Pristine levels of suspended sediment in large German river channels during the Anthropocene?

Back to pristine levels: a meta-analysis of suspended sediment transport in large German river channels.

Thomas O. Hoffmann[1], Yannik Baulig[1], Stefan Vollmer[1], Jan H. Blöthe[2], Karl Auerwald[3], Peter Fiener[4]

[1]Bundesanstalt für Gewässerkunde, 56068 Koblenz, Germany
[2]Institute of Environmental Social Sciences and Geography, University of Freiburg, Schreiberstraße 20, 79098 Freiburg, Germany
[3] Aquatic Systems Biology Unit, Technical University of Munich, Mühlenweg 22, 85354 Freising, Germany
[4]Institute of Geography, University of Augsburg, Alter Postweg 118, 86165 Augsburg, Germany

Correspondence to: Thomas O. Hoffmann (thomas.hoffmann@bafg.de)

Abstract. Suspended sediment is an integral part of riverine transport and functioning that has been strongly altered during the Anthropocene due to the overwhelming human pressure on soils, sediments, and the water cycle. Understanding the controls of changing suspended sediment in rivers is therefore vital for effective management strategies. Here we present results from a trend analysis of suspended sediments covering 62 monitoring stations along the German waterways (catchment sizes range between 2000 and 160 000km²) with more than 440 000 water samples taken between 1990 and 2010. Based on daily monitoring of suspended sediment concentration (*SSC*), we found significant declines of mean annual *SSC* and annual suspended sediment loads (*SSL*) at 49 of 62 monitoring stations between 1990 and 2010. On average *SSC* declines by -0.92 mg l^{-1} yr^{-1}. At some stations decreases during the 20 years represent up to 50% of the long-term average *SSC*. Significant decreases of *SSC* are associated with declining *SSL* despite an increase in sheet and rill erosion by almost 150% derived from modelling due to changes in land use and management as well as rainfall erosivity. The contemporary suspended sediment loads of the Rhine at the German-Dutch border approaches the natural base level of ~1 Mt yr^{-1}, which was achieved by the Rhine during the mid-Holocene when the suspended sediment load was adjusted to the Holocene climatic conditions and before the onset of increased loads due to human induced land use changes in the Rhine catchment. At this point we can only speculate regarding potential reasons for a decline in sediment transport in supply to larger rivers despite erosion increase. We argue that changes in soil erosion within the catchments and/or the increased sediment retentionconnectivity in upstream headwaters, e.g. due to the construction of small rainwater retention basins, are presumably is the major reason for declining *SSC* in the studied large river channels.

1 Introduction

Suspended sediment transport from land to ocean is a key component of the global sediment budget that strongly changed in response to human impacts during the Anthropocene. Recent estimates of the pre-Anthropocene magnitude of the land-ocean transfer range around ~15 Gt yr^{-1}~~per year~~ with suspended sediment transport representing the largest fraction (~14 Gt yr^{-1}) (Syvitski et al., 2022; Syvitski and Kettner, 2011). Human-induced land cover changes accelerated hillslope erosion compared to natural background rates by several orders of magnitude (Golosov and Walling, 2019; Montgomery, 2007; Nearing et al., 2017), strongly increasing the supply of fine sediments to river systems in large parts of the world. During the same time, increased sediment supply is counter-balanced by sediment retention due to the rapidly increasing number of large dams (Vörösmarty et al., 2003), disrupting the flow path of almost all large rivers in the world, with less than 23% of the global rivers flowing uninterrupted to the ocean (Grill et al., 2019). Global sediment retention in reservoirs increased by a factor of ~23 from 2.8 Gt yr^{-1} in 1950 to 65 Gt yr^{-1} in 2010 (Syvitski et al., 2022). Owing to the large retention of sediment behind dams, global sediment supply to the oceans ceased by ~50% to about 7.3 Gt yr^{-1} in 2010.

The evolution of regional sediment budgets during the Anthropocene may strongly deviate from the global figures due to multiple trajectories of socio-environmental changes around the world. While countries with strongly increasing population typically show intensified erosion (Golosov and Walling, 2019) and sediment retention in reservoirs (Annandale et al., 2018), high-income countries start to demount large dams and reestablish the sediment continuity in river systems as a necessary prerequisite of healthy riverine ecosystems. ~~A prominent example for dam removal is the Elwha River restoration project in Washington state (USA), which started in 1992 and resulted in a fully reconnected river after the removal of the last dam in 2014 (East et al., 2018).~~ In Europe, where more than one million barriers fragment rivers (Belletti et al., 2020), efforts are undertaken to reestablish the sediment connectivity and natural functionality of rivers ~~to achieve a good ecological status or potential~~ as requested by the European Water Framework Directive (EC-WFD, 2000). ~~Where possible this includes the removal of dams, esp. in Finland, Sweden, France, Spain and the United Kingdom where almost 5000 old, abandoned or out of use dams were removed (see map on https://damremoval.eu).~~ However, dam removal is hardly possible along waterways (i.e. navigable river channels). Here sediment management plans were developed to maintain navigability, hydro power, flood protection and other usages, while reducing the negative effects of dams and to increase the (sediment) connectivity without dam removal (BAW and BfG, 2016).

Kommentiert [TH, M31]: Line 44: Waterways may need a definition

Kommentiert [TH, M32]: Lines 34-47: this paragraph is a bit too long. I suggest reducing it by 50%

Different trajectories of socio-environmental change can be found in Germany after the re-union of the former German Democratic Republic in the East and the Federal Republic of Germany in the West. In particular land use and management affecting soil erosion, developed differently since 1990. While farm size in the East decreased, there was a strong increase in farm sizes and in turn in field sizes in the West (BMLE, 2021). The acreage of potatoes, which is the most erosion prone crop in rotations (Auerswald et al., 2021) halved in the East, while there was a pronounced increase in silage maize, another erosion-prone crop, in the West for biogas production (DESTATIS, 2021a, b). In the East, soil conservation is widely applied with more than 70% in some administrative regions, while this is far less popular in the West with less than 20% in some administrative regions. These changes in land use should have caused different trajectories of soil erosion and sediment supply in the East and in the West, which are overlain and dominated, however, by a strong increase in rain erosivity due to climate change (Auerswald et al., 2019).

Additionally, soil conservation programs are implemented in many of regions worldwide with the aim to reduce the loss of soils and to mitigate negative on- and off-site effects of accelerated human-induced soil erosion. The first nation-wide soil conservation program was started in the USA with the foundation of the Soil Erosion Service in response to the damages of the Dust Bowl in the American prairies in the 1930 ties (Montgomery, 2007a). Following the implementation of large scale soil conservation measures, soil erosion rates strongly decreased from the 1930s to the 1990s (Trimble, 1999).

In China, large-scale vegetation restoration projects started in 1999. In particular, the Grain-for-Green program which established a perennial vegetation cover in the Loess plateau resulted in decreased soil erosion rates in the Yellow river catchment after 1999 (Wang et al., 2015). However, it is important to note that measures taking highly productive but erosion prone areas out of agricultural use might result in enhanced production and erosion in other regions of the world compensating reduced crop production in China.

In Germany the Federal Soil Protection Act, which was passed in 1999 (BMUV, 2002), builds the basis for the large scale implementation of soil conservation measures. In Germany the implementation of soil conserving agricultural management slowly increased during the last decades. In 2009/10 about 38% of arable land were was under soil conservation (reduced, no inversion tillage), while only about 1% was under no-till (DESTATIS, 2011). However, the tendency of increasing agricultural soil conservation practice is counteracted by a number of processes, which increase the erosion and sediment transport potential. These are (i) a mean increase in rainfall erosivity due to increasing frequency and intensity of erosive storm events in Germany between periode 1960 to 1980 and 2001 to 2017 of 66% (Auerswald et al., 2019), (ii) an increase in erosion prone maize cultivation mainly due to biogas production from about 7400 km² to 10 500 km² (i.e. by ~70.3%) between the periode 1991 to 2000 and 2012 to 2017 (total area of about 10 500 km²) (DESTATIS, 2021a, b), and (iii) an increase in sediment connectivity due to increasing field sizes and an associated loss in linear landscape feature between fields, which are best approximated via the substantial increase average in farm size from about 39 ha in 1991 to 67 ha in 2016 (BMLE, 2021). Overall, the effect of potential changes on the sediment supply to rivers and their effect on suspended sediment in Germany remains unknown so far.

In this study we use data from the long-term suspended sediment monitoring network that is maintained by the German Waterways and Shipping Authority for sediment management purposes to study the changing suspended sediment dynamics during the last decades. The monitoring started in the 1960s based on work daily sampling of suspended sediment at ~60 monitoring stations along the German waterways to secure navigability in the context of efficient sediment management. The dataset provides valuable information to study long-term changes of the suspended sediment and to study the control of land use, river management and climate change on suspended sediment dynamics in Germany. So far, no systematic study of changing *SSC*suspended sediment concentrations and *SSL* loads using this dataset has been undertaken. Here we aim to detect changing suspended sediment concentrations (*SSC*) between 1990 and 2010 and discuss potential drivers for the observed

Kommentiert [TH, M33]: Line 60: “In 2009/10 about 38% of arable land were under soil conservation” should be “In 2009/10 about 38% of arable land was under soil conservation

Kommentiert [TH, M34]: Line 63: Rainfall erosivity needs a definition here

Kommentiert [TH, M35]: Line 65 “periode” should be “period”

Kommentiert [TH, M36]: Line 65: The original area could be included to add some further contextualisation about the impact of this change.

Kommentiert [TH, M37]: Line 72: It is not immediately clear what is meant by Work-daily. Perhaps a short definition is required.

changes. The time scale from 1990 and 2010 was chosen because most monitoring stations were active during this time ~~period~~ and therefore allows to compare the trends between the different stations and between Western and Eastern Germany.

In this study we mainly focus on *SSC* instead of suspended sediment loads (*SSL)* as the former is the primary characteristic of the river system, and the latter is calculated based on the product of *SSC* and discharge (*Q*). In most river systems *SSC* is strongly conditioned by *Q* but it is an independent variable that does not require the estimation of *Q*. Thus, we argue that changing *SSC* is an immediate response of changing sediment sources and dynamics and less likely due to climatic driven changes in *Q*.

2 Methods

2.1 Suspended sediment monitoring

SSC in German inland waterways has been monitored ~~using work daily water samples taken manually~~ by the Federal Waterways and Shipping Administration (Wasserstraßen- und Schifffahrtsverwaltung des Bundes, WSV). *SSC* monitoring started in 1963 at Hitzacker (Elbe River) and in 1964 in Maxau (River Rhine). Further stations were added to the monitoring network in the 1960s (10 stations), 70s (23 stations) and in the 80s (17 stations). In East Germany (i.e. in the former Democratic Republic of Germany) monitoring began only in November 1991 adding 20 stations, along the Elbe, Oder, Havel and Spree. By 2020, many monitoring stations provide long-term records that cover more than 30 years. Due to the decommission of some stations after 2000, the maximum number of stations were maintained during 1991 and 2010. For the ease of comparability of the calculated trends between stations, we focus the trend analysis for all stations on this time interval ~~despite~~ even though~~the fact that~~ single stations ~~have~~ monitored much longer~~ monitoring intervals~~. For selected stations we discuss the stability of the trend analysis in comparison to extended time-periods.

At each monitoring site, 5-liter water samples are taken each work day (i.e. excluding weekends and public holidays). During floods the sampling frequency is increased to up to 3 samples per day, unless sampling was prohibited due to safety reasons. At some stations sampling gaps resulted from shortages of the technical staff or from technical issues. Typically, data gaps during weekends and holidays (i.e. shorter than or equal to ~~than~~ two days) were filled using linear regression. Larger data gaps were not considered in the trend analysis of *SSC* (for a sensitivity analysis of calculated trends for selected stations using data with data gaps and with filled data gaps see Fig. S1). Water samples are filtered using commercial coffee filters, which are weighed before and after filtering in dry conditions to calculate the daily *SSC* (mg l^{-1} = g m^{-3}). The use of coffee filters is cost-efficient and facilitates measuring *SSC* at a large number (i.e. ~70 samples per day at the national scale) and of sufficient quality. However, these filters do not have a well-defined pore diameter and a significant fraction of clay is lost (compare Hoffmann et al. 2020). ~~Calculated~~ Furthermore, calculated *SSC* values presented in this study include both the mineral and organic material of suspended sediment and are therefore equivalent to the concentration of the total suspended solids (for more details on sampling of suspended sediment see Hoffmann et al., 2020).

Work-daily *SSC* time series for each monitoring station covers variable times due to variable start of the monitoring at each site, decommissioning of monitoring stations and larger data gaps due to maintenance issues. Therefore, we only analyzed the long-term *SSC*-trends of those stations that cover more than 15 years with more than 150 samples per year (representing approx. 50% of the samples taken during a year at a station) between 1990 and 2010 resulting in 62 monitoring stations that are included in this study. The monitoring stations are located along 18 waterways in Germany, including the rivers Danube, Rhine, Ems, Weser, Elbe, Oder, and their larger tributaries (Fig.1). The gauging stations cover contributing areas from 2,076 to 159,555 km² (Tab. S1). The topography of the river catchments includes the steep high mountain terrain of the European Alps (e.g. Alpine Rhine and Danube) as well as the mountainous regions with various geological settings in Central Europe and the flat terrain of Northern Germany, which is mainly composed of glacial and fluvial Quaternary deposits. Daily discharge for each station was taken from the water information system (WISKI) of the Federal Waterways and Shipping Administration, from gauging stations at or nearby the suspended monitoring station. The long-term annual average discharge of the stations ranges from 7.5 to 2261 $m^3 s^{-1}$ (Tab. S1).

Kommentiert [TH, M38]: Line 109: is there a rationale for choosing 150 sample/year as the cutoff number of samples for considering annual SSC representative? Or is it a value chosen arbitrarily? (Which is fine, but maybe specify it in the main text)

Annual suspended sediment loads (*SSL* in t yr^{-1}) were calculated based on the discharge-weighted averaging according to Walling (1981):

$$SSL = k \frac{\sum_{i=1}^{n} \overline{Q_i} \times \overline{SSC_i}}{\sum_{i=1}^{n} \overline{Q_i}} \bar{Q} \qquad (1)$$

where $k = 60^2 \times 24 \times 10^{-6} = 0.0864$ is a unit conversion factor ~~(translating mg l^{-1} to t day^{-1})~~, $\overline{Q_i}$ ($m^3 s^{-1}$) and $\overline{SSC_i}$ (mg l^{-1}) are daily averages of discharge and *SSC*, respectively, during days with *SSC*-measurements and $\bar{Q}$ is the annual average discharge. Eq.1 considers time gaps without *SSC* measurements and interpolates them based on the ratio of the mean annual discharge ($\bar{Q}$) and the average discharge during days with *SSC*-observations. As mentioned above, years with less than 150 measurements (e.g. due to operational issues at the monitoring station) were ignored in the trend analysis.

Infrequent sampling or large data gaps may result in strong underestimation of the annual average *SSC* or the annual suspended load especially in small and flashy river systems (Horowitz et al., 2015; Moatar et al., 2006; Walling and Webb, 1981). The monitoring stations considered in this study are all located along larger rivers that show a smoothed and buffered behavior compared to smaller river systems (Slabon and Hoffmann, accepted) and no major data gaps were observed during severe floods. Therefore, we are confident that existing data gaps did not strongly alter the conclusions drawn from our analysis.

2.2 Trend analysis

The trend analysis of the *SSC* from 1990 and 2010 was performed on annual average *SSC*s for hydrological years starting with the flood period at 1st November and ending at 31st October. We applied linear least-squared regression (LSR), Mann-Kendall test and Sen's slope, which are frequently used in trend analysis of suspended sediment transport (Pohlert, 2018; Walling and

Fang, 2003). We applied the LSR due to its simplicity, well knowing that i) residuals of the LSR may not be normally distributed (e.g. due to the existence of extreme *SSC*-values), or ii) mean annual *SSC* data may show autocorrelation. Thus, we checked for normality of the residuals using qq-plots with 95% confidence intervals and for autocorrelation using the Box-Pierce test. 12 stations show ~~non-linear~~ non-normally distributed residuals of the LSR, ~~indicating~~ indicated by ~~that the assumption of LSR is violated~~ (italic p_{lin}-values in Tab. S2 ~~in italic~~). Furthermore, 46 of the 62 stations show auto-correlation of the mean annual *SSC* at $p<0.05$ level, indicating limited applicability of the LSR for trend analysis.

To evaluate the limitations of the linear regression on time series data we additionally used the non-parametric Mann-Kendall test to detect monotonic trends of *SSC* for each station. In contrast to LSR, the rank-based Mann-Kendall test does not rely on normally distributed residuals and does not make any assumptions about the type of trend (i.e. linear or non-linear) as long as values are changing monotonically. In case of significant trends at a 5% level (i.e. Mann-Kendall's $p<0.05$), we estimate the magnitude of the annual *SSC* trend in $mgL^{-1}a^{-1}$ using the Sen's slope. ~~The Mann-Kendall test and the Sen's slope are calculate using the R package 'trend' (Pohlert, 2018). The rank-based Mann Kendall test is suitable for data with non-normal distributions and does not make any assumptions about the type of trend (i.e. linear or non-linear) as long as values are changing monotonically.~~ The calculation of the magnitude using Sen's slope provides robust estimates in the presence of extreme values. The Mann-Kendall test and the Sen's slope are calculated using the R package 'trend' (Pohlert, 2018).

To check for seasonal differences, we calculated trends based on annual averages for the summer months from June to August and winter seasons from December to February. The winter season covers large parts of the flood period of large rivers and is controlled by prolonged advective rainfalls with little evapotranspiration, while the summer months are characterized by frequent short and intense convective rainfalls of small spatial extension and high rainfall erosivity (Fiener and Auerswald, 2009; Fiener et al., 2013) that cause floods in small catchments. ~~The winter season covers large parts of the flood period and is controlled by prolonged advective rain falls with higher rainfall amounts, while the summer months are characterized by lower rainfall magnitudes (compared to the winter months) but short and intense convective rain falls with high rainfall erosivity (Fiener et al., 2013).~~

Under the assumption that *SSC*s change linearly with time ($SSC = a + bt$, where t is time in years since an arbitrary chosen date, and a and b coefficients) and that the discharge Q remains unchanged, changes of *SSC* translate to changes of the suspended sediment load (SSL):

$$SSL(t) = k \times Q \times SSC(t) \quad (2a)$$

$$\frac{dSSL(t)}{dt} = k \times Q \times \frac{dSSC(t)}{dt} = kbQ \quad (2b)$$

Kommentiert [TH, M39]: Line 141 "the assumption of LSR is violated" It would be clearer if you stated what this assumption was first in case people are not familiar with linear least squares regression

Kommentiert [TH, M310]: Line 144: It is not clear why the Mann-Kendall test is being used or what it tests from this description.

Kommentiert [TH, M311]: Line 145: I also found the description of the Sen's slope unclear. What is the magnitude of the trend?

with the conversion factor $k = 0.0864 * 365.25$ to obtain annual SSL in units of tonnes per year for units of SSC and Q in mg l^{-1} and m³ s^{-1} (compare Eq. 1). Eq. 2b implies a linear decline of annual SSL for negative b, as suggested by the trend analysis in this study (see results on *SSC* trend).

2.3 Trend of rating parameters

In many studies, sediment rating curves of the form

$$SSC = \alpha Q^{\beta} \qquad (3)$$

are used to predict SSC (Doomen et al., 2008), or to understand source/transport characteristics in form of hysteresis analysis (Asselmann, 2000; Hoffmann et al., 2020). In this study, we do not use the rating approach to predict SSC for infrequent measurements or for SSC data gaps, but use the rating coefficients to identify changes ins suspended sediment transport conditions. The rating coefficients α [mg l^{-1}] and β [-] represent the suspended sediment concentration at unit discharge and the steepness of the increase of SSC with Q, respectively. The steepness β is often related to the reactivity of river catchments with increasing to the topography of the contributing catchment area, with higher increases of *SSC* for a given increase in *Q* for steeper catchments that supply more sediment than gentle contributing catchments (Syvitski et al., 2000). Changing conditions of suspended sediment in rivers are translated to changes in the rating coefficients (Warrick, 2015). An increase or decrease of α relates to parallel upwards or downward shift of the rating curve, and thus changing *SSC* equally at all discharges. Changes in β modifies the frequency-magnitude of suspended sediment transport, with increasing steepness raising the effect of large magnitude events, while decreasing steepness shifts the formative events towards smaller discharges (Warrick, 2015). Here we calculate the rating coefficients in Eq. 3 using log-linear regression for each station and for each year with more than 150 measurements per year between 1990 and 2010. Rating coefficients for a certain year were only used for the trend analysis if the log-linear regression analysis resulted in significant p-values < 0.05. Hoffmann et al. (2020) showed that rating curves of almost all monitoring stations used here are characterized by a bi-linear relation in the log-log diagram, with a scale break at discharges close to the geometric mean discharge Q_{gm} of each station. Therefore, we normalized all *SSC* and *Q* data by the geometric mean of each station: $(SSC/SSC_{GM}) = \alpha(Q/Q_{GM})^{\beta}$ and used only data for the high-flow regime $Q/Q_{GM} > 1$, which is mainly controlled by sediment supply from hillslopes during surface runoff generating rain-fall events. According to Warwrick (2015) the use of normalized data minimized the effect of the interrelation of α and β, which arises if rating curves are estimated on non-normalized data.

Kommentiert [TH, M312]: Lines 130-132 and 170-171: what are the reason(s) for not using rating curves to correct for missing measurements? A sensitivity test (e.g. in the supplementary materials) for a few rivers comparing mean SSC with and without correction for missing measurements using rating curve approach and discharge may be useful here to demonstrate that the data gaps do not affect the calculated mean SSC and observed trends. Also, are the 150 data points evenly distributed throughout seasons for all rivers?

Kommentiert [TH, M313]: Line 171: "identify changes is suspended…" should be identify changes **in** suspended…

Kommentiert [TH, M314]: Line 172: Units of these metrics would help to explain them.

Kommentiert [TH, M315]: Line 173: I am not sure what is meant by "reactivity of river catchments"

Kommentiert [TH, M316]: Line 180: When is the log-linear regression analysis used?

2.4 Driving factors

A multitude of natural and anthropogenic factors potentially control *SSC* in German waterways, some ~~of which~~ are inherently difficult to quantify. Changes of *SSC* are either linked to changes of sediment supply to river systems, or sediment retention along the flow path within the river channels or their neighboring floodplains.

Here, we tried to grasp the influence of drivers that are frequently discussed in context of changing *SSC* and *SSL* in large river systems. With respect to changes in the sediment supply from the contributing catchments, the considered drivers include changes in (i) rainfall amount and characteristic, (ii) river discharge (as an integrative parameter for water supply to river systems) and (iii) land cover (i.e. coverage by plants protecting the soil from erosion).

~~Daily rainfall data are taken from the gridded HYRAS dataset (Rauthe et al., 2013) with a spatial resolution of 1 x 1 km² derived from 6200 precipitation stations. The dataset covers the river basins in Germany and parts of the neighboring countries that drain into these basins. Daily rainfall data are aggregated to summer and annual sums for the years between 1990 and 2010 for nine selected river catchments including the Rhine upstream of Maxau, and some of its tributaries (Lahn, Neckar, Main, Moselle), the German part of the Danube catchment upstream of Straubing, as well as the Ems, Weser and Elbe catchments (see Fig. S1 for location of gauging stations and contributing catchments). Due to the low temporal resolution of the rainfall data, we did not calculate the rainfall erosivity, which is strongly conditioned by short and intense rainfall events, as daily rainfall data strongly smooth maximum rainfall intensity. Instead, we used the rainfall erosivity maps for Germany representing the central years of 1975 (Sauerborn, 1994) and 2009 (Auerswald et al., 2019) to derive the trend of rainfall erosivity in Germany.~~

Discharge for all *SSC* monitoring stations is taken from the Water Information System (WISKI) of the German Waterways and Shipping Authority. Here we used daily discharge data from gauging stations located at or close to the suspended monitoring stations. For the trend analysis, daily discharge data are aggregated to mean annual discharges ~~aggregated~~ using the hydrological year (similar to *SSC* and *SSL*).

~~The trend analysis of the mean annual and summer precipitation per catchment and mean annual discharge for gauging stations is performed in the same way as for *SSC* using the Mann-Kendall test, and the magnitude of the Sen's slope.~~

To analyses changes in sediment supply due to changes in soil erosion within the catchments between 1990 and 2010 changes in the factors representing rainfall erosivity (*R* factor) and soil cover (*C* factor) are used in the framework of the Universal Soil Loss Equation USLE (Wischmeier and Smith, 1978) were utilized. The *R* factor quantifies rainfall erosivity, which linearly relates to the soil loss caused by rainfall under otherwise constant boundary conditions. Hence, rainfall erosivity of individual events can be summed up to yield the annual *R* factor. Until 2016 *R* is available annually from rain gauge measurements and since 2001 it is determined with 1 x 1 km² resolution from rain radar measurements (Auerswald et al., 2019). Land use and land management is quantified in the *C* factor of the USLE and mainly depends on the shares of grassland and arable land and the proportions of different crops on arable land.

Kommentiert [TH, M317]: Line 202: rainfall erosivity still needs a definition.

We used statistical yearbooks for the Federal Republic of Germany between 1990 and 2020 (provided at www.destatis.de) to derive the extend of arable land and grassland for each year, including proportions of grain and silage maize, potatoes, and sugar beets on arable land. These data were converted to *C* factors following Auerswald et al. (2021). Since land use and management developed differently in West and East Germany after the reunification in 1990, we separately present the changes in C for West and East Germany. We did not consider changes in the length of the erosive slopes, which is quantified by the *L* factor of the USLE, because such data are not available, and the effect is small because many fields are larger than geomorphologic slope length. The change in erosion over time is then given by the product of *R* and *C* because all other factors of the USLE are assumed to remain constant between 1990 and 2010.

~~CORINE land cover data provided by Copernicus, the European Union's Earth observation programme (https://land.copernicus.eu/pan-european/corine-land-cover). Here we used the rasterized land cover data (Version 2020_20u1) with a spatial resolution of 100 m x 100 m for years 1990, 2000, 2006, 2012 and 2018, to derive i) artificial areas, ii) arable land, iii) forest and iv) pasture. The data of each year were clipped with the polygons derived for the nine river catchments (Fig. S1) and the coverage for each of the 44 land use classes estimated for the nine river catchments. Artificial areas were derived from the sum of CORINE-classes 1 to 11, arable land from the sum of CORINE-classes 12 to 17, and forest from the sum of CORINE-classes 23 to 25. Pasture is given by CORINE-class 18. These land use classes cover the majority of the considered catchments with remaining land uses range between 1,4 to 19 % for the various years and river catchments (excluding the Rhine catchment upstream of Maxau). The Rhine catchment shows a somehow larger fraction of other land cover classes (approximately 25%) due to high fraction of alpine areas in this catchment.~~

Kommentiert [TH, M318]: Line 214 "artificial areas" I see this is how CORINE names this group of classes (which contains Urban fabric, industrial units, mining and construction sites, artificial vegetated areas) but the name itself is a bit vague. Maybe at line 216 you could specify the kind of land cover class this refers to.

Drivers affecting sediment retention in river systems are represented here by the numbers of dams along the German waterways and the volume of reservoirs in Germany (taken from Deutsches Talsperrenkomitee e.V., 2013). The latter is limited to reservoirs with a dam height larger than 15m. This excludes many small barriers and dams that disconnect sediment transport in medium and small river systems as indicated by Belletti et al. (2020), who assume a total barrier number of more than 18000 in Germany. ~~The cumulative increase of both numbers between 1900 and 2010 is used as a first order proxy for the timing of sediment retention.~~ While reservoirs are typically located in smaller headwater catchments, their cumulative volume is a first order proxy of disconnectivity of sediment supply from hillslopes to river channels. In contrast, dams along the waterways (constructed mainly to produce hydro power and to improve navigation) retain suspended sediments within the river channel. Their trapping efficiency in terms of suspended sediments is typically much lower than that of reservoirs. The cumulative increase of both numbers between 1900 and 2010 is used as a first order proxy for the timing of sediment retention.

3 Results

3.1 *SSC* trends

For both trend-algorithms (i.e. linear regression and Sen's slope) 56 stations showed significant changes of mean annual *SSC*s between 1990 and 2010 (Fig. 2+3 and Tab. S2). Only 6 stations show no significant change at the 5% level. *SSC*-gradients of

Kommentiert [TH, M319]: Line 231: Why is there no change seen at these 6 stations? Could there be any information derived from these stations? (and again on lines 255 and 260 for the seasonal data).

stations with significant changes derived from the linear regression (b_{lin}) range between -2.02 to -0.38 mg l^{-1} yr^{-1} with a mean of -0.92 mg l^{-1} yr^{-1}. Relative to the mean *SSC*, the gradients represent declines of -0.2 to -8.7 % yr^{-1}. Sen's slopes (b_{sen}) for stations with significant p-values at 5% level range in the same order between -1.99 to -0.37 mg l^{-1} yr^{-1} (or -8.9 to -0.26 % yr^{-1}) with a mean of -0.92 mg l^{-1} yr^{-1} (3.7 % yr^{-1}) (compare Fig. 2).

Negative *b* values indicate that 56 out of 62 stations are characterized by a significant decline of mean annual *SSC*s between 1990 and 2010. Both trend algorithms show comparable trends with only marginal differences between the Sen's-slope and the linear gradient (compare Fig.04 for examples from stations at Maxau (207) and Emmerich (215) along the Rhine or ~~also~~ Fig. S02 for all stations). The similarity of both approaches suggests that in our case autocorrelation of annual averaged *SSC*s and outliers (due to extremes) do not play a major role for the trend estimation. However, for statistical correctness we use the Sens's slope for further analysis as residuals of the LSR are mostly not normally distributed, which violates the assumptions of the LSR.

Stations without significant changes for both trend algorithms ~~over the time period~~between 1990 to 2010 include: Straubing (ID 102) and Jochenstein (ID 107) along the Danube River, Weil (202) at the Rhine ~~r~~River ~~(202)~~, Rheine (301) at the Weser ~~r~~River and Hitzacker (502) the most downstream station along the Elbe ~~r~~River (Fig. 3~~b~~). Additionally, for linear regression station Brodenbach (258) at the Moselle River and for the Sens-slope regression station Viereth (231) at the Main River show no significant decreases (see Fig. 3~~a~~).

The magnitude of the decline seems to be unaffected by the average discharge at the stations but is weakly controlled by the average *SSC* between 1990 and 2010 (Fig. ~~4~~5). Stations with high average *SSC*s show generally stronger declines than stations with low average *SSC*s. This is especially evident along the Rhine, where *SSC*s at the stations in the Upper Rhine show lower average *SSC*s and either no (stations Weil, ID 202) or lower (station IDs 203, 205, 206 and 207) declining trends than the stations at the Middle and Lower Rhine (station IDs 212, 215, 216 and 217), where average *SSC*s are higher and trend magnitudes are larger (Fig. ~~5~~3). Strongest declines along the German waterways with b_{sens} < -1.5 mg l^{-1} yr^{-1} are overserved at four stations in the Elbe and Weser catchments (station IDs 531, 516, 520 and 421). However, ~~Fig. 3 does not indicate~~there is no indication of a general spatial pattern of the *SSC* decline (Fig. 3).

The seasonal trend analysis confirms the general picture of the annual trends (see Tab. S2 and Fig. ~~5~~ 4 for examples at Maxau and Emmerich). 52 of 62 stations show a significant trend of the average *SSC* during June, July and August (summer trend) from 1990 to 2010. Except for Hitzacker, the most downstream station at the river Elbe, all significant summer trends of the monitoring stations in Germany are negative ranging from -2.87 to -0.36 mg l^{-1} yr^{-1} (or -10.6 to -0.3 % yr^{-1}). At Hitzacker the summer trend is increasing with 0.76 mg l^{-1} yr^{-1} (or 2.3 % yr^{-1}). Interestingly, the largest summer decline is also observed at the river Elbe in Magdeburg (b_{summer} = -2.87 mg l^{-1} yr^{-1} or 10.2 % yr^{-1}) approximately 190 km upstream of Hitzacker. Average SSCs during the winter months (December to February) decline significantly at 49 of 62 stations, with 13 stations showing no significant change and no station showing a significant increase. b_{winter} ranges -3.55 and -0.39 mg l^{-1} yr^{-1} (or -11.6 to -0.2 % yr^{-1}), while most station scatter between -1.5 and 0.5 mg l^{-1} yr^{-1}. At Hitzacker, the winter months show a significant decline with

Kommentiert [TH, M320]: Lines 247-248: in figure 4, is the "average SSC" the average during the 1990-2010 period?

-0.61 mg l^{-1}yr^{-1} (or -1.8 % yr^{-1}), despite the increase of *SSC* during the summer months. ~~This~~ These contrasting seasonal trends result in insignificant changes at Hitzacker during the whole year.

The comparison of the seasonal trends (Fig. 6) indicates that declines during the summer months are ~~somehow~~ somewhat larger (i.e. more negative) for 30 stations, and only 10 stations show stronger decreases during the winter. This agrees with the slightly stronger average decrease in the summer months (-1.11 mg l^{-1}yr^{-1}, or -4.7 % yr^{-1}) than in the winter months (on average -0.94 mg l^{-1} yr^{-1} or -3.7 % yr^{-1}).

*SSC*s changes for all 62 monitoring stations covering their full monitoring period between 1970 and 2020 are shown in Fig. 7 using annual residual *SSC*s. The annual residuals are calculated based on the annual average *SSC*s and the average *SSC* of the entire monitoring period for each station (compare Tab. S1). The annual *SSC* residuals of all stations show a strong interannual variability before 1995 without any major trend (Fig. 7). After 1995, *SSC* residuals declined for almost all stations. Interestingly the pattern of the variability also changes; before 1995, the interannual variability of many stations showed the same pattern as indicated by the variability of average residuals (thick red line in Fig. 7), while after 1995, the stations show a random pattern with arbitrary up and downs with respect to the annual SSC residuals (smooth course of the average SSC). After 2010, the decline stopped at ~ -7 mg l^{-1} relative to the long-term average *SSC* of each station. The compilation of the residual *SSC*s suggest that the SSC decline between 1990 and 2010 is mainly characterized by a gradual decline, which was accentuated between 1995 and 2010 at most stations. Due to the strong variability of the annual *SSC* residuals, single stations might have a different trajectory than the average behavior (bold blue line in Fig. 7). However, the consistent behavior of the majority of stations indicates a major change between 1995 and 2010 of the environmental factors controlling the suspended sediment dynamics in the Germany waterways.

Kommentiert [TH, M321]: Line 390 "SSCs changes between 1970 and 2020 are unraveled by the compilation of the residual SSCs which were calculated using the daily SSCs and the long term average SSC for each station." This is not really clear. Are these the residuals from your Sen slope regression?

3.2 Trends of rating parameters

We were able to calculate a significant annual sediment rating with more than 15 years per station for 59 stations. 41 stations show~~ed~~ a significant decline of the α coefficient with $d\alpha/dt$ ranging between -1.08 and -0.28 mg l^{-1} yr^{-1} (or -6.0 % yr^{-1} and –1 % yr^{-1}). Stations with an insignificant change of α include the stations of Jochenstein (107), Viereth (231), Rheine (301) and Hitzacker (502), which show insignificant Sen's slopes. Interestingly, Straubing (102) and Weil (202) show insignificant Sen's slope but significant changes of α. The mean and median value of $d\alpha/dt$ for all stations is -0.71 and -0.72 mg l^{-1} yr^{-1} (-3.2 % yr^{-1}), respectively, which is a little smaller than the average Sen's slope. Strongest declines are observed at the stations along the Rhine (Tab. S2) and none of the 59 stations showed a significant increase of α. Only 14 of 59 stations show a significant change of the rating exponent β; 9 stations show an increase in β (increasing reactivity) and 5 stations show a decrease in β (decreasing reactivity). Overall $d\beta/dt$ ranges between -0.072 yr^{-1} and +0.078 yr^{-1} (Tab. S2). At some stations with a strongly increasing rating exponent the α coefficient strongly declines, indicating an inverse relationship between changes in α and β despite the normalization of the rating analysis.

Kommentiert [TH, M322]: Line 270: Do these analysis techniques identify the same stations as not changing?

3.3 *SSL* trends

Only one station (i.e. Marktbreit (231) at the ~~river~~ Main River) of 63 stations shows a significant change of the mean annual discharge at 5% significance level based on the Mann-Kendall test all other stations show strong interannual variability of mean discharge, but no general trend (not shown). In conjunction with the declining *SSC* at the studied monitoring stations, *SSL* is expected to strongly decrease between 1990 and 2010. 48 of 63 stations show a significant negative trend of *SSL* with annual declines ranging between 0.1 and 94.9 kt yr^{-2}, with an average of 14.7 kt yr^{-2}. As suggested by Eq. 2 the magnitude of the SSL-decline ~~of *SSL*~~ grows ~~with increasing~~linearly with discharge (Fig. ~~7~~8). For instance, the annual load at Maxau (207) declined on average by 28.5 kt yr^{-2} from around 1.3 Mt yr^{-1} to 0.8 Mt yr^{-1} between 1990 and 2010, the decline in Emmerich (215) was twice as high (i.e. 66.3 kt yr^{-2}) from 2.8 Mt yr^{-1} to 1.8 Mt yr^{-1} for the same time.

Based on Eq. 2, ~~A~~ a mean decline of *SSC* between 1990 and 2010 of $dSSC/dt = b = -0.92$ mg l^{-1} yr^{-1} ~~can be~~was used to calculate an annual decline of SSL of ~30 kt yr^{-2} per 1 m³ s^{-1} of discharge, which is in general accordance with regression of $-dSSL/dt$ and Q_m resulting in a regression slope of 31.5 kt yr^{-1} per 1 m³ s^{-1} as shown by the blue dotted line in Fig. 7. The linearity of the relationship between $-dSSL/dt$ and Q_m indicates that the assumption of a linear decrease of SSC is valid and results in the simple relationship as derived in Eq. 2b.

3.4 Trends of erosion factors

Despite the declining trend of *SSC* at the majority of monitoring station, soil erosion by rainfall derived from the combined change of the *R* and *C* factors of the USLE almost doubled in Germany between 1990 and 2020 (Fig. 9a). This increase is entirely caused by the increase in *R*, while *C* almost did not change and the national level, because of the different changes in East and West Germany, which exhibit opposing trends (Fig. 9b). In East Germany, the *C* factor dropped by about 10%, mainly due to the breakdown of potato production following the reunification, which mainly occurred from 1990 to 1991 (potato acreage about halved; data not shown) and caused a sudden drop of the *C* factor. Most other changes in East Germany were similar but weaker to those in West Germany and almost levelled out when combined. In contrast, land used change in West Germany increased the *C* factor by about 25%. This was largely due to a 20 % loss of grassland, which mainly occurred between 1990 and 2000, while the increase between 2000 and 2010 was mainly caused by a 50 % increase in the acreage of silage maize due to incentives for biogas production (data not shown).

Due to the strong change in *R*, erosion has increased in both parts of Germany, but the increase in West Germany must have been much stronger than in East Germany due to stronger increase of land use effects. From this, an increase in *SSC* over time could be expected that should be larger in West than in East Germany. In contrast to this expectation, stations in East Germany show on average slightly larger SSC decreases (average b_{sens}~1 mg l^{-1} yr^{-1}) than stations in West Germany (average b_{sens}~0.8 mg l^{-1} yr^{-1}).

4 Discussion

The presented trend analysis is based on 62 monitoring stations along large river channels, with an average monitoring interval of 19.9 years and almost 440 000 *SSC* samples in total. Overall, the monitoring stations are characterized by a low fraction of data gaps, with an average rate of only 4% of missing data with data gaps longer than two days. ~~(excluding the w~~Weekends and federal holidays ≤ 2 days add approximately 30%. However, these data gapes are filled by linear interpolation as long as no major floods took place~~).~~. Due to the large size of the studied rivers, their variability is ~~reduced~~ small compared to much smaller tributary streams. In large rivers~~, which are considered in this study,~~ floods with increased *SSC*s and loads last several days, suggesting that daily sampling is sufficient to cover the importance of floods (Slabon and Hoffmann, accepted). In contrast to the calculation of annual loads, which require a continuous sampling, irregularities in sampling frequency less strongly affect the average annual *SSC*, which is the focus of this study. Thus, we are confident that the data gaps are not substantially affecting our trend analysis. Furthermore, we can exclude that changes in monitoring techniques are affecting our results, since the measuring and monitoring approach has not been changed since its introduction in the 1960s. Furthermore, for the analysis of the time span between 1990 and 2010 we only used sampling stations without change in sampling location. As mentioned above, sampling is limited to surface water samples suggesting an underestimation of the cross-sectional average *SSC*. The sampling design was not changed over time and thus could not affect the temporal trends, while it may lead to an underestimation of the cross-sectional average *SSC* and in turn of *SSL*~~The point sampling certainly effects affects the estimation of the total fluxes, but should not affect the trend analysis, as SSC~~*SSC* ~~likely change in the entire cross section and not preferentially at the water surface~~ (as supported from unpublished results from the suspended sediment monitoring of the cross-sectional variability).

Kommentiert [TH, M323]: Lines 303-305: this is important. Many large river studies have shown that SSC increases (sometimes by a factor 2 to 5) with depth. This increase SSC with depth often related to increase of suspended silt and sand content above the riverbed. Is there any existing study on the Rhine or other German rivers reporting the extent of possible suspended sediment concentration change with depth? Although probably unlikely, a change in the proportion of fine/coarse sediment supply could lead to a decrease of surface SSC (fine sediments) but increase of SSC at depth and therefore an increase of depth average SSC?

In summary, we are confident that the estimated trends are real and not biased due to the techniques and approaches of the suspended sediment monitoring in the German waterways. Furthermore, the similarity of results derived from the Man-Kendall test in combination with the Sens's slope test and the trends derived from the least square linear regression suggest that the calculated trends are robust.

4.1 Declining trends of *SSC* and *SSL* in German river system

Despite the strong year to year variability of the annual average *SSC* at each station, our trend analysis shows a widespread declining trend of *SSC* at 58 out of 62 monitoring stations. At some stations annual average *SSC* declined by 50% between 1990 and 2010. No station shows increasing trends ~~of annual average *SSC*s between 1990 and 2010~~during the same time. This consistent decrease of *SSC* is surprising as ~~it~~ the stations cover~~s~~ a broad range of river catchments with different sizes (ranging between about 2000 and 160 000 km²), and variable topographic and geological conditions. Topographic conditions range from mountain topography of the European Alps, which cover parts of the Rhine and Danube catchments, to the lowland topography of Northern Germany, mainly covering the Ems, and northern parts of the Weser and Elbe catchments. Climate conditions range from maritime in West Germany to more continental climates in the East. Furthermore, land use history in West and East Germany followed different trajectories before and shortly after the reunification in 1990. Despite these differences in controlling factors, *SSC* declines consistently without any larger spatial pattern of the observed trends.

~~Based on the Sen's slope, on average SSC*SSC* declinesd by -0.92 mg l^{-1} yr^{-1}, representing -3.7 % yr^{-1} relative to the long-term average SSC*SSC* of each station. For instance, SSC*SSC* at the station Emmerich located at the Lower Rhine (Fig. 4) declined by 0.95 mg l^{-1} each year or in total by approximately 50% from ~40 mg l^{-1} in 1990 to roughly 20 mg l^{-1} in 2010. Declines during the summer months at this station were somehow larger (-1.21 mg l^{-1} yr^{-1}) than during the winter months (-0.99 mg l^{-1} yr^{-1}) (Fig. 4). However, due to the strong interannual variability of the annual mean SSC*SSC*, the differences between summer and winter months are were not statistically significant~~.

The station at Hitzacker belongs to the few monitoring stations that do not show a significant decline at the annual scale. Here declining *SSC* in the winter months and increasing *SSC* in the summer months counterbalance each other at the annual scale (Tab. S2). However, a trend analysis by Hillebrand et al. (2018) using the same data, but a longer timescale from 1964 to 2014, indicated a significantly declining trend. This monitoring station is located at the downstream end of the Elbe River and shows strong plankton growth during the summer months. Since *SSC* represents here the total suspended matter (including mineral and organic particles), increasing *SSC* during the summer months ~~are~~ may be mainly controlled by the autotrophic production within the river channel~~, and~~ while decreasing winter *SSC* likely results from changing supply conditions~~., either from reduced soil erosion and/or reduced sediment connectivity in river channels.~~ While many monitoring stations show evidences of increased autotrophic production during the summer months ~~(Hoffmann et al., 2020)~~ this effect is most pronounced at Hitzacker at the lower Elbe River (Hardenbicker et al., 2014; Hoffmann et al., 2020). The higher frequency of low-flow conditions during dry and warm summer months in combination with reduced flow velocities in the impounded sections of the ~~tributary~~ waterways increased the potential for strong algal blooms in in these rivers as an effect of future climate changes and likely effect future *SSC* trends.

Similar to the station at Hitzacker, the negative trend at Straubing (102, Danube River) becomes significant ($p<0.01$ with a Sens slope of -0.3) if the full monitoring period between 1982 and 2019 of this station is considered, indicating a consistent declining trend for the Danube River upstream of its confluence with the Inn River. The station Jochenstein (107), which is located downstream of that confluence, shows no significant change at any time interval. Suspended sediment at Jochenstein strongly influence by the high *SSC*s of the Inn River, which drains a large part of the Austrian Alps with high sediment contributions by glacial erosion and gravitational mass movements. Similarly, the station Weil located at the transition between the High and Upper Rhine is also strongly characterized by a glacial discharge regime with no significant changes in *SSC*. This further supports the notion that rivers with strong alpine contributions are less or even not affected by declining *SSC* levels.

A positive ~~sediment rating~~relationship of *SSC* and discharge at almost all monitoring stations (Hoffmann et al., 2020) suggest that declining *SSC* levels might be related to decreasing discharges. The trend of the rating parameters indicate that changes are mainly related to the rating coefficient a, which shows a significant decrease at 41 out of 59 stations. Changes of the rating coefficient a are related to parallel shifts of the rating curve (Warrick, 2015) and therefore represent the changing *SSC* at all

Kommentiert [TH, M324]: Lines 322 and 325: technical correction, replace "Fig. 4" by "Fig. 5" discharge levels. Significant changes of the rating exponent *b*, which represents *SSC*-shifts between high and low magnitude discharges, are much less pronounced (only 14 of 59 stations show significant changes) and more or less equally distributed ~~between increased and decreased reactivity~~around zero.

In addition to the changes of the sediment rating relationship, mean annual discharges did not significantly change between 1990 and 2010. Therefore, we argue that changes in *SSC* are mainly driven by decreased sediment supply to the large river channels or decreased connectivity (e.g. sedimentation within the river channels) within the river network ~~and~~ while they are not related to changing discharge conditions. Furthermore, we argue that the strong decline of the suspended load, which is dominated by fine fraction (i.e. silts and clays), has no major impact on the channel morphology, which is dominantly formed by sand and gravels. Therefore, decreases in suspended loads had no major impact on sediment management in the German waterways, which is mainly related to the nourishment and dredging of sand and gravels to secure navigability in the waterways (Frings et al., 2019).

In contrast to the general and widespread decreasing trend in the German waterways, trends of suspended sediment transport in neighboring river systems outside of Germany are more variable. Poulier et al. (2019) studied the annual, flow-averaged suspended matter concentration (fw-*SSC*) at six stations in the Rhone catchment in France between 2000 and 2016. The Rhone catchment is characterized by alpine topography in the North and steep torrential characteristics with Mediterranean climate in the South. Since the end of the Second World war, river management strongly altered the flow characteristics and hydro-morphology of the rivers. However, none of the stations show a significant change of the *SSC* between 2000 and 2016 due to the strong interannual variability and the rather short time period. Mean annual *SSC* in the Warta River (Poland) increased between 1961 and 1980 by 2.6 mg l^{-1} per year (Skolasińska and Nowak, 2018). The increase is mainly attributed to the river channel management (i.e. deepening and cleaning of channel bed), the opening of a large lignite mine and the increased growth of phytoplankton during the summer months in response to ~~higher~~ increased nutrient levels and rising summer temperatures (similar to our results from the lower Elbe river).

The stations along the upper Danube River, upstream of the German-Austrian border, are characterized by declining trends (station 105 Vilshofen and 106 Kachlet) or insignificant changes (station 102 Straubing and 107 Jochenstein), as discussed above. Habersack et al. (2016) present marginal declines of ~~the~~ suspended sediment loads along the Middle Danube River for the ~~time~~ period between 1985 and 2000 compared to loads before 1960 ~~AD~~. In contrast to small decreases of the suspended load upstream of the Iron Gate I and II hydropower complex in Romania ~~which were constructed in 1972 and 1984 in Romania,~~ downstream of these reservoirs, which were constructed in 1972 and 1984, suspended sediment loads of the Lower Danube River massively decreased, with suspended sediment supply to the Black Sea ~~see~~ decreasing from more than 1 Mt yr^{-1} around 1960 ~~AD~~ to 0.4 Mt yr^{-1} from 1985~~-~~ to 2000 (Habersack et al., 2016). Therefore, ~~in the lower Danube,~~ the strong declines of *SSL* in the lower Danube are related to the ~~primary~~ control of the two dams in the main river channel.

The trend of decreasing *SSC* in Germany is paralleled by ~~strong~~ the ~~declining~~ decline of nutrient (C, N and P) and contaminant levels in the river channels in Germany (UBA 2014). ~~Strong reductions in point and diffusive nutrient inputs – f~~For instance ~~the~~ total organic carbon (TOC) declined from 5-6 mg l^{-1} in 1990 to ~3 mg l^{-1} in 2010 in the river Rhine at Koblenz (FGG Elbe,

Kommentiert [TH, M325]: Line 349 "decreases sediment loads had no major impact" should be "decreases in sediment loads had no major impact" or "decreasing sediment loads had no major impact"

2013). This suggests that declining *SSC*-levels in the German waterways may be~~is~~ related to decreased nutrient supplies, either because both trends have a common origin or because one trend is the reason for the other. ~~Certainly, the decrease of the nutrients and contaminants do not directly account for decreases of the SSC, since nutrient and contaminant levels are at least an order of magnitude smaller than that of the SSC. However, measures that caused decreased nutrient supply, such as construction of buffer strips between arable land and river systems or improved waste water treatment, might also affect sediment supplies to river systems (see also discussion on drivers of SSC decrease).~~

Due to the consideration of total suspended matter, which includes mineral and organic fractions, differences between changes in summer and winter *SSC* can be partially explained by the effect of decreasing TOC. TOC in the German waterways originates from aquatic biomass-derived organic matter and mineral-associated organic matter originating from eroded hillslopes (Hoffmann et al., 2020). Biomass-derived organic matter dominates during summer months, which are characterized by low flow conditions with long residence times of biomass in the river system, high availability of light and warm temperatures promoting algal growth and causing higher TOC contents during the summer. Thus, declining TOC between 1990 and 2010 is mainly observed during the summer months, as in the case of the station at Hitzacker, which is strongly influenced by biomass-derived organic matter (Hardenbicker et al., 2014; Hillebrand et al., 2018).

4.2 Long-term context of contemporary *SSC* and *SSL* changes

In this paper we focus on the timeframe from 1990 to 2010, as most monitoring stations were active during that time and calculated trends are therefore directly comparable to each other. However, looking at longer-term changes is helpful to evaluate the trends and to derive primary controls of these trends.

~~*SSCs* changes between 1970 and 2020 are unraveled by the compilation of the residual *SSCs*, which were calculated using daily *SSCs* and the long-term average *SSC* for each station (compare Tab. S1). The average *SSC* residual of all stations shows a strong variability before 1995 without any major trend (Fig. 8). After 1995, *SSC* declined for almost all stations with a decreased interannual variability. After 2010, the decline stopped at ~ -7 mg l^-1^ relative to the long-term average *SSC* of each station. The compilation of the residual *SSCs* suggest that the declining trend between 1990 and 2010 is mainly caused by a gradual decline of SSC, which was accentuated between 1995 and 2010 at most stations. Due to the strong variability of the annual *SSC* residuals, single stations might have a different trajectory than the average behavior (bold blue line in Fig. 8). However, the consistent behavior of the majority of stations indicate a major change between 1995 and 2010 of the environmental factors controlling the suspended sediment dynamics in the Germany waterways.~~

To evaluate the long-term context of the contemporary decline of the *SSC* and *SSL* beyond the start of suspended sediment monitoring in Germany, we use reconstructed suspended sediment supply rates to the Rhine delta below the Dutch/German border (Erkens, 2009). The suspended sediment load to the Rhine delta for the last 9000 years stratified into 500 years' time slices was reconstructed by Erkens (2009) using a sediment budget approach based on a detailed stratigraphical analysis of alluvial deposits of the Rhine/Meuse delta. Based on various assumption of the trapping efficiency of the Rhine/Meuse delta,

Kommentiert [TH, M326]: Line 390 "SSCs changes between 1970 and 2020 are unraveled by the compilation of the residual SSCs which were calculated using the daily SSCs and the long term average SSC for each station." This is not really clear. Are these the residuals from your Sen slope regression?

the author relates the deposition of silt and clay to the sediment supply from the upstream contributing catchment. Increased early Holocene suspended sediment loads ~ 2.3 Mt yr^{-1} are associated to the delayed response of the river Rhine to environmental changes from Postglacial to Holocene conditions (Fig. ~~9~~10). This transition is completed around 6000 BP, when suspended sediment loads achieve a minimum of around 1 Mt yr^{-1} under a well-established forest cover in the Rhine catchment during the mid-Holocene. Suspended sediment loads at the delta apex coincide with a low geomorphic activity during that time as indicated by a low frequency of dated alluvial deposits in Central Europe (Hoffmann et al., 2009). The increase of the reconstructed suspended load in the Late Holocene is related to the intensified deforestation and agricultural land use starting during the Bronze Age and continuing during the Roman and Medieval periods. Again, this increase is evidenced by enhanced overbank deposition in Central European floodplains starting in the Bronze age and culminating during the Medieval period (Hoffmann et al., 2009). In summary, low mid-Holocene sediment yields of around 1 Mt yr^{-1} can be considered as the natural baseline during the Holocene before the start of human impact (Fig. ~~9~~10).

*SSL*s at the station in Emmerich (215) in the 1980s and early 1990s are in the same order but slightly larger than reconstructed loads during the late Holocene. Due to the temporal gap between the reconstruction and the start of the monitoring ~~it remains unclear when~~the timing and magnitude of the maximum *SSL* in the Rhine River ~~river was approached~~ in response to the increased human-induced impact is unknown. ~~Furthermore, the magnitude of this maximum remains unknown.~~ However, measured annual loads of the Rhine River at Emmerich (blue dots in Fig. ~~7~~10) indicate that *SSL* declines from 3-4 Mt yr^{-1} in the 1980s to 1 Mt yr^{-1} in 2010 and therefore approaches the ~~natural baseline, which represents~~minimum during mid-Holocene conditions without a strong human impact. Assuming an increase of ~2 Mt yr^{-1} since the mid-Holocene (approx. 3000 years) and a similar decrease between 1980 and 2010 (30 years), indicates a 100 times faster decrease compared to the long-term increase. The similarity of suspended sediment loads during the mid-Holocene and the contemporary load at Emmerich can be pure coincidence and does not imply that the ~~river~~ Rhine River and its catchment is in a natural or good ecological state. Interestingly, in fact, Frings et al. (2019) point out that the largest sediment budget components of the river Rhine are induced by sediment management measures along the Rhine River, supporting the notion that the functioning of the Rhine River is dominated by human controls during the Anthropocene. However, ~~it~~ our results ~~implies~~ imply that the suspended sediment loads ~~is~~ are approaching the ~~natural baseline~~Holocene minimum with an overwhelming pace. Furthermore, it raises the question of the driving forces causing the ~~strong~~ rapid decline of *SSL* and *SSC*~~ing trend~~ in the large German river systems.

4.3 Causes of decreasing *SSC* and *SSL*

Soil erosion is a major source of suspended sediment of river systems in agricultural landscapes. Therefore, it has been shown that suspended sediment loads adjust to changing supply conditions in many parts of the world during the Anthropocene (Syvitski et al., 2022). However, numerous studies highlighted the buffering and delaying effects of sediment transport through the channel network (Hoffmann, 2015; Richards, 2002), which might even lead to constant sediment yields despite rapid increases and decreases of hillslope erosion, as evidenced for Coon Creek Basin, Wisconsin (Trimble, 1999).

Kommentiert [TH, M327]: Line 419: The reference to Figure 7 should be to figure 9.

Kommentiert [TH, M328]: Line 423: Is the rate of the decline between 1990 and 2010 worth discussing? It is 10x times faster than what is potentially seen in the stratigraphy.

strongly conditioned by the total rainfall amount, or more precisely by its kinetic energy and the intensity of the rainfall (McGehee et al., 2021). The rainfall amount, which was derived for the nine selected catchments (Fig. S1) with a cumulative catchment area of 318 000 km² based on daily precipitation HYRAS-data, shows no significant trends for the summer and annual precipitation sums (Fig. S2). While total rainfall sums may not change, rainfall extremes are intensifying as Earth's climate warms (Fowler et al., 2021), suggesting that soil erosion will increase in response to climatic changes, as the number of erosive rainfalls (in Germany defined as rainfalls with more than 10 mm and a maximum 30-min intensity of > 10 mm h^{-1}) increases. Long-term records of rainfall erosivity at 10 stations in West Germany indicate an increase in rainfall erosivity between April and November by 2.1 % per year or 42 % from 1990 to 2010 (Fiener et al., 2013). This growth is in the same order as the 1.7 % increase per year estimated by Auerswald et al. (2019), who compared the rainfall erosivity map by Sauerborn (1994), representing the climate conditions in Germany between 1960 and 1980, with their own map derived from contiguous radar rain data for the central year 2009 (Auerswald et al., 2019). In addition to the general growth of the annual rainfall erosivity, increases of winter erosivity between October and March affect the cropping factor (C-factor) of the USLE, as winter rains fall in arable land with a low vegetation cover, furthermore enhancing the erosivity (Auerswald et al., 2019)

We demonstrate that soil erosion in Germany must have increased between 1990 and 2010 as indicated by the temporally variable $R \times C$-factor of the USLE (Fig. 9). This increase mainly results from increasing rainfall erosivity and the intensified agricultural land use, especially in West German. There might be some effects due to potential changes in soil conservation measures between 1990 and 2010, but there are only data available for Germany since 2009/10 (DESTATIS, 2011). If soil conservation changed substantially, one would expect larger effects in the East Germany where 53.7% of arable land is under soil conservation compared to 29.7% in West Germany. However, most soil conservation measures include reduced, no inversion tillage, while only about 1% was under no-till. Therefore, we argue that the effects of soil conservation are small and (if at all) only slightly modify the increases in soil erosion (Auerswald et al., 2018).

The substantial intensification of rainfall erosivitysoil erosion is in stark contrast to the declining *SSC* at most monitoring stations in Germany. While higher rainfall erosivityerosion likely increases the sediment supply to river systems, decreasing *SSC* in large rivers suggest lower sediment supply to from the headwater basins and tributary rivers. The decoupling of the *SSC* trends in the large river systems and increased erosivity might be partially explained by the change of the delivery process from from large scale adventive rainfalls and snowmelt happening in many catchments simultaneously to very localized impacts of intense convective summer extremes (Fiener and Auerswald, 2009; Fischer et al., 2018), that result in massive fluxes in small to medium scale river systems, but hardly affect rivers with contributing catchment areas that are more than 100 times larger than large convective summer cells. Therefore, we argue that changes in precipitation magnitude and frequency unlikely explain the declining trends of suspended sediment in the river systems.This change is evident from the residual SSCs in Fig. 7. Before 1995 residual SSCs synchronously increased/decreased at many stations in certain years due to large scale processes. In contrast, after 1995 interannual variability of residual SSCs is still present but show a more random patterns and a much smoother course of the average SSC-residuals (i.e. red line in Fig. 7), as expected by more localized delivery processes. This process may explain decreased sediment connectivity with respect to large river systems, however, it

Kommentiert [TH, M329]: Line 433: It is not clear what "an increase in rainfall erosivity between April and November by 2.1 % per year or 42 % from 1990 to 2010" means. Is there an increase in erosivity each year between April and November?

Kommentiert [TH, M330]: Line 438: The acronym USLE is not defined does not explain the stronger decreases of SSC during the summer months, as observed in Fig.6. Therefore, we argue that additional processes must be in action that decouple the increasingly eroding headwaters from the large river systems, that are characterized by decreasing SSC levels.

Insignificant changes of the annual precipitation in each catchment is in line with the results of the Mann-Kendall test for mean annual discharges. Only one station (i.e. Marktbreit at the river Main) of 49 stations show a significant change at 5% significance level. Even when increasing the significance level to 10% only 6 stations (232, 233, 237, 242, 502 and 543) show significant changes. Close linkages between catchment-average annual precipitation and mean annual discharge (Fig. 10) indicate that year to year variability of discharge is linked to the inter-annual variability of annual precipitation, which did not significantly decrease for the considered stations and their contributing catchments between 1990 and 2010 (Fig. 10). Thus, meteo-hydrologically driven changes of SSCSSC and SSL can be excluded as a major driver of suspended sediment dynamics in the German river systems between 1990 and 2010, which is also indicated by the strong differences of SSLSSL between the decade 1990-1999 and 2000-2010 for some of the stations in Fig. 10. This statement is further corroborated by the weak tendency of increasing discharges at some of the considered gauging stations (all of the six stations with significant changes of mean annual discharge at 10% level show a slight increase of discharge), which would rather explain rising instead of declining SSCSSC levels. However, given the strong increases of rainfall extremes during the last decades, SSCSSC declines might have been slowed after 2010 or may even inverted in the near future in response to projected changes (Fowler et al., 2021).

Kommentiert [TH, M331]: Line 455: It is not clear where this data can be seen in figure 10.

Scientific evidence shows that soil erosion under arable land is orders of magnitude larger than under forest or otherwise natural land cover (Montgomery, 2007b). In Germany the estimated mean erosion potential under arable is 5.2 t ha^{-1}yr^{-1}, while it is only 0.5 and 0.2 t ha^{-1}yr^{-1} under grassland and natural forest, respectively (Auerswald et al., 2009). Generally, it is assumed the erosion rates under forest are even smaller, which is partly counterbalanced as forests are often located on steeper slopes, not suitable for agricultural use. These land use specific erosion rates suggest that the extent of arable land is an important control for the erosion and sediment supply to river systems. Here we use changes of the extent of arable land and forest cover – the latter is the native vegetation in Central Europe – as a first order proxy for land use driven changes (Tab. 1). SSCWhile the extent of arable land decreased by several percent in the Lahn, Weser and Elbe catchments (3.3, 3.7 and 7.2%) between 1990 and 2012, other catchments listed in Tab. 1 show only marginal changes, or even increases of the arable land. For instance, in the Upper Danube and Neckar catchments the extent of arable land increased by 4.1 and 3.9%, respectively, implying increases of catchment-average soil erosion rates. This contradicts the observed SSCSSC trends and cannot be explained by marginal increased forest covers (e.g. in the Danube catchment by 0.4% or in the Elbe catchment by 1.8%) in the same time. Despite the importance of arable land, it remains questionable whether these modest and inconsistent changes of the extent of various land cover classes may explain the overall large-scale decrease of SSCSSC at the majority of the gauging stations.

Another factor potentially leading to a decline in sediment supply is the increase in soil conservation applied on arable land. Following DESTATIS (2011) 38% of arable land was under soil conservation in 2009/10. Unfortunately, it is not clear to which extent the soil conservation increased between 1990 and 2010 as there is no statistical information available for soil management in Germany before 2009. However, based on the agricultural development after the reunification in 1990, it can be assumed that the proportion of soil conservation practice most substantially increased between 1990 and 2010 in the former eastern part, which in 2009/10 had the largest proportion of soil conservation (53.4 ± 9.52%) (DESTATIS, 2011). Partly the effect of increasing soil conservation will have been counteracted via the substantial increase in maize production since the early 2000s following the support of biogas production in Germany (Clearingstelle EEG/KWKG, 2002). Overall, the proportion of maize cultivation increased by 70.3% between the periode 1991 to 2000 and 2012 to 2017 (total area of about 10 500 km²) (DESTATIS, 2021a, b).

Another reason for different trends between the former Western and Eastern part of Germany might result from different developments regarding field layouts and linear landscape structures, e.g. hedges, grass strips. While Eastern Germany was already in 1990 dominated by large fields with little landscape structures in-between, field sizes substantially increased in many areas of Western Germany, which can be approximated by a mean increase in farm size mostly in Western Germany from 39 ha in 1991 to 67 ha in 2016 (BMLE, 2021). Larger fields generally increase sediment connectivity in arable landscapes (Fiener et al., 2011), and thus, should increase sediment supply to rivers. However, neither the potentially stronger increase in soil conservation practice in the former eastern part of Germany (which should reduce sediment supply), nor the increase in field sizes and the loss of landscape structures between fields in the former western part of Germany (which should increase sediment supply), result in substantially different trends in SSC*SSC* between the rivers draining West and East Germany (Fig. 4).

Reservoirs strongly decrease the longitudinal connectivity of suspended matter in river channels and are the primary cause of the strong global decline of sediment supply to the world's oceans (Syvitski et al., 2022). The Upper Rhine between Basel (CH) and Iffezheim (GER) is controlled by 10 barrages. Furthermore, all tributary waterways are managed by sequences of barrages that halt bed load transport and retain substantial amounts of suspended sediment. The barrages along the Upper Rhine retain suspended matter in the order of 0.3 Mt yr^{-1} between the gauging station at Weil (202) and Plittersdorf (203) (Frings et al., 2019; Hillebrand and Frings, 2017), representing 20% of the 1.45 Mt yr^{-1} upstream inflow at Weil. Therefore, it is frequently argued (van der Perk et al., 2019) that suspended sediment load in the Lower Rhine is reduced in response to the construction of barrages and reservoirs in the catchment. However, barrages along the German waterways were mainly constructed between 1930 and 1940 and between 1955 and 1970 (Fig. 11). Furthermore, the construction of large reservoirs for hydro power generation along the main waterways and for storage of drinking water in the upstream headwaters was almost completed by 1990 and only a small number of upstream reservoirs were built after 1990 in single regions. In many cases, river systems react with immediate, step-wise declining sediment transport rates in response to dam closures (Habersack et al., 2016; Kondolf et al., 2018; Sun et al., 2016; Walling and Fang, 2003), suggesting that post-damming loads remain constant and low after dam construction.

SSC and *SSL* changes indicate that there are no abrupt declines of the suspended sediments in the German river systems but continuously declined between 1990 and 2010 declines over at least 20 years, indicating that the supply to the river systems must decrease or sediment retention must increase more or less continuously each year. The decline of the annual *SSL*s provides a benchmark for the evaluation of the effects of dams in river systems. For instance, along the Rhine ~~river~~ River upstream of Emmerich (215), *SSL* declines by 66.3 kt each year between 1990 and 2010. Continued declines in response to dams however requires that each year after dam closure, the amount of sediment deposited in the reservoir must increase. However, as reservoirs fill up with sediment, trapping efficiencies decrease and the amount of deposited in the reservoir likely decrease (Brune, 1953; Kondolf et al., 2014). Therefore, we argue that the construction of barrages and reservoirs unlikely ~~are able to~~c explains the widespread and continued decline of SSL in the larger river channels in Germany. This notion is further supported by the constant *SSC* level between 1970 and 1990 (Fig. ~~8~~7) and the 'delayed' decline, which mainly starts around 1995 (see Fig. ~~8~~7) two decades after the construction of the last dams in the German waterways.

Little is known about the evolution of soil erosion and sediment supply to river systems in Germany in the last century including the time between 1990 and 2010. Fig. 9 suggests that there was a maximum of sediment supply to the Rhine system sometime between 1750 AD and 1970 AD. Furthermore, the magnitude of that maximum is not known. It is very likely that the construction of barrages in the river systems and reservoirs in the headwater river systems resulted in an initial decline in the middle of the last century (Fig. ~~9~~11). However, the decline of the *SSC* after 1990 must be related to decreasing sediment supply from ~~hillslopes (see discussion on potential sources of declining sediment supply above)~~tributary river systems.

At the global scale, the discussion on disconnected sediment fluxes focuses mainly on large reservoir as dams (i.e. dams with a height exceeding 15m) that are included in global inventories, ignoring the effects of many small barriers and dams that disconnect sediment transport in medium and small river systems. The European database of dams and reservoirs, which was compiled by Belletti et al. (2020), indicates that their total number exceed 18000 in Germany. While the construction of large reservoirs and dams ceased by the 1980s, many small-scale rainwater retention basins were built between 1990 and 2010 to reduce the flooding potential of small to medium sized creeks and rivers. The trapping efficiency of such a single small-scale feature is certainly low, but given the large number of the features, their overall cumulative effect might be significant for the reduction of suspended sediment in the large rivers. Furthermore, artificial (urban) surfaces strongly increased between 1990 and 2010 (Tab. 1) and waste~~-~~water treatment plants that collect surface runoff from these surfaces became more effective during the same time. Thus, an increasing fraction sediment is trapped i) in head water river systems, which are characterized by strong siltation (Geist and Auerswald, 2019), ii) stormwater reservoirs~~ and by~~, iii) waste~~-~~water treatment plants and iv) a large number of small-scale sedimentary sinks in response to urban construction (e.g. sediment disconnection through road construction).

Overall, there are several potential reasons for the disconnection between increasing hillslope erosion and decreasing sediment supply to the waterways, which are associated with changing land use and infrastructure within the tributary catchments and/or climate driven changes in rainfall characteristics. ~~Therefore, we argue that the widespread and consistent trend of declining *SSC* in the large German river systems is mainly driven by the expansion of conservation agriculture and the increasing number of headwater retention basins in Germany.~~

5 Conclusion

Based on daily monitoring of *SSC* along large German river channels, we found significant declines of mean annual average *SSC* at ~~47~~ 56 of ~~49~~ 62 monitoring stations between 1990 and 2010. On average *SSC* declines by -0.92 mg l^{-1} yr^{-1}. At some stations decreases during the 20 years represent up to 50% of the long-term average *SSC*. Significant decreases of *SSC* are associated with declining *SSL*s ~~loads~~.

The decline contrasts with the strong increase in soil erosion resulting from increases in rain erosivity as a result of climate change and partly erosion-inducing changes in land use and management. Furthermore, different land-use induced trajectories of erosion in Eastern and Western Germany did not translate into different developments of changing SSC in the waterways. The coherent and strong decline of suspended sediment concentrations and loads is difficult to explain due to multiple influences acting the flow path between erosive hillslopes and sediment transport in large river channels. At this point we can only speculate regarding potential reasons for a decline in sediment supply to larger rivers. We argue that changes in sediment connectivity in micro- to mesoscale catchments, which result from a combination of changes in rainfall characteristics (reduced spatial extend of large-scale advective rainfall events and shifts in snow cover and hence snow melt events) as well as increasing number of retention basins and infrastructure-driven barriers, are the major reason for declining SSC in the studied river channels. In contrast to the unclear situation in the catchments, there were little changes in the construction of dams and reservoirs along the large river channels during the observation period 1990-2010. Therefore, management changes along the large rivers seemed to be less important for the change in SSC. However, it remains questionable if increasing rainfall extremes during the last years and which is predicted to be continued in the next decades will shift the trends of SSC and result in increasing SSC levels in large German river channels after two decades of SSC decline.

In the context of long-term changes of suspended sediment transport, the contemporary suspended sediment loads of the Rhine River at the German-Dutch border approaches ~~the pristine level of~~ ~1 Mt yr^{-1}, which ~~was achieved by the Rhine during the~~is similar to the natural conditions of the Rhine system in the mid-Holocene when the suspended sediment load was adjusted to the Holocene climat~~eic conditions~~ and before the onset of increased loads due to human induced land use changes in the Rhine catchment. However, it must be stressed that the similarity of modern suspended sediment loads of the Rhine River and the pristine mid-Holocene load is simple coincidence as sediment dynamics in German river systems are strongly conditioned by human actions within the contributing catchments and along the river channels during the Anthropocene.

~~The coherent and strong decline of suspended sediment concentrations and loads is difficult to explain by a mono-causal response to a change of a single driving factor. At this point we can only speculate regarding potential reasons for a decline in sediment supply to larger rivers. We argue that changes in soil erosion within the catchments and/or the sediment connectivity in upstream headwaters, e.g. due to the construction of small rainwater retention basins, are the major reason for declining SSC in the studied river channels. In contrast to the unclear situation in the catchments, there were little changes in the construction of dams and reservoirs along the large river channels during the observation period 1990–2010. Therefore, changes~~

~~along the rivers seemed to be less important for the change in SSC. However, it remains questionable if increasing rainfall extremes during the last years and which is predicted to be continued in the next decades will shift the trends of SSC again and result in increasing SSC levels in large German river channels after decades of SSC decline.~~

Author contributions. TH performed the trend analysis of all stations and prepared the manuscript with the cooperation of all co-authors. PF and KA provided land cover data and calculate R and C factors of the USLE and provided feedback on data analysis and discussion of results. YB provided SSC data and analysed the spatial distribution of the trends. JB contributed to the trend analysis and supported discussion on the results. SV provided support regarding SSC data analysis and discussion on river management of German waterways.

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

Acknowledgements

The data used in this paper was provided by the suspended sediment monitoring network of the German waterways that was established in the 1960ties by the Federal Waterways and Shipping Administration (Wasserstraßen- und Schifffahrtsverwaltung des Bundes, WSV). We acknowledge the WSV for maintaining the monitoring network and for suspended sediment sampling. Furthermore, we thank Oliver Francis and an ~~XY and XY~~ anonymous reviewer for their helpful comments and suggestions that greatly improved the quality of this paper.

References

<SdW_Kompakt_Turbulenzen.pdf>.

Annandale, G. W., Randle, T. J., Langendoen, E. J., Hotchkiss, R. H., and US National Reservoir Sedimentation and Sustainability Team: Reservoir Sedimentation Management: a Sustainable Developement Challange, hydrolink, 3/2018, 72-75, 2018.

Asselmann, N.: Fitting and interpretation of sediment rating curves, Journal of Hydrology, 234, 228-248, 2000.

Auerswald, K., Ebertseder, F., Levin, K., Yuan, Y., Prasuhn, V., Plambeck, N. O., Menzel, A., and Kainz, M.: Summable C factors for contemporary soil use, Soil and Tillage Research, 213, 2021.

Auerswald, K., Fischer, F. K., Kistler, M., Treisch, M., Maier, H., and Brandhuber, R.: Behavior of farmers in regard to erosion by water as reflected by their farming practices, Sci Total Environ, 613-614, 1-9, 2018.

Auerswald, K., Fischer, F. K., Winterrath, T., and Brandhuber, R.: Rain erosivity map for Germany derived from contiguous radar rain data, Hydrology and Earth System Sciences, 23, 1819-1832, 2019.

BAW and BfG: Sedimentdurchgängigkeit der Bundeswasserstraßen im Binnenbereich. Metastudie, Bundesanstalt für Wasserbau (BAW) und Bundesanstalt für Gewässerkunde (BfG), 2016.

Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Borger, L., Segura, G., Castelletti, A., van de Bund, W., Aarestrup, K., Barry, J., Belka, K., Berkhuysen, A., Birnie-Gauvin, K., Bussettini, M., Carolli, M., Consuegra, S., Dopico, E., Feierfeil, T., Fernandez, S., Fernandez Garrido, P., Garcia-Vazquez, E., Garrido, S., Giannico, G., Gough, P., Jepsen, N., Jones, P. E., Kemp, P., Kerr, J., King, J., Lapinska, M., Lazaro, G., Lucas, M. C., Marcello, L., Martin, P., McGinnity, P., O'Hanley, J., Olivo Del Amo, R., Parasiewicz, P., Pusch, M., Rincon, G., Rodriguez, C., Royte, J., Schneider, C. T., Tummers, J. S., Vallesi, S., Vowles, A., Verspoor, E., Wanningen, H., Wantzen, K. M., Wildman, L., and Zalewski, M.: More than one million barriers fragment Europe's rivers, Nature, 588, 436-441, 2020.

BMLE: Entwicklung der Betriebsstruktur landwirtschaftlicher Betriebe ab 5 ha LF in Deutschland., Bundesministerium für Ernährung und Landwirtschaft, 2021.

Brune, G. M.: Trap efficiency of reservoirs, EOS Transactions AMerican Geophysical Union, 34, 407-418, 1953.

DESTATIS: Anbaufläche (Feldfrüchte und Grünland): Deutschland, Jahre, Fruchtarten, Wiesbaden, Germany. Statistisches Bundesamt, https://www-genesis.destatis.de/genesis//online?operation=table&code=41241-0001&bypass=true&levelindex=1&levelid=1626847204889#abreadcrumb, 2021a.

DESTATIS: Land- und Forstwirtschaft, Fischerei - Bodenbearbeitung, Bewässerung, Landschaftselemente Erhebung über landwirtschaftliche Produktionsmethoden (ELPM) 2010. Fachserie 3 Heft 5., Statistisches Bundesamt, Wiesbaden, 2011.

DESTATIS: Land- und Forstwirtschaft, Fischerei -Bodenfläche nach Art der tatsächlichen Nutzung 2020. Fachserie 3 Heft 5.1., Statistisches Bundesamt, Wiesbaden, 2021b.

Deutsches Talsperrenkomitee e.V. (Ed.): Talsperren in Deutschland, Springer-Vieweg-Verlag, Wiesbaden, 2013.

Doomen, A. M. C., Wijma, E., Zwolsman, J. J. G., and Middelkoop, H.: Predicting suspended sediment concentrations in the Meuse river using a supply-based rating curve, Hydrological Processes, 22, 1846-1856, 2008.

EC-WFD: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, Official Journal of the European Communities, L 327, 1-72, 2000.

Erkens, G.: Sediment dynamics in the Rhine catchment. Quantification of fluvial response to climate change and human impact, Utrecht, 2009.

FGG Elbe: Sedimentmanagementkonzept der FGG Elbe - Vorschläge für eine gute Sedimentmanagementpraxis im Elbegebiet zur Erreichung überregionaler Handlungsziele, Flussgebietsgemeinschaft Elbe, Magdeburg, 85 pp., 2013.

Fiener, P. and Auerswald, K.: Spatial variability of rainfall on a sub-kilometre scale, Earth Surface Processes and Landforms, 34, 848-859, 2009.

Fiener, P., Neuhaus, P., and Botschek, J.: Long-term trends in rainfall erosivity–analysis of high resolution precipitation time series (1937–2007) from Western Germany, Agricultural and Forest Meteorology, 171-172, 115-123, 2013.

Fischer, F. K., Winterrath, T., and Auerswald, K.: Temporal- and spatial-scale and positional effects on rain erosivity derived from point-scale and contiguous rain data, Hydrology and Earth System Sciences, 22, 6505-6518, 2018.

Frings, R. M., Hillebrand, G., Gehres, N., Banhold, K., Schriever, S., and Hoffmann, T.: From source to mouth: Basin-scale morphodynamics of the Rhine River, Earth-Science Reviews, 196, 2019.

Geist, J. and Auerswald, K.: Synergien im Gewässer-, Boden-, Arten- und Klimaschutz am Beispiel von Flussauen, Wasserwirtschaft, 11, 11-16, 2019.

Golosov, V. and Walling, D. E.: Erosion and sediment problems: Global Hotspots, UNESCO - Intergovernmental Hydrological Programme, Paris, 40 pp., 2019.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., Nilsson, C., Olden, J. D., Opperman, J. J., Petry, P., Reidy Liermann, C., Saenz, L., Salinas-Rodriguez, S., Schelle, P., Schmitt, R. J. P., Snider, J., Tan, F., Tockner, K., Valdujo, P. H., van Soesbergen, A., and Zarfl, C.: Mapping the world's free-flowing rivers, Nature, 569, 215-221, 2019.

Habersack, H., Hein, T., Stanica, A., Liska, I., Mair, R., Jager, E., Hauer, C., and Bradley, C.: Challenges of river basin management: Current status of, and prospects for, the River Danube from a river engineering perspective, Sci Total Environ, 543, 828-845, 2016.

Hardenbicker, P., Rolinski, S., Weitere, M., and Fischer, H.: Contrasting long-term trends and shifts in phytoplankton dynamics in two large rivers, International Review of Hydrobiology, 99, 287-299, 2014.

Hillebrand, G. and Frings, R.: Von der Quelle zur Mündung: Die Sedimentbilanz des Rheins im Zeitraum 1991 – 2010, Bericht KHR/CHR II-22. Internationale Kommission für die Hydrologie des Rheingebietes, Lelystad. ISBN: 978-90-70980-39- 9, DOI: 10.5675/KHR_22.2017., 2017.

Hillebrand, G., Hardenbicker, P., Fischer, H., Otto, W., and Vollmer, S.: Dynamics of total suspended matter and phytoplankton loads in the river Elbe, Journal of Soils and Sediments, 18, 3104-3113, 2018.

Hoffmann, T.: Sediment residence time and connectivity in non-equilibrium and transient geomorphic systems, Earth-Science Reviews, 150, 609-627, 2015.

Hoffmann, T., Erkens, G., Gerlach, R., Klostermann, J., and Lang, A.: Trends and controls of Holocene floodplain sedimentation in the Rhine catchment, Catena, 77, 96-106, 2009.

Hoffmann, T. O., Baulig, Y., Fischer, H., and Blöthe, J.: Scale breaks of suspended sediment rating in large rivers in Germany induced by organic matter, Earth Surface Dynamics, 8, 661-678, 2020.

Horowitz, A. J., Clarke, R. T., and Merten, G. H.: The effects of sample scheduling and sample numbers on estimates of the annual fluxes of suspended sediment in fluvial systems, Hydrological Processes, 29, 531-543, 2015.

Kondolf, G. M., Rubin, Z. K., and Minear, J. T.: Dams on the Mekong: Cumulative sediment starvation, Water Resources Research, 50, 5158-5169, 2014.

Kondolf, G. M., Schmitt, R. J. P., Carling, P., Darby, S., Arias, M., Bizzi, S., Castelletti, A., Cochrane, T. A., Gibson, S., Kummu, M., Oeurng, C., Rubin, Z., and Wild, T.: Changing sediment budget of the Mekong: Cumulative threats and management strategies for a large river basin, Sci Total Environ, 625, 114-134, 2018.

Moatar, F., Person, G., Meybeck, M., Coynel, A., Etcheber, H., and Crouzet, P.: The influence of contrasting suspended particulate matter transport regimes on the bias and precision of flux estimates, Sci Total Environ, 370, 515-531, 2006.

Montgomery, D. R.: Soil erosion and agricultural sustainability, Proc Natl Acad Sci U S A, 104, 13268-13272, 2007.

Nearing, M. A., Xie, Y., Liu, B., and Ye, Y.: Natural and anthropogenic rates of soil erosion, International Soil and Water Conservation Research, 5, 77-84, 2017.

Pohlert, T.: trend: Non-Parametric Trend Tests and Change-Point Detection. 2018.

Poulier, G., Launay, M., Le Bescond, C., Thollet, F., Coquery, M., and Le Coz, J.: Combining flux monitoring and data reconstruction to establish annual budgets of suspended particulate matter, mercury and PCB in the Rhône River from Lake Geneva to the Mediterranean Sea, Science of The Total Environment, 658, 457-473, 2019.

Richards, K.: Drainage basin structure, sediment delivery and the response to environmental change. In: Sediment Flux to Basins: Causes, Controls and Consequences., Jones, S. J. and Frostick, L. E. (Eds.), Geological Society, London, Special Publications, Londron, 2002.

Skolasińska, K. and Nowak, B.: What factors affect the suspended sediment concentrations in rivers? A study of the upper Warta River (Central Poland), River Research and Applications, 34, 112-123, 2018.

Slabon, A. and Hoffmann, T.: Uncertainties of Annual Suspended Sediment Transport Estimates Driven by Temporal Variability, Water Ressources Reserach, #2022WR032628, accepted.

Sun, L., Yan, M., Cai, Q., and Fang, H.: Suspended sediment dynamics at different time scales in the Loushui River, south-central China, Catena, 136, 152-161, 2016.

Syvitski, J., Ángel, J. R., Saito, Y., Overeem, I., Vörösmarty, C. J., Wang, H., and Olago, D.: Earth's sediment cycle during the Anthropocene, Nature Reviews Earth & Environment, 3, 179-196, 2022.

Syvitski, J. P. and Kettner, A.: Sediment flux and the Anthropocene, Philos Trans A Math Phys Eng Sci, 369, 957-975, 2011.

Syvitski, J. P., Morehead, M. D., Bahr, D. B., and Mulder, T.: Estimating fluvial sediment transport: The rating parameters, Water Resources Research, 36, 2747-2760, 2000.

Trimble, S. W.: Decreased Rates of Alluvial Sediment Storage in the Coon Creek Basin, Wisconsin, 1975-93, Science, 285, 1244-1246, 1999.

van der Perk, M., Sutari, C. A. T., and Middelkoop, H.: Examination of the declining trend in suspended sediment loads in the Rhine River in the period 1952-2016, Land of Rivers. NCR Days 2019, Utrecht, 73-73, 2019.

Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, J. P. M.: Anthropogenic sediment retention: major global impact from registered river impoundments, Global and Planetary Change, 39, 169-190, 2003.

Walling, D. E. and Fang, D.: Recent trends in the suspended sediment loads of the world's rivers, Global and Planetary Change, 39, 111-126, 2003.

Walling, D. E. and Webb, B. W.: The reliability of suspended sediment load data. Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981), IAHS Publ., 133, 177-194, 1981.

Warrick, J. A.: Trend analyses with river sediment rating curves, Hydrological Processes, 29, 936-949, 2015.

Figures

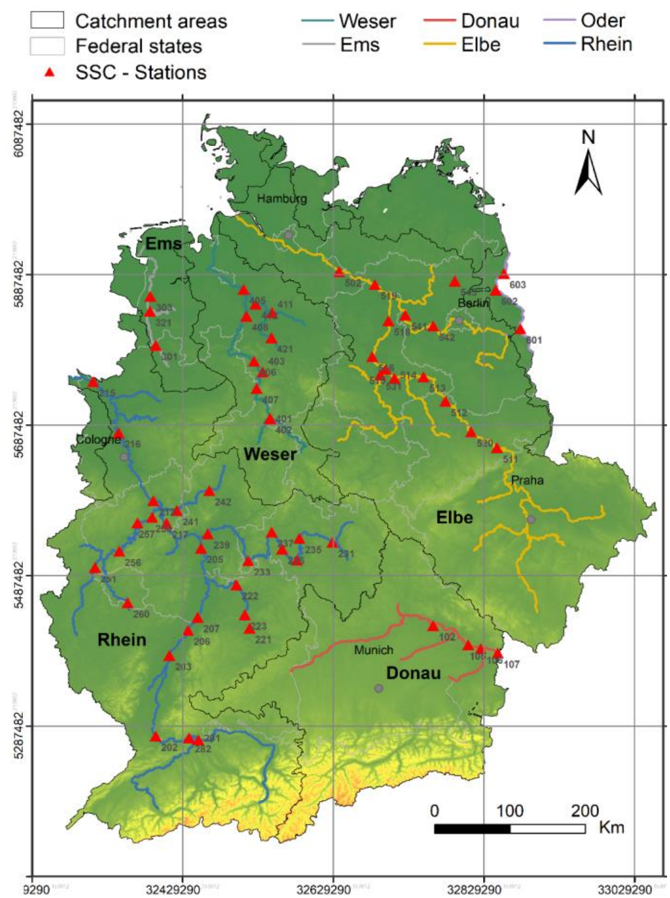


Figure 1: Spatial distribution of sampling stations and major river systems and catchment boundaries in Germany.

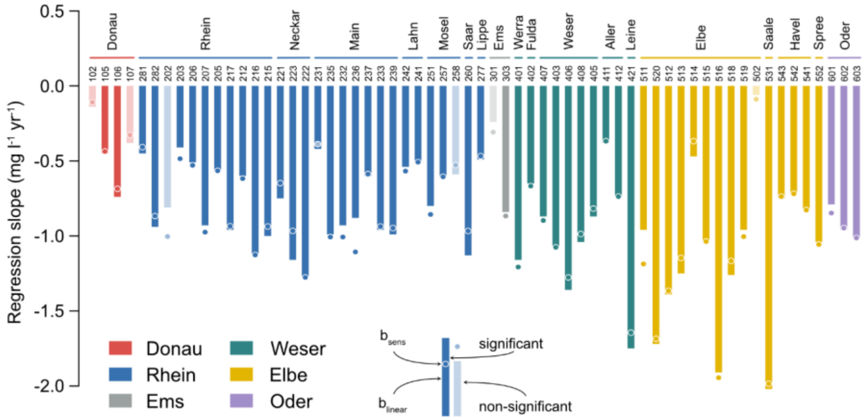


Figure 2: Overview of *SSC*-trends for all 62 stations ordered according the river systems and flow path from upstream (left) to downstream (right) showing the trends from least-square linear regression and Sen's slope

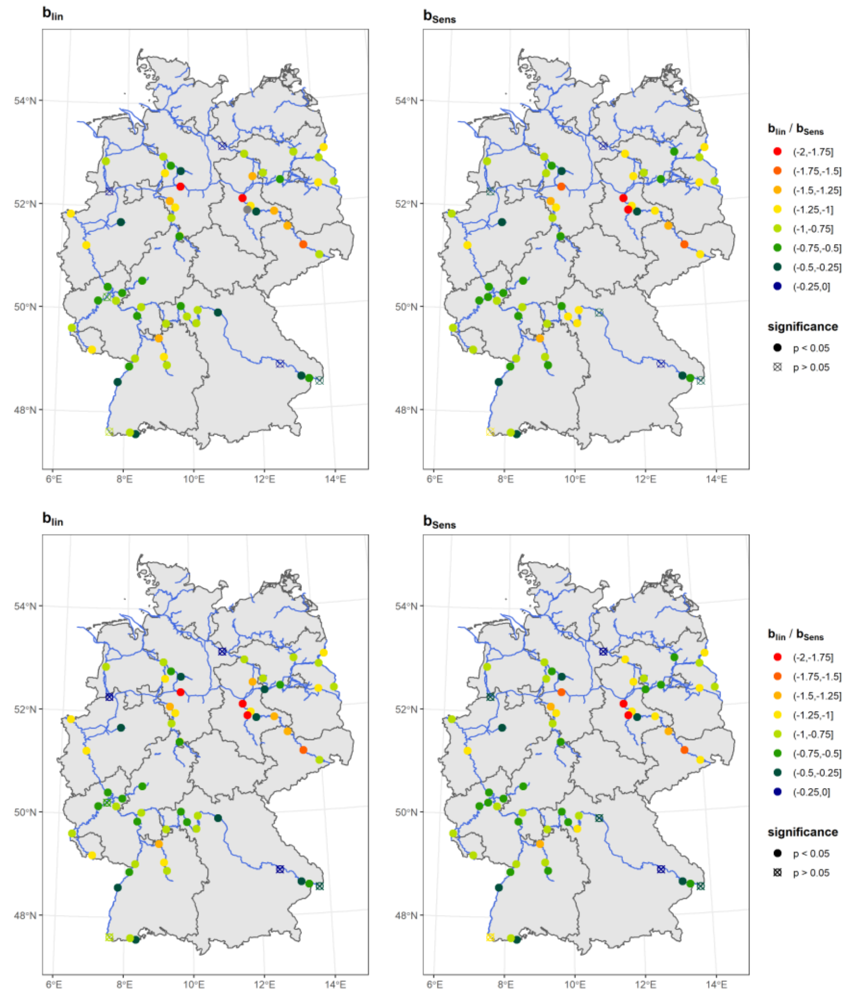


Figure 3: Spatial distribution of trends of annual average *SSC* (in mg lL^{-1} yr^{-1}) between 1990 and 2010 along the waterways in Germany. Left map shows trend magnitudes derived from linear regression, right maps shows trend magnitudes derived from Sens' slopes.

Kommentiert [TH, M332]: Figure 3: The points for stations with no significant difference are not always easily visible

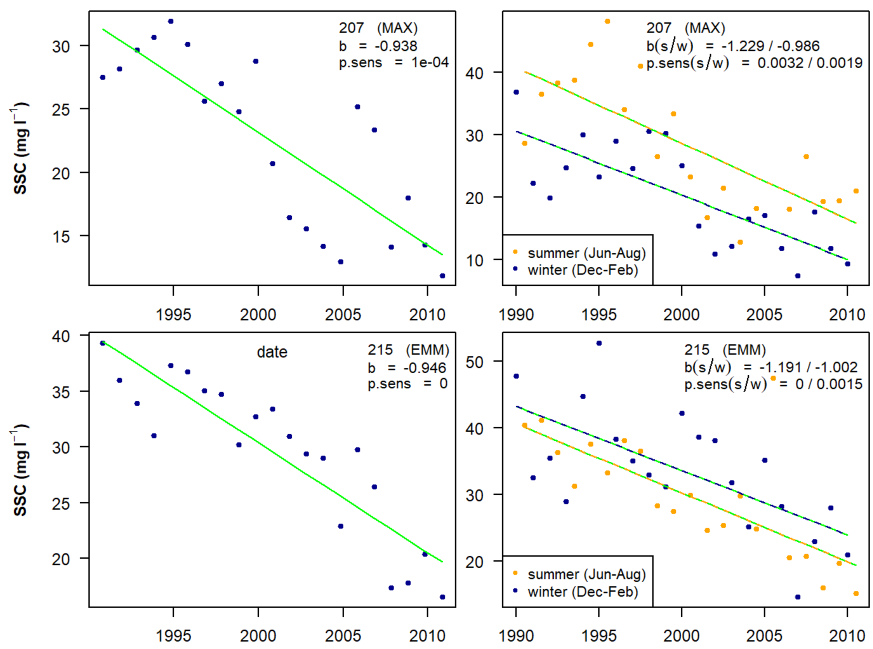


Figure 4: Examples of *SSC* trends between 1990 and 2010 for monitoring station Maxau (top) and Emmerich (bottom). Left panel shows annual average *SSC*, right panel show trends **during** summer and winter months.

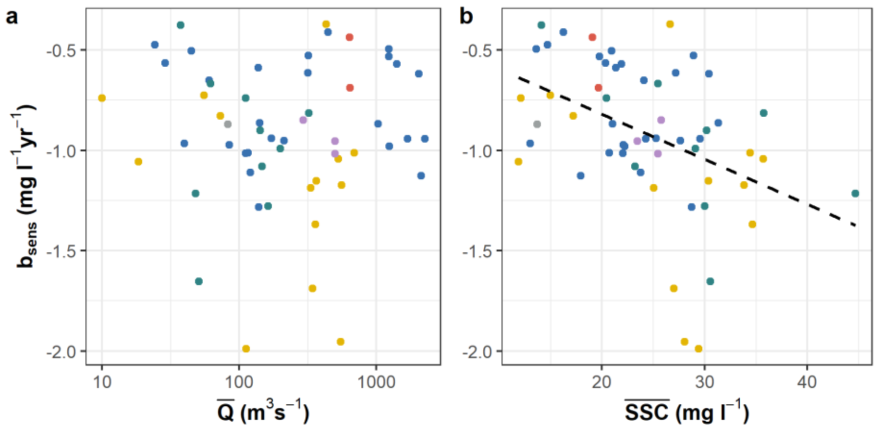
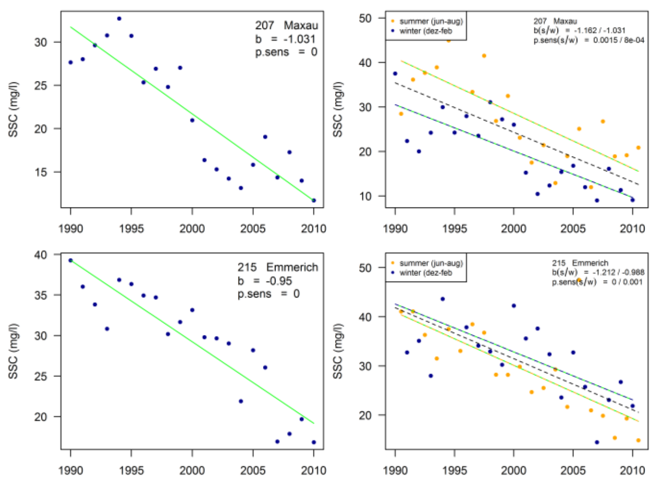


Figure 45: Sens slope for *SSC* of all stations as a function of mean discharge and mean *SSC*. Mean values refer to the period between 1990 and 2010. Colors represent river systems (for legend see Figure 2). The dashed line in b) shows the linear regression between $\overline{SSC}$ and b_{Sens}, with p~0.007, R^2=0.18.



~~**Figure 5: Examples of *SSC* trends between 1990 and 2010 for monitoring station Maxau (top) and Emmerich (bottom). Left panel shows annual average *SSC*, right panel show trends for summer and winter months.**~~

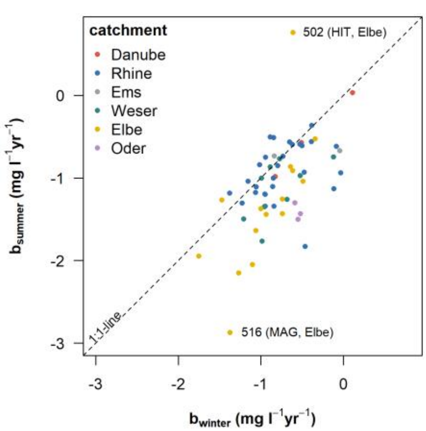


Figure 6: Scatterplot of Sens' slope for winter and summer months.

875

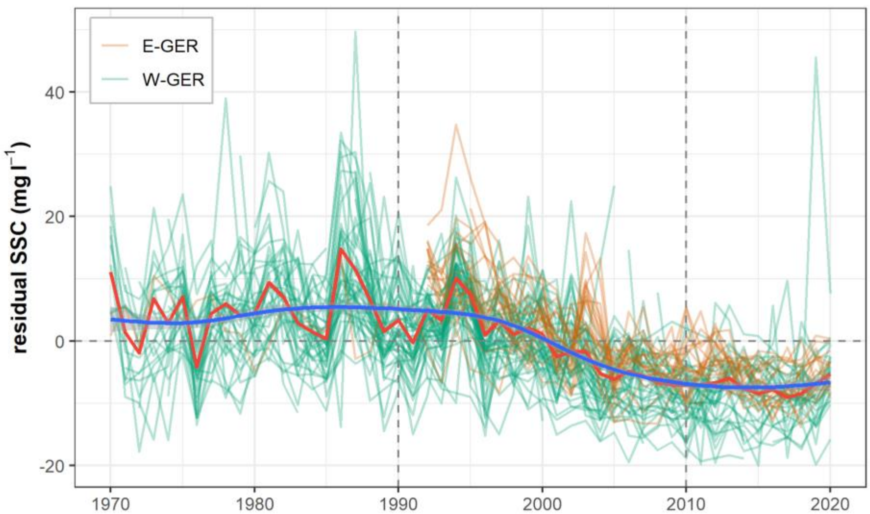


Figure 7: Trends of residual *SSC* between 1970 and 2020. *SSC* residuals are calculated based on daily *SSC* data and the average *SSC* of all available *SSC*s covering the full monitoring length for each station. Light red lines indicate the annual average of *SSC* residuals for each station. The bold red line represents the average annual *SSC* residual of all stations. The blue line represents a smooth spline of the average annual *SSC* residuals.

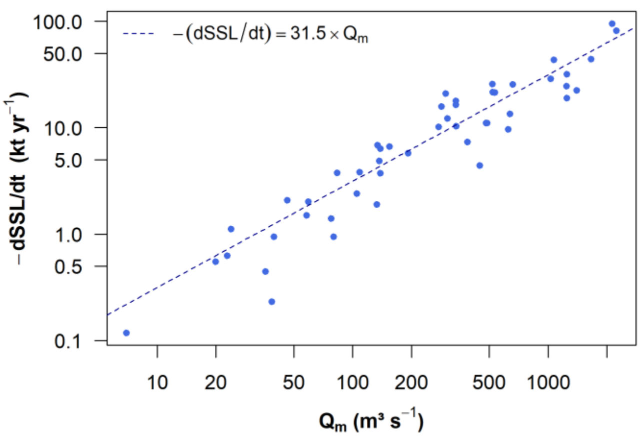


Figure 8: SSL-decline (-dSSL/dt) as a function of discharge for all stations with a significant change of SSL between 1990 and 2010. Linear regression

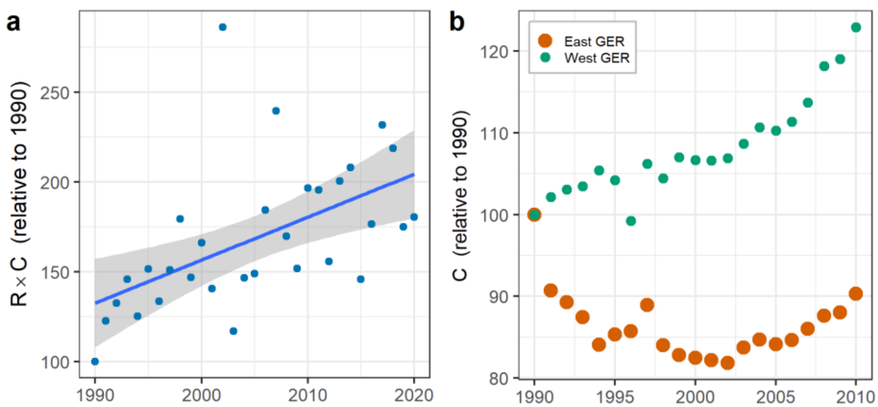


Figure 9: Change in erosion as quantified by the Universal Soil Loss Equation relative to erosion in 1990. Left: Combined influence of rain erosivity (R factor) and land use (C factor). Right: Influence of land use and management in West and East Germany upon C factor.

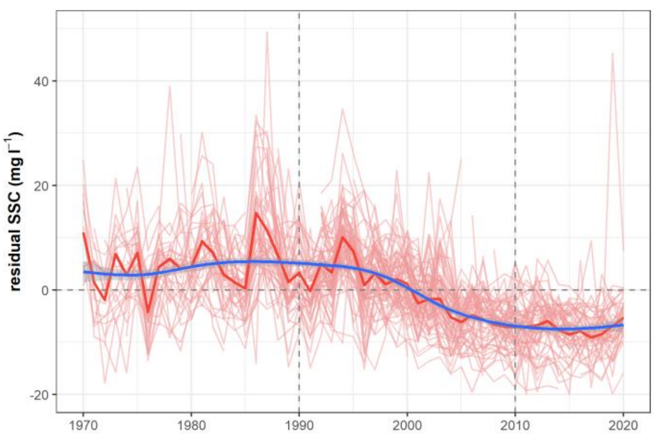


Figure 98: Trends of residual SSCSSC between 1970 and 2020. SSCSSC residuals are calculated based on daily SSCSSC data and the average SSCSSC of all available SSCSSCs covering the full monitoring length for each station. Light red lines indicate the annual average of SSCSSC residuals for each station. The bold red line represents the average annual SSCSSC residual of all stations. The blue line represents a smooth spline of the average annual SSCSSC residuals.

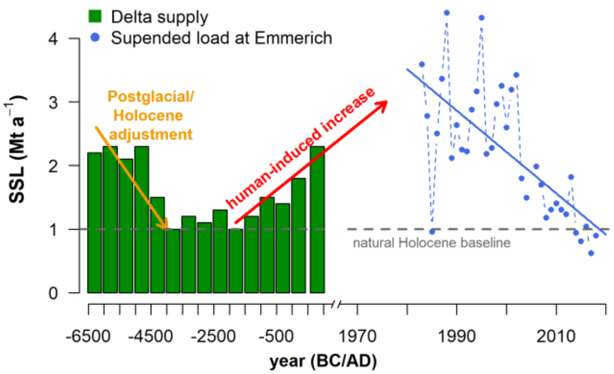
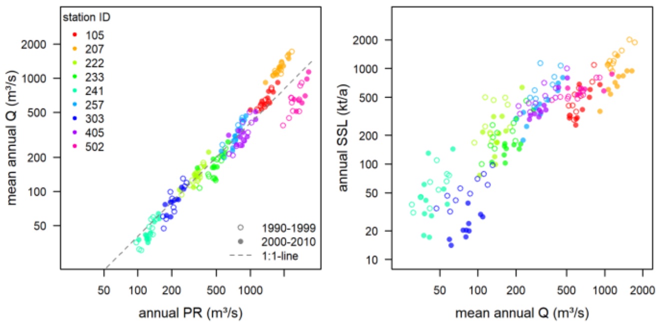


Figure 10: Reconstructed and monitored suspended sediment loads (SSL) of the Lower Rhine at the Dutch/German border. Reconstructed loads (green bars) are derived from a long-term sediment budgets analysis of the Rhine-Meuse delta in the Netherlands (Erkens, 2009). Blue points represent the suspended annual loads at the monitoring station in Emmerich (representing the most downstream station of the German suspended monitoring network).



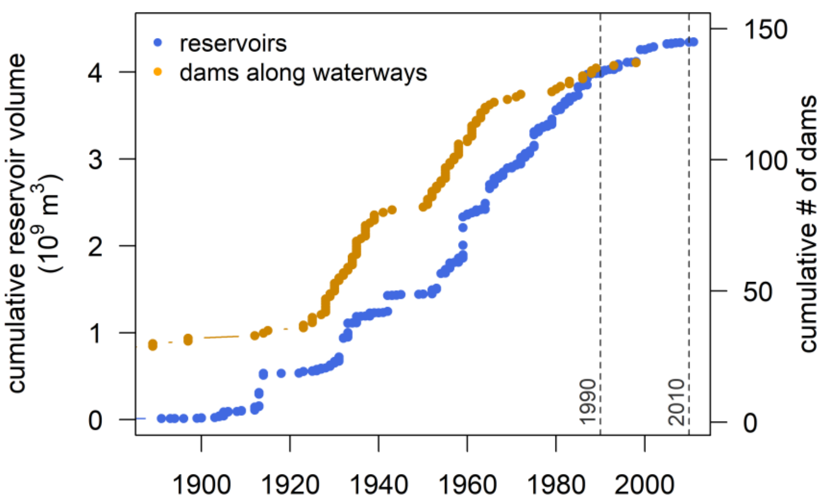


Figure 11: Cumulative volume of reservoirs in Germany and number of dams (barrages) along the German waterways since the start of construction in the 1880ies. The cumulative volume of reservoirs includes only large reservoirs with volumes > 0.04 Mio. m^3 and is taken from Wikipedia ("Liste der Talsperren in Deutschland", accessed at January 2021)

Kommentiert [TH, M333]: Figure 11: The dashed lines show the start and end of your study period. It might be clearer if you labelled them

Tables

Table 1: Fraction of land cover classes derived from the CORINE land cover data for major river catchments in Central Europe (© European Union, Copernicus Land Monitoring Service 2022, European Environment Agency (EEA)).

year	Danube	Rhine	Neckar	Main	Lahn	Moselle	Ems	Weser	Elbe
arable land									
1990	27,8		30,7	36,8	25,2	24,5	65,5	43,3	47,6
2000	27,5	21,9	30,3	36,4	24,3	23,7	64,3	42,4	44,2
2006	27,3	21,9	30,1	36,0	24,1	24,1	63,4	41,9	43,5
2012	31,9	20,7	34,6	37,9	21,9	24,8	63,2	39,7	40,5
2018	31,9	20,7	34,5	38,1	21,9	24,8	63,2	39,6	40,4
Forest									
1990	34,0		35,3	37,9	43,0	36,5	13,0	33,7	29,9
2000	33,3	35,6	34,6	37,9	43,1	36,5	13,0	33,7	30,6
2006	33,1	35,3	35,0	38,1	43,1	36,4	13,0	33,8	30,8
2012	34,4	35,0	37,0	39,6	44,3	37,5	14,0	34,5	31,6
2018	34,4	35,1	36,9	39,6	44,2	37,6	14,0	34,5	31,7
Pasture									
1990	14,4		8,7	6,3	16,5	18,4	3,0	8,4	5,5
2000	14,5	11,4	8,6	6,3	16,7	19,2	3,2	8,8	8,0
2006	14,3	11,3	8,6	6,3	16,3	19,1	3,2	8,7	8,5
2012	20,2	11,9	15,1	14,2	23,4	21,1	10,5	14,8	12,6
2018	20,1	11,9	15,1	14,0	23,3	21,0	10,4	14,8	12,5
artifical (urban & industial) surface									
1990	5,4		9,5	5,2	7,2	6,9	6,6	7,0	7,1
2000	5,8	7,5	10,3	5,5	7,5	7,2	7,5	7,4	7,3
2006	6,1	7,8	10,7	6,0	8,0	7,7	8,1	7,8	7,4
2012	6,9	8,2	11,9	6,9	9,0	8,6	10,4	8,8	7,8
2018	7,0	8,3	11,9	6,9	9,0	8,7	10,4	8,8	7,9
remaining area									
1990	18,4		15,8	13,9	8,1	13,6	11,8	7,7	10,0
2000	18,9	23,6	16,1	13,9	8,4	13,4	11,9	7,7	9,9
2006	19,1	23,7	15,6	13,7	8,6	12,6	12,3	7,9	9,8
2012	6,6	24,1	1,5	1,4	1,5	8,0	1,9	2,2	7,6
2018	6,7	24,1	1,5	1,4	1,5	7,9	1,9	2,2	7,5