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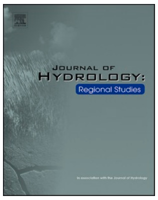

An overview of controlled sediment flushing operations: Perception, issues and management strategies across the European Alps

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ABSTRACT

Study region: European Alps

Study focus: The increasing demand for water and renewable energy, along with climate-induced hydrological changes, is driving the development of strategies to counteract reservoirs siltation, including sediment flushing. This review first examines the social perception of this desilting technique, then outlines related current legislation, key research progress, and ongoing criticisms, with specific focus on the European Alps. It also compares alternative sediment management strategies, highlighting their pros and cons.

New hydrogeological insights from the region: Due to societal concerns and stakeholder pressure, flushing operations have evolved into more controlled processes, reducing fish mortality and long-term impacts over river ecosystem. As a result, regulations have been updated, generally requiring environmental considerations in support of desiltation strategies. However, fragmented management of freshwater resources—particularly water and sediment flows—still hinders more ambitious environmental goals.

While sediment flushing remains a key technical solution, further advancements are needed in flushing methods, post-flushing mitigation, and planning and monitoring practices. In the study region, research on this topic is limited, mostly focusing on specific operational aspects and case studies. To our knowledge, this is the first review offering a comprehensive analysis that integrates social, technical, and legislative dimensions, providing a foundation for improving reservoirs sediment management by flushing.

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List of acronyms

CSFO	Controlled Sediment Flushing Operations
DO	Dissolved Oxygen
SBT	Sediment By-pass Tunnel
SEV	Severity of ill effect
SSC	Suspended Sediment Concentration
WFD	Water Framework Directive

1. Introduction

1.1. River damming in the European Alps

Owing to their position, spatial extension, topographic gradients, and their variety and amount of water supplies, the European Alps (also referred to as Alps in the following) are known as “the water tower” of Europe (Vanham, 2012). These water sources are pivotal for several species, making the Alps a hotspot of biodiversity at the continental scale (Trizzino et al., 2015; Jardim de Queiroz et al., 2022). At the same time, human populations of different countries and geographical areas, even far from the tops of Alpine mountains, rely on these irreplaceable water supplies for fundamental needs and ecosystem services (e.g., agriculture, drinkable water, hydropower, recreational activities). While in the past the anthropogenic pressure was limited to agricultural purposes and consisted mainly in limited water diversions and mills, in the last two centuries hydropower development has involved a proliferation of small to large reservoirs. Dam building peaked in two different periods across the European Alps: 1920–1930 and 1950–1970. In the French Alps, there were already 35 large dams (i.e., height >15 m and/or reservoir volume larger than 1000,000 m^3 and hundreds of small dams (i.e., height <15 m and/or reservoir volume lower than 1000,000 m^3 at the beginning of the 20th century, but the first hydropower dams were built during the inter-war period (Dalmasso, 2008). Both in the Italian and Swiss Alps, the first hydropower dams were built at the end of the 19th century, but most of them just after the Second World War (Comiti, 2012; Pougatsch and Schleiss, 2023). Although these dams have contributed to social and economic growth, concerns on their utility and associated costs and benefits are still debated (Annandale, 2013). Among the major costs, the impacts on river ecosystems, including the alteration of natural hydro-sedimentary regimes (Owens et al., 2005) and the fragmentation of habitats for several species (Dugan et al., 2010), deserve careful consideration. In fact, damming has been identified as one of the most diffuse sources of impairment of the 32 largest rivers in the world (Best, 2019) and has been listed among the main threats for freshwater biodiversity at global scale (Dudgeon, 2019; Albert et al., 2021).

1.2. Reservoirs sedimentation

Interrupting the longitudinal continuity of rivers, dams and reservoirs significantly modify the downstream sediment transport. Sediment accumulation behind dams reduces reservoirs storage capacity, compromising their proper functioning (Morris and Fan, 1998; Schleiss et al., 2016). According to the International Committee on Large Dams (ICOLD), in 2009, the worldwide total potential reservoirs storage capacity was ~7000 km^3, nearly half of which had been lost due to sedimentation, occurred at an annual average rate of 0.96 % (ICOLD, 2009). In 2016, the Italian branch of ICOLD (ITCOLD), analyzing a sample of 472 reservoirs (93 % of the Italian asset), estimated that nearly half (44 %) was suffering from sedimentation; 35 % out of these reservoirs are in the Alps, mostly below 1000 m asl (ITCOLD, 2016). These data agree with the results of a recent study, estimating in 33 % the storage loss in the Italian Alpine area, compared to 43 % in the Apennine area (Patro et al., 2022). Additionally, studies highlighting the relationship between accelerated glacier melting due to climate change and increased sediment yield (e.g., Carrillo and Mao, 2020; Delaney and Adhikari, 2020; Zhang et al., 2022) suggest an augmented sedimentation rate in the near future, before reaching a peak due to glacier exhaustion.

Sediment accumulation behind dams also impairs downstream river ecosystems. Sediment trapping by dams, estimated as 28 % of the global sediment flux (Vörösmarty et al., 2003), induces sediment starvation in downstream rivers. In turn, this determines channel incision and riverbed coarsening under the action of "hungry water" (Kondolf, 1997). Morphological alteration due to the interruption of sediment connectivity in dammed rivers has been widely documented with severe effects on river biocoenoses and ecosystems (McCartney et al., 2001; Schmutz and Moog, 2018), frequently overlapping with the impacts of other human activities (e.g., Wohl, 2006; Wohl, 2015; Brenna et al., 2021; Szmańda et al., 2021; Scorpio et al., 2024).

Reservoirs sedimentation can thus be described as a double waste of non-renewable resources: of storage capacity, and of fluvial sediment. This has led researchers to solicit the adoption of an "environmental sediment flow" (Wohl et al., 2015).

1.3. Sediment flushing

In the last decades, the push to the transition from fossil fuel-based energy to renewable alternatives (Zarfl et al., 2015) has boosted the development and application of strategies to mitigate the effects of reservoirs sedimentation (Wang and Hu, 2009; Annandale, 2014; Kondolf et al., 2014). Existing methods can be divided into different categories depending on the adopted strategy (Morris and

Fan, 1998): (i) deviation of the incoming sediment flux to bypass the reservoir, (ii) capacity restoration through periodical sediment removal, and (iii) minimization of the incoming sediment flux. Among these, only the methods belonging to the first and second categories address the problem of the sediment "restitution" to river ecosystems. However, the choice between different methods mainly depends on the site-specific features of the dam, as well as of the river and its basin. In existing reservoirs, remediation measures often fall into the second category and the storage restoration is conducted through mechanical (dry excavation, dredging) or hydraulic (drawdown or pressure flushing) removal (Sumi and Kantoush, 2011; Castillo et al., 2014, 2015).

Due to relatively moderate cost, drawdown flushing has been widely adopted, especially in the Alpine area (e.g., Grimardias et al., 2017; Legout et al., 2018; Espa et al., 2019), where the typically elongated and narrow shape of the reservoirs favors the creation of a river-like channel after the bottom outlets opening. At present, such operations are regulated by national and regional prescriptions, which mainly set limits on the Suspended Sediment Concentration (SSC) at the dam outlet, both in quantitative and temporal terms, to mitigate the downstream ecological impacts. Flushing operations managed to meet such requirements are defined as Controlled Sediment Flushing Operations (CSFOs).

Therefore, CSFOs are often a convenient strategy to restore the reservoirs capacity and elongate their lifetime (Best, 2019). However, despite the limits set by the competent authorities, some environmental issues persist and should be adequately monitored and managed. The impulsive release of sediment-laden waters can impair river ecosystems at least in the short and mid-term, with direct and indirect negative effects on different aquatic organisms and potential detrimental cascade effects on food webs and ecosystem services (Espa et al., 2019; Quadroni et al., 2024). Apart from the immediate effects of relatively high SSCs (usually in the order of few up to several tens grams per liter) on the aquatic fauna or the drifting induced by the increased streamflow (e.g., Crosa et al., 2010; Baoligao et al., 2016; Quadroni et al., 2016a; Pisaturo et al., 2021), the excessive deposition of the evacuated sediment in the hyporheic zone can affect its role as an ecotone (Wharton et al., 2017; Dubuis and De Cesare, 2023), as well as the quality and quantity of energetic inputs (i.e., in-stream primary production and organic detritus) (Bona et al., 2016; Doretto et al., 2016).

1.4. Review goals

This work aims to provide a comprehensive evaluation of the magnitude, frequency, impacts and possible benefits of sediment flushing operations from reservoirs in Alpine areas. Different facets of this environmental management practice are considered. At first, we examine the varying perception of the utility and importance of these operations by managers, river ecologists and local communities. This allows us to better elucidate the social impacts associated with sediment flushing operations that are rarely included in their evaluation. Then, by providing an overview of the related legislation across countries sharing the European Alps, Italy in particular - since this reflects our own expertise - we illustrate parallels and contrasts in the approach of different authorities to these operations. Finally, we discuss the more recent advances aimed at minimizing issues related to the sediment flushing operations. While previous research focused mostly on singular aspects of these operations (e.g., impacts on riverine biota, engineering techniques, etc.), this review integrates them with the stakeholders' perspectives and normative guidelines, thus offering a multifaceted analysis that is seldom applied. In turn, this can provide a shared knowledge basis for implementing upgraded reservoirs sediment management in the Alps as well as in other similar geographical settings.

2. Stakeholders' perceptions of dams and sediment flushing operations

Dams have contributed to human welfare until they became an important part of the socio-environmental landscape and imaginary of progress in the 20th century (Richter et al., 2010; Boucher and Hudson, 2023). However, drawbacks of dams and related management strategies are nowadays widely acknowledged (Fencl et al., 2015; Brummer et al., 2017).

Similarly to other conflicts about natural resources, decisions on dams involve complex trade-offs between different uses, also connected to the specificities of the developed system and the concerned stakeholders, claiming different and often conflicting interests (Fox et al., 2016; Diessner et al., 2020). Decisions regarding the future of centenary dams - whether through sustainable sediment management or decommissioning - must carefully balance the positive and negative effects on ecosystem services (World Commission on Dams, 2000; Annandale, 2013). Given the increased complexity of contemporary issues of this scale, stakeholders have increased their participation in environmental governance and natural resource management decisions (Miller et al., 2014).

The sustained long-term preservation of reservoirs storage (Kondolf et al., 2014; Randle et al., 2021) would greatly benefit from an integrated watershed management approach, with the active participation of all beneficiaries, including water resource managers, urban/industrial/agricultural users, tourism/fisheries developers and research organizations (Rao et al., 2014). To date, in the investigated context, reservoirs operators (i.e., mainly hydropower companies) are responsible for the management of impounded sediment according to guidelines recently updated under the push of a growing environmental concern (see Chapter 3).

In this regard, the case of the dams on the Upper-Rhône River (Switzerland-France) is illustrative. At the beginning of 2000s, due to relevant ecological impacts (e.g., water quality deterioration, fish altered behavior and mortality, bird nesting perturbation) and growing societal discontent from the Swiss and French stakeholders, sediment desiltation of Verbois and Génissiat reservoirs shifted from empty flushing to CSFOs, with the implementation of multiple SSC-duration thresholds, mainly addressed to preserve fish (Peteuil et al., 2013; Grimardias et al., 2017; Cattanéo et al., 2021). A similar process occurred almost concurrently in Austria and in Italy. As highlighted by Reckendorfer et al. (2019) for reservoirs located along the Mur River (Austria), the increase in environmental awareness has led to the recognition that sediment management includes a responsibility to protect the natural resources that depend on water. As a result, considerable effort has been performed by the dam operators in cooperation with planners, authorities, and fishermen in developing approaches to reduce the damaging effects of flushing operations. These schemes have been further improved during the ALPRESERV EU INTERREG IIIB project and now include recommendations for SSC thresholds and duration of flushing events, hydrological and seasonal restrictions, and clear water releases after flushing events. Comparably, in Italy, between 2005 and 2010, the search for environmentally responsible alternatives to uncontrolled flushing was led by projects guided by local Authorities and involving wide partnerships, including Universities, such as the case of the ECOIDRO project (in the framework of the Italy-Switzerland INTERREG). In that case, the focus was on the conservation of local salmonids and on the preservation of the good ecological status of impacted watercourses *sensu* Water Framework Directive (2000/60/EC, WFD) (Crosa et al., 2010; Espa et al., 2013, 2019). Evidently, these controlled operations displayed lower efficiency (i.e., the volume of evacuated sediment divided by the volume of water required for removal, equal to approximately 0.1–0.6 %) and higher costs (5–45 € per m^3 of removed sediment) compared to uncontrolled operations. Furthermore, despite the efforts, the trade-off between technical/economical factors (pushing high flushing efficiency, i.e., minimal use of regulated water for diluting evacuated sediment and reduce SSC) and minimization of environmental impact (implying SSC control below selected thresholds and resolution of remaining environmental issues) is still under debate (Espa et al., 2013, 2019; Reckendorfer et al., 2019; Cattanéo et al., 2021).

Finally, although involvement of the general public is strongly emphasized by the WFD,[1] the interaction between reservoirs operators, in charge of sediment removal operations, and a broad audience is generally limited, with the notable exception of fisheries agencies that, in some cases, are part of the decisional board. Consequently, societal discontent arises when the effects of downstream sediment evacuation are evident (i.e., muddy waters, large and smelly deposits of silt, and dead fish) and not anticipated, and the efforts to limit environmental impacts are not properly publicized. This is more likely in case of uncontrolled events or mismanagement, concurrently to miscommunication, as shown in experiences documented by local newspapers and TV channels, and by social media. The word cloud in Fig. 1, generated from a sample of eight sources (including local newspapers and websites from environmentalist associations and mountain enthusiast groups, as listed in Table S1), highlights general attention on fisheries activities and environmental aspects related to the release of sediment-laden waters.

A more participatory approach at local scale (i.e., from one-way to two-way interactions, involving and engaging the public in collaborative problem solving, or empowering the public through consensus building and shared agreements) is needed to achieve the social sustainability of decision making, also on sediment management strategies. As stated by Habel et al. (2020), issues related to dams and reservoirs should be approached carefully considering the interrelations between people and the environment. In general, people favor keeping dams in operational conditions for their industrial history, property values, hydropower generation, flood protection or recreation. However, people also benefit from the services provided by the rivers downstream of the dams and care about the preservation of their aquatic environments (Reilly et al., 2018). Thus, the least-cost sediment management practice that is environmentally and socially acceptable should be preferred for implementation.

3. Regulations and technical guidelines

3.1. Italy

Italian legislation about sediment management strategies in reservoirs evolved over time. Briefly, the first normative act dates to 1959 (DPR 1363/1959), attributing management responsibilities to national or regional authorities for large or small dams, respectively. Later, DLgs 152/2006 incorporated the assumptions and requirements of the WFD, extending the normative aspects to water quality assessment and protection, also including the potential impacts associated with dams. In 2022, a new normative act, DM 205/2022, was adopted with the goal of updating and implementing all the previous laws about dams (e.g., DM 262/2004).

When addressing the management of impounded sediment, current law emphasizes the need to assess multiple operational methods on a case-by-case basis. This evaluation considers costs, effectiveness, and potential negative impacts on the downstream river ecosystem to ensure the selection of the most appropriate approach. To achieve this, all critical aspects and decisions on sediment management are documented in a formal Management Project. Reservoir managers must redact this document for each reservoir, detailing the planned operations, and submit it for approval to the Regional (or Provincial, in special cases) Authorities, at least three months in advance. These Authorities may establish thresholds for reservoir capacity restoration and request additional information about the reservoir hydro-morphological and silting conditions. They are also responsible for defining monitoring methods to be implemented before, during, and after operations, specifying the essential parameters to be monitored. Furthermore, Regional Authorities may impose specific and additional standards as part of the Management Project approval process. These standards may include the types of operations, specific operational methods, timing, monitored parameters, and required mitigation or compensation actions.

Typically, the Management Project includes a cognitive framework describing the geographical context, with a focus on:

- river basin characterization in terms of presence of other reservoirs and/or protected areas, anthropogenic pressures, and sediment transport,
- complete characterization of the reservoir, discharges, and water diversion structures,

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[1] "To ensure the participation of the general public including users of water in the establishment and updating of river basin management plans, it is necessary to provide proper information of planned measures and to report on progress with their implementation with a view to the involvement of the general public before final decisions on the necessary measures are adopted." (*Directive 2000/60/EC*, Whereas 46).

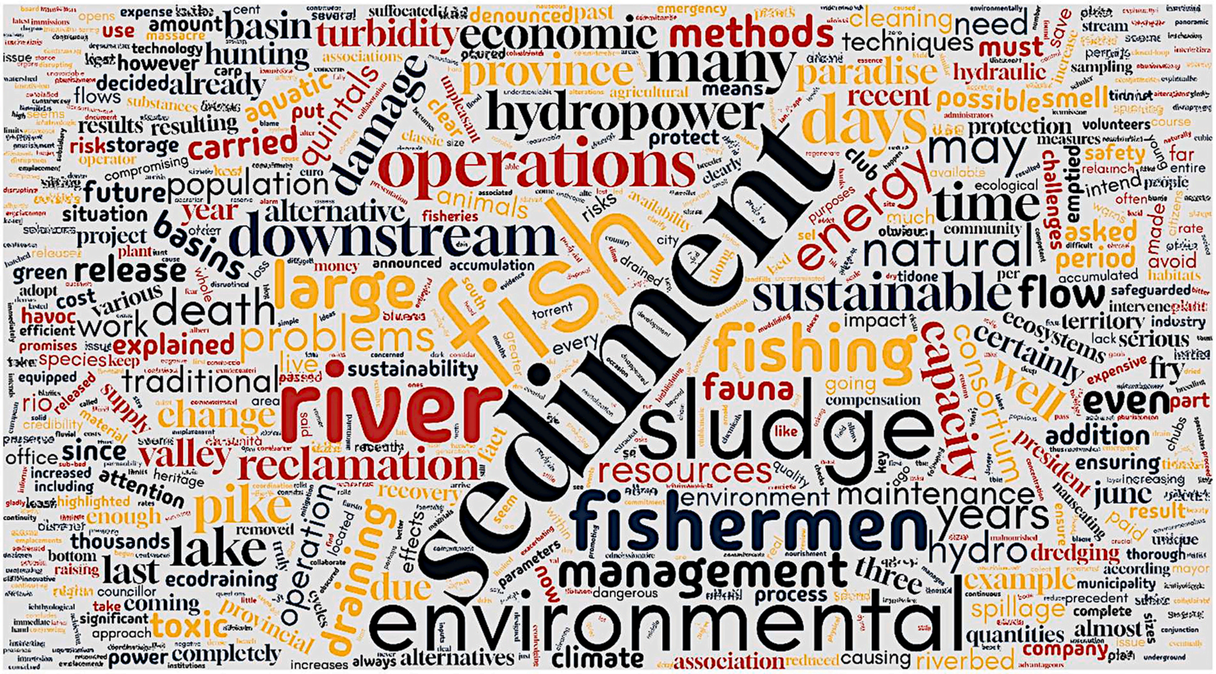


Fig. 1. Word cloud on sediment flushing perceptions generated from local newspapers and websites of environmentalist associations and mountain enthusiast groups from the Alps (data from 2013 to 2024 - Table S1. Generated with https://www.wordclouds.com). We excluded the words “dam”, “reservoir”, and “flushing” from the list, whose abundance is implicit.

- characterization of sediment deposition in the reservoir through bathymetric surveys and additional sampling (e.g., grab sampling and grainsize analysis),
- characterization of downstream water bodies, with reference to the hydrological regime, flow rates and estimates of SSC and bedload transport.

The core of the Management Project addresses the technical and operative aspects, specifying the adopted operational approach, along with details on expected operations frequency, timing, and specific requirements. These decisions must be guided by a socio-economic and environmental assessment to ensure that the operations provide benefits to all the stakeholders involved. For example, operations involving the release of sediment downstream of the reservoir, such as CSFOs, must consider the biological cycles

Table 1
List of physico-chemical and hydro-morphological parameters to be measured during the execution of sediment removal operations.

Parameter	Measurement mode	Unit of measurement	Station	Frequency
Flow	Released flow rate	m^3 / s	Reservoir	Continuous
	Changes in the water level in the reservoir and reservoir rating curves	m^3 / s	Reservoir	Continuous
	Instrumented section	m^3 / s	Downstream monitoring site	Continuous
	Portable instruments	m^3 / s	Downstream monitoring site	Occasional
Sediment transport (concentration of suspended and settleable solids, and bedload)	Turbidity probe	NTU or g/L	All the monitoring sites	Continuous or relatively high frequency (at least one sample every 15 min)
	Imhoff cone	mL/L	All the monitoring sites	Every 30 min during the first phases of the operation
	Gravimetric sample	g/L		
	Sensors or sediment traps	kg/min	Case-by-case assessment	Continuous with sensors and case-by-case assessment with traps
Dissolved oxygen	Portable or fixed probe	mg/L or %	Downstream monitoring site	Continuous or at close intervals (minimum 15 min)
pH		pH unit		
Temperature		°C		
Ammonium nitrogen	Portable probe	mg/L or %	Case-by-case assessment	Continuous or at close intervals (minimum 15 min)

of fish species, with reference to the reproductive period, to minimize impacts. Additionally, it is essential to evaluate the hydrological regime, the duration of the operations, and the natural sediment transport patterns that would occur in the absence of the reservoir. Finally, reservoirs managers must report thresholds and persistence of concentrations which cannot be exceeded during the operations, the expected volume of removed material along with the expected volume of released water, as well as minimum, maximum and mean flow rates.

Regarding the downstream effects of sediment removal operations, the mentioned DM 205/2022 mandates monitoring activities to ensure that these operations do not compromise the environmental quality standards and/or the designated uses of downstream water bodies. If necessary, mitigation measures should be implemented.

Field data are collected over two distinct periods, each defining specific parameters to be monitored:

- Monitoring during the operations aims to detect chemical, physico-chemical and hydro-morphological parameters (Table 1). A monitoring site must be selected downstream of the dam, as close as possible to the reservoir, and representative of the river reach. Additionally, it is advisable to set up an upstream control site.
- Pre- and post-operation monitoring aims to provide an overview of both biotic and abiotic conditions of the water body before and after the operations (Table 2), thus determining the magnitude of the environmental impact. Among the mandatory parameters and indicators to be monitored, the analyses of benthic macroinvertebrate and fish communities are required (in terms of composition and abundance - and only for fish fauna biomass and age class structure), along with water chemistry and hydro-morphological characteristics (e.g., riverbed modification, substrate alteration, habitat availability).

Due to the expected increase in SSC and decrease in oxygen concentration, the DM 205/2022 provides reference values, to be adjusted case by case. Specific thresholds should be included in the Management Project, depending on the specific characteristics of the watercourse and its vulnerability. The minimum allowed daily concentration of dissolved oxygen ranges from 4 mg/L (5 mg/L as average) in rhithron sections to 3 mg/L (4 mg/L as average) in potamon sections. SSC thresholds are calculated based on the hydrology, turbidity and ecosystem characteristics of the water bodies investigated, including their maximum duration (see examples in Espa et al., 2019). In addition, ammonia must be included if deemed necessary by the results of the investigations, with acute and chronic thresholds defined considering pH and water temperature (US-EPA, 1986, 2013).

DM 205/2022 also sets guidelines for the grainsize and physico-chemical characterization of the sediment settled in the reservoir before its removal. Particular attention is paid to the chemical characterization of the inorganic fraction with diameters finer than 2 mm, requiring quantification of water content, total organic carbon, pH, arsenic, cadmium, chromium, mercury, lead, nickel, total polycyclic aromatic hydrocarbons, nitrogen and phosphorus. In addition, the characterization must be implemented by eco-toxicological tests including at least three organisms belonging to different trophic levels and to phylogenetically distant taxa (e.g., bacteria, crustaceans, mollusks, insects, algae, annelids and higher plants).

3.2. Other Alpine countries

Despite sediment flushing operations are documented in the whole Alpine area, as expected, the various Alpine countries have different related normative frames.

The Swiss Regulation for the protection of watercourses (Gewässerschutzverordnung, GSchV) is the main legislative reference for this country and has the general purpose of protecting water from impacts allowing, at the same time, its sustainable use. According to this normative act, related guidelines are issued by each Canton and reservoir managers must perform sediment releases (duration of the event and the maximum SSC in particular) in agreement with the competent Authority, to minimize damage to animal and plant communities downstream of the reservoirs. As in the Italian legislation, defined quality standards and parameters are listed and must be respected before, during and after the operations. The first requirement relates to the oxygen content, which should not be modified because of excessive deposition of fine sediment; the second requirement concerns the temperature, which may vary by a maximum of 3°C (1.5°C in reaches where trout are present). When sediment flushing operations cause documented impacts on the flora, fauna and habitats, Cantons are allowed to ask managers for remediation and/or compensatory measures, depending on site-specific conditions.

France does not have specific laws and regulations on reservoirs sediment management practices; the potential negative impacts of sediment flushing operations are generally examined case-by-case in the framework of the Environmental Impact Assessment procedure and in compliance with the national WFD implementation. Some French-Swiss studies reported on specific complexities of

Table 2
List of the main parameters and indicators to be monitored before and after sediment removal operations and related timing. When necessary and depending on the investigated area, additional indicators, such as diatoms, amphibians or embeddedness, can be included.

Parameter / Indicator	1–4 weeks PRE	3–4 weeks POST	3 months POST	6 months POST	9 months POST	1 year POST
Macroinvertebrates	X	X	X	X	X	X
Fish	X	X		X		X
Macrophytes (optional)	X			X		X
Dissolved oxygen	X	X	X	X	X	X
Polluting substances	X			X		X
Turbidity (optional)	Continuous					

transboundary cases, where different regulations are applied on the two sides of the border: Peteuil et al. (2013) and Grimardias et al. (2017) analyzed different aspects of the flushing carried out in 2012 through the Génissiat Dam, on the Rhone River, France. Upstream from the Génissat Dam, along the Rhone River in Switzerland, the Verbois and Chancy-Pougny dams are periodically subjected to flushing, particularly to preserve the safety of the city of Geneve from flood hazards connected to excessive aggradation of the river. At the same time, to prevent excessive aggradation due to the sediment release operated upstream, the Génessiat Dam is also subjected to a coordinated flushing. However, the maximum limits set for SSC downstream of the Génissat Dam during the flushing in 2012 (i.e., 5 g/L average value over the entire operation, 10 g/L average value over 6 h, and 15 g/L average value over 30 min) were more restrictive compared to limits for the Swiss operators. This peculiar situation offered an illustrative comparison between different degrees of environmental impact connected to different extents of sediment flushing control. Accordingly, in 2016, the coordinated flushing was carried out adopting a controlled strategy also on the Swiss side, where the same threefold thresholds were implemented, mitigating the consequence of the sediment release on the river segment more severely impacted by the flushing in 2012 (Cattanéo et al., 2021).

In Austria, Article 30 of the Water Rights Act 1959 (WASSERRECHTSGESETZ 1959), updated by the Official Gazette I No. 73/2018 (BGBl. I No. 73/2018), explicitly recognizes the importance of preserving the natural resources of surface waters and of ensuring a gradual improvement in their quality, with explicit reference to hydro-morphological conditions. The federal law also provides criteria for chemical, physico-chemical and biological monitoring in accordance with WFD standards. For instance, the Ordinance on Quality Objectives for Surface Water Ecology (Qualitätszielverordnung Ökologie Oberflächengewässer, published in the BGBl. II Nr. 99/2010 and amended in BGBl. II No. 128/2019) acknowledges the significant impact that flow alterations, particularly those caused by reservoirs and associated with hydropower operations, have on the hydro-morphological quality of water bodies, mainly depending on factors such as duration, frequency and speed of operations. However, while the ecological impacts of flow fluctuations are explicitly considered, the impact of the sediment release during flushing operations is overlooked, as reported in the Austrian water management document (Nationaler Gewässerbewirt-schaftungsplan) drafted in 2015. Sediment management operations are planned case-by-case, depending on the characteristics of the sites involved and the amount of sediment trapped in the reservoirs. The competent Authority defines operational management, SSC limit and the predisposition of possible mitigation actions in downstream water bodies. For instance, the case study published by Hauer et al. (2020a, 2020b) provides a good example of an approach to the issue of managing sediment removal by drawdown flushing in Austria (Gepatsch Reservoir). In that case, SSC limit was 1 g/L, except for the first two hours, when a maximum of 10 g/L was permitted. Threshold values were defined also for dissolved oxygen, ammonium and pH. The monitoring was set up according to two different perspectives. The first part considered the monitoring of the effects of the operations at the reach scale, through the continuous measurement of turbidity, the assessment of fine sediment deposition, and fish sampling. The related results indicated that continuously releasing sediment from reservoirs is generally effective in preventing SSC peaks that

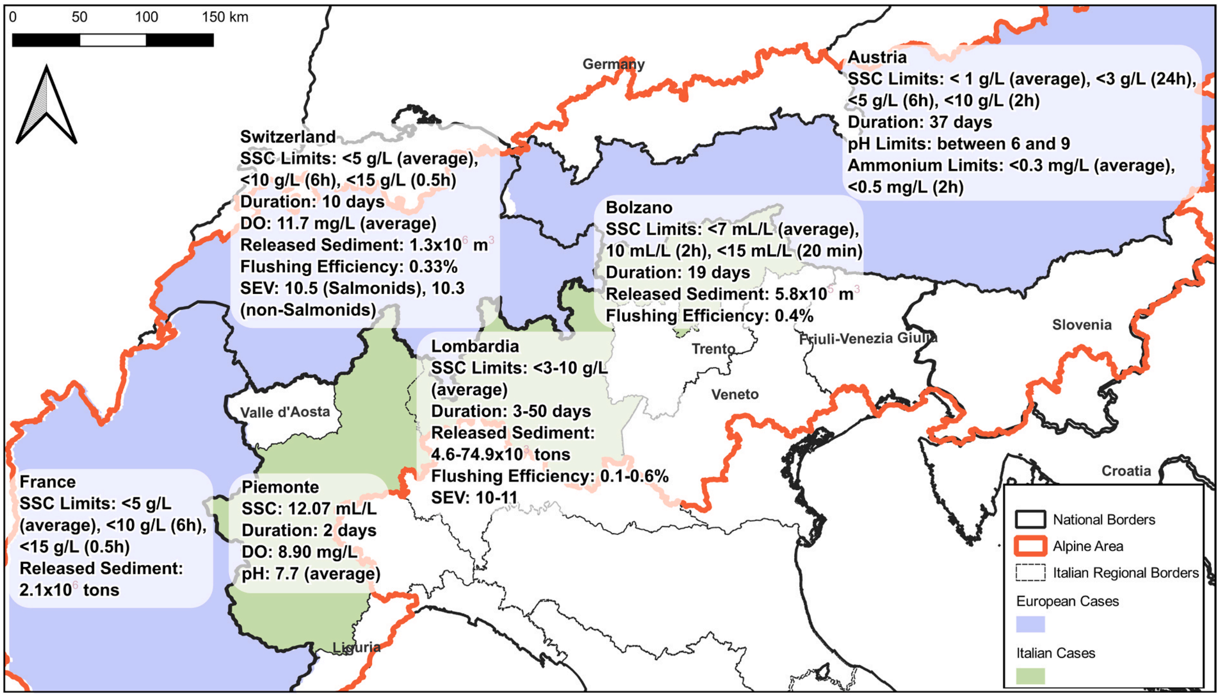


Fig. 2. Comparison between monitored parameters for different CSFOs documented in the literature in the Alpine area (France: Peteuil et al., 2013; Switzerland: Cattanéo et al., 2021; Italy-Piemonte: Doretto et al., 2019; Italy-Lombardia: Espa et al., 2019; Italy-Bozen-Bolzano: Folegot et al., 2021; Austria: Hauer et al., 2020a). SSC = suspended sediment concentration, DO = dissolved oxygen, SEV = severity of ill effect *sensu* Newcombe and Jensen (1996).

typically occur when sediment release is resumed after a period of interruption. Authors suggested that 3–5 stations were adequate for continuous SSC measurement and also demonstrated the onset of possible impacts of increased fine sediment loads on aquatic biota, even if in that case they were not directly attributable to the operation of the reservoir (increases in mortality and migration were found only for grayling; not for trout and bullhead). Conversely, the second part of the study was focused on local-scale impacts and modifications. Monitoring was performed by evaluating the abrasion of the turbine and the turbidity patterns in different habitats. Benthic macroinvertebrates were used as indicators, confirming their reliability especially in terms of density, diversity and biomass. However, the Authors emphasized the crucial role played by the natural development of the community at a site-specific level, particularly considering the seasonal effects, when evaluating potential causes of compositional variation observed during monitoring. Moreover, the Authors demonstrated that respecting the threshold values for turbidity and the other physico-chemical parameters prevented significant sediment deposits along the investigated watercourse. This, in turn, helped to avoid significant ecological impacts on the involved aquatic communities.

Fig. 2 shows a comparison between thresholds and monitored parameters in some selected Alpine cases documented in the literature, in France (Peteuil et al., 2013), Switzerland (Cattanéo et al., 2021), Italy (Piemonte: Doretto et al., 2019; Lombardia: Espa et al., 2019; Province of Bozen-Bolzano: Folegot et al., 2021), and Austria (Hauer et al., 2020a).

4. Recent trends in sediment flushing operations

4.1. Operation count in the Italian Alps

As introduced in Chapter 1, many reservoirs in the Italian Alps are losing storage by siltation, and sediment removal strategies, including sediment flushing, have been widely implemented since the beginning of the 21st century. A unified database of sediment flushing operations performed in the Italian Alpine area is currently unavailable, therefore we asked for related relevant data to each competent local Authority. The map provided in Fig. 3 displays the reservoirs so identified. Overall, from west to east, we received data regarding 3 reservoirs in Valle d'Aosta (over the period 2014–2024), 1 in Piemonte (over the period 2011–2019), 21 in Lombardia (over the period 2003–2024), 2 in the Province of Bozen-Bolzano (over the period 2001–2024), 10 in the Province of Trento (over the period 2014–2024), 7 in Veneto (over the period 2008–2024), and none in Friuli-Venezia Giulia. Accordingly, starting in 2014, around ten operation per year have been carried out in the Italian Alps, with a rather stable temporal pattern in the last decade (Fig. 4).

Considering the information provided by Lombardia Region only (i.e., the most complete dataset), we calculated a median value of 25,000 m^3 (min-max: 3500–120,000 m^3) of flushed sediment per operation and 12 days (min-max: <1–81 days) of duration. An example of consolidated practice in this region is the management of the Valgrosina Reservoir (i.e., the only red circle in Lombardia - Fig. 3), where sediment has been flushed annually from 2006 to 2012 and then every two years (2015–2024, Quadroni et al., 2024), thus cumulatively removing approximately 300,000 m^3 of sediment in two decades (by a total of 11 CSFOs).

4.2. Paper count in the Alpine area

As previously introduced, the global need to tackle loss of reservoir storage by siltation is receiving increasing attention within the scientific community, both in technical and environmental perspective. A systematic search of all the fields in the Web of Science Core Collection database (executed on August 13, 2024, without time restriction) through the words:

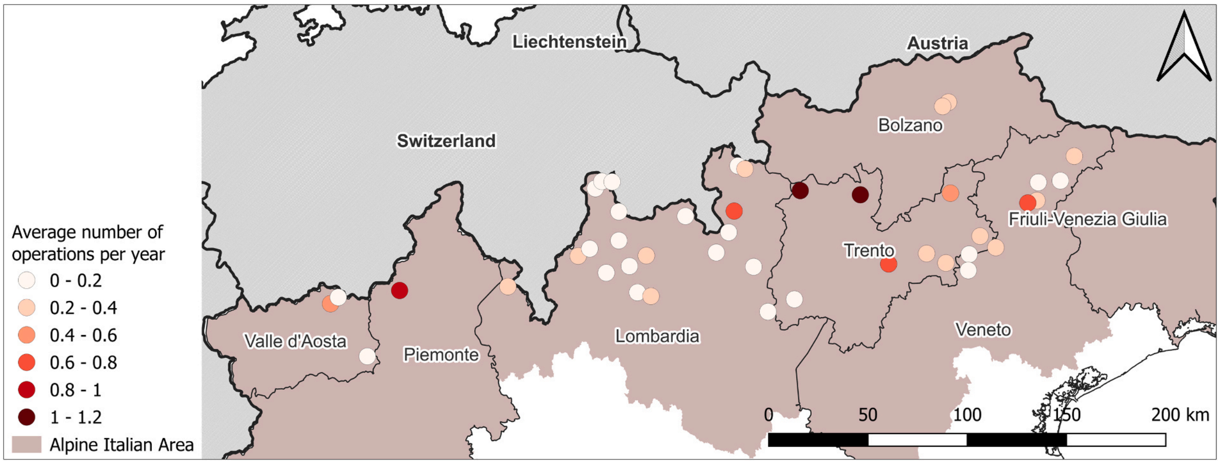


Fig. 3. Locations of the reservoirs where sediment flushing operations have been systematically recorded in the Italian Alpine area. The coloring of the dots refers to the average yearly number of operations on each reservoir. We note that the averaging periods are different for different Regions/ Provinces (see Fig. 4).

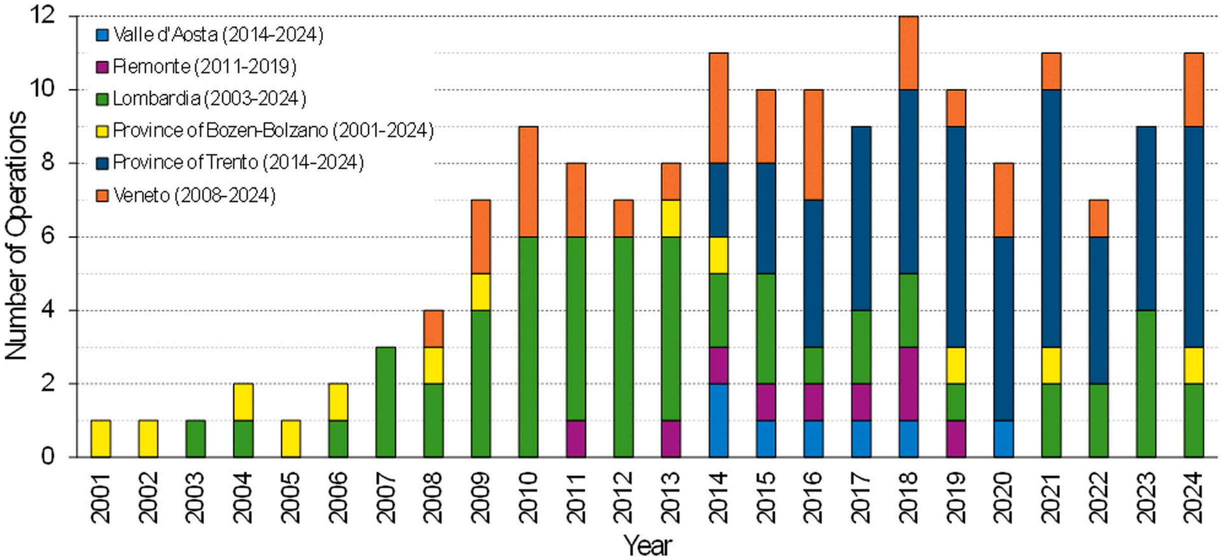


Fig. 4. Number of sediment flushing operations per year in Regions/Provinces of the Italian Alpine area.

i. "sediment+flushing" OR
ii. "reservoir+flushing" OR
iii. "pressure+flushing" OR
iv. "drawdown+flushing" OR
v. "controlled+flushing" OR
vi. "artificial+flushing" OR
vii. "flushing bottom outlets" OR
viii. "flushing clogging",

limited to the Alpine area through the addition of "Alps" OR "Alpine" by means of the connector AND, yields to 38 papers (from journals or conference proceedings) examining sediment flushing from multiple perspectives. A parallel search on Scopus, through i-viii in the keywords field and "Alps" OR "Alpine" in all the fields, provided a larger dataset of 74 entries. After discarding duplicates

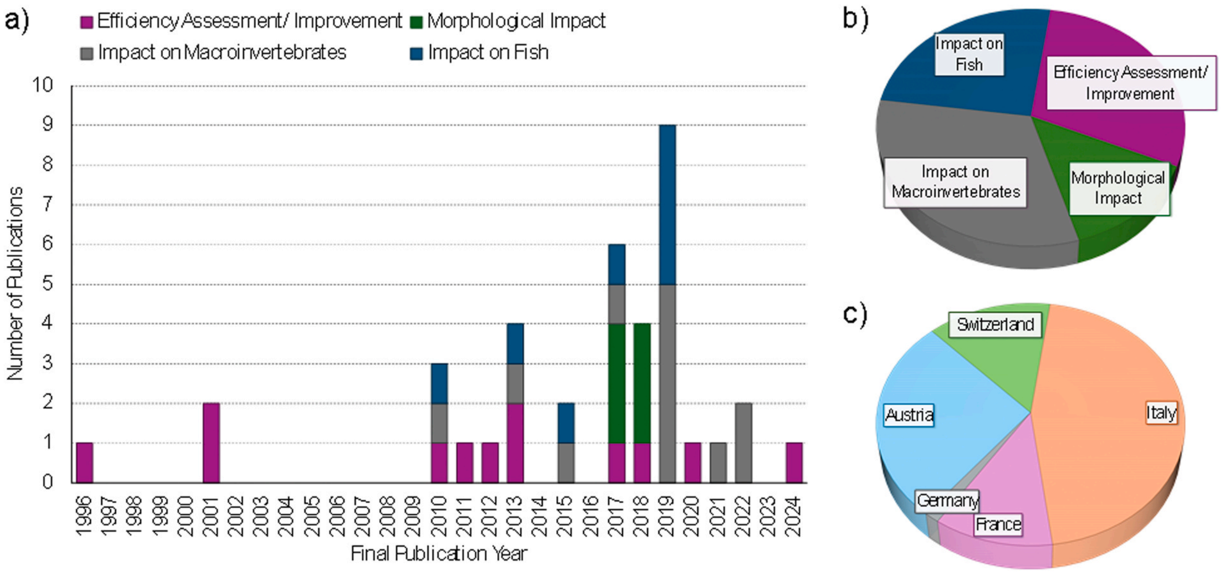


Fig. 5. a) Number of papers on sediment flushing in the European Alps, divided by publication year and colored according to the main topic. b) Papers distribution by main topic. c) Papers distribution by alpine countries. In the few papers unrelated to a specific study area, we defined the country according to the Authors' affiliation.

and the ones irrelevant to the topic or the geographic area, we obtained a final dataset of 35 papers, predominantly published in the last 10 years (Fig. 5a). 35 % of the studies focuses specifically on the managing perspective, assessing or suggesting measures to improve its efficiency (Wagner et al., 1996; Durand, 2001; Poirel, 2001; Crosa et al., 2010; Gallerano and Cannata, 2011; Harb, 2013; Plörer, 2013; Sindelar et al., 2017; Ehrbar et al., 2018; Reiterer et al., 2020; Reisenbüchler et al., 2021; Shoarinezhad et al., 2024), 18 % focuses on the impact of sediment laden water on river morphology (Gallerano and Cannata, 2011; Brignoli et al., 2016, 2017; Sindelar et al., 2017; Camenen et al., 2018; Legout et al., 2018; Ludeña et al., 2018), 41 % on its impact on macroinvertebrates (Crosa et al., 2010; Gallerano and Cannata, 2011; Espa et al., 2013, 2015, 2016, 2019; Quadroni et al., 2016a, 2016b, 2022; Doretto et al., 2019, 2021, 2022; Gabbud et al., 2019a, 2019b; Tritthart et al., 2019a; Folegot et al., 2021), and 32 % on fish (Crosa et al., 2010; Gallerano and Cannata, 2011; Espa et al., 2013, 2015, 2016, 2019; Quadroni et al., 2016a, 2016b; Tritthart et al., 2019a, 2019b; Reckendorfer et al., 2019; Pisaturo et al., 2021) (Fig. 5b). We note that some of the studies, especially those regarding the impacts on macroinvertebrates and fish, are not monothematic, thus previous percentages do not sum up to 100 %. While initial studies were mainly oriented towards the managing perspective, environmental attention increased in the following years (Fig. 5a). Moreover, a dominance emerges of Italian case studies and/or Authors' affiliation (Fig. 5c).

5. Residual criticisms of CSFOs

Overall, efforts to control sediment flushing operations have significantly reduced the ecological impact on downstream rivers if compared to unpredictable and uncontrolled sedimentation events (Salmaso et al., 2020, 2021; Servanzi et al., 2024).

Specifically, the widespread use of the Newcombe and Jensen (1996) model to predict the CSFO effects on fish, thus supporting proper planning of SSC thresholds and duration of the operations, has allowed to mitigate the impact over fish assemblages (Grimardias et al., 2017; Espa et al., 2019; Quadroni et al., 2024). However, short-term effects mainly on fry and benthic communities persist. The impact magnitude and the subsequent recovery time largely depend on the extent of the perturbation, but also on the grain-size of the flushed material, the flushing season, and to further site specificities such as biological recolonization sources (Espa et al., 2019). The adoption of mitigating strategies as removal by electrofishing before and repopulation after CSFO may help to preserve fish communities, along with the avoidance of the most vulnerable time window for fish (i.e., during the egg to young fry stages) as flushing season.

Although several authors (e.g., Kondolf et al., 2014) pointed out that the high-flow season should be preferred for flushing sediment, thus mimicking the natural occurrence of increased sediment load, in most cases technical reasons can prevent CSFOs during this season (e.g., Espa et al., 2016). Additionally, it should be emphasized that CSFOs are usually carried out in managed environments where, due to hydropower development, the streamflow is significantly lower than the natural flow (i.e., residual flow reaches) and displays reduced seasonal variability (Quadroni et al., 2021). The reduced amount of flowing water increases the persistence of sediment deposits after CSFOs (Fig. 6), thus extending recovery times. Though the release of clean water (flushing flow) is commonly implemented after CSFOs as a mitigation measure to accelerate biological recovery (Doretto et al., 2019), the subject is poorly documented so far. The implementation of artificial floods may act as a reset mechanism, enhancing resilience of the system to sediment disturbance and sustaining ecosystem dynamics over time (Robinson et al., 2018; Hashemi et al., 2024). In fact, by reducing fine sediment content of shallow benthic (ca. 10 cm) and hyporheic (depths of 25 and 50 cm) substrates, flushing flows can be an effective management tool to restore spatial heterogeneity in sediment composition and pore space and improve vertical connectivity for benthic organisms (Mathers et al., 2021). Therefore, proper quantification of flushing flow magnitude, considering clearly designed

Fig. 6. Sediment deposits detected after CSFOs in managed environments characterized by minimum flow releases from upstream dams. Photographs of the Roasco Stream (Lombardia, northern Italy) after the 2018 CSFO (unpublished photographs by authors S. Quadroni & P. Espa).

environmental objectives and related cost–benefit analyses could support a more informed and accepted diffusion of sediment flushing, supporting the transition from reservoir desilting to a more sustainable management of the hydro-sedimentary regime in regulated rivers. As introduced in Chapter 1, environmental flows would be upgraded to "environmental sediment flows" (Wohl et al., 2015), even if difficulties and delays in the implementation of environmental flows (Moccia et al., 2020) indicate that huge efforts are needed to achieve more advanced sustainable management goals.

Further issues emerging from previous studies (Espa et al., 2019; Quadroni et al., 2024) include the suitability of the tools currently adopted to predict and assess CSFOs impacts, currently mainly limited to aquatic fauna. Due to its simple structure, the model by Newcombe and Jensen (1996) might be questioned when significant temporal variation of SSC occurs during the CSFO or when an accurate estimate of fish (especially fry) mortality is required (e.g., in case of protected areas and species). In this regard, the improvement of the model or the development of more advanced modeling tools, also considering different bioindicators, appear necessary to support further progress in the CSFO practice. Moreover, traditional monitoring techniques sometimes fail to comprehensively assess the effects of streambed siltation. Acting as a specific pressure, siltation determines changes in the structure and functions of river biocoenosis not adequately detected by generalist biological indices, such as the ones developed to determine the ecological status of watercourses within the WFD (Espa et al., 2015). In this regard, new stressor-specific biomonitoring indices, as those based on the analysis of benthic macroinvertebrate communities (Doretto et al., 2018, 2021; Gieswein et al., 2019), have been recently proposed, but still need extensive implementation and validation.

Regardless of the adopted methodology, another basic issue is to quantify the specific impact of CSFOs in river reaches already affected by other anthropogenic pressures (mainly streamflow regulation operated by the upstream dams). Several studies (Espa et al., 2019; Folegot et al., 2021; Quadroni et al., 2024) demonstrated that biological recovery to pre-CSFO conditions occurred in a few months up to one year, but the pre-CSFO standard might be seen as a poorly ambitious ecological target. In fact, an eco-sustainable water resource management addressed to achieve the release of “environmental sediment flow” from dams would guarantee the improvement of the ecological quality of regulated rivers, targeting near-natural conditions.

6. Candidate ameliorative solutions and strategies

Sediment flushing is not the only alternative for removing sediment from silted reservoirs and to reestablish, at least partly, downstream sediment flux in dammed river systems. Further possible strategies include dredging, sluicing, and sediment bypass tunnels (SBTs) (Table 3).

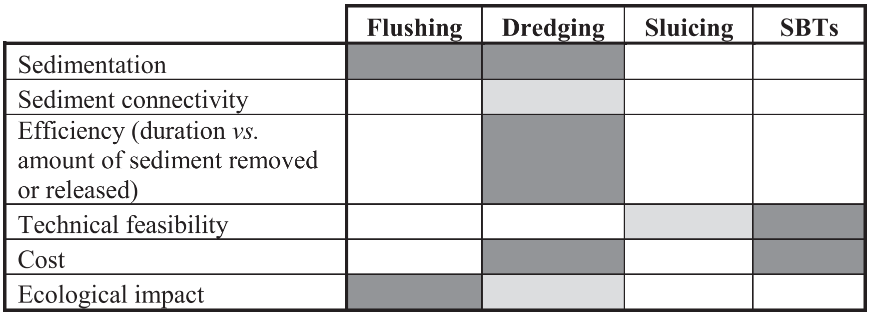
6.1. Dredging

As sediment flushing, dredging is a remediation measure, i.e., it is operated to recover the lost storage volume once sedimentation has already occurred in the reservoir. Differently from sediment flushing, however, it is carried out through the excavation of the silted material from beneath the water, without interfering with normal impounding operation (Kondolf et al., 2014). There are two main ways to carry out dredging: (i) mechanical-lift dredging, i.e., sediment removal and subsequent evacuation by barge or truck; (ii) hydraulic dredging, i.e., suction of a mixture of sediment and water, later transported in a slurry pipeline; in this case, the muddy water may be pumped to the river below the dam or to a containment area for dewatering (Morris, 2020). When sediment-laden water is discharged into the downstream river, the high sediment concentration can be detrimental for riverine environment and biocoenosis, to a degree comparable to sediment flushing.

To our knowledge, hydro-morphological and ecological effects of hydraulic dredging and release of sediment-laden water downstream of dams are poorly documented in the literature. An exception is a study by Quadroni et al. (2023), which provides a field investigation of the impact of hydraulic dredging on the physical habitat and the biological communities downstream of a reservoir in

Table 3

Qualitative comparison between advantages and disadvantages of different methods for managing reservoirs sediment. Dark grey boxes indicate negative features, light grey boxes slightly positive features, and white boxes positive features. In the case of dredging, sediment connectivity and ecological impact are indicated as light grey depending on whether the removed sediment is released in the downstream river. In the case of sediment bypass tunnels (SBTs), technical feasibility is indicated as dark grey since they are commonly built as retrofitting of existing facilities.



	Flushing	Dredging	Sluicing	SBTs
Sedimentation	■	■	□	□
Sediment connectivity	□	▨	□	□
Efficiency (duration *vs.* amount of sediment removed or released)	□	■	□	□
Technical feasibility	□	□	▨	■
Cost	□	■	□	■
Ecological impact	■	▨	□	□

the Eastern Italian Alps. Results for fish and benthic macroinvertebrate communities indicated weak differences in the density (~20 % reduction) and diversity of these organisms between pre- and post-dredging samplings. Specifically, the Authors underlined some key management factors that limited the ecological impact of the operation: a relatively low SSC limit over a relatively long operation, the allocation of large clear water volumes for diluting the sediment load and reducing fine sediment deposition, and precautional fish removal from the area closest to the reservoir before dredging.

Overall, though being expensive, dredging can be considered an effective alternative to counteract reservoir siltation. However, when sediment-laden water is not discharged below the reservoir, the availability of land for sediment disposal represents a significant economic and physical limitation (Morris, 2020). Therefore, dredging is often preferred to remove sediment from strategic areas, e.g., near power intakes (Kondolf et al., 2014; Waluyo et al., 2024). Limited cost containment can be achieved at hydropower sites by using self-generated electrical energy for dredging, or by sale of dredged material to mining companies (Waluyo et al., 2024).

6.2. Sluicing

An effective alternative to addressing siltation is to minimize sediment deposition when reservoir inflow carries large amounts of sediment, i.e., typically during floods. A way to achieve this is sediment sluicing, which involves lowering the water level during flood events to maximizing the sediment flow through the reservoir, thereby reducing its accumulation (Morris, 2020).

A coupled drawdown and sluicing strategy may be employed at reservoirs of all sizes, if outlet facilities of adequate capacity are installed; notable examples of this practice are provided by mega reservoirs in China (e.g., Three Gorges Reservoir, Ren et al., 2021). In contrast, full drawdown and riverine flow inside the reservoir can be achieved only in hydrologically smaller reservoirs (i.e., characterized by small capacity to inflow ratio) (Kondolf et al., 2014).

The main advantage of sluicing is that while the deposition in the reservoir is minimized, the sediment is transported downstream during the flood season, when natural sediment yield is maximum in the river, partially restoring a before-dam regime. However, in general, only fine-grained sediment is effectively transported through the reservoir (Kondolf et al., 2014).

Nukazawa et al. (2020) provided a preliminary assessment of the impacts on stream insects of sediment sluicing events operated in two cascade dams in the lower Mimi River, Japan. Shortly after the events, density and richness dramatically dropped, and the benthic community significantly differed from pre-impact conditions. However, density, richness, and community composition recovered in about one year. More recently, in the same river, Nakano et al. (2024) evaluated the restoration effects of sediment sluicing on macroinvertebrate assemblages using a more accurate before–after control–impact design. After sediment sluicing operations, the taxa richness of macroinvertebrates increased at sites downstream of the dam where free flow conditions were achieved, i.e., where the reservoir was completely lotic and large amounts of sediment were transported. Overall, the study suggests that sediment sluicing is an effective restoration method not only for macroinvertebrate assemblages but also for ecosystem functions.

6.3. Sediment bypass tunnels (SBTs)

While flushing, dredging, and sluicing act at the reservoir level, a further option is available implying the diversion of sediment before it reaches the outlet structures of reservoirs. SBTs are structures used to transport inflowing sediment downstream, through a tunnel built beside the dam (Sumi, 2015). Typically, they are operated during high flows, when the sediment input to reservoirs is significant (Auel et al., 2010). SBTs can re-activate the longitudinal sedimentary regime, providing sediment to the downstream river system impacted by the dam, generally determining marginal influence on further physico-chemical properties along these reaches (Martín et al., 2017).

Japan and Switzerland are the worldwide leader countries in terms of operating SBTs (Auel et al., 2017), consequently, the hydro-morphologic effects and response of benthic macroinvertebrates to SBTs operation has been mostly investigated in these countries (Auel et al., 2017; Martín et al., 2017; Serrana et al., 2018). These studies emphasized that the riverbed substrate grainsize downstream of the dam was equivalent or finer than upstream of the dam, and that a better recovery of the invertebrate community was achieved when the durations of SBTs operations were kept longer.

Specifically, Kobayashi et al. (2023) investigated the response of the invertebrate community to SBT operation downstream of a hydropower dam in Japan, overall observing positive effects on benthic macroinvertebrates. In fact, before SBT installation, the community similarity between the upstream and downstream sites was low. Long-term changes after the SBT installation were evident, including a hump-shaped change with an early increase and later decrease for the total density and taxon richness, and a monotonic increase in the inter habitat community similarity. The decreases in the taxon richness and inter-habitat difference detected in the latter half of the study period were justified by significant deposition of sand and gravel, embedding cobbles and relevant habitats of some taxa (e.g., coarse and stable substrate, pools and riffles).

SBTs are expensive because of the cost of construction, frequently carried out as a retrofit to existing projects; nevertheless, the diversion of sediment and the low interference with the reservoir ordinary operation represent the key strengths of this solution. By contrast, a serious limitation in bypass systems is the abrasion of the tunnel floor caused by the coarse bed load, that, in certain cases, can be excluded from the bypassing (Auel and Sumi, 2016).

7. Conclusions and perspectives

Due to the increasing demand of water and renewable energy and climate-related hydrological changes, the occurrence of sediment flushing operations has increased in the last decades and is expected to further increase over the next decades, with potentially severe effects on the biodiversity and ecosystem services of Alpine rivers. Consequently, there is an urgent need for shared sustainable practices and science-based management criteria to minimize the ecological impact of these operations, hopefully orienting sediment management practices towards "environmental sediment flows". Under the pressure of general societal discontent and specific requests by different stakeholders, flushing operations have become controlled, thus limiting fish mortality and long-term impairment of river ecosystem. In some Alpine countries, such as Italy, the normative framework has evolved to prescribe reservoir management strategies considering environmental repercussions, but the fragmentation of the different aspects (i.e., sediment and flow) of water resource management still prevents to pursue more ambitious goals.

If sediment flushing is one best choice among other possible techniques, management solutions could be upgraded in terms of flushing procedure, post-flushing mitigation measures and improved planning and assessment. For instance, flushing flows have been identified as a strategy to remove fine sediment from the riverbed for achieving restoration goals. However, their application is still restricted to a few case studies so that further research is needed to test their applicability before considering these mitigation measures suitable.

An ongoing national project funded by the Italian Ministry of University and Research and carried out by the Authors of this review, i.e., the FluEMMA (An interdisciplinary approach to study sediment Flushing operations from alpine reservoirs: Ecological, hydro-Morphological and Management Aspects) project, aims to fill the knowledge and methodological gaps associated with the sustainable management of sediment flushing operations from reservoirs in alpine areas. Specific aims include: (i) the identification and validation of the best biomonitoring metrics based on macroinvertebrate communities to properly assess the impacts of these operations; and (ii) the investigation of management alternatives for reducing the impacts associated with sediment flushing operations and promoting the post-flushing recovery (i.e., resilience) of both physical habitat and benthic macroinvertebrate communities. Results gained by an interdisciplinary and intensive, but still deserving proper development, data collection will be used to suggest some possible management strategies and/or alternatives (i.e., science-based criteria) for the mitigation of flushing impacts, thus supporting reservoirs operators and stakeholders in the planning and monitoring of these operations.

The performance of more eco-sustainable flushing operations will support preserving both hydropower production and high levels of the ecological quality of rivers. This can be translated into a twofold social impact: the long-term beneficial use of both reservoirs and rivers, and thus intergenerational equity. All these aspects appear even more important if considered within the international policy framework, particularly accounting for the sustainable development goals adopted by the United Nations General Assembly as well as some missions and targets (by 2030) of the new European Union latest funding program for research and innovation "Horizon Europe".

CRediT authorship contribution statement

Quadroni Silvia: Writing – review & editing, Writing – original draft, Visualization, Investigation, Funding acquisition, Conceptualization. **Doretto Alberto:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Imbalzano Giacomo:** Writing – review & editing, Investigation. **Pisaturo Giuseppe Roberto:** Writing – review & editing, Visualization, Funding acquisition, Conceptualization. **Talluto Niccolò:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Righetti Maurizio:** Writing – review & editing, Funding acquisition. **Servanzi Livia:** Writing – review & editing, Writing – original draft. **Stradiotti Giulia:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Espa Paolo:** Writing – review & editing, Funding acquisition, Conceptualization. **Crosa Giuseppe:** Writing – review & editing, Funding acquisition.

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Data statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study. However, data on the case studies monitored by the authors of this publication are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102570.

Data availability

Data will be made available on request.

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