.2	1.8	7	1	1.0	10.5-11
Paved area	17	12.9	0.1	2	17	7.3	0.1	2.4

* The number of parcels varied with the specific year of a period

Table 2 Crop statistics of arable land for Periods I and II; Crop statistics for the years 1946 to 1949 represent Period I, crop statistics for the years 2007 to 2012 represent Period II; Erosion risk for a particular crop is classified as high or low according to the classification of management in the RUSLE.

Period I	Period II

	Area (ha)	**Area (%)**	**Area (ha)**	**Area (%)**	**Erosion risk**
Meadow	9-15	18-30	0.8	2	low
Alfalfa	11-18	22-33	-	-	low
Wheat	5-14	9-26	3-35	5-66	low
Rye	3-13	5-24			low
Beets	2-12	3-22	-	-	high
Oats	2-10	4-18	2	4	low
Barley	0.3-8	5-15	2-29	5-55	low
Potatoes	3-7	6-14	-	-	high
Maize	0.3-0.8	0.6-1.1	6.3-34	12-63	high
Rape	-	-	0.7-23	1-43	low
Sunflower	-	-	0.2-2	0.3-4	high

3.3 Change in sediment transport regime

3.3.1 Direct comparison of the fitted SRCs

Figure 5 shows the fitted sediment rating curves (p<0.05) for both periods. Although rainfall erosivity of Period II_G was similar to that of Period I_G (Figure 3a) and streamflow of Period II was generally lower than that of Period I (Figure 4), the fitted SRC of Period II_G was steeper than that of Period I_G (Figure 5a), with the coefficients ***b*** being 0.32 and 1.65for Period I_G and Period II_G, respectively (Table 3). The rating curves of the dormant seasons demonstrated a faster response of sediment concentration to increasing flow in Period II_D (Figure 5b), the coefficients *b* being 0.75 and 1.69 for Period I_D and Period II_D, respectively. However, the rainfall *ED* in Period II_D was generally lower than that of Period I_D (Figure 3a), suggesting a lower probability of a substantial increase in sediment availability. These results indicate that neither changes in rainfall erosivity nor the hydrological regime could explain the increase in sediment dynamics.

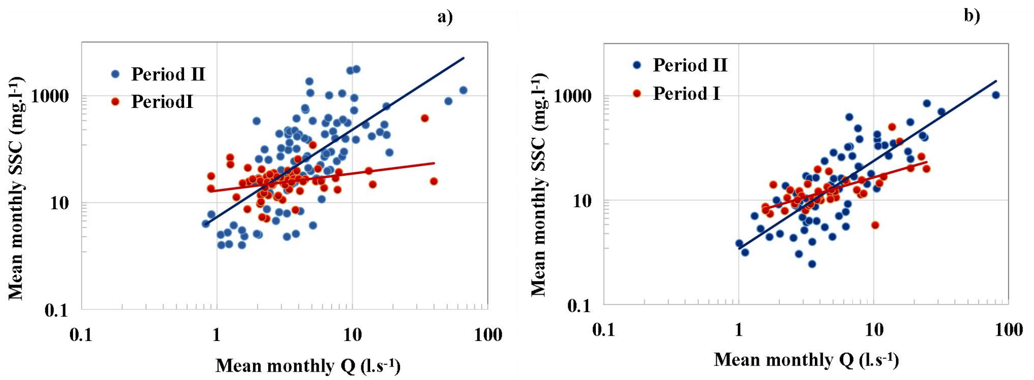

Figure 5 Sediment rating curves for a) the growing seasons and b) the dormant seasons in the two periods. Each point represents one mean monthly observation.

Table 3 Parameter values for the coefficients of the SRC for different periods and seasons according to Equation (2).

Period	Coefficient		r^2
	a	*b*	
Period I_G	16.72	0.32	0.11
Period I_D	4.90	0.75	0.42
Period II_G	5.38	1.63	0.45
Period II_D	1.17	1.69	0.64

3.3.2 Relationship between coefficient *a* and *b*

The changing steepness of a fitted SRC does not necessarily imply a change in sediment regime as slopes of fitted SRC sometimes are affected by catchment size or the distribution of samples (Asselman, 2000). To minimize possible interference of other factors in identifying variation or shift of SRC, we investigated the relationship between coefficients *a* and *b* of the SRC. This technique was used by Asselman et al. (2000) and Fan et al. (2012) to examine the differences in sediment regimes between

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spatially different sites. Additionally, Sheridan et al. (2011) used the relationship to reveal post-fire temporal shifts of a sediment regime.

Figure 6 displays the coefficients log *(a)* plotted against *b* for the four investigated time frames. Even though monthly averages were used for the sake of consistency, the different sampling strategies of Periods I and II caused a biased distribution of log (*a*) and *b.* Data of Period I is concentrated in the right-lower area (blue points). In contrast, data of Period II is more concentrated in the left-upper area, which is especially true during the dormant season.

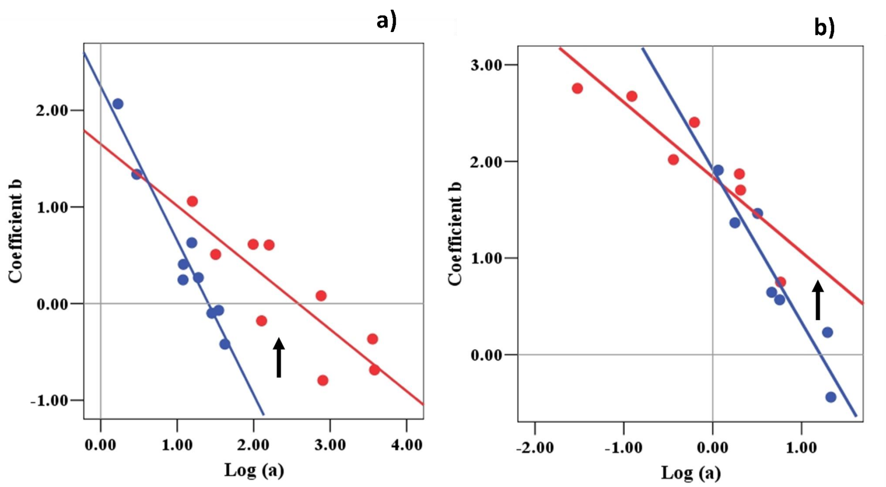

Figure 6 Relationship between coefficients *a* and *b* for a) growing season and b) dormant season of Period I (blue) and Period II (red), respectively. All regressions are significant at $p<0.05$.

Nevertheless, it is evident that the regression line exhibits a shift between the periods, the slopes of the regression line changing from -1.60 to -0.94 in the growing season and from -1.58 to -0.80 in the dormant season (Figure 6). The shift of the line to the

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upper direction at log (a) larger than around 0.6 suggests that in Period II, most of the sediment was transported at relatively high flow rates. Since climate change was not responsible for the increased hydrological regime (see section 3.1), we mainly attribute this shift to the increase in hydrological connectivity, such as flow path density and flow length, and a change in land use and land cover statistics.

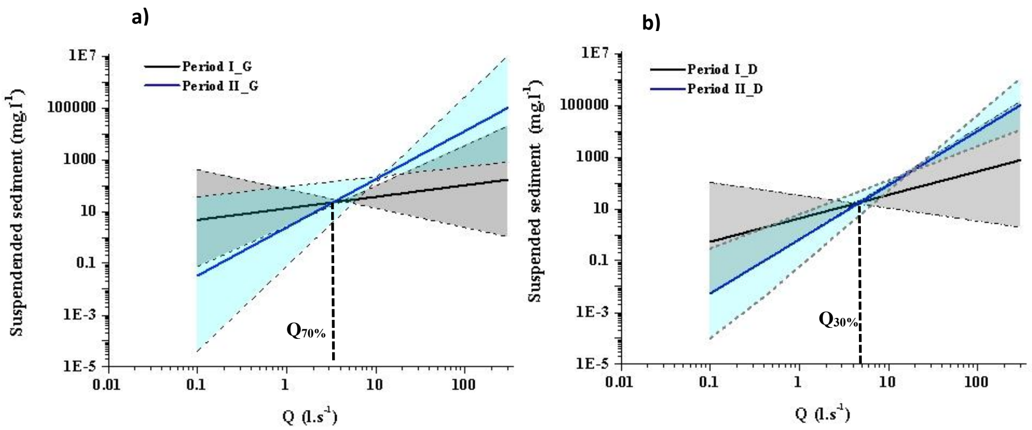

Figure 7 tSRC for the growing seasons (a) and the dormant seasons (b) of Period I and II. Solid lines denote the 50 percentile of the tSRC for each period. The grey area denotes the range of the predicted tSRC composed of 5 and 95 percentiles. $Q_{30\,\%}$ and $Q_{70\,\%}$ and represent the flow conditions of 3.9 $l{\cdot}s^{-1}$ and 2.0 $l{\cdot}s^{-1}$,respectively.

Figure 7 displays the tSRC with their uncertainties for the different periods and seasons, to allow for directly discriminating the change in sediment regime with uncertainty. During most of the time, *i.e.* at flow rates larger than approximately $Q_{70\%}$, sediment concentrations for a given Q in Period II_G were considerably higher than in Period I_G (Figure 7a), whilst at flow rates below this value, sediment concentrations were not different. This finding is supported by the significant change in the sediment

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load of 6.3±19.9 ton per month during Period II_G compared to 0.8±3.3 ton per month during Period I_G. Sediment concentration in the dormant season of Period II was considerably higher than that of Period I at flow rate exceeding $Q_{30\%}$ (Figure 7b). Again, this confirms the shift of sediment transport regime in Period II_D and is in line with the increase in sediment load in Period II_D, resulting in mean monthly sediment loads of 5.4±18.3 ton per month compared to 1.3±3.9 ton for Period I_D.

3.4 Parcel_effect versus LUCC_effect

Figure 8 demonstrates the dynamic contributions of land structure and land cover changes on sediment concentrations with increasing flow. Land consolidation and the substantial increase in cropland at the expense of a decrease in grassland explained the increase in sediment yield. However, the trends of their contributions to this increase differed. Generally, with higher flow rates, the contribution of the LUCC_effect gradually decreased, whilst the contribution of the Parcel_effect increased. The Parcel_effect accounted for more than 50% of the Total_effect after the flow rate exceeded 20 $l{\cdot}s^{-1}$ approximately (*i.e.* $Q_{2\%}$) (Figure 8), exhibiting a dominant role in sediment production. The opposite trend of the contributions between LUCC_effect and Parcel_effect suggests that, even though land consolidation and an increase in cropland both have unbeneficial effects on erosion control, their hydrological consequences may be different, with land structure change probably explaining much of the variation of sediment load at high flow conditions.

Unlike the situation during high flow rates, the Total_effect showed an almost zero

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value at flow rates less than approximately 2 $l{\cdot}s^{-1}$ (*i.e.* $Q_{70\%}$) (Figure 8), suggesting no difference in sediment load between Periods I and II at low flow conditions. The increase in sediment load, at flow rates of 2 up to around 20 $l.s^{-1}$, seemed mainly due to the increase in the cropland of Period II, as the contribution from LUCC_effect was consistently higher than that of the Parcel_effect.

One may note that forest cover increased considerably from Period I to Period II. It, however, did not show an influential role in erosion control. We hypothesize that even though a beneficial effect of forest increase (accounting for 11% around of the catchment) may have appeared in Period II, it was offset by the negative effect of crop land changes, particularly the increase in erosive row crops, which contribute substantially to sediment yield compared with other land uses and other crop types (Kijowska - Strugała et al., 2018).

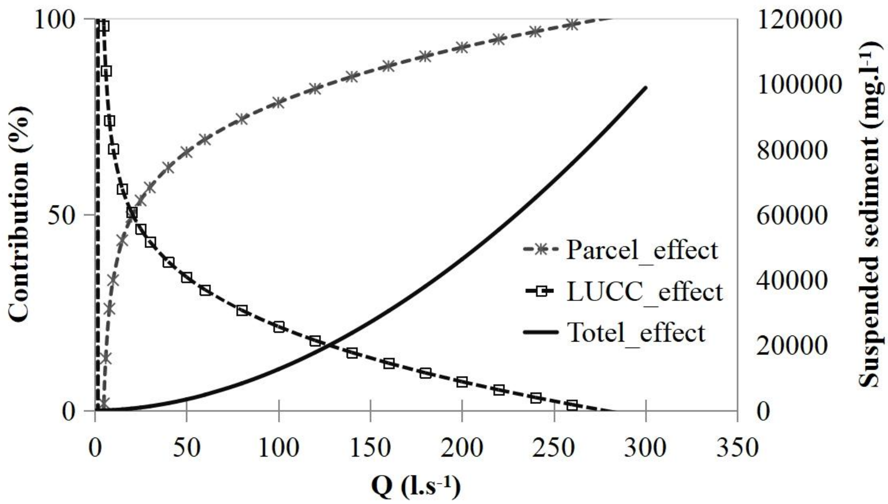

Figure 8 Contribution of Parcel_effect and LUCC_effect to the Total_effect across various flow rates. Total_effect (Equation 3) is displayed in terms of suspended sediment concentration. Parcel_effect and LUCC_effect was estimated by Equations

(4) and (5), respectively; their contribution to the Total_effect was estimated by Equations (6) and (7), respectively.

4. Discussion

Industrial intensification of agriculture implemented in the last 70 years has raised considerable concern regarding erosion and sediment loading of rivers (e.g. Bakker et al., 2008; Chevigny et al., 2014). However, with global climate warming, the different contributions to sediment load from land use and land cover change, land policy adjustments such as land consolidation and climate change are not well understood. This paper aims at evaluating the relative roles of climate change, land use and land cover changes, and land consolidation in sediment production, particularly for varying flow rates.

We found that sediment load increased substantially from Period II to Period I. Climate change in terms of both monthly *ED* and *P* was not responsible for this effect, instead it can be explained by land cover and land consolidation changes. Their relative contributions varied with streamflow. For flow conditions below around 5 $l.s^{-1}$(*i.e.* Q_{20}%), land consolidation had no apparent adverse effect on erosion control, but with increasing flow, the contribution to sediment load increased continuously, leading to a dominant role at extremely high flow rates. This finding is partially in line with David et al. (2014) and Cantreul et al. (2020). They reported that landscape structure was less important for soil erosion during most normal flow conditions than land use and land cover. However, they did not investigate whether the effect of landscape structure showed a dynamic behavior with increasing flow. In contrast, the

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LUCC_effect, i.e. the increase of crops with high erosion risk, continuously affected sediment load with gradually decreasing importance for high and extreme flow conditions. Similar results have been reported by Vaughan et al. (2017), who showed that sediment concentration at low and median flow conditions was considerably associated with a change in catchment characteristics, primarily land use and land cover.

Although the effect of land use changes was dominating for flow conditions below Q_{20}%, it's contribution to the total annual sediment load was small. More than 75% of the total sediment load was transported during a small number of events (25 events in Period I, 8 events in Period II) and all events had flow rates above 15 $l.s^{-1}$., which underlines the importance of land structure for sediment loading.

This behavior is associated with the processes and mechanisms of vegetation controlling overland flow as a transporting agent for sediment (e.g. Sun et al., 2013; El Kateb et al., 2013; Nearing et al., 2017; Kijowska - Strugała et al., 2018; Silasari et al., 2017). A change in land use and land cover implies alterations of surface characteristics, such as above ground structure morphology, litter cover, organic matter components, root network (Gyssels et al., 2005; Wei et al., 2007; Moghadam et al., 2015; Patin et al., 2018) and soil properties (Costa et al., 2003; Moghadam et al., 2015). These properties influence the protective role of vegetation in soil detachment, flow capacity to transport sediment particles, and runoff flow paths to river channels (Van Rompaey et al., 2002; Lana-Renault et al., 2011; Sun et al., 2018). Nevertheless,

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the protective effects do not linearly increase with increasing surface runoff. Accelerated discharge and stronger scouring effects of upslope discharge might impair the protective role of vegetation (*e.g.* Zhang et al., 2011; Santos et al.,2017; Yao et al., 2018; Bagagiolo et al., 2018; Wang et al., 2019). Vegetation usually exhibits a smaller interception capacity at high rainfall intensity, resulting in enhanced splash erosion and availability of mobile soil particles (Cayuela et al., 2018; Magliano. et al., 2019; Nytch et al., 2019). However, the decreasing contribution of the LUCC_effect does not directly imply an absolute decrease of the magnitude of the LUCC_effect. The absolute change in SSC resulting from LUCC reveals an increasing trend as flow rates increases. Thus, the contribution of the LUCC_effect stands for the relevance of LUCC in erosion control compared to the change due to land consolidation. The magnitude of the LUCC_effect probably depends mainly on where within the catchment the land cover was replaced and how the proportional area of various land uses changed. We will address this issue in future analyses.

Unlike land cover and land use change, landscape structure is usually combined with other catchment properties, such as slope characteristics and soil properties (Gascuel-Odoux et al., 2011) and additional erosion and transport factors (Verstraeten et al., 2000), exerting a more complicated influence on erosion control. For example, the effect of landscape structure on soil erosion may be identified on moderate slopes, while on steep slopes it may be concealed by on-site severe soil erosion (Chevigny et al., 2014). However, the key process for erosion control is the fact that landscape elements and their structural position (i.e. parcel structure, field boundaries, hedges and similar) alter hydrological connectivity between land and water. This is particularly true when the land cover on both sides of boundaries is different (Van Oost et al., 2000). Reducing parcel size and heterogeneity increases hydrological connectivity significantly and results in a substantial off-site damage effect, irrespective of on-site erosion of the investigated land use (Boardman et al., 2018; Devátý et al., 2019). During low and median flow conditions, surface runoff and sediment may arrive to a lesser extent at field boundaries due to efficient interception effects of the vegetation cover. This may explain the identified dynamic relevance of land structure change in sediment load herein.

Our findings are also supported by the calculation of the management factor (C-Factor) and the slope and slope length factor (SL-Factor) of the RUSLE for Period I and Period II. While the mean C-Factor of the HOAL catchment increased from 0.16 during Period I to 0.33 for Period II, the SL factor increased from 0.76 to 0.96 from Period I to Period I. Taken together, the changed values for these two factors increase the theoretical soil loss within the catchment by over 150%. This is smaller than the changes observed, however it should be noted that the RUSLE has not been designed to account for sediment loads of catchments but to estimate field scale soil loss within catchments. This may explain the observed differences to a certain extent.

5 Conclusions

Climate change, land use and cover change, and other human-associated activities are widely regarded as potential agents driving hydrological change. Understanding the

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relevance of each of these factors in the hydrological cycle is critical for implementing adaptive catchment management measures and addressing climate change. For some hydrological cycle components, very significant climate change influences in the last decades have been identified (e.g. Haslinger et al., 2019; Duethmann and Blöschl, 2018). However, we found that climate change in rainfall erosivity and precipitation cannot explain the increased sediment production between 1946-1954 and 2002-2017 in the investigated catchment. Instead, both land cover and land consolidation played dynamic roles in controlling erosion.

Still, the relevance of land use and land cover change versus land consolidation change varied dynamically with changing flow conditions. The reduction in parcel density undoubtedly increases soil erosion risk, particularly at higher flows due to the decreased capacity of trapping sediment particles between parcels and increasing flow lengths inside parcels. Meanwhile, unfavorable land use or land cover change will increase sediment load at most normal flow conditions, although the relevance of this process would decrease at high or very high flow rates. Therefore, when addressing soil conservation measures at the catchment scale, the distribution of fields, land structure, and vegetation cover should be simultaneously considered. Such a strategy would be conducive to dealing with the risk of soil erosions at different flow rates.

Land use policy adjustments resulting from technological development have been vital to deal with food security issues in the past. However, now we have to experience the negative influence of these adjustments on the hydrological cycle. Therefore, rather than focusing on climate change solely, we need to pay increased attention to anthropic management activities to counteract their negative impact on hydrological change effectively.

Author contributions

Shengping Wang has led the data analysis, drafted the manuscript, and revised the manuscript; Peter Strauss was responsible for the project design, oversaw the whole analysis, and conduct manuscript revision as the project leader; Carmen Krammer was responsible for data collection and data preparation; Elmar Schmaltz has contributed to figure drawing and manuscript revision; Borbala Szeles has helped to revise the manuscript, and Günter Blöschl oversaw and critically reflected on the manuscript revision as the senior scientist.

Competing interests

The authors declare that they have no conflict of interest.

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