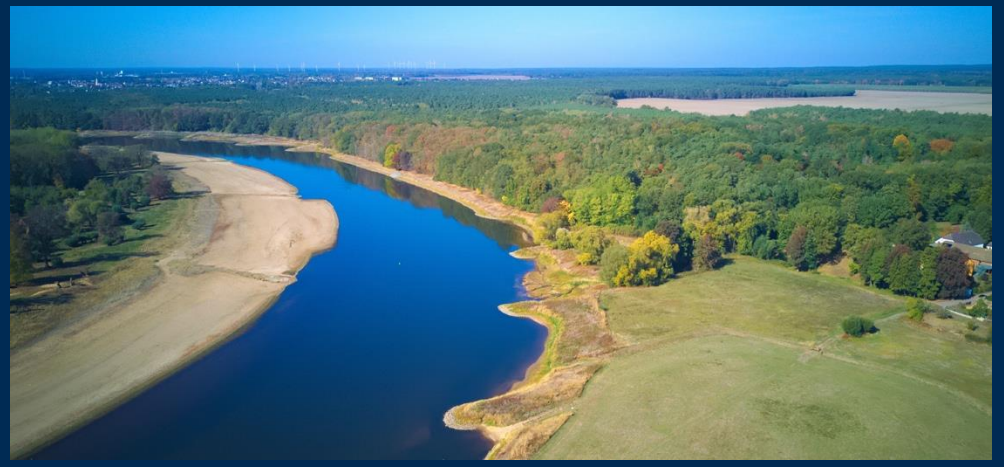
Past, present and future suspended sediment transport in large German rivers



Hoffmann, Thomas

(Thomas.Hoffmann@BafG.de)

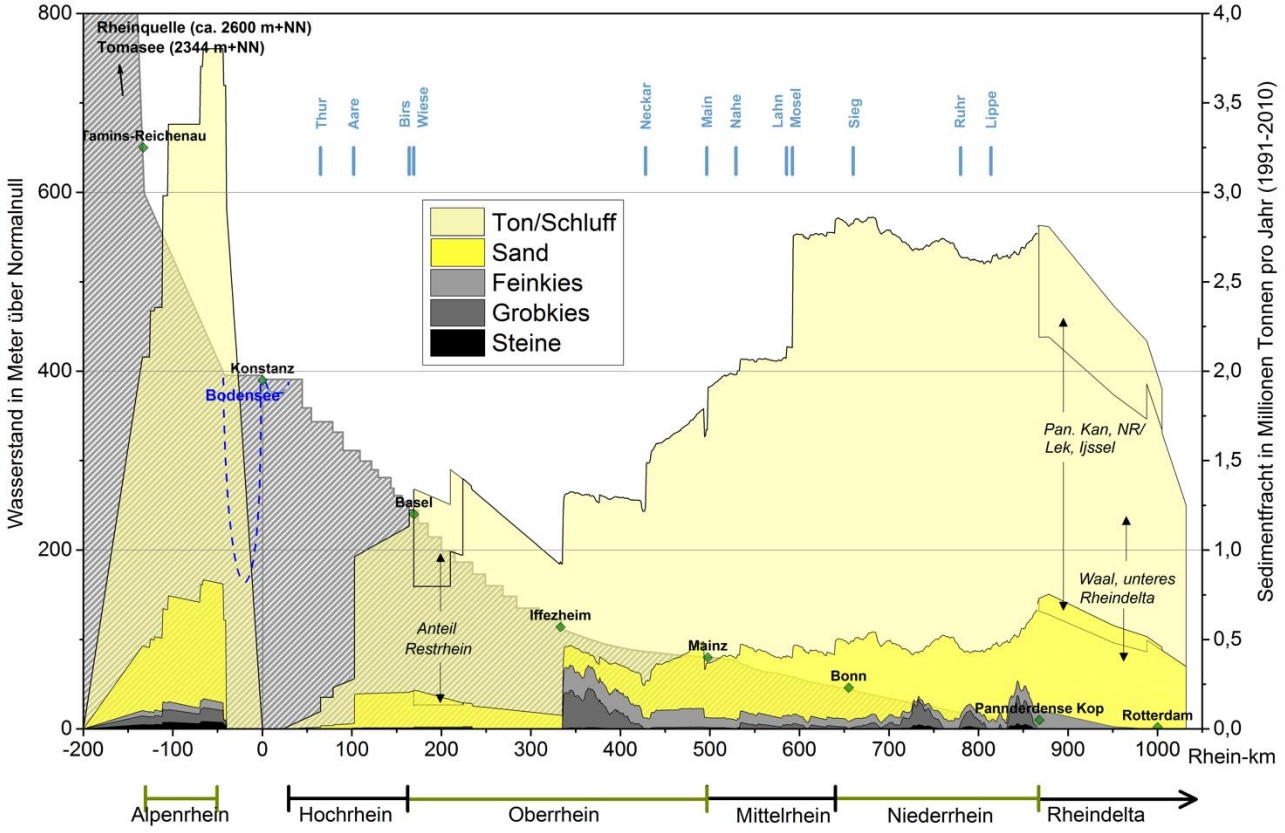
SedNet, Madrid, 6th-10th Oct. 2025

BfG Federal Institute of Hydrology

Suspended Sediment Transport

- ✓ Controls water quality (transport medium: nutrients & contaminants)
- ✓ Effects fluvial habitat suitability
- ✓ Impacts channel morphology
  - Effects bank stability
  - Sand: interacts between suspension and bed load

Sediment budget: River Rhine



? Largest fraction of sediment transport

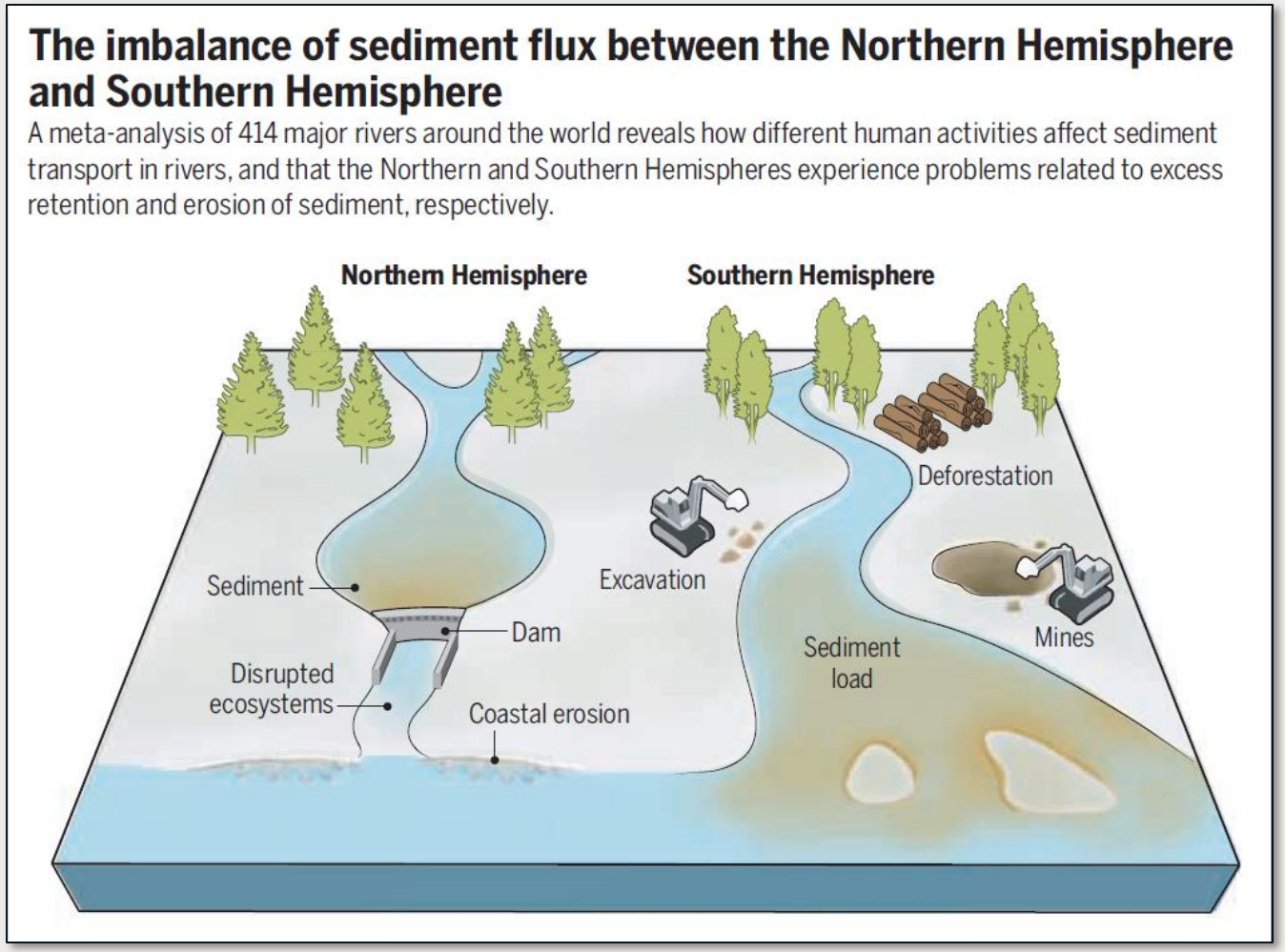
Hillebrand & Frings (2017)

Suspended Sediment Transport…

… is changing due to changing …

a) … **soil erosion** (dominant source of suspended sediment)
   - Climate change: may increase or decrease soil erosion
   - Agricultural land use changes increase soil erosion
   - Conservation agriculture decrease soil erosion

b) … **sediment connectivity** (between source and river)
   - Dams and reservoirs decrease connectivity
   - Conservation agriculture decrease connectivity



Zarfl & Dunn (2022, Science)

Anthropogenic Stresses

ENVIRONMENTAL SCIENCE

The delicate balance of river sediments

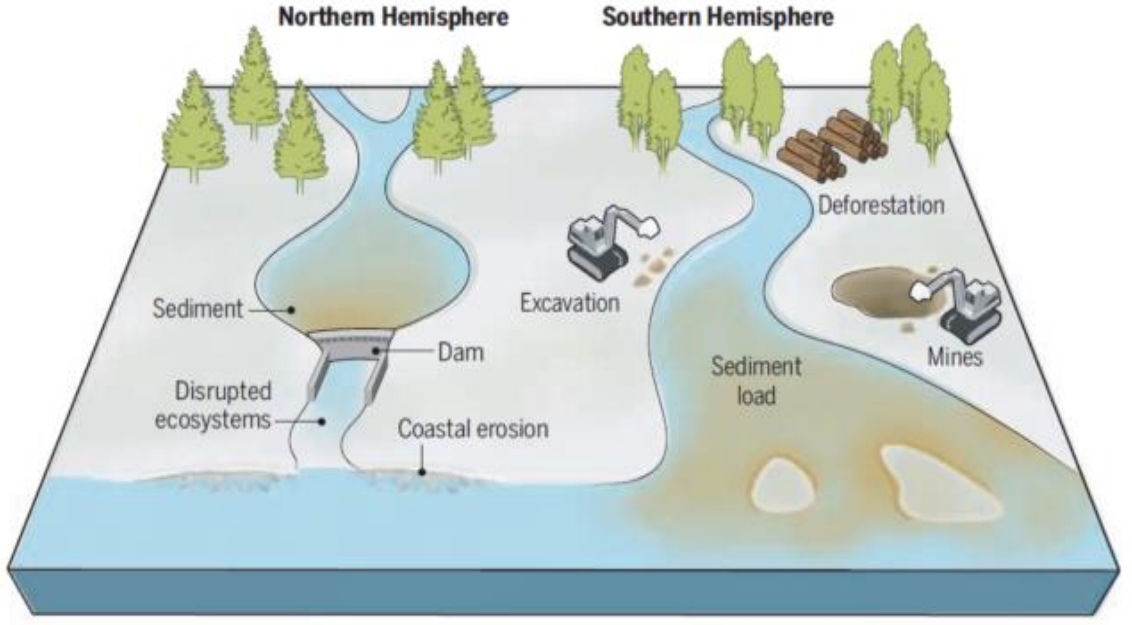
Global satellite data quantify changes in sediment flux in 414 rivers

By **Christiane Zarfl**[1] *and* **Frances E. Dunn**[2]

Rivers are more than just streams of water; they also carry sediments from the land, riverbeds, and riverbanks and deposit them downstream or into oceans. Sediments play a pivotal role in defining river morphology on small scales

The imbalance of sediment flux between the Northern Hemisphere and Southern Hemisphere

A meta-analysis of 414 major rivers around the world reveals how different human activities affect sediment transport in rivers, and that the Northern and Southern Hemispheres experience problems related to excess retention and erosion of sediment, respectively.



Zarfl & Dunn (2022, Science)

Objectives

1. How did suspended sediments evolved during the last decades in Germany?
2. How will it change in the future?
3. What are the driving factors of change?
4. What are the implications for sediment management?

- Focus on waterways (navigable rivers), which are maintained by German Water and Shipping Authority

Earth Surf. Dynam., 11, 287–303, 2023
https://doi.org/10.5194/esurf-11-287-2023

Earth Surface Dynamics
Open Access
EGU

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

Thomas O. Hoffmann[1], Yannik Baulig[1], Stefan Vollmer[1], Jan H. Blöthe[2], Karl Auerswald[3], and 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 Augsburg, Alter Postweg 118, 86165 Augsburg, Germany

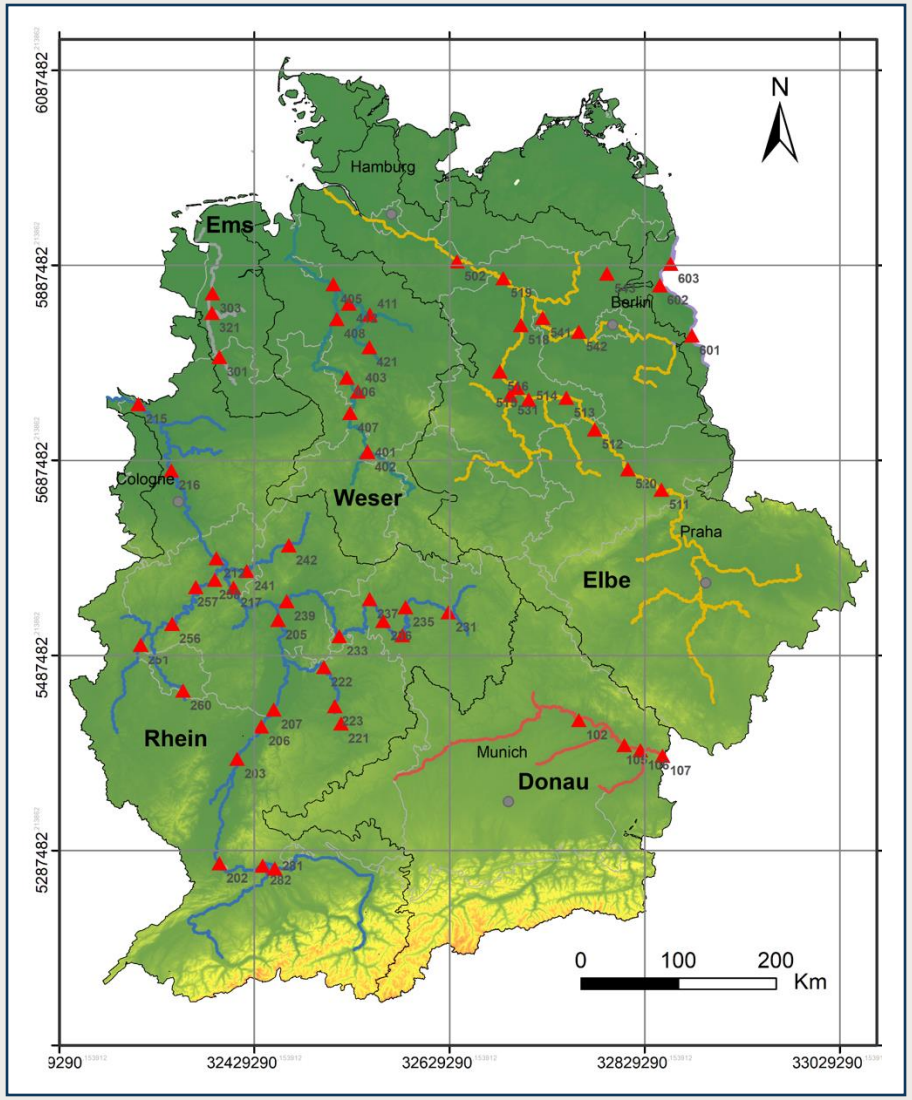
Correspondence: Thomas O. Hoffmann (thomas.hoffmann@bafg.de)

Received: 15 July 2022 – Discussion started: 6 September 2022
Revised: 21 January 2023 – Accepted: 20 March 2023 – Published: 14 April 2023

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 160 000 km^2) 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 in mean annual SSC and annual suspended sediment loads (SSLs) at 49 of 62 monitoring stations totaling $-0.92\,mg\,L^{-1}\,yr^{-1}$. At some stations decreases during the 20 years represent up to 50 % of the long-term average SSC. Significant decreases in SSC are associated with declining SSL despite an increase in sheet and rill erosion by almost 150 % derived from modeling 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 are approaching the natural base level of $\sim 1\,Mt\,yr^{-1}$, which was reached 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 larger rivers despite erosion increase. We argue that increased sediment retention in upstream headwaters is presumably the major reason for declining SSC in the large river channels studied.

Suspended Sediment Monitoring in Germany

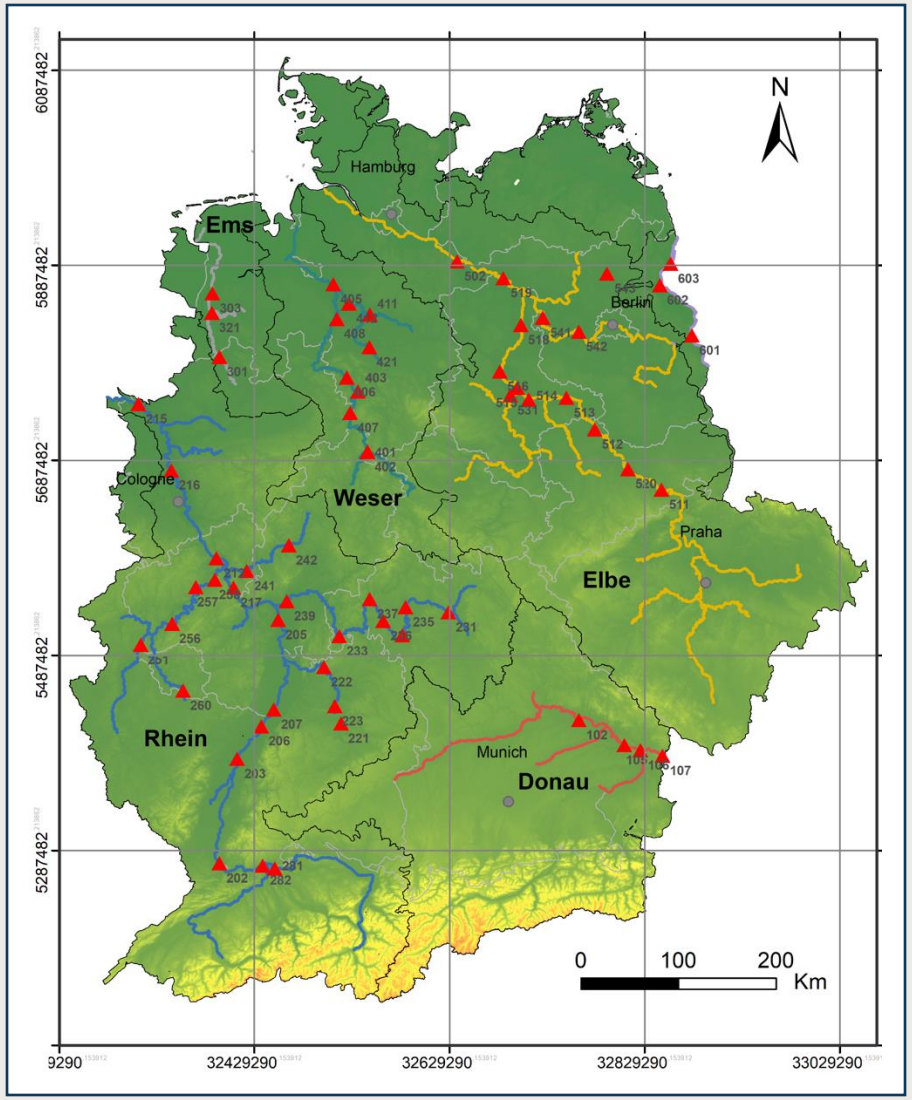
- ✓ Monitoring network of the German Water and Shipping Authority (WSV) starting in 1970
- ✓ Approx. 65 stations along the German Waterways



Hoffmann et al (2023, ESurf)

Suspended Sediment Monitoring in Germany

- ✓ Monitoring network of the German Water and Shipping Authority (WSV) starting in 1970
- ✓ Approx. 65 stations along the German Waterways
- ✓ Daily sampling of 5l water
- ✓ Gravimetric filtration
  - ➢ Total Suspended Matter: mineral + organic

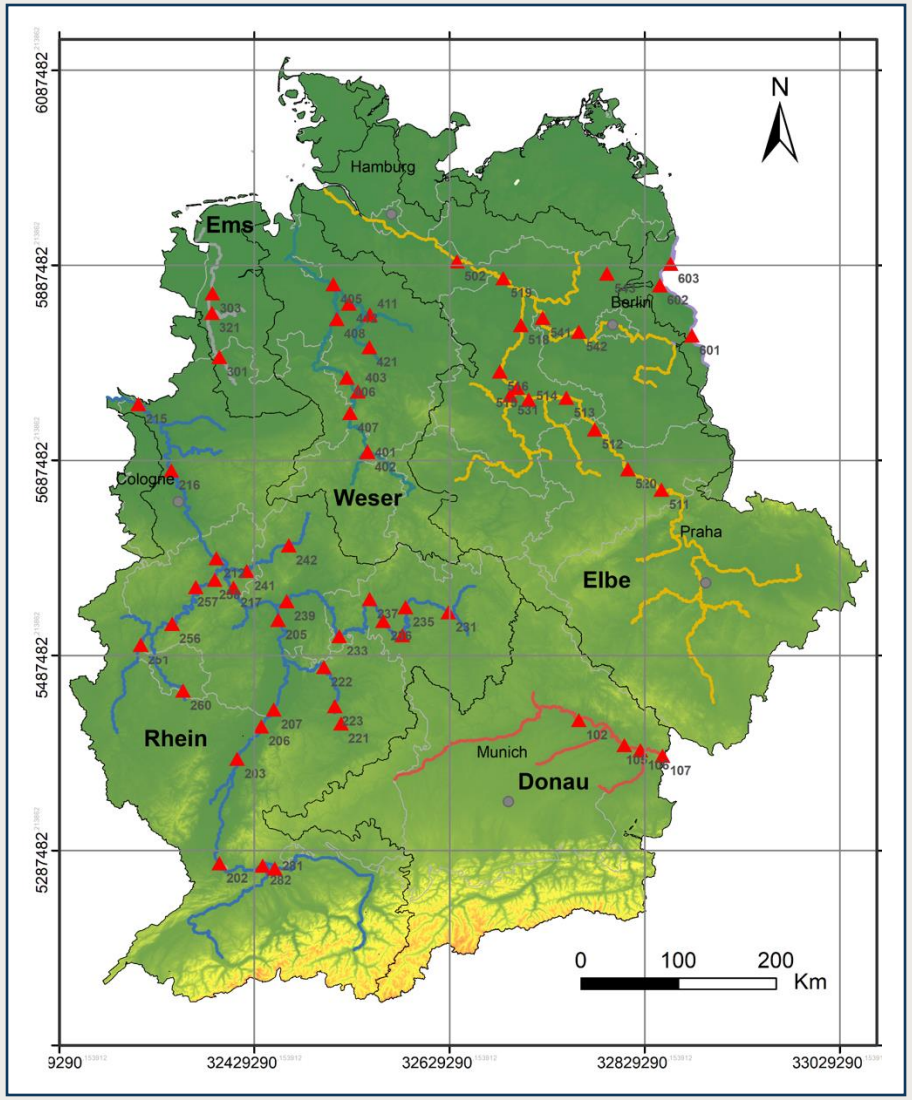


Hoffmann et al (2023, ESurf)

Trend Analysis: Suspended Sediment

Method:

Mann-Kendall trend test of mean annual discharge and suspended sediment concentration (SSC)

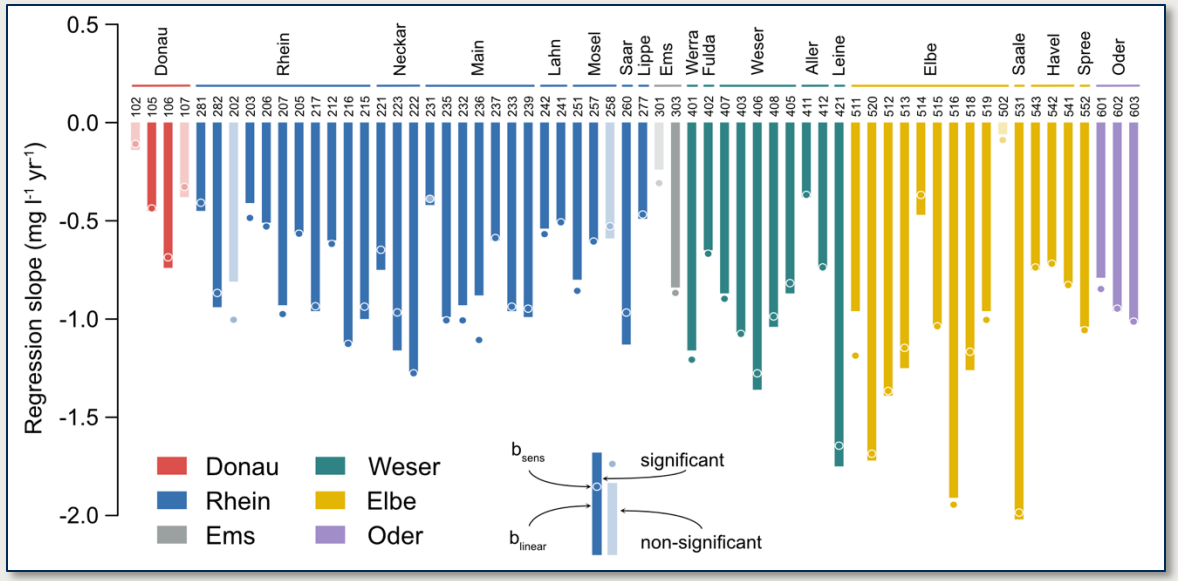


Hoffmann et al (2023, ESurf)

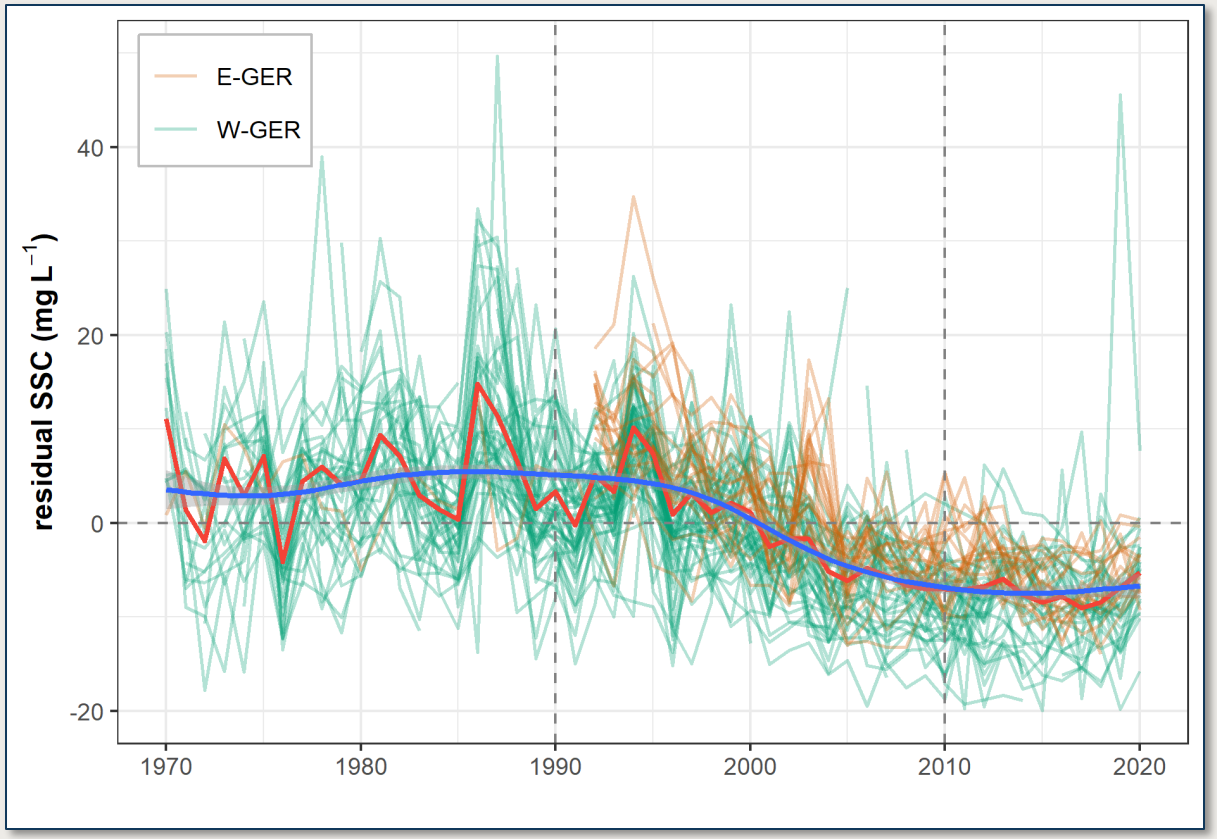
Trend Analysis: Suspended Sediment

Results:

- ✓ 47 of 49 stations show coherent decline of suspended sediment concentration
- ✓ Up to 50% decline between 1990 & 2010
- ✓ No spatial patterns



Hoffmann et al (2023, ESurf)

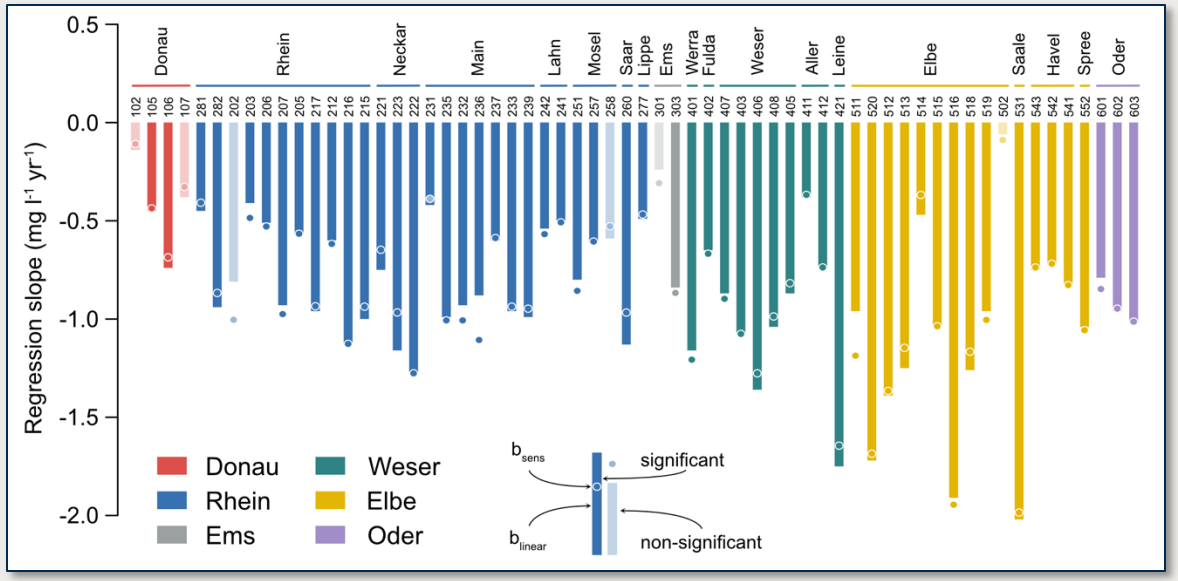


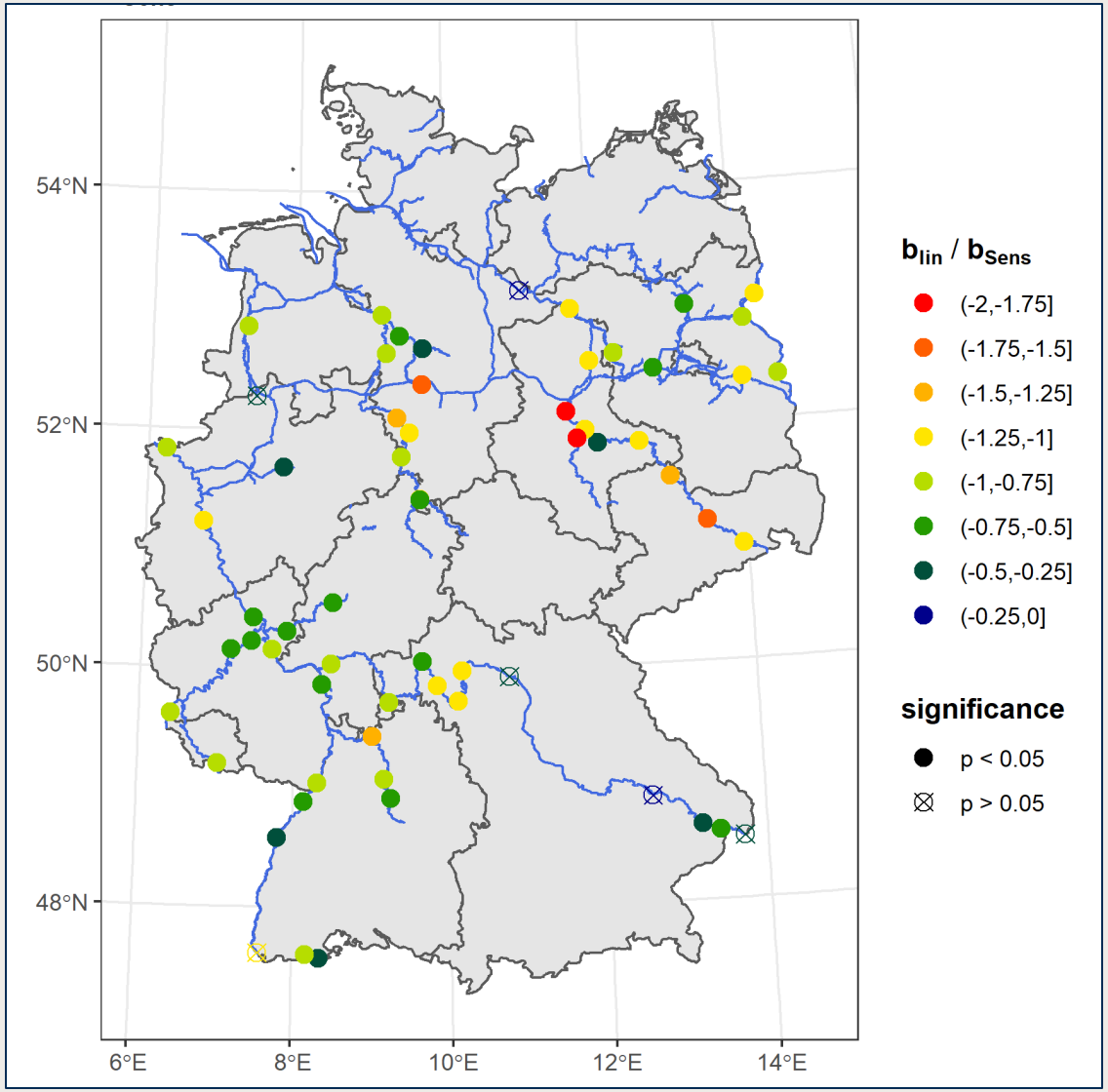
Trend Analysis: Suspended Sediment

Hoffmann et al (2023, ESurf)

Results:

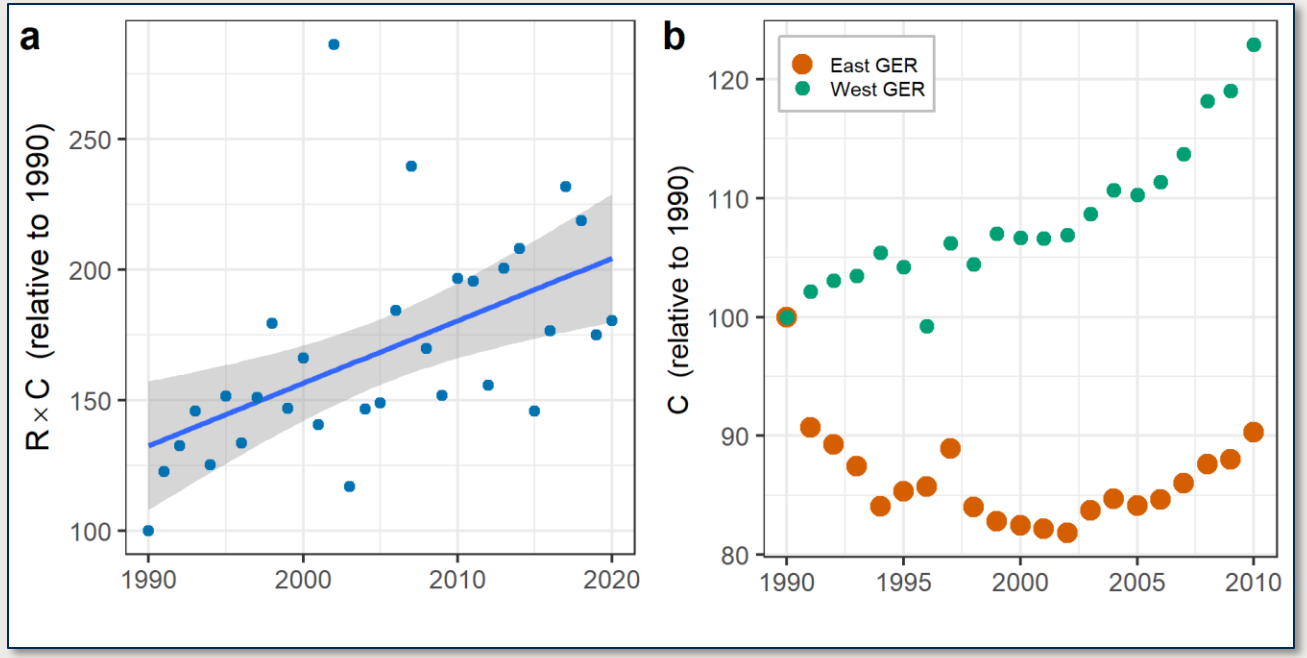
- ✓ 47 of 49 stations show coherent decline of suspended sediment concentration
- ✓ Up to 50% decline between 1990 & 2010
- ✓ No spatial patterns





Potential factors of observed SSC trends

Soil Erosion ?



(1) **Factors of soil erosion indicate increasing sediment supply**

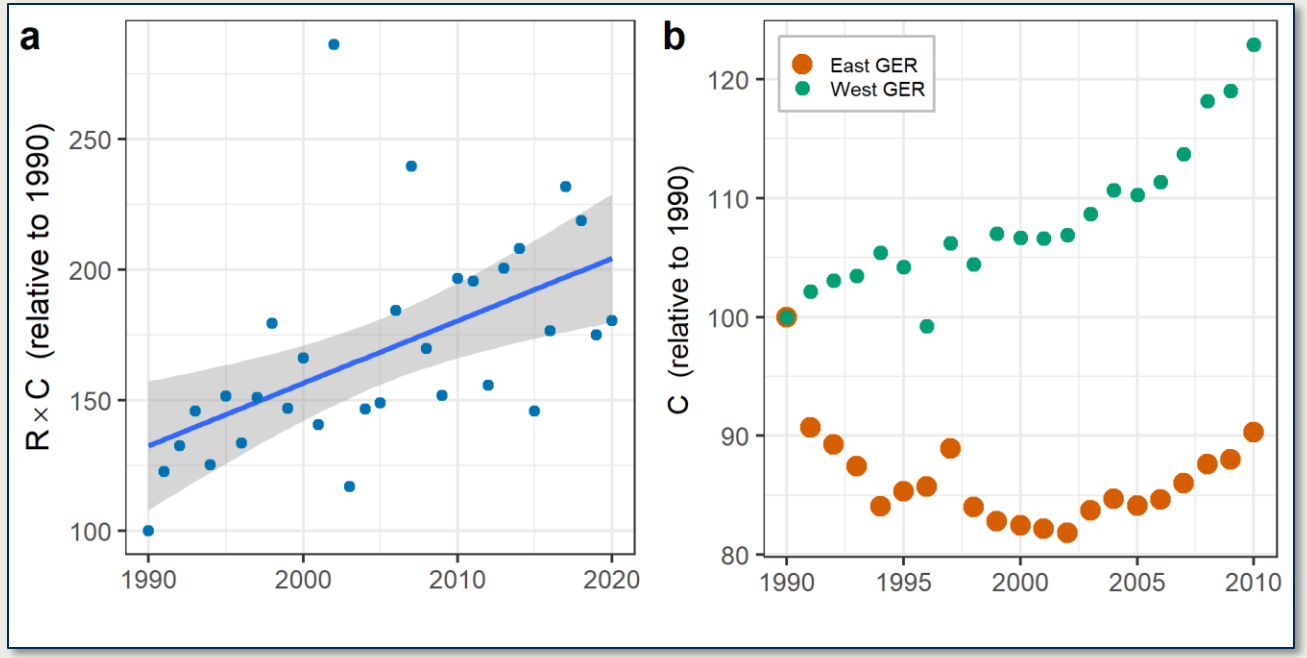
(2) Construction of dams and reservoirs mostly finished by 1990

(3) Decreasing SSC due to declining sediment retention in tributaries

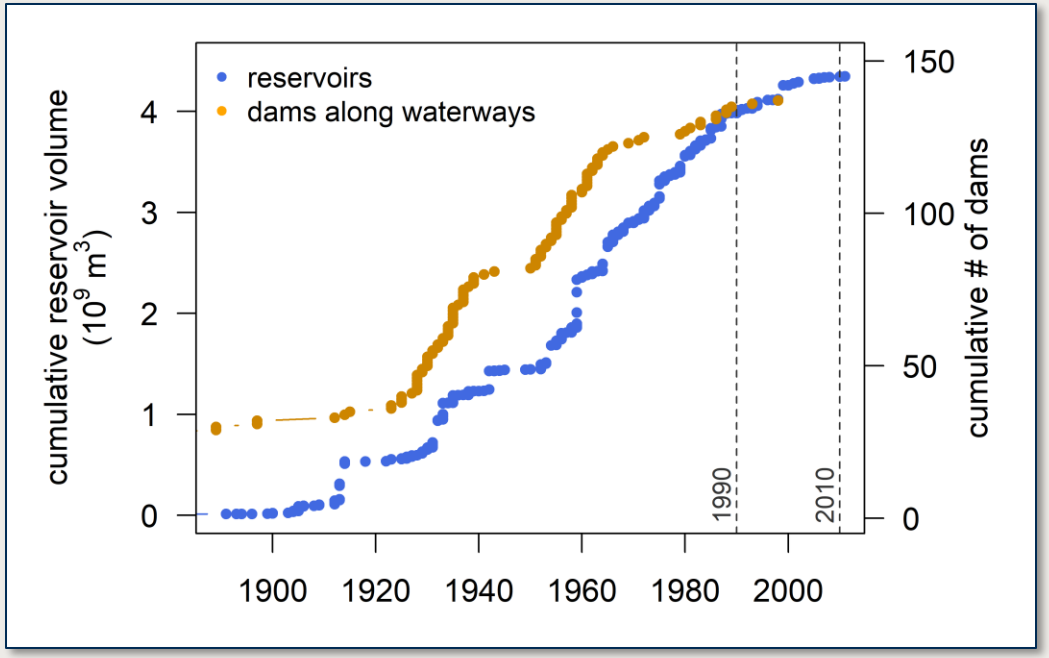
Hoffmann et al (2023, ESurf)

Potential factors of observed SSC trends

Soil Erosion ?



Dams and Reservoirs ?



(1) Factors of soil erosion indicate increasing sediment supply

(2) Construction of dams and reservoirs mostly finished by 1990

(3) Decreasing SSC due to declining sediment retention in tributaries

Hoffmann et al (2023, ESurf)

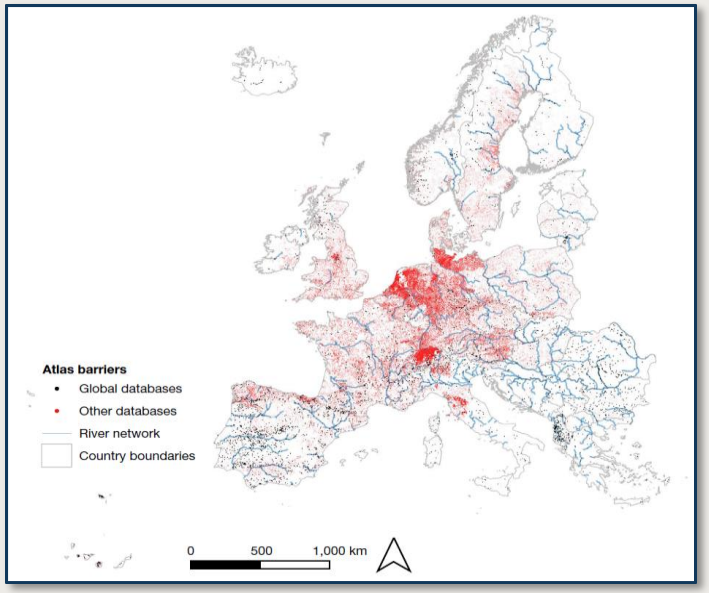
Potential factors of observed SSC trends

Buffer Strips

- Effeciency is debatable

© www.lfu.Bayern.de

More than 1 Mio. barriers in Europe



Belletti et al (2020, Nature)

Expert insight into current research

News & views

Figure 1 | The weir at Pulteney Bridge, Bath, UK. Belletti *et al.*[1] estimate that more than 1.2 million artificial constructions, such as weirs, dams and locks, alter the flow of Europe's rivers and streams.

Hydrology

Small barriers are a big deal for Europe's rivers

Christiane Zarfl & Bernhard Lehner

An atlas of European river barriers has been made, by curating and correcting existing records, and by surveying 2,700 kilometres of waterways. It reveals that rivers are fragmented by an amazing number of obstructions. See p.436

If you asked a child in Europe to draw a river, what would this picture look like? Would it resemble a natural, wild and scenic river, with braided and meandering flow paths in a vast floodplain, fringed by riverine vegetation? Or would it show a modern, well-managed river

survey of river barriers in Europe, which suggests that the second picture would be much more likely.

Free-flowing rivers have become increasingly rare, because centuries of human activities have altered their passage and

or human use; locks and canals have been used to ensure and expand navigable waters; and river flows have been trapped or diverted for power-generating applications ranging from ancient waterwheels to modern hydroelectricity plants. Diverse in-stream structures have been constructed for these purposes, such as large concrete dams, wooden locks, small weirs and partially submerged fords. All of these interventions fragment the rivers and disturb the flow in various ways across different spatial and temporal scales, affecting the transport and delivery of sediments and nutrients[2,3], and the migration and dispersal of aquatic organisms[4].

Researchers and water managers who want to investigate the consequences — both beneficial and harmful — of these modifications must first ask some fundamental questions. How many barriers have been installed, and what types? And, most importantly, where have they been built?

Perhaps surprisingly, the answers are largely unknown. No comprehensive inven-

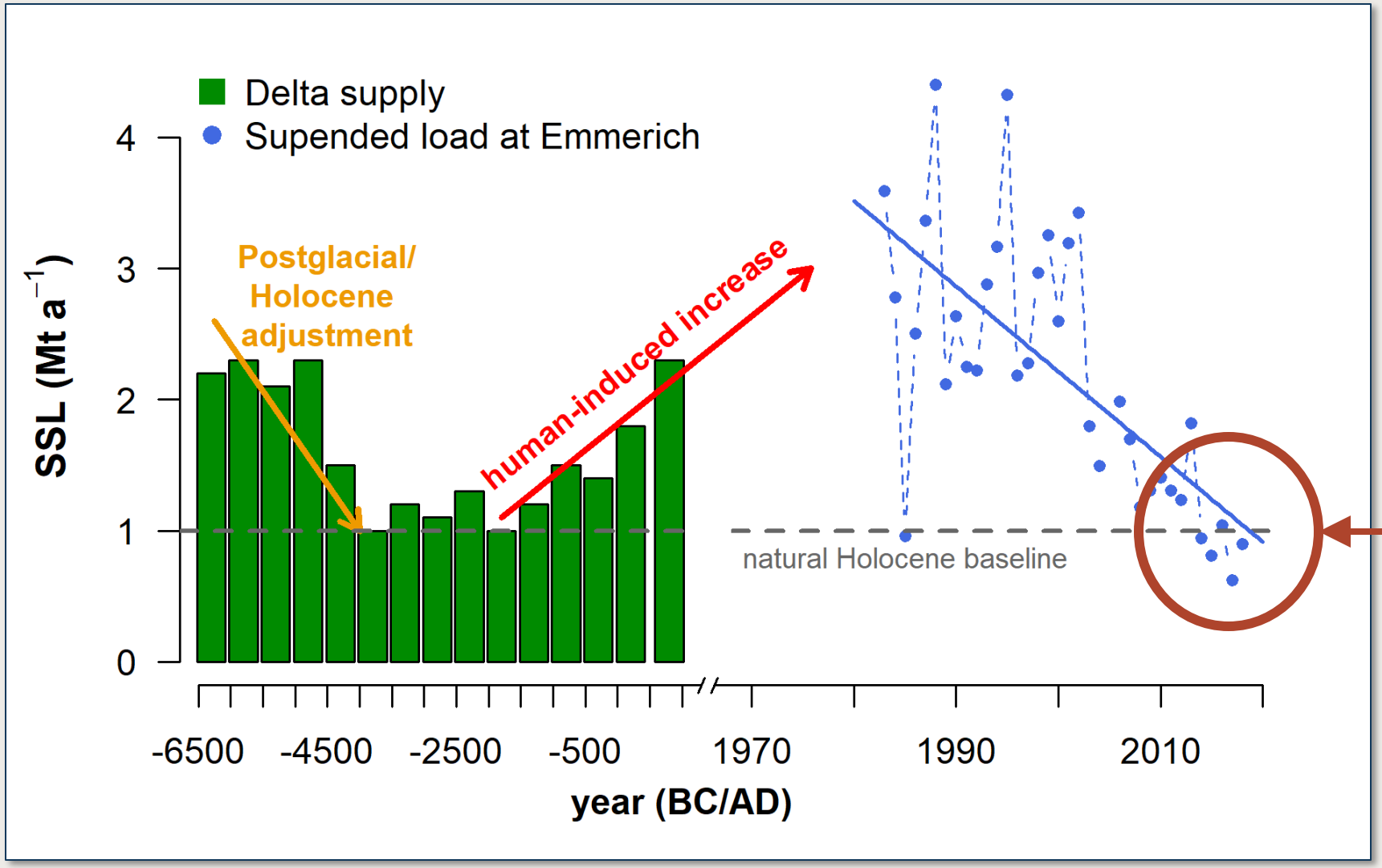
(1) Factors of soil erosion indicate increasing sediment supply

(2) Construction of dams and reservoirs mostly finished by 1990

(3) Decreasing SSC due to declining sediment retention in tributaries

Hoffmann et al (2023, ESurf)

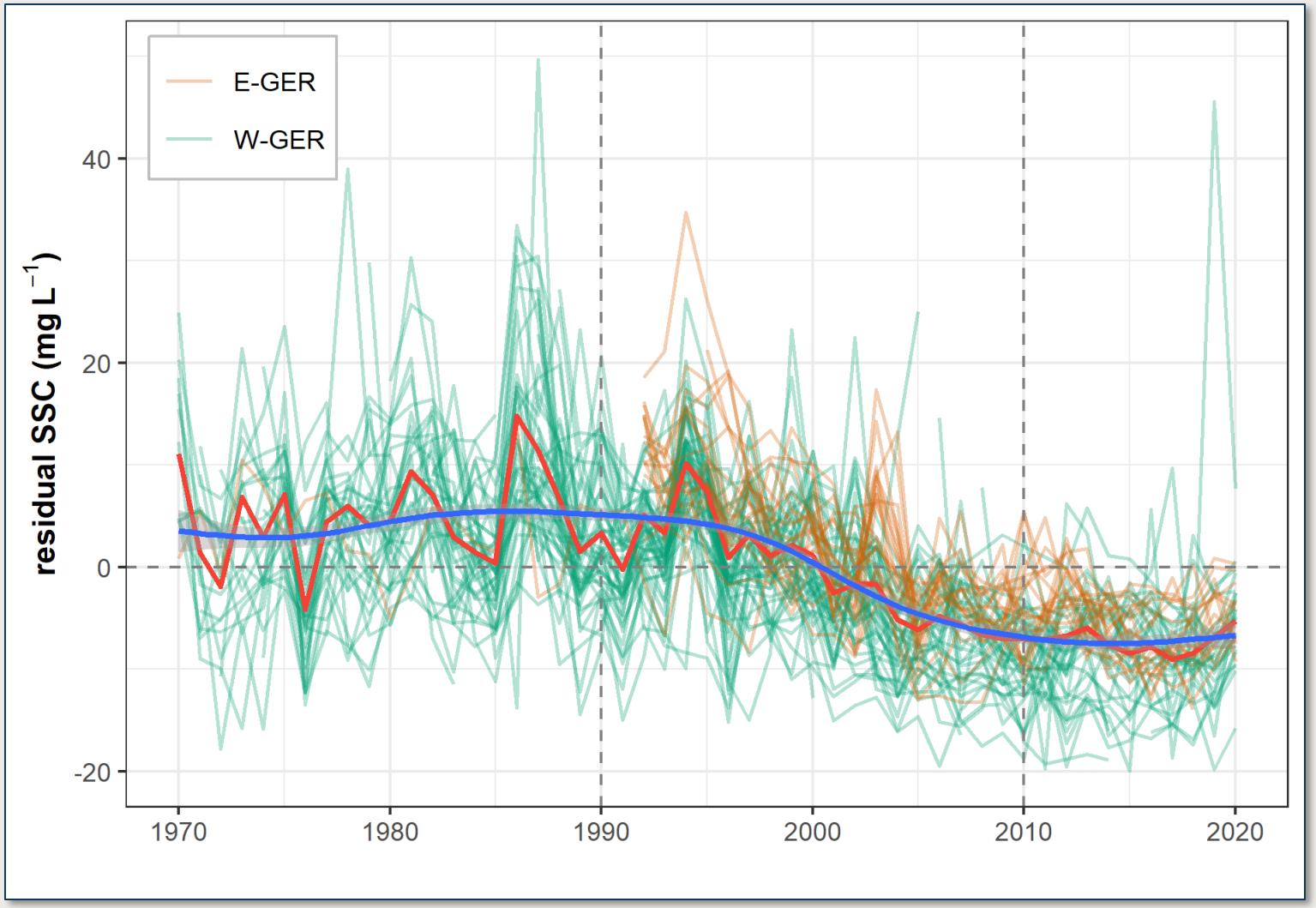
Holocene/Anthropocene evolution



Recent loads in order of natural baseline

Hoffmann et al (2023, ESurf)

Future developments ?



Hoffmann et al (2023, ESurf)

- Decreasing trend seem to have stopped around 2010
- Likely increase of high magnitude thunder storms

Future developments ?

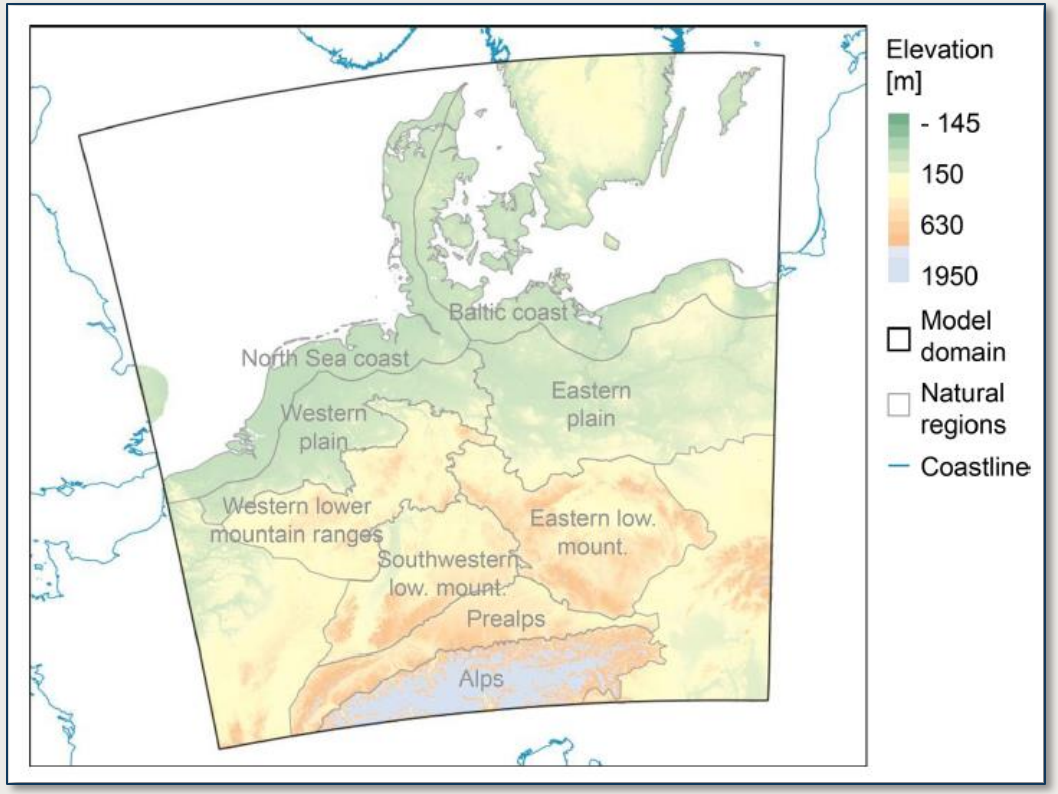
➢ Prediction of rainfall erosivity

- Problem: evolution of rainfall due to thunderstorms insufficiently resolved in GCM convection is a sub-grid-scale process that is parametrized

Future developments ?

➢ Prediction of rainfall erosivity

- Problem: evolution of rainfall due to thunderstorms insufficiently resolved in GCM convection is a sub-grid-scale process that is parametrized
- Solution: convection-permitting simulations (CPSs)
  - ➢ explicit model convection at higher resolution (<4km) regional climate models
  - ➢ Time consuming: no model ensembles, mostly applied at shorter time scales
- Here: COSMO-CLM (DWD-standard) using the Representative Concentration Pathway 8.5 (RCP8.5) emission scenario hourly rainfall
- Time periods: historical period: 1971–2000, near future: 2031–2060; far future: 2071–2100



Uber et al. (2024, HESS)

Future developments ?

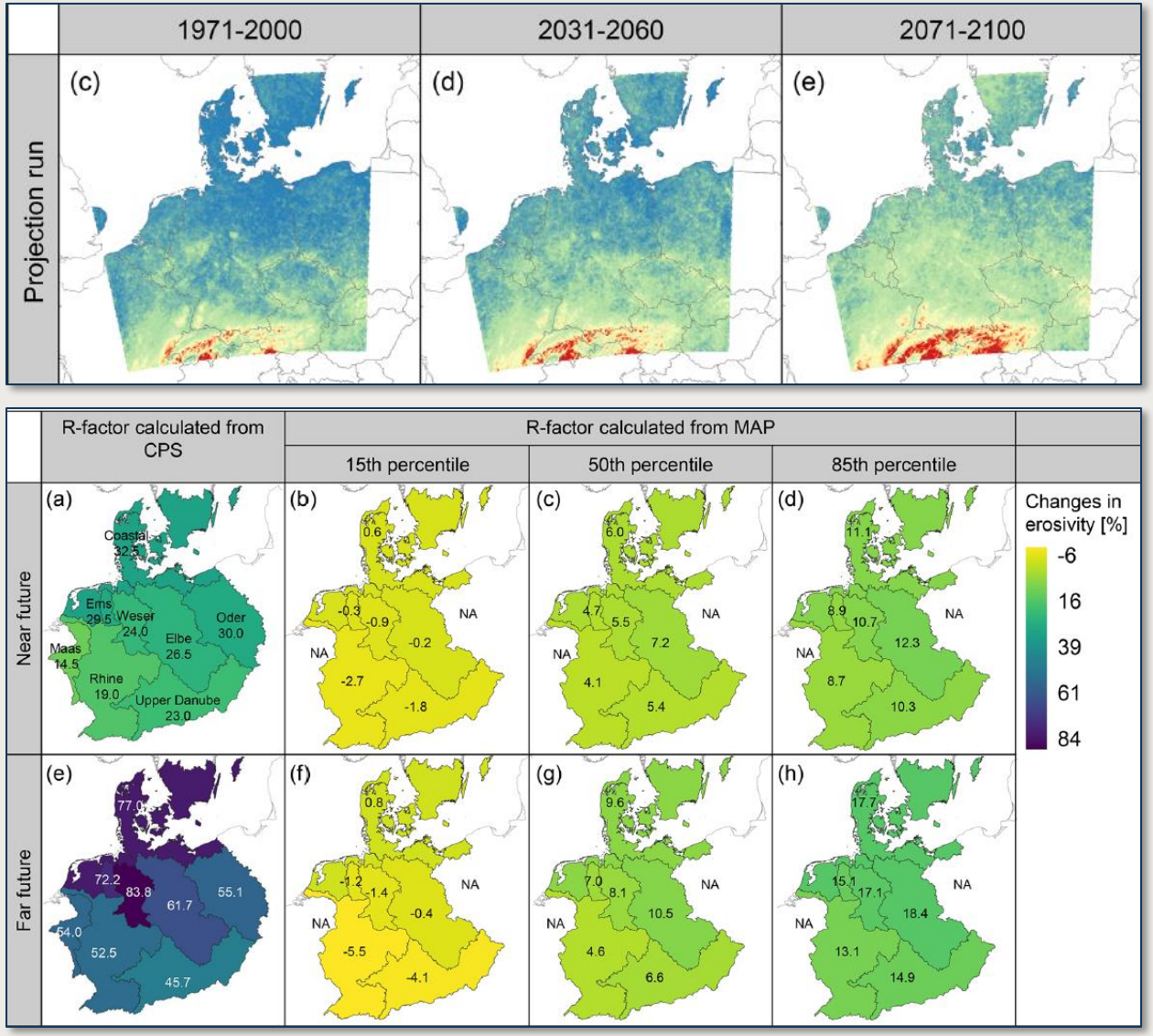
➢ Prediction of rainfall erosivity

Time period	Mean R-factor
1971-2000	96.3 $Nh^{-1}a^{-1}$
2031-2060	119.3 $Nh^{-1}a^{-1}$
2071-2100	149.7 $Nh^{-1}a^{-1}$

Results show …

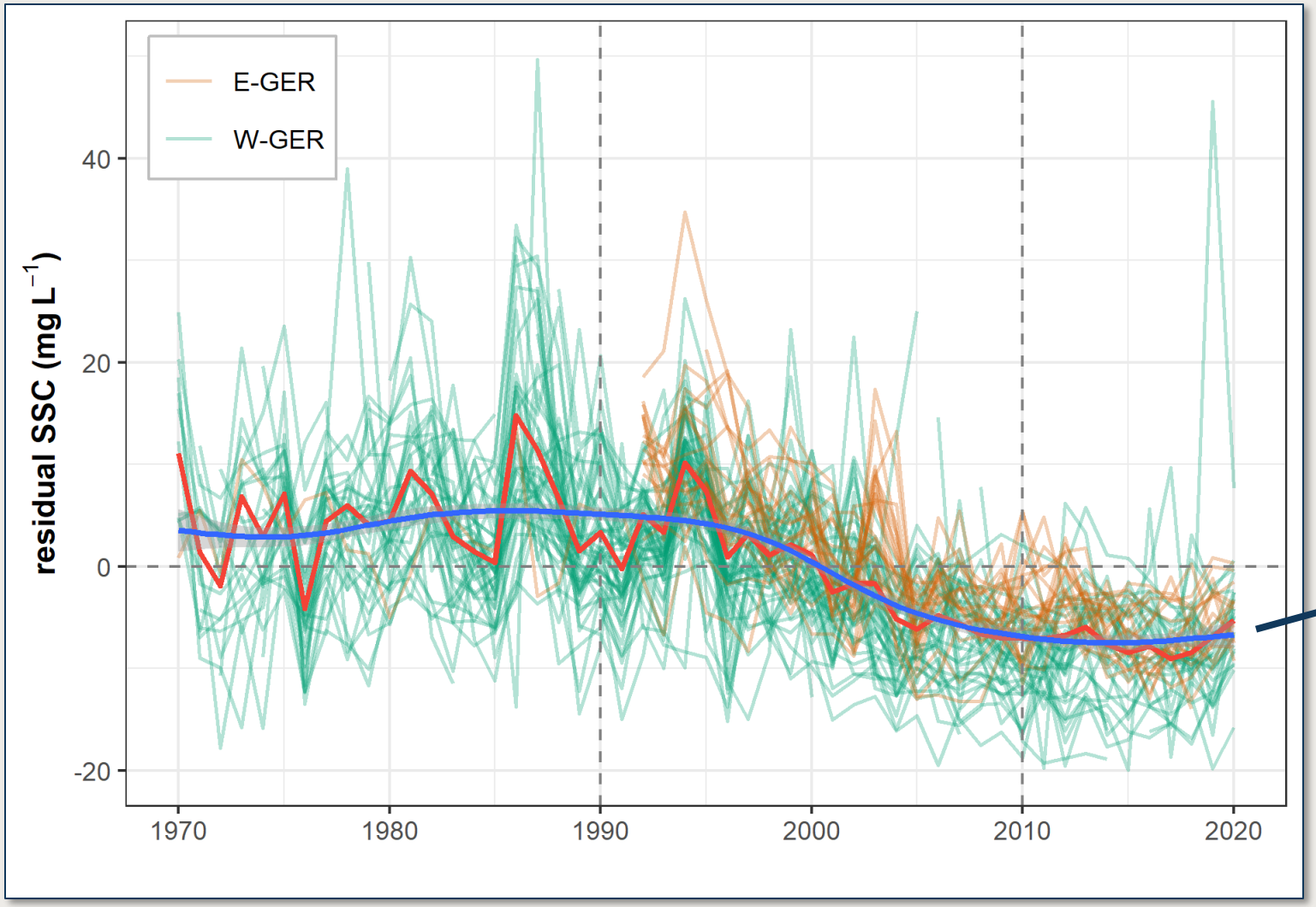
… good agreement with empirical rainfall erosivity map (RADOLAN rainfall) by Auerswald et al. (2019)

… much higher increases than those derived from scenarios of MAP



Uber et al. (2024, HESS)

Future developments ?



Climate-driven increase is very likely

…unless biofuel production drops

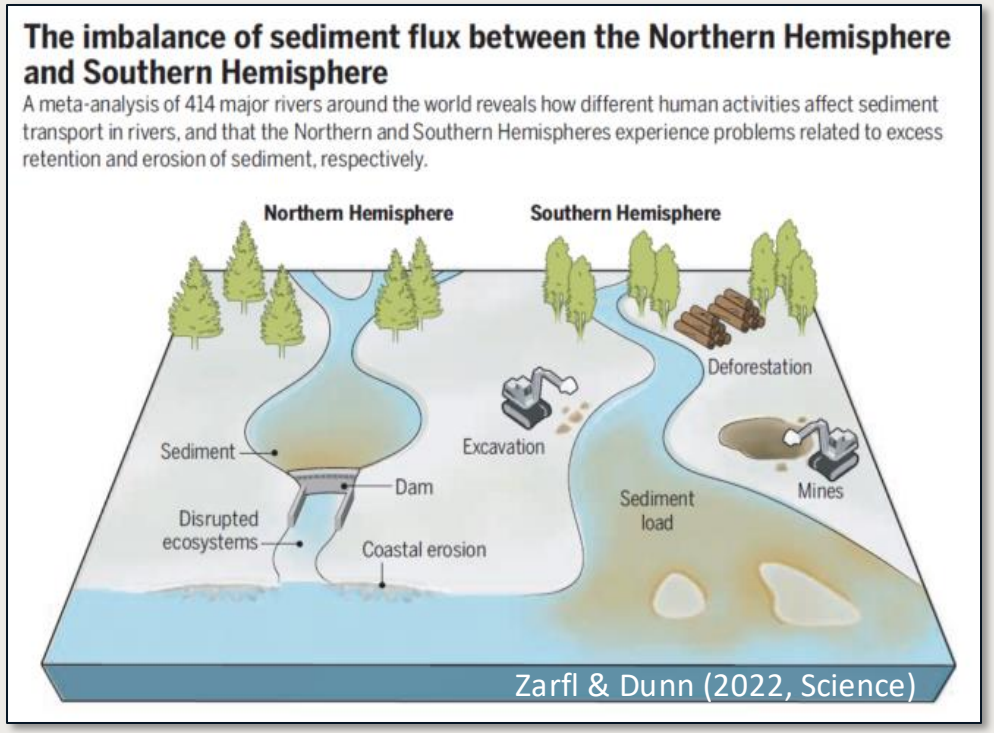
Hoffmann et al (2023, ESurf)

Take home message

(1) Suspended sediment concentration / transport declined by up 50% between 1990 and 2010 despite increased soil erosion

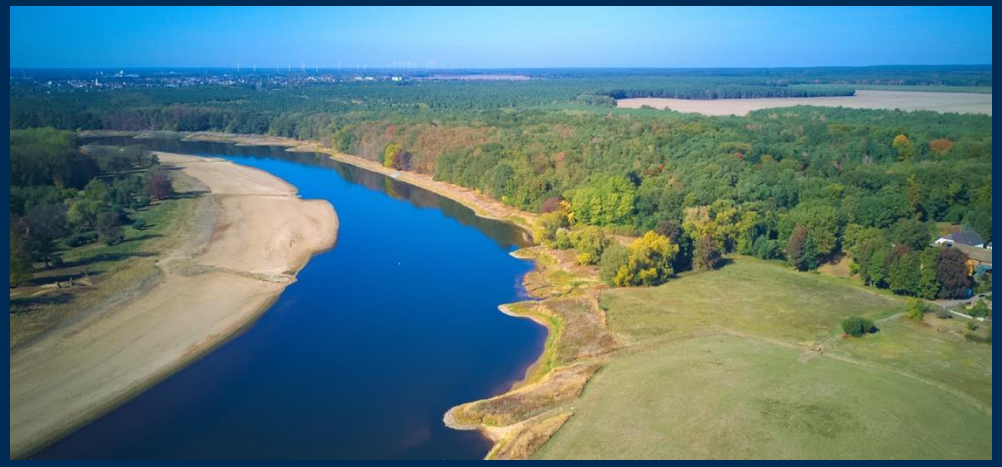
(2) Decline stopped likely due to introduction of bio-fuels

(3) Rainfall erosivity will increase up to 84% (far future) and likely increase fine sediment supply to river systems



(4) Implication for <u>sediment management</u>: Tributaries play a major role for routing sediment through large scale river systems

Thanks very much for your attention!



Hoffmann, Thomas

(Thomas.Hoffmann@BafG.de)

SedNet, Madrid, 6th-10th Oct. 2025

BfG Federal Institute of Hydrology