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Understanding the cost of soil erosion: An assessment of the sediment removal costs from the reservoirs of the European Union

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ABSTRACT

Soil erosion is both a major driver and consequence of land degradation with significant on-site and off-site costs which are critical to understand and quantify. One major cost of soil erosion originates from the sediments delivered to aquatic systems (e.g., rivers, lakes, and seas), which may generate a broad array of environmental and economic impacts. As part of the EU Soil Observatory (EUSO) working group on soil erosion, we provide a comprehensive assessment of the existing costs of sediment removal from European Union (EU) catchments due to water erosion. These quantifications combine continental average and regionally explicit sediment accumulation rates with published remediation costs, integrating numerous figures reported in the grey literature. The cost of removing an estimated 135 million m^3 of accumulated sediments due to water erosion only is likely exceeding 2.3 billion euro (€) annually in the EU and UK, with large regional differences between countries.

Considering the sediment delivered through all soil loss processes (gullies, landslides, quarrying, among others) through extrapolating measured reservoir capacity losses, the sediment accumulation in the circa 5000 EU large reservoirs exceeds 1 billion m^3 with a potential cost of removal ranging between 5 and 8 billion € annually. These estimates, although not accounting for already implemented catchment mitigation measures, provide insights into one of the off-site costs of soil erosion at both the continental scale as well as the regional differences in economic burden. The provided estimates contribute to support policies such as the Soil Monitoring Law, the Zero Pollution Action Plan, the Farm to Fork strategy and the Water Framework Directive.

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1. Introduction

The European Commission's Green Deal prioritizes the protection of soils as a means to enhance biodiversity, respond to climate neutrality objectives, become a zero-toxic continent and contribute to sustainable food systems. In this transition towards more sustainable food systems, the European Union (EU) has to protect its natural resources, and in particular soils. The European Commission's vision of being the first climate-neutral continent includes an ambitious package of environmentally friendly measures within the Biodiversity Strategy 2030, Farm to Fork, Zero Pollution Action, Fit for 55 and the EU Soil Strategy 2030 (Panagos et al., 2022).

In July 2023, the European Commission proposed the Soil Monitoring Law as the main policy instrument for protecting soils in the European Union (EU). An important new policy development which aims to help achieving healthy soils by 2050, with concrete actions by 2030. Accordingly, it requires a comprehensive assessment of the current status of soil and land degradation in the EU alongside an impact assessment of the proposed legislation (Radaelli and Meuwese, 2010). This impact assessment also covers the estimation of policy measures' costs and compares these to a "no action" scenario. In the historical proposal for a Soil Framework Directive in 2007, the relevant impact assessment was almost devoid of any economic costs of land degradation processes (Kuhlman et al., 2010), in particular for the specific case of reservoir siltation in which no reference was provided. Currently, and as far as the authors of this study are aware, there is no study consolidating knowledge on sediment management to quantify siltation costs in European reservoirs at the EU level.

Soil erosion, with an estimated global total annual gross soil loss of c. a. 36 billion tonnes through interrill and rill processes (Borrelli et al., 2017), is considered the most serious threat to food production globally, with cascading detrimental impacts on biogeochemical cycles and land productivity (Alewell et al., 2020; Van Oost et al., 2007). Soil erosion may generate on-site costs which burden mostly farmers; including, among others, the decline of agricultural productivity, yield reduction, damage of plantations, and loss of farming area (García-Ruiz, 2010; Vanwalleghem et al., 2011). The economic loss due to the decline of land productivity (on-site effects) caused by water erosion is estimated at about 1.25 billion € per year in the EU (Panagos et al., 2018). Eroded sediments transferred across the catchment hillslopes can cause a further plethora of issues in terrestrial and aquatic systems. These off-site costs of soil erosion may include sedimentation in reservoirs, impacts on fisheries, loss of wildlife habitat and biodiversity, increased flood risk (extreme deposition), destruction of infrastructures such as roads, railways and other public assets, impacts on recreational activities, and also water pollution and eutrophication from upstream agricultural fields utilizing pesticides and fertilizers (Ferreira et al., 2022; Kalantari et al., 2019). Recent estimations in Normandy (France) suggest that the feasibly quantifiable total off-site costs of soil erosion are about 800–4300 € ha^{-1} yr^{-1} of farmed land (Patault et al., 2021).

A key off-site impact of eroded soil and rock is the infilling of reservoirs with sediment, limiting their water storage and energy production capacity. Without spatially distributed estimations, the continental and global knowledge base is restricted to lumped extrapolations. For example, the mean annual sedimentation rates in reservoirs vary globally from 0.2% to some 2–3% in loss of storage capacity, with an annual average rate of about 1%. In the first decade of the 21st century it was estimated that in Europe, 0.65% of the water reservoir volume, or reservoir storage capacity, is annually lost due to sedimentation, compared to 0.22–0.68% in the USA, and 0.83–2.3% in China (Schleiss et al., 2016). According to the latest ICOLD database, around 4490 registered large reservoirs in the EU have a capacity of 258 billion m^3 (ICOLD, 2023); half of these are multi-purpose reservoirs and mainly used for hydropower production. Assuming a sedimentation rate of 0.65% per year (ICOLD, 2009), a rough, spatially lumped estimation is that 1.67 billion m^3 of sediments remain trapped in these reservoirs annually. In the absence of mitigation strategies, which have been already implemented in many reservoirs, this cumulative increase in the total sedimentation volume will entail a further gross storage loss in future years (Annandale et al., 2016; ICOLD, 2009; Schleiss et al., 2016). Additionally, sediment yield increases in the future will pose further challenges displaying regional disparities which require a spatially-explicit understanding. In particular, key pressures will come from the projected impacts of climate change on soil erosion (Eekhout and de Vente, 2022; Panagos et al., 2021) and continued glacial retreat (Beyer and Schleiss, 2000; Sommer et al., 2020).

Currently, sediment management to minimize the loss of storage capacity in reservoirs through siltation is achieved with a variety of techniques categorized into three main strategies: 1) sediment yield reduction, 2) sediment routing around or through the reservoir, and 3) recovering volume by sediment removal (Annandale et al., 2016; ICOLD, 2009; Kondolf et al., 2014). The first strategy aims at catchment-wide strategies to reduce the sediment inflow into the reservoir, i.e., soil erosion control by reforestation and upstream sediment trapping in check dams. The second refers to routing of sediments into the tailwater downstream of the dam, preventing or significantly mitigating sedimentation. Effective techniques include: direct bypassing around the dam using tunnels or channels, diverting to an off-channel reservoir, or passing sediments through the reservoir by either sluicing or turbidity current venting, techniques that are applied mainly during flood events. The third strategy refers to restoring the reservoir capacity by removing or reallocating the deposited sediment using mechanical or hydraulic power. The former is mainly carried out by means of dry excavation during complete water level drawdown, hydraulic dredging with pumps during high reservoir levels, and redistribution of sediments inside the reservoir, while the latter pertains to sediment flushing through the outlets either during complete water level drawdown or pressure flushing at high reservoir levels (examples are shown in Fig. 1). The appropriate sediment management options, which can ensure a sustainable use of a reservoir, depend on the capacity-inflow ratio (CIR) which is the ratio between the reservoir volume (CAP) and the Mean Annual Sediment inflow volume (MAS) (Annandale et al., 2016).

At the global scale, the removal of accumulated sediment in reservoirs incurs significant economic costs, reaching 21 billion $ per year worldwide (Basson, 2009), or roughly 37% of the overall maintenance costs, which are placed at an estimated at 57 billion $ per year (ICOLD, 2009). An economic haemorrhage of this magnitude makes it imperative to address the problem. The cost of sediment management is primarily attributed to both sediment removal operations and to hydropower loss during these operations over the typically assumed 100-year lifespan of a dam (Shrestha et al., 2021; Wild et al., 2016). Besides that, construction costs may play a crucial role if facilities have to be newly built or rehabilitated (e.g., bypass tunnels or large bottom outlets) (Sumi et al., 2015). With regard to sediment removal, dredging cost can be as low as 5 € m^{-3} when dredging fine sediment (personal communication) and discharging it to the river downstream of the dam, without booster pump stations. However, access limitations, handling and disposal requirements, permitting, environmental mitigation, and other factors can drive full project unit dredging costs up by a factor 10 (Omelan et al., 2016).

The objective of this study is to provide a comprehensive and regionalized understanding of the requirements and costs from sediment management through capacity restoration in European reservoirs. To do so, we combine information on rates of sedimentation in reservoirs with cost estimations from available mechanical techniques used for sediment removal. Based on available catchment estimations of sediments delivery to river basins due to water erosion, we apply a flat rate and a regional assignment method. A third method focus on potential reservoir capacity losses as a result of siltation from all soil loss processes. By applying those three different methodologies for the total cost estimation (2 lumped EU averages and 1 regionalized quantification), we also provide insights on the strengths and weaknesses of different

Fig. 1. Examples of sediment removal by: a) Mechanical dredging (Lago Maggiore, Lombardy, Italy); b) emptied reservoir during sediment flushing operations, c) starting of flushing event closing the upper dam's gate and opening the bottom outlets, d) top view of the water surface immediately upstream of the dam (Pictures b, c and d are taken in Alto Adige, North of Italy); e) pressure flushing f) mechanical dredging (Fusino dam in Valgrosina).

methodologies to quantify both the sediment accumulation rate and monitory cost. We aspire this work, which was previously missing from literature, to create a priming effect for the efficient treatment of the reservoir sedimentation problem in the EU.

2. Methods and study area

2.1. Study area

The study area includes all lands of the European Union (EU) and the United Kingdom (UK) for which estimates of soil losses due to water erosion (interrill and rill processes) and sediment delivery to river channels are available (Borrelli et al., 2018).

2.2. Review of the costs for sediment removal

In this method component, we identify the mechanical techniques to remove quantities of sediment and establish an associated cost per unit volume (€ per m^3) for upscaling across the study area. To do so, we first compile a table of recorded techniques and their costs from a combination of 33 literature studies and feedback from scientists in 20 European countries (Table 1). Thereafter, these values per volume of sediment are used to provide continental and regional estimations of the costs of reservoir siltation management based on estimated annual volumetric sedimentation rates (Section 2.3). Due to the historical nature of some price estimations (Table 1), we consider some figures to be an underestimation due to the effects of inflation on the operation costs, however these were not accounted for in this study.

Table 1 gives a compilation of the operational costs and management techniques for sediments removal per region and country. For example, sediment removal techniques include, among others, mechanical dredging and drawdown flushing (hydraulic dredging) (Hauer et al., 2018). The main drawback of mechanical dredging is the substantial cost associated with the use of excavators (Bianchini et al., 2019), as well as other costs related to the transport and disposal of dredged material in on-site and off-site landfills, confined disposal facilities, or for beach nourishment. In Europe, other techniques such as suction dredging, sediment nourishment or replenishment, and automated robots are also applied (Table 1). This review (Table 1) includes the area (region, country), the method for sediments removal, the costs per m^3 and the reference in the literature. Additional studies are also listed in Supplementary material.

2.3. Quantifying pan-European sediment inputs to river systems due to water erosion

We quantified the potential spatial displacement and delivery of soil sediments to river systems (net erosion) (Borrelli et al., 2018) due to

Table 1
Methodologies and costs for estimating sediment removal in European Union (EU) and Switzerland.

Methodology	Costs	Region-Location	Country	Reference
Treatments of sediments deposits	20 € per m^3	Not Available (NA)	Austria	Hauer et al. (2018)
Dredging	20 € per m^3	Locations in Danube basin	Austria	Hartl (2023)
Mechanical dredging	10-50 € per m^3	Flanders	Belgium	Verstraeten et al. (2003)
Mechanical dredging	11 € per m^3	Limburg	Netherlands	Kwaad, F.J.P.M. et al. (2006)
Mechanical dredging	20 € per m^3	Normandy	France	Patault et al. (2021)
Mechanical dredging	20-25 € per m^3	Bourgogne-Franche-Comté	France	MISEN (2010)
Mechanical and hydraulic dredging	17-20 € per m^3	Auvergne-Rhône-Alpes	France	Hydrostadium (2022)
Mechanical dredging	up to 30 CHF per m^3	NA	Switzerland	Jenzer Althaus et al. (2015)
Automated robot (mechanical dredging, novel technology)	5 € per m^3	NA	Switzerland	Personal communication
Mechanical dredging	15-20 € per m^3	Lombardy	Italy	Personal communication with excavation company
Mechanical dredging in dry conditions and landfill disposal	25 € per m^3	NA	Italy	ITCOLD (2009)
Mechanical dredging in wet conditions and landfill disposal	28 € per m^3	NA	Italy	ITCOLD (2009)
Hydraulic dredging	Between 5-10 and 30–40 € per m^3	NA	Italy	Personal communications with dam managers
Mechanical dredging	4.2€ per m^3	Molise	Italy	De Vincenzo et al. (2018)
Mechanical floating (fluitazione)	30 € per m^3	Lombardy (Diga di Cancano)	Italy	ITCOLD, 2016
Mechanical dredging	10-20 € per m^3		Spain	Rovira and Ibàñez (2007)
Suction dredging	6-13 € per m^3		Spain	Rovira and Ibàñez (2007)
Dredging	5-20 € per m^3	Andalusia	Spain	Universidad de Granada, n.d.
Sediment nourishment	2 € per m^3	Barra-Vagueira	Portugal	Coelho et al. (2022)
Dredging	10 € per m^3	Óbidos lagoon	Portugal	Mendes (2015)
Dredging	5-12 € per m^3	Etoloakarnania	Greece	Dagzi (2015)
Dredging	10-100€ per m^3	NA	Germany	Henkel (2014)
Excavation	5€ per m^3	NA	Finland	Västilä et al. (2021)
Dredging and transport	13-27 per m^3	NA	Finland, Sweden, Denmark, Estonia	Saikkonen et al. (2021)
Dredging	26€ per m^3	NA	Sweden	Andersson et al. (2018)
Mechanical dredging (including transport)	15 € per m^3	Veľké Kozmálovce reservoir	Slovakia	UVO (2018)
Mechanical dredging (including transport)	20 € per m^3	Mlýnka River	Czechia	PRO MISTNI ROZVOJ (2022)
Dredging	7.5 € per m^3	Reservoirs Štikada and Razovac	Croatia	EOJN (2022)
Dredging	3 € per m^3	Danube river basin	Bulgaria	Schwarz (2008)
Dredging	3.5€ per m^3	Danube river basin	Romania	Lower Danube Galati (2022)
Dredging	3.5€ per m^3	Galati	Romania	Viata (2007)
Mechanical dredging from check dams	15 € per m^3	Selška Sora River catchment	Slovenia	Personal communication
Mechanical dredging from bed load sediment trap	2.4–5.8 € per m^3	Upper Sava River in Slovenia	Slovenia	MINISTRSTVO (2018)

water (rill and interill) erosion at the European scale (Panagos et al., 2015). Here, WaTEM/SEDEM was used to simulate the spatially explicit erosion, deposition, and sediment delivery to river channels (Van Oost et al., 2000). The model comes with the benefit of being widely tested in Europe (Van Rompaey et al., 2005). WaTEM/SEDEM provides spatially averaged quantifications of annual average net soil erosion from rill and interrill processes, not considering other sediment detachment processes such as landslides and other mass wasting processes as glacial erosion, bank erosion, gully erosion, quarrying, piping, etc. (Poesen, 2018). Depending on the European region, the sediment supply from these processes can deliver significant sediment loads to the river systems. Despite potential missing erosion processes which may affect the long-term quantity of sediment yield, the spatial patterns of these predictions (Fig. 2) correspond to the established higher sediment yields from all integrated erosion processes in Mediterranean and Mountainous regions of Europe (Vanmaercke et al., 2011).

For the entire study area, the sediment yield is estimated at roughly 164 (±13) million tonnes per year (Borrelli et al., 2018). This quantification done by Borrelli et al. (2018) includes the potential annual spatial displacement and transport of soil sediments due to water erosion at European scale using the WaTEM/SEDEM model. Assuming an average bulk density for drained soils of 1.2 t m^{-3} (Ballabio et al., 2016), this mass of sediments corresponds to about 135 (±10) million m^3 of volume that are potentially transported to the nearest river network each year in the EU and UK. This volume is used as an input for quantifying the associated sediment removal costs. The net erosion (sediment losses) is about 15% of the estimated gross on-site erosion. We also provide the total sediment destined for each major sea outlet (Fig. 2), assuming zero trapping efficiency from dam networks and other mechanical interventions. Implicit in the quantification of remediation costs from modelled sediment delivery rates is the assumption that all sediment delivered to river channels are trapped in reservoirs at least once, and need to be remediated over the reservoir lifetime. This is in line with estimations in Europe that the flow of a small proportion (~10.5%) of rivers, with length >1000 km, is uninterrupted (Grill et al., 2019).

2.4. Potential reservoir capacity loss including all erosion processes

Reservoir sedimentation rates naturally include all types of sediment sources from erosion processes (gully, water, glacial, badlands, landslides, bank erosion, etc.), rather than limiting the assumed sediment supply just to interrill and rill erosion, as is the case of WaTEM-SEDEM predictions of sediment delivery (section 2.3). Extrapolations from reservoir sedimentation rates may overcome some of the limitations of the omitted processes in WaTEM-SEDEM. However, given that rates of

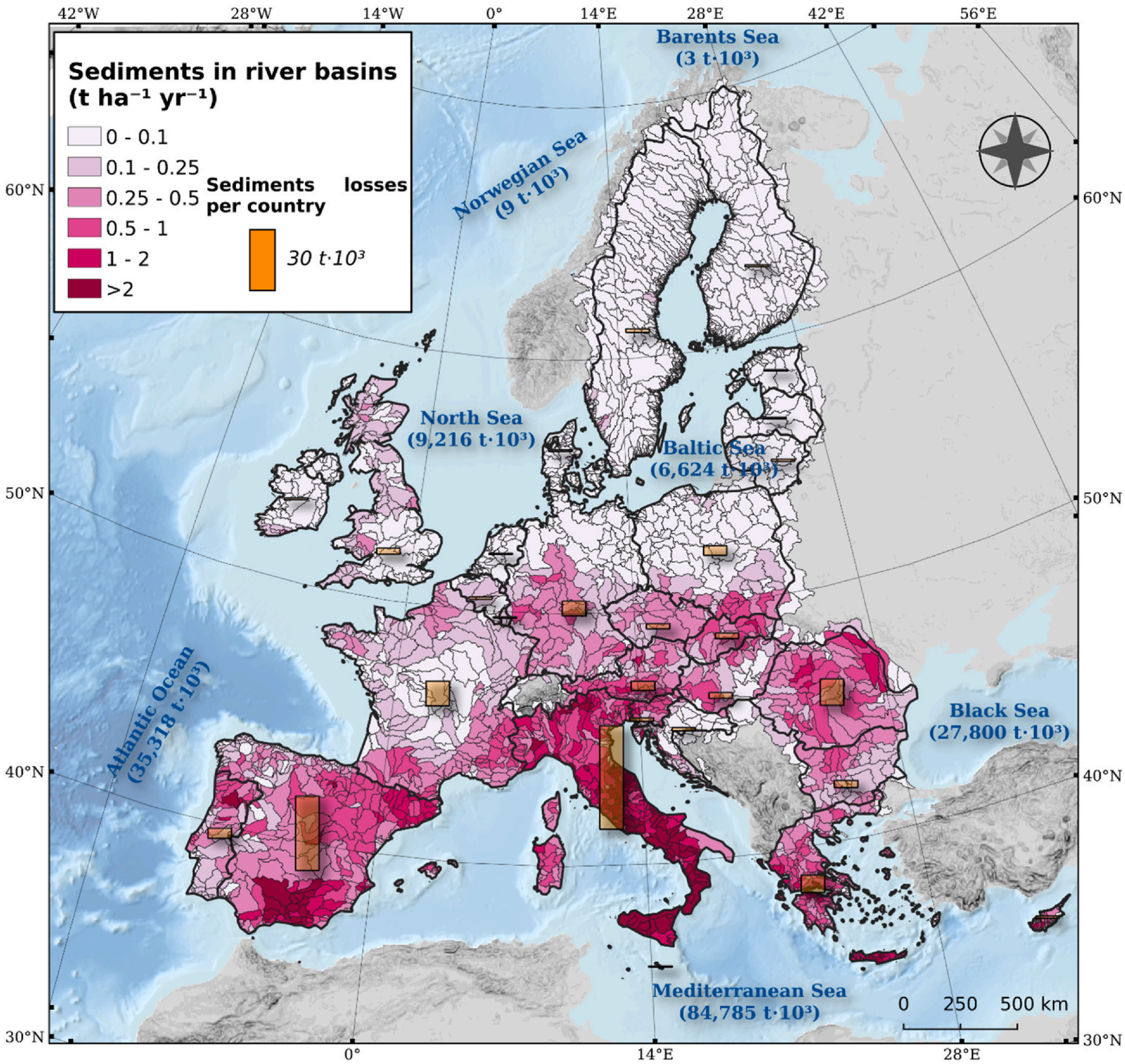

Fig. 2. Estimated sediments input to river systems (long-term average net soil losses due to water erosion) per catchment and aggregated sums per country. Totals per sea outlet are also provided (assuming no reservoir trapping).

sediment yield vary across orders of magnitude in rivers, using a singular value to upscale sediment accumulation rates comes with its own set of limitations in the presence of large regional variations.

The total annual sedimentation was estimated based on the losses of storage capacity in reservoirs, which is a proxy for the cumulative sediment yield from upstream areas. In this methodology, we extrapolated results from the study of Verstraeten et al. (2006), who measured the mean storage capacity losses from reservoirs across a large sample size in Europe. These measured mean values were then extrapolated across the entire known European reservoir capacity (258–383 billion m^3) reported by the International Commission on Large Dams (ICOLD, 2009; ICOLD, 2023), to estimate the total annual capacity losses and thereafter the annual sedimentation per reservoir:

As our objective is to have a pan European estimate on reservoir storage capacity losses, we sum-up the results of Eq. (1) for all reservoirs in the EU.

Dam constructions are the most globally significant source of sediment sequestration in modern river systems, and in some cases, there are numerous dams along a single river course (Syvitski et al., 2022). To give an indication of the dam abundance per catchment, we display a count of the spatially localised dams contained within the Georeferenced global Dams and Reservoirs (GeoDAR v1.1) dataset (Wang et al., 2022) (Fig. 3). The GeoDAR dataset contains geocoded locations for 71% of dams in the study area included within the comprehensive ICOLD dataset. Across the study area, the majority of catchments, especially those in countries with a high sediment yield (Fig. 3), have

$$\text{Annual sedimentation } \left(m^3\right) = \text{mean annual capacity loss } (\%) \text{ X Total potential capacity } \left(m^3\right) \quad \text{(Eq.1)}$$

Of course, this method has uncertainties as the storage capacity loss in dams varies each year as a result of the erosion processes magnitude.

dam infrastructure. Considering the omitted proportion of dam infrastructure without known spatial coordinates, alongside abundant small

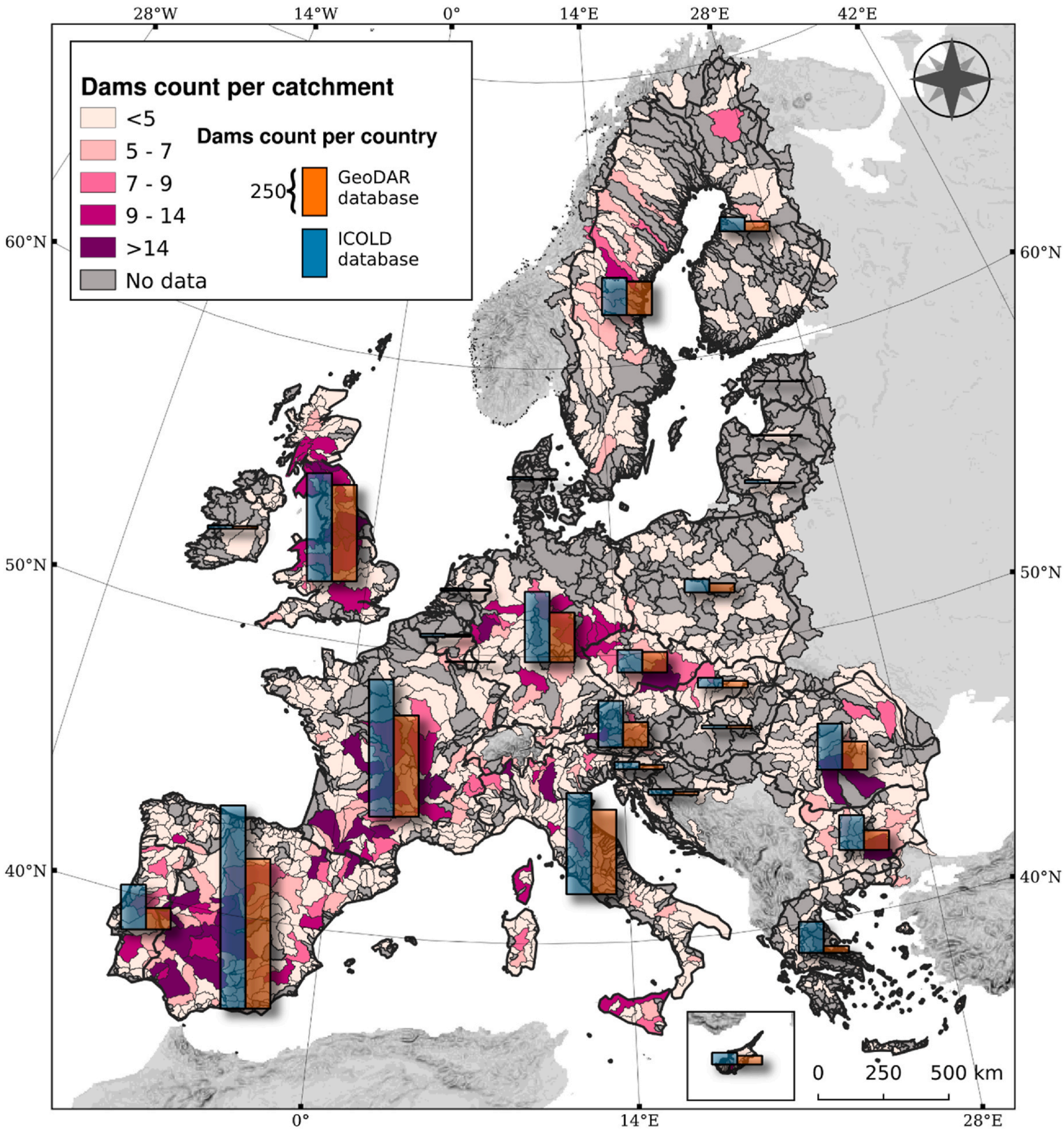

Fig. 3. Recorded reservoir distribution across Europe. The coloured catchment polygons refer to the contained number of geo-localized dam points with known spatial locations in Europe from the Georeferenced global Dams and Reservoirs (GeoDAR v1.1) dataset. On a per-country basis, the bars refer to the total dam count in the GeoDAR dataset (orange) vs the comprehensive but non geo-localized ICOLD dataset (ICOLD, 2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ponds and other river blockages (e.g. due to small dams, weirs or navigable channels) which also require remediation, we consider this assumption to be representative for the majority of the total sediment yield in the study area.

2.5. Quantifying the economic costs of reservoir sedimentation

Based on the review of existing costs in various studies (Table 1), we developed a pan-European empirical assessment using an assigned sediment removal cost per m^3 of sediment delivered to reservoirs. We used three quantification methods to represent the broad differences in the estimated monetary cost based on the applied method and information input (Fig. 4). As such, the variety of methods are intended to give complementary infromation and outline the uncertainty when understanding the contenintal-scale situation. We further discuss the advantages and limitations of each method. In all cases, the sediment remediation cost is calculated as follows:

$$\text{SedCostRem}\ (€) = \text{Price}\ \left(€\ \text{m}^{-3}\right)\ \text{x Annual sedimentation}\ \left(\text{m}^3\right) \qquad \text{(Eq. 2)}$$

where:

- SedCostRem is the total estimated annual cost of removing sediments,
- Price (€) per cubic meter of sediment removal,
- Annual sedimentation (m^3) is the estimated volume of sediment delivery to reservoirs

2.5.1. Flat rate and regional assignments from modelled sediment delivery

Based on the catchment-wise estimations of sediment delivery to

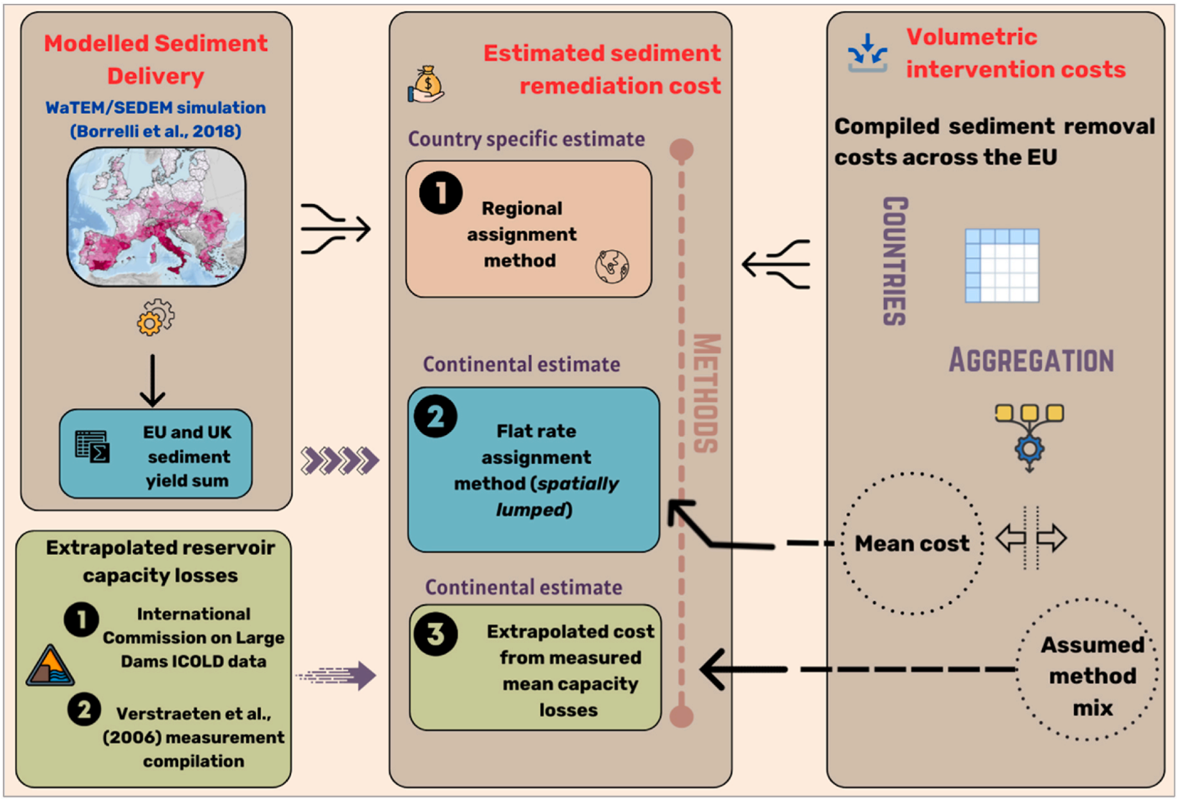

Fig. 4. Methods and inputs for estimating sediment remediation costs.

river systems due to water erosion (Fig. 2), we define 2 methods to quantify the total sediment remediation cost (SedCostRem (€)): 1) a continental flat rate assignment cost of sediment remediation (continental flat rate), and 2) a regionally variable cost based on varying sediment delivery rates and remediation costs (regional assignment) (Fig. 4).

Within the continental flat rate assignment, we define a mean rate for the mechanical removal of sediments for the whole EU. In this case, regional differences in sediment delivery are implicitly expressed within the annual sedimentation input but a singular price of sediment removal is applied for the study area. The determination of the flat rate was made by combining the total volume of sediment delivered to river channels (Section 2.3) with the mean value (Price: 16.8 € m^{-3}) from the compiled list of remediation costs across the study area (Table 1).

The regional assignment method includes a regionalized cost of sediment removal based on the cost findings per region (Table 1). The Price (€ m^{-3}) variable in Eq. (1) is allowed to regionally vary, recognising that different parts of the EU have different costs for sediment removal based on the methods used and their economic costs. Correspondingly, the regional values of sediment delivery to river channels (annual sedimentation (m^3)) are considered per country to account for regional variations in the potential sediment accumulation rates. For most countries, multiple price entries in Table 1 allowed a range of costs to be assigned, for which a mean and the standard deviation (SD) are given (Table 3). To eliminate large price discrepancies due to the registered remediation methods per country, we only use the outputs of

Table 2
Methods and shares for the sediment removals from Italian reservoirs for estimating costs using reservoir sedimentation rates (method 3 referred to in the text).

Method	% of sediment removal
Flushing	50
Mechanical dredging (wet)	16
Mechanical dredging (dry)	30
Specialized landfill	4

Table 3
Sediment removal costs per country using the regional assignment method.

Country	Volume of sediments to river basins (1000 m^3)	Estimated mean cost (€ m^{-3})	Standard deviation cost (€ m^{-3})	Cost of sediment removal (million €). Amount in () is the range
AT	3357	20.0	10.0	67.1 (33.7–100.7)
BE	319	30.0	15.0	9.6 (4.8–14.3)
BG	2599	3.0	1.5	7.8 (3.9–11.0)
CY	489	*16.8*		8.2
CZ	1737	20.0		34.7 (17.4–52.1)
DE	5799	55.0	25.0	318.9 (159.4–477.7)
DK	181	20	10	3.6 (1.8–5.4)
EE	55	20.4		1.1 (0.5–1.6)
EL	7045	8.5	4.2	59.9 (30.0–90.0)
ES	31,603	12.3	2.8	389.8 (302.7–477.2)
FI	274	12.5	10	3.4 (0.5–6.3)
FR	10,088	20.3	2	205.1 (184.7–225.4)
HR	847	7.5	3.7	6.3 (3.1–9.5)
HU	1923	*16.8*		32.2
IE	217	*16.8*		3.6
IT	44,070	23.9	9.8	1050.3 (617.9–1487.8)
LT	275	*16.8*		4.6
LU	46	*16.8*		0.8
LV	153	*16.8*		2.6
MT	8	*16.8*		0.1
NL	25	*11*	5.5	0.3 (0.2–0.4)
PL	3469	*16.8*		58.2
PT	3863	6.0	5.6	23.2 (12.0–45.0)
RO	10,784	*3.5*	1.7	37.7 (18.9–56.6)
SE	1050	*23*	5	24.1 (19.7–28.6)
SI	960	*9.5*	7.6	9.1 (1.7–16.5)
SK	1963	*15*	7.5	29.4 (14.8–44.1)
UK	1989	*16.8*		33.3
Total	**135,189**	20.4		**2302 (1355–3248)**

the mechanical dredging, given that this is the most applied technique. In countries without registered values, the mean value of the whole dataset (16.8 € per m^3) is assigned.

2.5.2. Sediment remediation costs from extrapolated potential reservoir capacity losses

The third method, based on potential reservoir capacity losses (Section 2.4), as compiled by Verstraeten et al. (2006), focuses on extrapolating measured reservoir sedimentation rates which reduce the dam storage capacity (Asthana and Khare, 2022; Patro et al., 2022). This method considers the potential capacity loss rate from the entire known European reservoir capacity (383 billion m^3), comprising 5500 reservoirs in Europe (Fig. 3). We also used a different database, the International Commission on Large Dams (ICOLD) which includes 4490 reservoirs having a total potential capacity of around 258 billion m^3 in the EU (ICOLD, 2023) (Fig. 4).

To quantify the associated costs, a mix of different techniques in addition to only mechanical dredging, are assumed to remove sediments from reservoirs (Fig. 4). According to the report of the Italian Committee of large dams, two main methods (flushing, mechanical dredging) are applied for the removal of sediments (ITCOLD, 2009). Given that quantifications of the costs of specialized landfill are not available, a simplified version of the shares in Table 2 is applied, using a weighted average of the two main methods (flushing: 5 € per m^3, mechanical dredging: 16.8 € per m^3). Therefore, 52% of the sediments are assumed to be removed with flushing and 48% with mechanical dredging, equalling a mean cost of 10.7 € per m^3.

3. Results

3.1. Costs based on the flat assignment method

The modelled total sediment delivery of 164 (±13) million tonnes corresponds to about 135 (±10) million m^3 of sediment which are potentially transported into river network each year in the EU and UK. Of this total budget, channels draining into the Mediterranean Sea dominate proportionally, comprising 50% of the total net soil erosion (Fig. 2), followed by the Atlantic Ocean and the Black Sea. Channels draining into the North Sea and the Baltic Sea receive together slightly more than 10% of the total EU and UK budget, while the Norwegian and Barents receive negligible volumes. This estimation includes sediments due to water erosion and can be considered as the maximum potential supply from the river systems to the oceans due to the modelled erosion sources, given that a large proportion of sediment is trapped for long time periods or extracted for anthropogenic activities.

The mean cost of removing sediments with mechanical dredging across the different regions with quantifications is 16.8 € m^{-3}. Using this average flat rate, a first gross estimation of sediments removal costs at EU scale is about 2.3 (±0.2) billion € per year. Despite the regionalized economic costs associated with removing these accumulated sediments, there are significant regional differences within this aggregated quantification, particularly in Mediterranean basins, due to variations in regional sediment yield. When the regionalized economic costs of mechanical interventions are considered, such a lumped estimation can neither consider the relatively lower intervention costs in Greece, Spain and Portugal (Table 1), leading to regionalized discrepancies that potentially balance out the pressures of higher sediment accumulation.

3.2. Costs based on the regional assignment method

The use of regional estimates for sediment removal incorporates more information into the estimation of the total costs, by weighting regional differences in sediment delivery against differences in remediation costs. Uniting this information shows the uneven economic burden across different countries (Fig. 5), which should also be considered alongside catchment and country-wise knowledge on reservoir distribution (Fig. 3). In regions with a high reservoir density, these remediation costs may multiply in cases where sediment is trapped multiple times within a catchment. For 20 countries, we also estimate a range of costs (Fig. 5; Table 3) due to uncertainties as multiple costs have given. For most of the smallest EU countries (CY, LT, LU, LV, MT) plus Hungary, Ireland and UK, we have no data on costs of sediments removals. Therefore, the mean value of the whole dataset (16.8 € per m^3) is assigned and no uncertainties and range are estimated (Table 3).

As shown in Table 1, both this method and the flat rate assignment method build on an extensive review to find costs for a majority of the EU (20 countries). The total costs for sediment removal based on the regional assignment method is about 2.3 billion € per year (similar to flat rate assignment method). This cost may range between 1.35 and 3.25 billion € per year according to the uncertainty analysis in which a range of sedimentation remediation costs is considered (Fig. 5). Italy has the highest estimated cost with a spending of 1 billion € per year followed by Spain and Germany.

3.3. Costs based on potential reservoir capacity losses

Verstraeten et al. (2006) estimated for a sample of 352 reservoirs in Europe, an average annual storage capacity loss of 0.26% with measured

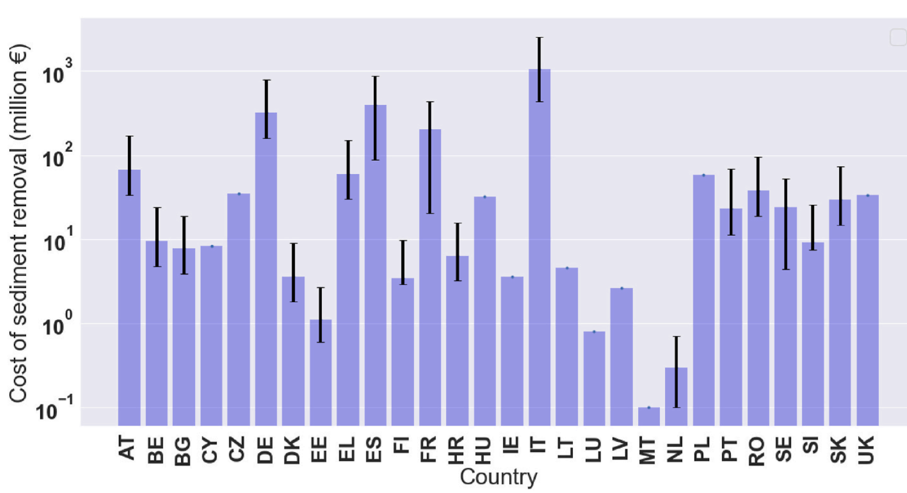

Fig. 5. Quantified cost of sediment remediation per country based on regional sediment delivery and price estimates. Uncertainty (black) bars represent the uncertainty range based on the cost of the sediment removal method applied per country when multiple figures were made available. The data is also provided in Table 3.

storage capacity losses of 62.7 million m^3 (Verstraeten et al., 2006). By extrapolating this measured rate to almost 5500 reservoirs in Europe having a potential capacity of 383 billion m^3, the total annual sedimentation is close to 1 billion m^3. While this continental average value may seem high, one must consider that Spain alone has a measured total annual capacity loss in big reservoirs of 170 million m^3 with a rate of annual loss of 0.3% (Batalla, 2002).

According to a different source, the International Committee of Large Dams (ICOLD) database, in the EU the 4490 reservoirs have a total potential capacity of around 258 billion m^3 (ICOLD, 2023). Compared to the estimation of Verstraeten et al. (2006), the mean annual storage capacity loss is higher (0.65%) taking into account the estimates from the International Commission on Large Dams (ICOLD, 2009) but the number of reservoirs is slightly lower in EU. These estimates are in line with the global median estimate of annual storage loss of 0.55% (Perera et al., 2023; Wisser et al., 2013). Based on these data of total capacity loss, the total annual sedimentation in EU and UK is approximately 1.67 billion m^3. Therefore, there is high uncertainty about both the storage capacity loss and the total capacity of dams in EU.

The estimation of 1–1.67 billion m^3 of sedimentation is one order of magnitude higher compared to the estimated sediments due to water erosion alone (135 million m^3) as the former includes all soil loss processes (water erosion, tillage erosion, glacial erosion, gullies, piping, soil quarrying, landslides, erosion in badlands and erosion due to trampling) (Poesen, 2018). A recent research estimated that in the EU the soil losses due to wind, harvest crops and tillage are almost equal to the ones due to water erosion (Borrelli et al., 2023). Therefore, around 80% of sediments are likely to correspond to processes mentioned before that have not yet been quantified and spatially distributed at continental scale.

Using the mean flat rate of 16.8 € per m^3 (as per mechanical dredging), the potential removal of sediments from all EU reservoirs could cost 16–27 billion € per year without sedimentation mitigation measures. However, this estimated cost is much less, as other techniques (venting, sluicing, flushing or hydraulic dredging) are commonly used for sediment removal from dams. The use of the weighted average (shares of sediment removal as in Table 2) implies a cost of 10.7 € per m^3 which results in a total cost of 10–18 billion € per year. In a more conservative estimate, with the use of flushing (mean rate of 5 € per m^3) the costs can be around 5–8 billion € per year.

4. Discussion

This study quantifies the costs of removal and management sediments in EU and UK reservoirs. Prevention measures against soil erosion and sediment retention techniques at the catchment scale have not been included, although they constitute effective methods to mitigate the problem at its source (Quaranta et al., 2023). Although these measures may be numerous and incur their own costs, their distribution across the study area is poorly known.

Rather, this study focusses on pan-European estimates of the economic costs of sediment accumulation in reservoirs, combining known remediation costs (Table 1) with both modelled estimates of sediment delivery and extrapolations of measured capacity losses of reservoirs in Europe. While the off-site impacts of erosion processes include a wide array of quantifiable and non-quantifiable costs, the trapping of a large amount of the modern-day flux of eroded sediment in reservoirs gives the issue a high priority.

4.1. Overview of the estimates and uncertainties

The estimation of costs using the three different outlined methods highlights 2 key components of uncertainty: 1) uncertainties on the pan-European and regional estimations of sediment accumulation rates, and 2) the uncertainty on the sediment removal costs per volume of sediment (Table 4). We evidence an order of magnitude difference between the applied methods using total modelled sediment accumulation rate

Table 4
Summary of costs for sediment removal following the three applied methodologies.

Methodology	Processes	Estimated sediments (m^3)	Annual costs for sediment removal
Continental flat rate assignment for the entire EU	Soil loss by water erosion	135 (±10) million	2.3 (±0.2) billion € (mechanical dredging)
Regional assignment rate	Soil loss by water erosion	135 (±10) million	2.3 (±0.9) billion € (mechanical dredging)
Extrapolated potential reservoir capacity losses	All soil loss processes (water erosion, gully erosion, badlands, bank erosion, landslides, piping, quarrying, etc.).	1000–1670 million	5-8 billion € (hydraulic flushing) 10-18 billion € (mixed dredging-flushing) 16-27 billion € (mechanical dredging)

applying WaTEM-SEDEM (flat rate and regional assignment methods), versus extrapolations from measured reservoir capacity losses (potential reservoir capacity losses). The range of known uncertainties increases when remediation costs are evaluated regionally as some regions/countries provided multiple cost entries. In addition, the removal costs per unit volume of sediment have high uncertainty due to the variety of methods applied. We propose that further data collections from relevant reservoir management authorities can bridge this gap in knowledge on the array of costs per country and method mixes.

The soil erosion and sediment delivery predictions through WATEM/SeDEM account only for sediment losses due to interrill and rill erosion processes. Although standardized, allowing for regional intercomparisons, these simulations do not account for gully erosion, mass wasting, and construction and mining activities which can strongly contribute to sediment yield in some regions. The absence of these processes from annual sedimentation estimations in the flat rate and regional assignment methods likely means an overall cost underestimation, as well as a reduced knowledge of the regional differences in sediment accumulation rate from omitted processes. The modelled spatial patterns of sediment yield likely capture the spatial disparities in sediment delivery across Europe (Vanmaercke et al., 2011), therefore providing important indications of the regional disparities in the burden of reservoir sedimentation. Future research to reduce uncertainty should further quantify the regional co-occurrence of omitted erosion processes with the spatial distribution of reservoirs. By integrating sediment inputs from all processes, measured losses in reservoir capacity provide a secondary option to overcome this. Nevertheless, variations in erosion and sediment yield with area, topography, climate, and lithology, mean that this approach has high uncertainty when used for evaluating regional differences in costs.

Despite uncertainties, this study sheds light on the regional patterns of reservoir siltation costs while sitting in line with established estimations. The nearly 59,000 reservoirs worldwide have an estimated storage capacity of about 7.0–8.3 billion m^3 (Mulligan et al., 2020). The European reservoirs represent around 5% of the total capacity according to ICOLD data (https://www.icold-cigb.org/GB/world_register/general_synthesis.asp). Considering that sediment removal costs are higher in Europe compared to other parts of the world, the 5–8 billion € per year is a rational estimate when evaluated in the context of the global estimate (21 billion $ per year).

Focusing to sediments removal due water erosion only, the regional assignment rate methodology is more suitable compared to the flat rate one as regional differences are considered. Despite its uncertainties, the potential reservoir capacity losses methodology presents a more comprehensive approach as it considers all soil loss processes. However, future works could better address the variability of reservoir capacity losses, regional differences and more precise costs on sediments removal. It is important to involve stakeholders such as private companies, dam owners, national and regional authorities who could provide more detailed data both in reservoir capacity losses and sediments removal costs.

Besides mechanical dredging and hydraulic flushing, novel emerging technologies in the hydropower sector also relate to sediment management and removal in Europe (Kougias et al., 2019). As an example, jet arrangement is a low-cost installation which shows high efficiency when dealing with reservoir sedimentation through high sediment release rates (Jenzer Althaus et al., 2015).

The cost of sediment removal can vary greatly, with expenses ranging from hundreds of thousands to tens of millions € depending on the type of operations, or the volume of sediments (Wang et al., 2018). The assumed mix of remediation techniques strongly determines the total estimated cost. Hydraulic dredging (commonly known as sediment flushing, venting and sluicing) is an economically efficient technique with the capacity to flush vast sediment quantities through the bottom gates of the dam. The duration of sediment flushing operations varies from few days or weeks (Kaffas et al., 2021) to several months (Morris and Fan, 1998), and depends on several factors such as the size of the reservoir, the amount of sediment accumulated, or the type of sediment. The most distinct drawback of sediment flushing is its association with severe pressures on river morphology (excessive depositions) and ecology (disturbance/burial of aquatic habitats) due to the extreme sediment volumes released downstream (Folegot et al., 2021). Nevertheless, if flushing is done during floods by opening low level outlets rather than operating the spillway, large quantities of fine sediments can be vented or sluiced without losing water and disturbing the river ecology. Such operation is even required to avoid downstream river incision. Replenishment of coarse sediments downstream of the dam, which have been dredged for example from the reservoir delta area, can even restore or maintain dynamic river morphology and aquatic habitats. There is a trend to release artificial floods in combination with flushing operations and replenishment of sediments downstream of the dam with the purpose to dynamize river morphology and its habitats (Stähly et al., 2019).

4.2. Sediments management and reuse

With modern technologies, the sediments extracted from reservoirs can be reused as a secondary raw material in multiple applications (concrete, roads, etc.). However, they often contain contaminants, organic matter (5–30%), high water content (>50%), and relatively small particle size (Amar et al., 2021), thus limiting their applicability. Here, we present several alternatives to manage dredged sediments and contribute to circular economy. In case sediments are reused, part of the estimated costs are reduced accordingly.

The use of excavated sediment for land management typically requires a reduction in its water content before being reused or landfilled (Allariz, 2018). This partial dewatering has the advantage of reducing the volume of sediment to be transported to the final management site, but also makes it reusable or suitable for landfill (e.g., acquisition of more suitable physical properties). However, this operation requires time (up to two years to dehydrate around 120,000 m^3 by lagooning), facilities (e.g., artificial lagoon, hydraulic pressure, centrifuge), consumes resources (e.g., power, geotextile tubes, flocculants), and needs adapted areas. All these aspects may have a significant cost, depending on the situation. For instance, in Luxembourg, a specific study showed that the partial dewatering using geotextile tubes was estimated to be more expensive (+10 € per m^3) than a dewatering by lagooning. Moreover, it is a measure of limited effectiveness as the dredging equipment may not be able to reach all areas, leaving behind sizeable residuals (De Vincenzo et al., 2018).

Sediments can be used for soil stabilization, land filling, construction of multifunctional soils (e.g., technosols) and building material (Fourvel et al., 2019). Dredged sediments are used in landfill sites mostly when they are contaminated with heavy metals (Hashim et al., 2018). In recent years, the dredged material from sediments is also used for cement in concrete production (Aoual-Benslafa et al., 2015) or as alternative material in road building (Maherzi et al., 2018). As sediments have high clay content, they can also be used for raw material production (e.g., bricks, ceramics) (Samara et al., 2009). In a recent review (Crocetti et al., 2022), authors describe the use of dredged sediments for construction material (cement, bricks, blocks) and road material presenting but also refer to the regulations relative to dredged sediment management in Italy, France and Spain. The brick factories in France and Germany have used advanced processes to treat polluted sediments for the production of cement based materials (Agostini et al., 2007; Cappuyns et al., 2015).

Moreover, sediments availability also presents an opportunity to add nutrients in agricultural fields (Kiani et al., 2023). The recycling of nutrient-rich sediments on agricultural soils close to reservoirs may be an environmental friendly alternative to fertilizers due to the rich phosphorus input, high rate of organic matter decomposition and increased plants growth (Kiani et al., 2023). Nevertheless, nutrient-rich sediment recycling in agriculture may not be possible, even in non-food agricultural sectors, due to the lack of a permissive legislation and of consolidated supply chains (Renella, 2021). Different approaches are observed in the EU, for example in Finland and the Czechia, whereas the direct reuse of sediment dredged from water bodies onto agricultural soils is allowed if the content of contaminants is below the threshold limits of the respective national legislation (Kiani et al., 2021).

4.3. Policy implications

This is the first attempt to estimate the off-site costs of soil erosion at the continental scale through reservoir siltation. Such costs are paid either by private companies, in the case of dam owners, or by national and regional authorities. The costs of sediment removal are also included in the Impact Assessment of the Soil Monitoring Law (Panagos et al., 2022b). The estimation of such costs can facilitate the cost/benefit analysis and allow a more informed decision-making process when introducing soil conservation measures to reduce soil losses. In addition, most watersheds are transboundary, resulting in transfer of sediments (but also nutrients, contaminants) between countries (Kiss et al., 2021). Therefore, the management of sediments is a pan European issue at the catchment scale of the large rivers.

Targeting sediment losses in agricultural soils will contribute to the objective of Farm to Fork Strategy which targets 50% reduction of nutrient losses. The phosphorus displacement in the EU due to erosion is estimated to about 374 thousand tonnes of which almost 100 thousand tonnes end up in river basins and sea outlets (Panagos et al., 2022a). Sediments also include contaminants, which contribute to the pollution of water bodies and sea outlets. The Zero Pollution Action Plan (ZPAP) proposed by the European Commission includes actions to better prevent, remedy, monitor and report on pollution in air, water, and soil. One of the objectives of this policy development is to better monitor the current state of diffuse pollution in soils (e.g., heavy metals included) and to estimate the pollution in waters due to contaminated sediments. Therefore, this assessment contributes to establishing baselines for sediment losses and possible pollution sources.

Due to the increase of global cement production in the world, reaching 5 billion tons in 2020, the use of sediment as supplementary cementitious materials represents one alternative to significantly reduce the CO_2 emissions (Amar et al., 2021), even if they require different treatment methods to improve the performance of sediment-substituted cementitious materials (Benzerzour et al., 2017). The “Fit for 55 in 2030” plan in the European Climate Law targets to reduce net greenhouse gas emissions by at least 55% by 2030 (from 40% currently) and makes legally binding climate neutrality by 2050. This assessment contributes to establish a baseline for potential of sediment reuse and CO_2 emissions reductions.

Considering the potential of recycling nutrient-rich sediments on the agricultural soils as alternative sources of nutrient and organic carbon, the EU regulation on fertilizers could consider facilitating their usage. For example, Renella (2021) suggested that nutrient-rich recycled sediments should be reconsidered as a component material category in the new EU regulation on fertilizers. Their availability in the form of fertilizers represents a key factor in the overall question of global food security (Szara-Bąk et al., 2023).

5. Conclusions

Despite the significant developments in improving soil erosion assessments over large spatial scales in the last 20 years, the availability of data concerning siltation and sediment management in European reservoirs is rather limited. In this study, we provide a first estimation of the off-site costs (sediment removal) of soil erosion in the EU, by combining local cost estimations and Pan-European soil erosion assessments. An advancement is the review of costs for sediment removal in at least 20 countries of the EU. Moreover, several cost-estimation methodologies were tested to account for management and costs differences between countries.

The results of these works evidence substantial differences among countries and within national reservoirs, often attributed to local costs, but also depending on sediment removal methods and reservoir characteristics. For the entire EU and UK, the cost of removing an estimated 135 million m^3 of accumulated sediments produced by water erosion is estimated at roughly 2.3 ($\pm$0.9) billion € per year. When applying a method that considers all types of soil loss processes, a simplistic extrapolation puts the sediment inputs at an order of magnitude higher (>1 billion m^3), but the removal cost (per m^3) may be less due to application of less costly techniques in silted dams. With a conservative estimation, the removal of sediments from EU dams may cost at least 5–8 billion € per year.

It is important to note that such costs estimation have substantial associated uncertainties and that these predictions could be improved with more detailed data on costs and sediment yields. In addition, the costs do not consider possible mitigation measures to reduce reservoir sedimentation. The insights provided by this study can contribute to the European Green Deal ambitions, by identifying sources of land degradation, fostering sustainable soil management practices, preserving biodiversity, mobilising industry for circular economy and by promoting a toxic free environment.

Data statement

All datasets are free to download in ESDAC and they are listed in the web address: https://esdac.jrc.ec.europa.eu/resource-type/datasets.

CRediT authorship contribution statement

Panos Panagos: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Francis Matthews:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Edouard Patault:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Carlo De Michele:** Data curation, Formal analysis, Resources, Writing – original draft. **Emanuele Quaranta:** Data curation, Methodology, Writing – original draft. **Nejc Bezak:** Data curation, Formal analysis, Methodology, Writing – original draft. **Konstantinos Kaffas:** Data curation, Formal analysis, Methodology, Resources, Writing – original draft. **Epari Ritesh Patro:** Data curation, Investigation, Writing – original draft. **Christian Auel:** Conceptualization, Data curation, Resources, Writing – original draft. **Anton J. Schleiss:** Data curation, Methodology. **Arthur Fendrich:** Conceptualization, Data curation, Methodology, Resources. **Leonidas Liakos:** Data curation, Methodology, Software, Visualization. **Elise Van Eynde:** Data curation, Resources, Writing – original draft. **Diana Vieira:** Data curation, Investigation, Methodology. **Pasquale Borrelli:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Panos Panagos reports article publishing charges was provided by European Commission Joint Research Centre Ispra. Panos Panagos reports a relationship with European Commission Joint Research Centre Ispra that includes: employment.

Data availability

Data will be made available in the European Soil Data Centre (ESDAC).

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Appendix A. Supplementary data

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