Aquatic Sciences (2023) 85:60
https://doi.org/10.1007/s00027-023-00960-0

Aquatic Sciences

REVIEW

A review of sedimentation rates in freshwater reservoirs: recent changes and causative factors

Laureano Gonzalez Rodriguez[1] · **Adrian McCallum**[1] · **Damon Kent**[1] · **Charith Rathnayaka**[1] · **Helen Fairweather**[1]

Received: 27 December 2022 / Accepted: 15 March 2023 / Published online: 1 April 2023

Abstract

Sediment deposition in water reservoirs has major implications for storage capacity, reservoir lifetime, and water quality. Changes in rainfall patterns and land use will consequently alter the rate of erosion and therefore have a direct effect on sedimentation rates. This literature review employed a systematic mapping approach to collate and describe evidence of contemporary sedimentation trends for impounded reservoirs and natural lakes with emphasis on studies which analysed impacts on water storage capacity. Fourteen studies determined an overall increase in sedimentation rate, 13 identified a recent decline and another 5 reported mixed results. Interestingly, 83.3% of the articles that studied natural lakes found an increase in recent contemporary sedimentation, while 54.5% of the articles on impounded reservoirs indicated recent declines in sediment deposition. Land use change was the main causative factor responsible for sedimentation rate increase followed by the combined effects of land activities and climate change. Soil and sediment management strategies, implemented in and upstream of some impounded reservoirs, have proved to be effective in mitigating and remediating reservoir sedimentation. From the 147 papers preselected, only 33 contain sufficient sedimentation data to infer recent rate trends with only about 45% of these articles reporting quantities of storage capacity loss caused by sedimentation. Across these 33 studies, assessments of sedimentation and associated storage capacity loss are compromised by the limited spatiotemporal resolution of current measurement methods, reinforcing the requirement to develop new, more robust techniques to monitor sedimentation and storage capacity changes.

Keywords Freshwater reservoirs · Sedimentation rate · Storage capacity · Land use change · Climate change · Measurement methods

Introduction

Over time, sediment deposition at the bottom of natural and impounded reservoirs limits their storage capacity and lifespan. This has serious implications for water supply, food production, electricity generation, and reservoir maintenance costs (Gao et al. 2016) as well as environmental consequences through degradation of water quality and loss of biodiversity (Xu et al. 2017). Global estimates indicate that annual water storage loss caused by sedimentation is between 0.5 and 1% (Kokpinar et al. 2015; Rahmani et al. 2018). It is projected that by 2100, the world's water storage capacity will decline by > 50% (Gopinath et al. 2014).

Due to the relevance of sedimentation to ecosystems and humans, various methods to determine sedimentation rate have been developed and used depending on conditions such as data accessibility, measurement purpose, and budget and

✉ Laureano Gonzalez Rodriguez
laureano.gonzalez@research.usc.edu.au

Adrian McCallum
amccallu@usc.edu.au

Damon Kent
dkent@usc.edu.au

Charith Rathnayaka
crathnayaka@usc.edu.au

Helen Fairweather
hfairweather@engineersaustralia.org.au

[1] School of Science, Technology and Engineering, University of the Sunshine Coast, Sippy Downs, QLD 4556, Australia

time available (Chamoun et al. 2016; Darama et al. 2019). Measurement of bathymetry is one of the most common and accurate methods to determine sedimentation rates. This method uses acoustic signals and geolocation technologies to reproduce the underwater topography (Banasik et al. 2021; Darama et al. 2019). Core chronology is another typical technique to measure sediment deposition with high temporal resolution over periods of up to 100–150 years (Chen et al. 2019; Rose et al. 2011; Xiang et al. 2002). Additionally, hydrological data can be used in mathematical formulae to calculate sedimentation and trap efficiency, where equations and models are selected according to the type, quality and frequency of the data available (Lemma et al. 2020; Morris and Fan 2010). More recently, satellite imaging and remote sensing techniques have been proposed as alternative methods to monitor sedimentation (Darama et al. 2019; Mbatya et al. 2019).

When searching for reservoir sedimentation studies, one realises that contemporary sedimentation trends have two main distinctive patterns. On one hand, some studies have found that the rate of sedimentation have increased in many reservoirs in recent decades because of higher soil erosion caused by land use changes and more intense rainfall events (Rose et al. 2011; Schiefer et al. 2013; Xu et al. 2017). Urban growth, decline in vegetation cover and intensified agricultural development are the main activities attributed to increased rates of soil erosion (Ahn 2018; Pope and Odhiambo 2014; Rose et al. 2011). Soil erosion analyses in catchment areas have been used to determine the impact of spatial human expansion on annual soil loss increase (Pope and Odhiambo 2014). Other studies have determined correlations between reservoir sediment accumulation and demographic growth that explain the increase in sedimentation with correlation coefficients of up to 0.96. (McCall et al. 1984; Ruiz-Fernández et al. 2005). Variation in seasonal rainfall events, triggered by global temperature rise, have been identified by some researchers as a secondary influence on soil erosion and sediment deposition rise (Nguyen 2019; Rose et al. 2011; Shrestha et al. 2018).

On the other hand, the results of other studies indicated that some reservoirs have experienced recent declines in sedimentation rate attributable to human intervention and climatic factors (Chen et al. 2019; Darama et al. 2019; Hsiao-Wen et al. 2018; Navas et al. 2009). For instance, Chen et al. (2019) concluded that sedimentation rates decreased in some lakes in the Yangtze Basin (China) because of conservation practices and upstream dam construction. Improved land management practices and afforestation are among the conservation practices behind the decline in soil erosion and sediment yield. Changes in reservoir management strategies such as construction of upstream sediment retention structures, sediment bypass tunnels, changes of the sluicing patterns and spillway reconstruction have proved to be effective in tackling sediment deposition (Auel et al. 2017; Chen et al. 2019; Hsiao-Wen et al. 2018). In some regions, fewer flooding events and decreased inflows attributed to climate change have also been reported to contribute to declines in sedimentation rates (Navas et al. 2009).

The motivation of this literature review was to gather evidence that validates contemporary sedimentation rate changes in many parts of the globe and to describe the main factors causing these changes. The authors gathered peer-reviewed papers containing temporal evolution of sedimentation and examined the advantages and limitations of current methods to determine sedimentation rate and storage capacity loss. This enabled new measurement techniques to be examined. This review employed a systematic literature mapping approach (James et al. 2016; Pickering and Byrne 2013) to reduce bias in searching for relevant literature and collect the evidence in a structured database that can be easily traced and updated. The study intended to describe the evidence in relation to the ensuing questions: (1) what are the current trends in sedimentation rate; (2) what are the causative factors affecting modern sedimentation; (3) how much storage capacity loss is caused by sedimentation; (4) what are the limitations of traditional methods used to determine sedimentation. We have produced a unique database with information about contemporary sedimentation rate, reasons for sedimentation rate changes, measurement methods and storage capacity loss for many natural and impounded reservoirs worldwide, which to the best of our knowledge is not available in any other peer-reviewed article.

Methods

Systematic literature mapping uses structured approaches to collect and categorise a body of evidence to describe the state of knowledge for a topic of interest (James et al. 2016). During the review process, reviewers initially populate a database with metadata of each study using predefined categories. By interrogating the database, authors start describing articles' generalities such as geographical location, data sample and number of studies per year, which is followed by the description of research evidence trends and association between categories (James et al. 2016; Petrokofsky et al. 2018). The main objectives of these types of reviews are to develop a greater understanding of the concepts, reveal knowledge gaps, and find more specific subtopics for further research (Petrokofsky et al. 2018). Systematic mapping enables the identification of areas where sufficient evidence exists that may be suitable for more detailed secondary research as well as unrepresented subjects that are an opportunity to conduct primary research (James et al. 2016).

This review followed the steps proposed by Pickering and Byrne (2013) for systematic reviews. In the initial stage the reviewers define the topic, formulate the research questions, identify the search keywords and databases, and assess the publications. In the second phase, a database with categories and sub-categories is developed in an iterative manner. This database is later used to generate tables and plots based on the metadata from the publications and findings related to the research questions. Finally, the method provides a structured approach to guide the paper layout and order in which each section should be written.

The first question around the topic of sedimentation rate examined evidence of recent changes in sedimentation rate, while two other questions address factors causing these changes and the impacts on water storage capacity. Hence, the search strings were designed to obtain a maximum number of articles to answer these questions. Two different search literature databases were used to reduce journal biases. The databases ProQuest (PQ) and Web of Science (WS) were chosen in accordance with the databases' relevance to areas of environmental science and engineering. Filters were applied to the search engines of both databases to only include peer-reviewed papers (subscription and open access) written in English and that were available in full text.

The advanced search option on each literature database was used to combine keywords, synonyms and operators such as AND, OR and NOT to narrow the search, particularly for the PQ database, which at the start of this iterative search process retrieved thousands of articles. The search strings were constrained to article titles (ti) and abstracts (ab) for the PQ database, and to the whole document in the case of the WS because this database always produced a significantly smaller number of articles. Multiple search strings were tested until most of the first 15–25 hits, arranged in order of relevance, were associated with the topic and questions. The iterative process was independent for each database and resulted in different search strings (Table 1). As of 3 March 2022, the PQ search engine has retrieved 624 articles that complied with the final search string for this database, whereas the WS engine retrieved 174 articles.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Fig. 1) was used to report the selection process of the articles reviewed. This diagram is recommended for systematic literature reviews because it clearly summarises the selection stages and shows the number of papers chosen in each stage (Liberati et al. 2009; Moher et al. 2009). In the screening stage, titles and abstracts were assessed for relevance to the research topic and questions. If these two components of the paper provided insufficient detail to make an assessment, then the papers' conclusions and full text were briefly reviewed. Finally, publications that passed the screening stage were read in detail and vetted against the following exclusion criteria:

(1) The study determines sedimentation rate at a specific time (average) or for a short period (< 2 years) instead of assessing long-term sediment deposition.
(2) The articles were about methods to measure sedimentation rate but did not examine a historical evolution of sedimentation rate.
(3) Sedimentation was examined in streamflow or catchment areas but not in water storages.
(4) Spatial variation of sedimentation rate was assessed but not temporal.
(5) The articles addressed changes of sediment characteristics on geological timescales (i.e., thousands of years).
(6) Articles focused on simulation and predictions of sediment yield, transport, load and discharge, soil erosion, and runoff, but they did not examine the historical variations of sedimentation.
(7) The studies only determine or model sediment yield, transport, load, discharge, soil erosion, runoff, sus-

Table 1 Final search strings used for each database to identify articles relevant to the research topic and questions. Note that truncated words followed by an asterisk were used in the search engines to retrieve variations of the same word

ProQuest database (PQ)	Web of science database (WS)
ti(("Sediment* impact*" OR "Sediment* assessment*" OR "Sediment* effect*" OR "Sediment* rate*" OR "Sediment* deposition*" OR "Sediment* yield*" OR silt*) AND ("reservoir capacit*" OR "storage capacit*" OR "reservoir volume" OR "water security" OR "water suppl*" OR watershed*)) OR ab(("Sediment* impact*" OR "Sediment* assessment*" OR "Sediment* effect*" OR "Sediment* rate*" OR "Sediment* deposition*" OR "Sediment* yield*" OR silt*) AND ("reservoir capacit*" OR "storage capacit*" OR "reservoir volume" OR "water security" OR "water suppl*" OR watershed*)) AND ("climate change*" OR "climatic impact*" OR "environmental change*" OR "land use*" OR "land-use" OR "human impact*" OR "human activit*") NOT ti((modeling OR modelling))	ALL = (("Sediment* impact*" OR "Sediment* assessment*" OR "Sediment* effect*" OR "Sediment* rate*" OR "Sediment* deposition*" OR "Sediment* yield*")) AND ALL = (("reservoir capacit*" OR "storage capacit*" OR "reservoir volume" OR "water security" OR "water suppl*")) AND ALL = (("climate change*" OR "climatic impact*" OR "environmental change*" OR "land use*" OR "land-use" OR "human impact*" OR "human activit*"))

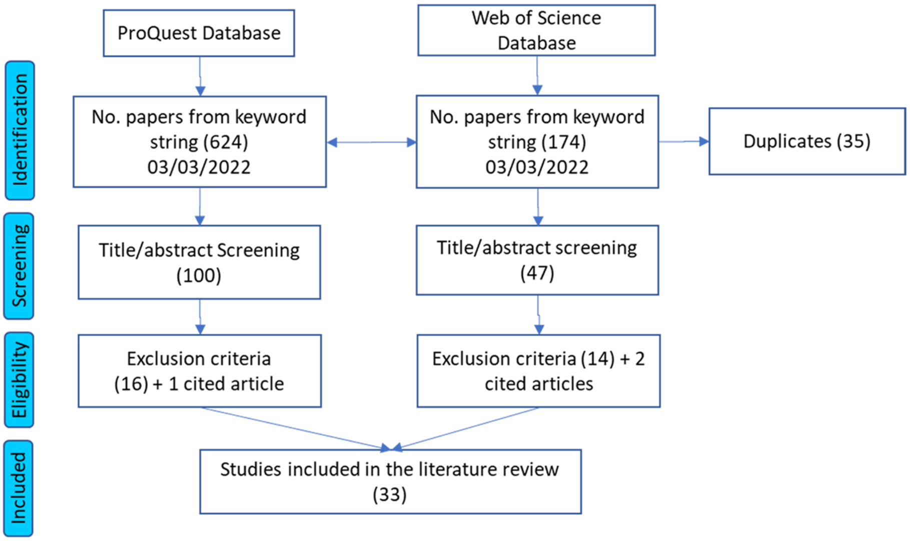

Fig. 1 PRISMA flow chart developed during assessment and selection process. Adapted from: Moher et al. (2009)

pended sediments and the reasons for changes of these parameters.
(8) Methods or strategies focused on controlling sedimentation.
(9) Articles addressed chemical/biological/physical sediment characteristics and/or evolution of sediment composition.
(10) Studies focused on detecting sediment sources.
(11) Review of policies and management strategies to control sedimentation.

Articles identified in the PQ and WS databases were uploaded into Endnote (EndNote 2021), where the software detected 35 duplicates. This resulted in 763 papers passing to the screening stage, from which 147 articles were selected after assessing their titles and abstracts (100 from PQ and 47 from WS). In the final stage of the PRISMA process (eligibility), only 33 papers from the previous stage were selected (22%), including 3 articles identified through citation by the selected papers (Fig. 1).

Most papers excluded during the screening stage did not examine sedimentation rate over multiple years. In many of these papers, only the average sedimentation rate was determined or reported. In some cases, the studies only presented the initial and most recent sedimentation rates, which were considered insufficient to extract trends in sediment deposition. Considering this finding, the scope of this literature mapping was expanded to include the types of methods used to determine sedimentation rates as an opportunity to assess their advantages and limitations in terms of temporal and spatial coverage.

The next block of steps in the systematic literature mapping aimed to extract, from each selected article, the information relevant to the research. Categories and subcategories that helped identify and extract the information were generated. In total, 6 categories and 38 sub-categories were defined based on the research questions, as well as articles' generalities such as geographical location, climatic zone, and reservoir type and dimensions (Table 2). NVivo 20 (NVivo 2021) was used to select and extract information related to each category. This tool quantifies the number of articles in each classification as the researcher highlights information from the articles, enabling straightforward identification of trends and comparisons across categories and sub-categories.

Results

The results are divided into those derived from the literature review in terms of study generalities and the research questions in each selected article. The studies' general aspects include categories such as country/region, climatic zone, annual precipitation, reservoir purpose and dimensions. Research question-related categories are sedimentation rate trends, reasons for rate change, storage capacity loss and measurement methods. A code was assigned to each article for easier identification; the two initial characters of the code indicate the data base (PQ: ProQuest or WS: Web of Science), followed by a number denoting articles from newest to oldest in each database (Appendix A).

Generalities of included articles

The review found that the largest number of the studies were conducted on water reservoirs in the USA ($n=7$) followed by China ($n=6$) then Turkey and Japan ($n=3$), with another 12 countries only represented in one or two articles. Europe was the region with the largest number of reservoirs analysed (210 out of 390 reservoirs; ~ 60% of these located in the UK)

Table 2 Defined categories and sub-categories in this review

Categories	Sub-categories
General information	Article objective
	Location
	Climatic zone
	Sediment composition
Reservoir general information	Types: impounded reservoirs, natural lakes
	Dimensions
	Number of reservoirs studied
	Purpose: conservation, hydroelectric, irrigation, multi-purpose, recreation, water supply, flood control
Changes in sedimentation rate	Increase
	Decrease
	Mixed results
	Inconclusive results
	Measurement frequency: continue, time intervals
	Value ranges
Causative factors	Climate change
	Land use
	Combined effect
	Trapping efficiency decline
	Sediment management
	Conclusion support: discussion, observation, mixed
Method to determine sedimentation	Bathymetry
	Core chronology
	Hydrological data and equations
	Remote sensing
	Combination
	Method flaws
Storage capacity changes	Value ranges
	Reservoir lifetime

followed by Canada (104) and China (33) (Fig. 2). The publication year for each article was also recorded, resulting in 15 papers published between 2015 and 2021, another 12 in 2009–2014, 3 during 2003–2008, 2 in the period between 1996 and 2002 and the oldest article in 1984.

From the 33 articles selected, 21 analysed impounded reservoirs (64%), while the rest of the papers ($n = 12$ or 36%) studied natural lakes. In the case of impounded reservoirs, it was found that most of the dams were built between the 1950s and 1970s. The primary reservoir purpose was relatively diverse (recreation, flood control, power generation, irrigation and water supply). The studied reservoirs were for single purpose in 18 papers, whereas another 8 examined multi-purpose reservoirs (Appendix A). Reservoir dimensions varied significantly as did their climatic zones (Appendix B). Many studies (17 out of 26) were in catchment areas where the annual rainfall was > 1000 mm and only 9 papers considered areas with annual rainfall < 1000 mm (Appendix B).

Research question-related results

In relation to the information specific to the research questions, this review found 14 articles (41.2%) that reported an overall increase in sedimentation rate and 13 articles (38.2%) determined a recent decrease in sediment deposition (Fig. 3). One of the articles which concluded that there was sedimentation decline (six reservoirs in a USA county) also found no clear silting trends for six reservoirs in another county (Renwick et al. 2005); this article was considered as two different studies when counting the category "changes in sedimentation rate". Another article indicated inconclusive results and the rest of the articles ($n = 6$ or 17.6%) were classified as mixed results that: (1) did not present a clear trend of sedimentation rate, (2) reported a constant sedimentation rate or (3) reported sedimentation rate stabilisation in the last 20 to 30 years after previous periods with increases and/or decreases. Tabulated results in terms of sedimentation rate trends, values and measurement methods are presented

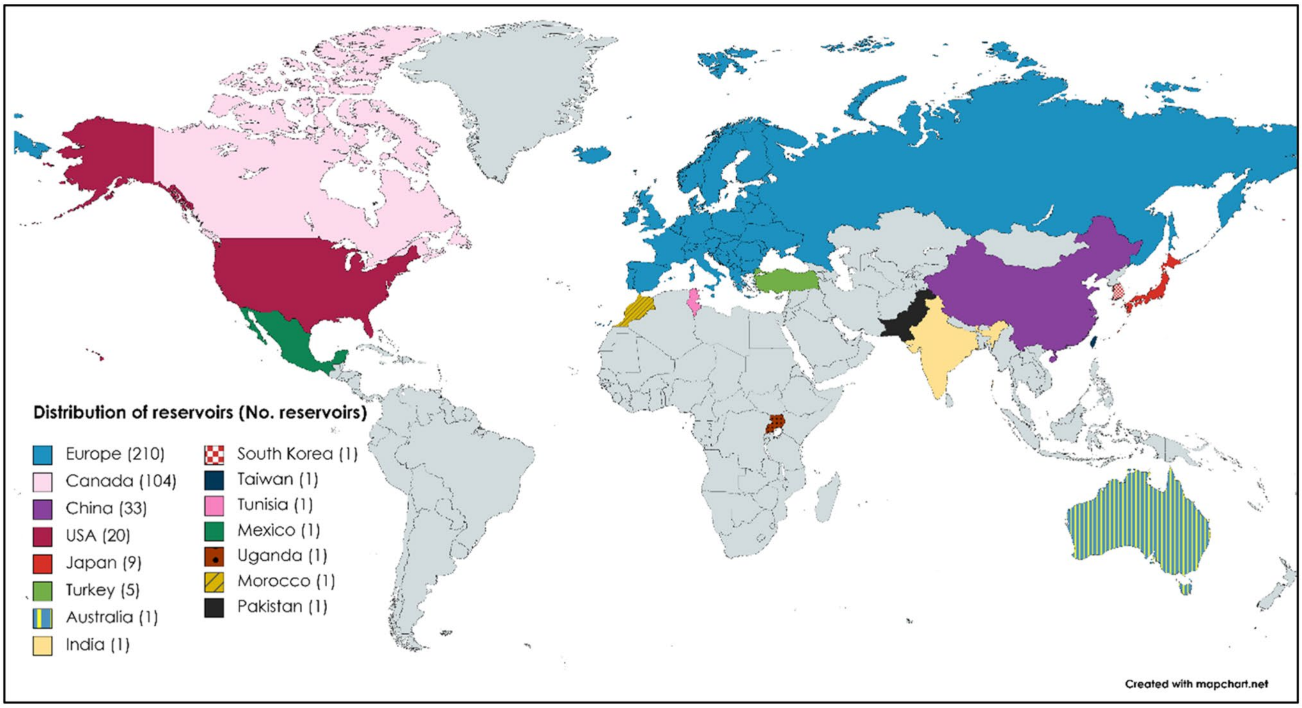

Fig. 2 Worldwide distribution and number of reservoirs per country or region

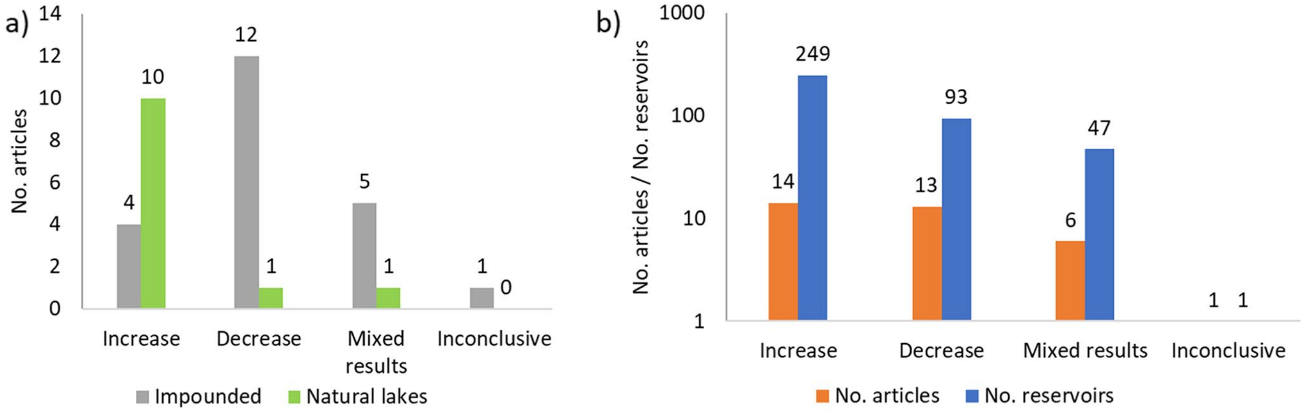

Fig. 3 **a** Breakdown of sedimentation rate change by type of reservoir, **b** Number of articles and reservoirs in each type of sedimentation rate trend

in Appendix C. The full information collected from the selected articles is available in the online version as supplementary information (Appendix D).

By comparing categories "reservoir type" and "sedimentation rate trend" (Fig. 3a), it is observed that 10 out of 12 articles that studied natural lakes found an increase in sedimentation rate (83.3%). The other two articles presented a decrease and mixed results, respectively. When analysing articles on impounded reservoirs, the proportions were significantly different with only 4 out of 22 articles reporting an increased rate (18.5%), 12 articles (54.5%) reporting a decrease in sedimentation, and another 5 reporting mixed results (22.7%). In terms of the number of reservoirs (Fig. 3b), the largest number was associated with an increase in sedimentation rate (249 out of 390 reservoirs; 63.8%). The number of reservoirs experiencing a decline in rate was 93 (23.8%), while 47 reservoirs (12%) were identified in the mixed-results category (Fig. 3b).

Most of the articles which determined either a reduction or rise in recent sedimentation rates presented explanations on the causative factors (28 out of 33 articles or 84.8%). These factors were categorised into five sub-categories: land use change, climate change, combined effects, soil or sediment management, and trap efficiency decline. In addition, another sub-category was used to record how authors determined the causative factors (i.e., discussion, observation or combination).

Overall, causative factors involving human intervention such as land use changes and sediment management have the highest impact (17 articles) on contemporary sedimentation rate change (increase or decrease). This is followed by the combination of factors such as land use change and climate change, or sediment management and climate change (7 articles). Climate change on its own and trap efficiency decline are the factors identified least in the papers reviewed (one paper for each of these two sub-categories). In five papers, the reasons for changes were not reported or the studies reported mixed results in sedimentation rate trends.

The proportion in the causative factors contributing to the increase and decrease in sedimentation rate varies significantly (Fig. 4). Twelve out of the 14 articles (85.7%) that reported an increase in sedimentation rate attributed this trend to land use changes (Fig. 4a). The two other papers (14.3%) indicated that increasing sediment deposition was mainly caused by the combined effects of land use change and climate change. Sediment or soil management was one of the main reasons for sedimentation rate decline in 5 of the 13 articles (38.5%, Fig. 4b). Another five articles (38.5%) indicated that the combined effect (sediment management and climate change) also contributed to the sedimentation rate decline. Climate change alone (1 article) and trap efficiency decline (1 article) were the two other reasons for sediment deposition decline (Fig. 4b).

Many of the studies identified the causative factors by observation (18 out of 28 articles, 64.3%). This means that the authors had evidence or records of the catchment conditions associated to the reported sedimentation rate changes. Another six studies only discussed the potential factors causing sedimentation rate change (21.4%) based on knowledge from other studies, and four studies used mixed sources (observation and discussion) to draw conclusions (14.3%).

Only 16 of the 33 articles (45.5%) quantified storage capacity loss due to sedimentation. Capacity loss rates (Table 3) were reported to vary significantly because of multiple factors such as climatic and geological conditions, reservoir dimensions, land use and climate change (Rose et al. 2011; Wisser et al. 2013). Reservoir lifetime was reported in five articles, from which two articles compared the difference between initial and more recent lifetime estimates after an update in the sedimentation rate input (Table 4). The median capacity loss rate across these 16 articles was 0.53%/year, and the minimum and maximum figures reported were 0.05 and 3.93%/year, respectively, illustrating the significant variability of this parameter. However, many capacity loss values reported (9 out of 20) were between 0.36 and 0.66%/year (Fig. 5).

The technique used to determine sedimentation rate was reported in 32 articles (Appendix C). Core chronology was the method employed to measure sedimentation rate change in 51.5% of the studies ($n = 17$), while bathymetry was used in another eight studies (Fig. 6). In another five articles, a combination of methods was used to determine sedimentation rate evolution. For instance, one study used remote sensing, bathymetric data and a Geographical Information System (GIS); another study employed core chronology together with sediment particle size and hydrological data. Two other articles indicated that sedimentation rates were obtained using one method (i.e., remote sensing and calculation from hydrological data, respectively). However, these two studies supported or calibrated their results with bathymetry data. The combined analysis of sub-categories "measurement methods" and "recent sedimentation rate trends" (Fig. 7) showed that 11 out of 14 articles indicated an increase in sedimentation rate used core chronology, whereas the studies that found sedimentation rate decline (13 articles in total) employed

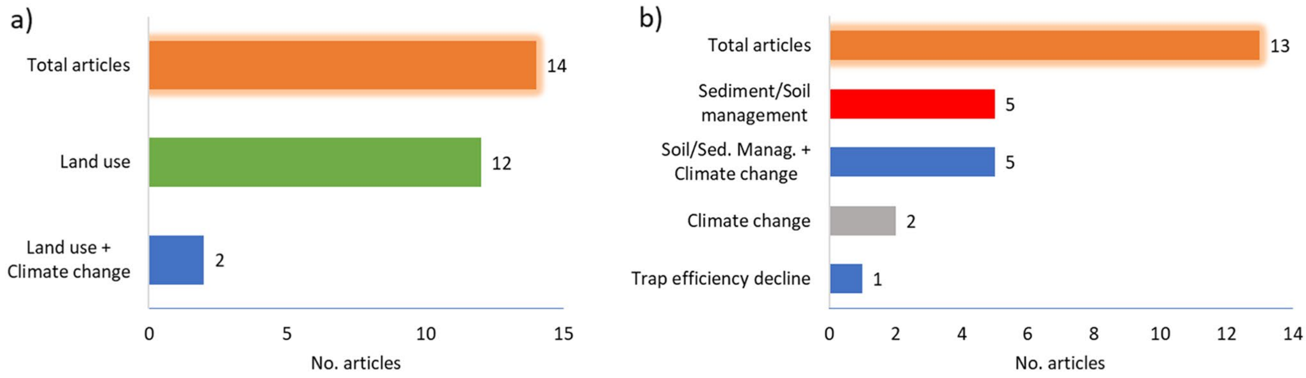

Fig. 4 The number of articles in each of the causative factor categories. **a** Causative factors of sedimentation increase and **b** causative factors of sedimentation decline. Glow orange bars represent the total number of articles for the increase and decrease sedimentation categories

Table 3 Most recent storage capacity loss rate reported in 16 articles

Article code	Country	No. reservoirs	Initial capacity, Mm^3	Most recent capacity, Mm^3 (@ year)	Capacity loss, % (time period, year)	Loss rate, %/year
PQ01	Turkey	1	50.63	37.41 (2014)	26 (40)	0.65
PQ02	Taiwan	14	–	–	50* (45*)	1.17*
PQ06	Turkey	3	1200	831 (2005)	30.75 (49)	0.63
			1320	1021 (1991)	22.4 (33)	0.68
			5980	5223 (1977)	12.65 (20)	0.63
PQ07	China	1	320	289 (2010)	10 (48)	0.21
PQ10	Republic of Korea	1	99	85.81 (2003)	13.32 (30)	0.44
PQ13	Pakistan	1	7254	5764 (2005)	20.54 (38)	0.54
PQ15	USA	1	0.183	0.134 (2007)	26.6 (54)	0.49
WS01	Poland	1	0.252	0.214 (2020)	15.2 (40)	0.38
WS03.1	USA	1	350	193 (2011)	44.86 (82)	0.55
WS03.2	USA	3	0.018	0.00892 (1982)	50 (44)	1.14
			5.57	5.03 (1977)	10 (38)	0.26
			7.42	6.20 (1977)	16 (63)	0.25
WS04	Turkey	1	0.05487	0.0452 (2006)	17.62 (25)	0.70
WS05	Uganda	1	0.091	0.0266 (2018)	70.76 (18)	3.93
WS07	Morocco	1	1507	1233 (2008)	18.18 (57)	0.32
WS08	USA	1	400	393 (2007)	2 (35)	0.06
WS09	Spain	1	471	450 (NA)	4.46 (27)	0.17
WS14	Spain	1	92	30.6 (1995)	33 (63)	0.52

The number in brackets in column 5 corresponds to the year where the capacity was last determined and in column 6 represents the number of years since storage capacity was first determined. Values with an asterisk (*) indicate the average of multiple reservoirs

Table 4 Estimated reservoir lifetime

Article code	Country	No. reservoirs	Reservoir lifetime, year	
			Initial estimate	Most recent estimate
PQ02	Taiwan	14		0–460**
PQ03	Japan	3		15/16/23
PQ07	China	1	1200	540
WS02	India	1		514–521
WS03.2	USA	3	- / - / 203*	5 / - / 67*

In articles analysing more than one reservoir, estimations of each reservoir are separated by forward slashes

*Initial and most recent estimates were only reported for one reservoir

**Lifetime range among the 14 reservoirs

mainly bathymetry (6 articles) and a combination of methods (4 articles).

This review also recorded the frequency at which the sedimentation rate was reported. The "continue" category implies a frequency of three or more values of sedimentation rate every 10 years, while the "time interval" category refers to reported values at ten or more years apart (see time intervals in Appendix C). Only eight articles presented continuous trends of sedimentation rate over time (24.2% of the articles). Core chronology was the method used in seven of these studies, and the other study determined high-frequency sedimentation rate using hydrological calculations combined with bathymetric surveys.

This review registered the advantages and limitations of the measurement methods employed in the selected articles (Table 5). A characteristic limitation of most of the methods is that they can offer high resolution in only one domain (i.e., time or space). While bathymetry can accurately reproduce reservoir topography, surveys are normally only taken a few times during the lifespan of a reservoir. Contrarily, core chronology can be used to determine the historical sediment deposition evolution for up to 100–150 years, but it is

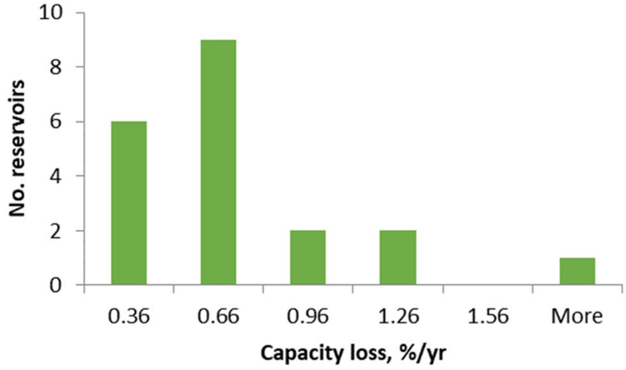

Fig. 5 Histogram of storage capacity loss

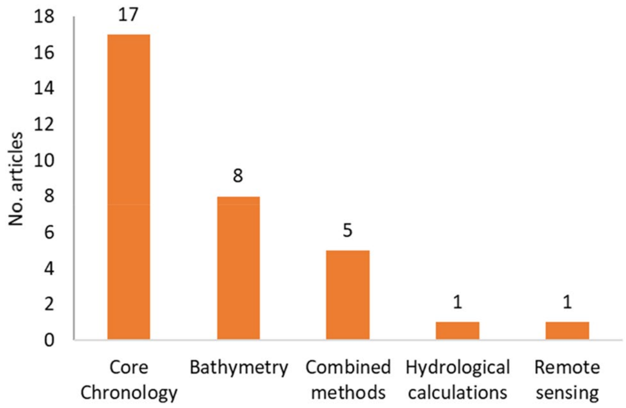

Fig. 6 Number of papers per measurement method

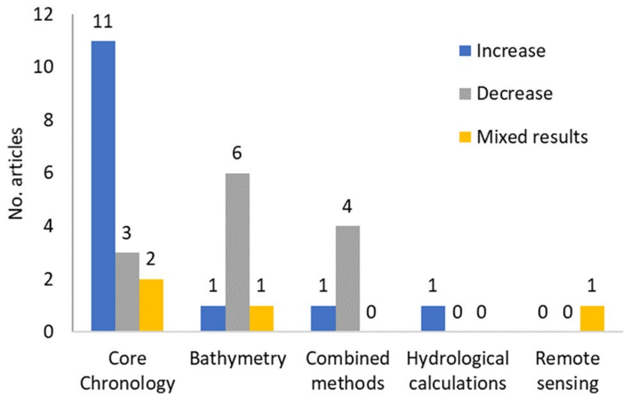

Fig. 7 Sedimentation rate change differentiated by measurement methods. Blue, grey and yellow bars are the number of papers indicating a sedimentation increase, decrease or mixed results, respectively. The sedimentation rate trend in one of the studies that used core chronology was classified as inconclusive, so it was not included in the graph

limited to point-in-space measurements, as are calculations from hydrological data. Point-in-space techniques are less suitable when the objective is to obtain accurate assessment of storage capacity across a water body because of the low spatial resolution nature of this method. In this review, only 2 of the 17 papers (11.7%) that used core chronology to determine silting rate presented assessments of storage capacity changes. Satellite imagery could provide spatial and temporal sedimentation, but this technique requires another method for calibration or reference (e.g., bathymetry, hydrological data).

Discussion

This literature review revealed that recent sedimentation rates are changing in most impounded and natural reservoirs, primarily because of factors such as human activities and climate change. In general, it has been estimated that recent sedimentation rates in natural lakes are two to ten times higher than sedimentation rates when lake catchment areas were undisturbed (Rose et al. 2011; Schiefer et al. 2013; Xu et al. 2017). In some reservoirs, sedimentation had increased for a long period, but more recently, less sediment is being deposited, mainly because of the implementation of erosion and sediment management practices. The results of a study analysing two groups of six reservoirs in Ohio (USA) clearly showed how two distinctive land development paths in two counties can affect trends of reservoir sedimentation (Renwick et al. 2005). Catchment areas in one of the counties were mostly developed for agricultural purposes (86% farmland, 12% forestland, 2% urban) managed with soil conservation practices. Most reservoirs in this county have experienced a significant decline in sedimentation rate since 1961. In contrast, catchment areas in the other county have experienced intensive urban development since the mid-twentieth century, representing 42% of the total land use by 2003 (with another 36% being forest land). The reservoirs in this county did not show sedimentation reduction even though forest land proportion was three times higher compared to the rural county.

Effect of human activities on sedimentation rate

With the global population reaching 7.8 billion by 2020, at a 1% annual rate of increase (Worldometer 2023), it is clear that urban expansion is necessary. Urban development surrounding reservoir catchment areas has reduced vegetation coverage and consequently increased the potential for soil erosion. The annual sediment flux in the catchment area reported in one of the selected articles surged 62% in a period of 8 years because of the residential development growth from 14–21% in proportion to the total land area (i.e., 54% increase in residential land in eight years).

Table 5 Advantages and limitations of common methods used to determine sedimentation rate

Method	Advantages	Limitations	Reference
Bathymetry	Direct measurement (accuracy). Excellent spatial coverage. Useful to determine reservoir water depth and area, enabling assessment of the storage capacity. Produce detailed maps of the reservoir floor.	Time-consuming (planning/execution) and expensive. Time interval measurements (required multiple surveys). Scarce data makes the inter-campaign and future estimations uncertain. Inconsistencies between surveys due to different technologies and/or methodologies.	Darama et al. (2019) Morris (2015)
Core chronology	Reconstruction of up to 150 years of sedimentation. Continuous estimation of sedimentation rates. Avoids data interpolation. Does not require periodic campaigns.	Elements can be dissolved/dispersed by flood events and are susceptible to post-depositional redistribution. Assumption of mathematical models not always fulfilled in nature (constant sedimentation rate and/or constant lead (Pb) concentration). Require ideally one independent tracer/marker to validate the chronology. It is a point-based method. Thus, it requires multiple cores to characterise the spatial distribution of sediment.	Singh and Vasudevan (2021) Chen et al. (2019) Palinkas and Russ (2019) McCall et al. (1984)
Calculations from hydrological data	Calibrated models can be used to generate scenarios of climate and land use changes. Can generate a continuous profile of sedimentation. Do not require extensive planning. Calculations can be updated once additional data is gathered without significant extra work.	Not able to characterise the spatial distribution of sediments. Non-unique solution (calibration parameters). Thus, interpretation becomes dependent on engineering judgment. Limitations of some equations/models to represent specific conditions (e.g., RUSLE equation not able to represent bedload).	Nguyen (2019) Oguz et al. (2019) Morris and Fan (2010)
Satellite and remote sensing imagery	Obtain a continues profile of sedimentation. Permanent monitoring. Reduce the number of bathymetry campaigns (cost).	Depend on additional sources of information (e.g., inflow, depth control points, bathymetry). Image resolution diminishes during cloudy days.	Condé et al. (2019) Darama et al. (2019)

A higher population increases the demand for land for food production, requiring land use changes (e.g., deforestation of floodplains and extensive cultivation on steep slopes) that increase erosion and sediment flux to reservoirs (Ahn 2018; Chen et al. 2015, 2019). Expansion of bare soil has been identified as the land change with the highest effect on erosion and sediment yield (Chen et al. 2015; Kim et al. 2014; Navas et al. 2009), whereas forestland is the land type contributing the least to sediment yield. Bare soil condition is caused by land overexploitation and abandonment, and expansion of undeveloped land (i.e., deforested land for future human development). In one of the selected articles, the annual soil erosion in a catchment increased 27% (from 2.18 to 2.76 million tonnes) in a period of 14 years (Kim et al. 2014). This was mostly associated with a 38% expansion of undeveloped land, even though this land type only represented 3.3% of the total catchment area. Road development (density), and drainage networks of urban areas and farmlands intensify rates of runoff and sediment fluxes that increase turbid water discharges (Ahn 2018; Ahn et al. 2009). Growth of human development and the associated land use changes are the main causative factors responsible for the contemporary increase in soil erosion and reservoir sedimentation documented in the sample. However, the importance of each land type on soil erosion can vary significantly because of factors such as soil type and geological characteristics (Kim et al. 2014).

Evidence of increased soil erosion and reduction of reservoir water storage capacity has triggered the implementation of sediment management strategies. In many reservoirs, mitigation and remediation measures have successfully minimised and even constrained the historical increase in contemporary sedimentation rates. The management measures can be grouped into actions that are focused on: (1) remediating soil erosion in catchment areas and (2) mitigation at the reservoir level to reduce sediment deposition.

Some of the effective soil erosion mitigation practices include afforestation at the upper basin and reforestation of hill slopes with trees such as cypress (Tang et al. 2014). For instance, a tenfold increase of forest land (equivalent to 55% of the total land) in a period of 45 years reduced the annual sediment yield of a Chinese basin by 48% (Zhang et al. 2020). In another case, the natural recovery of abandoned farmlands representing 22% of a Spanish basin (472 km^2) reduced the basin's annual runoff by 25%. The vegetation of the recovered area was predominantly forest followed by shrubs (Navas et al. 2009). In a lowland catchment in Poland (Banasik et al. 2021), farmland surface was reduced from 54 to 36% and replaced by forest and woodlands in a 40-year period, causing a 45% decline in annual sedimentation rate in the studied reservoir.

For steeply sloping land, the discontinuation of farming and conversion to forests and woodlands have reduced soil erosion, whereas for gently sloping farmland terraces, parts of the croplands have been converted to orchards (Tang et al. 2014). Conservation tillage has also been effective in reducing soil erosion rates as well as the reduction in the number of farms with outdoor feedlots for hogs (Renwick et al. 2005). Retention terracing has been shown to improve no-till management strategies in agricultural hillslopes because of slope length reduction that causes an increase in water infiltration and runoff volume and peak decline. This technique has reduced sediment yield by almost 65% and runoff by 78% in Brazilian catchments (Londero et al. 2018).

Actions at the reservoir level that have contributed to minimise sediment deposition include opening the sluice gates during the first flows of the rainy season to allow reservoir drawdown and avoid incoming sediment settling (Hsiao-Wen et al. (2018)). Sediment bypass tunnelling is another technique used to minimise sediment deposition by diverting sediment-laden water downstream through a tunnel or diversion channel (Auel et al. 2017; Kondolf et al. 2014). Other strategies implemented include the modification of the spillway to lower the sluice gate, increase of the sluice capacity, dredging, mechanical excavation and construction of check dams (Hsiao-Wen et al. 2018; Valero-Garcés et al. 1999). Drawdown flushing is a technique mostly used in small and elongated reservoirs to scour, re-suspend already deposited sediments, and discharge these sediments by completely depleting the reservoir through low-level gates (Kondolf et al. 2014). Although strategies at the reservoir level have been reported to be effective in controlling reservoir sedimentation, they do not assist in minimising soil erosion; hence, sediment yields continue to be transported within streams and deposited in other parts of the hydrological system. Downstream discharge of dam's sediments can have negative effects on river ecosystems such as dissolved oxygen decline due to higher concentration of suspended sediments, reduction of aquatic plants and invertebrates that constitute food for river fish, and increase in fish mortality (Espa et al. 2019).

According to the articles analysed in this review, sediment management efforts have been focused on impounded reservoirs. This could be attributed to the obvious impact of sedimentation on the dam's functions (e.g., hydropower generation, irrigation, consumption, recreation) and the economic implications of decommissioning fully silted reservoirs and constructing additional dams. However, increased sediment deposition in natural lakes presents critical threats to ecosystem, biodiversity and social security due to reduction in the lakes' storage capacity and water quality degradation (Schiefer et al. 2013; Xu et al. 2017). Agriculture activities surrounding lakes promote the increase of fine sediment inflow, which causes water pollution (by sediment-associated nutrients) and deterioration of aquatic habitat due to filling of riverbed interstitial spaces (Ahn et al. 2006). Conservation and expansion of swamps around lakes are an effective practice to trap sediments produced by surface erosion of cultivated lands (Ahn et al. 2009).

Effect of climate change on sedimentation rate

In general, the reviewed articles presented climate change as the second most influential factor affecting recent sedimentation rates. Factors such as rainfall frequency and intensity have a direct impact on runoff, flood events and sedimentation rates. Similarly, multiyear droughts cause vegetation cover reduction leaving soil more susceptible to erosion, which consequently increases runoff and sediment yields during periods of rain (Dunbar et al. 2010). However, the effects of temperature change on sedimentation are more difficult to predict. In some regions or climatic zones, higher temperature can result in rainfall increase leading to an increase in sedimentation (Schiefer et al. 2013). Higher temperatures can also cause wildfires leaving large expanses of bare soil that will eventually increase erosion (Dunbar et al. 2010). In contrast, in other cases, temperature rise may reduce runoff due to increased water consumption by vegetation and evaporation that can result in sedimentation decline (Navas et al. 2009).

Combined effect of climate and land use changes

The addition of climate change to the effect of land use change on sedimentation can be contrasting. For instance, aggravation of sedimentation increase can occur in reservoirs surrounded by overcultivated lands that have experienced severe flood and drought events (Xu et al. 2017). Higher temperature has been correlated with additional increase in sedimentation caused by land use change (e.g., urban development). This is attributed to the expansion of erodible soil or impermeable surfaces and to the fact that higher temperature can accelerate organic matter decomposition and increase biological productivity, elevating autochthonous and allochthonous input into water storages (Rose et al. 2011; Schiefer et al. 2013; Xu et al. 2017). Contrarily, conservation measures to minimise runoff and sedimentation can be enhanced by temperature increase because of additional evaporation in the catchment area (Navas et al. 2009).

Caveats in sedimentation rate measurements

An important aspect of measuring sedimentation rates of water storages is that they can be used to monitor storage capacity changes. Sedimentation rate measurements are also useful to estimate reservoir lifetimes during the design of dams. During the paper selection stage of this review, some papers presenting the storage capacity loss were excluded because they did not study the historical evolution of sedimentation rate. Conversely, some of the papers included in the review have a detailed history of sedimentation (mostly those utilising core chronology), but they do not study the effect on storage capacity. This evidence revealed there is an incompatibility between the spatiotemporal resolution of traditional methods to determine sedimentation rate (e.g., repeated bathymetric surveys and core chronology) and the resolution required to accurately monitor storage capacity.

A common limitation of current measurement methods is that they can provide only a snapshot of sedimentation in time or space. This limits their capacity to reliably identify sedimentation trends or extent, particularly under more frequent sedimentation rate changing conditions (Renwick et al. 2005). For instance, the typical frequency of bathymetric surveys is 10 years or more; hence, sedimentation rate and storage capacity forecasts may be affected by the limited datapoints used in the interpolation between surveys (Morris 2015). Point-in-space measurements or calculations from analytical models do not provide a detailed characterisation of reservoir topography, increasing the uncertainty in the estimation of storage capacity loss. This review identified core chronology as the preferred method to determine detailed evolution of sedimentation rate, but it is not the case when the outcomes of the study include ascertaining the effects on storage capacity.

Reservoir lifetime forecasts are also difficult to estimate accurately under conditions where there are frequent changes of sedimentation rate, unless the main input data (sedimentation rate) are updated regularly. Typically, the forecast is determined using the most recent sedimentation rate, which is considered constant in the forecast time period because of the lack of technical support to extrapolate future silting rate trends. McCall et al. (1984) found a difference of 136 years (203 vs. 67 years) in the estimation of the useful life of a reservoir when using long-term average versus recent sedimentation rate.

Given the evidence of modern sedimentation rate changes presented in this study, it is clear that traditional methods to quantify sedimentation rates need to be improved for more effective monitoring and understanding of sedimentation dynamics. Timely identification of increased sedimentation can enable effective mitigation and remediation strategies to optimise water storage capacity and avoid serious environmental issues such as water quality degradation and loss of biodiversity. This opens the door to research into new methods which can offer high spatiotemporal resolution measurements to monitor sedimentation and storage capacity loss.

Conclusion

This systematic mapping of research into sedimentation in freshwater reservoirs reveals that sedimentation rate is changing in most impounded reservoirs and natural lakes that have been studied with results published in peer-reviewed articles. Human activities were identified as the major factor responsible for sedimentation changes followed by changes in climatic conditions. While intensification in urban and agricultural development is increasing sedimentation of many water storages, sediment and soil management strategies have been effectively implemented, mostly in impounded reservoirs, to minimise sediment deposition. Due to the relevance of natural lakes in terms of ecosystem and biodiversity conservation, proven erosion mitigation practices must be broadly expanded to natural lakes experiencing significant sedimentation rate rises.

This review identified a gap in the number of peer-reviewed publications considering the historical evolution of sedimentation rates and their effect on storage capacities. The inclusion of grey literature (e.g., government reports) in a future review may increase the data sample size and strengthen the results of this work. Core chronology, with sufficient coverage of the reservoir floor, could prove valuable in those reservoirs with scarce records of past sedimentation. Due to the current (and most probably future) high variability of sedimentation rate in freshwater storages, measurement methods need to be improved or developed to provide higher spatiotemporal resolution assessments. This will be a more effective approach to understand sedimentation changes and impacts on water storage and quality.

Appendix A

General aspects of the reviewed articles

Article code	Country	No. reservoirs	Reservoir purpose	Type of reservoir	Impoundment year	Reference
PQ01	Turkey	1	Multipurpose	Impounded	1974	Darama et al. (2019)
PQ02	Taiwan	1	Multipurpose	Impounded	1953	Hsiao-Wen et al. (2018)
PQ03	Japan	3	–	Natural lakes	–	Ahn (2018)
PQ04	China	14	Conservation	Natural lakes	–	Xu et al. (2017)
PQ04.1	Canada	104	–	Natural lakes	–	Schiefer et al. (2013)
PQ05	China	1	Water supply	Impounded	1956	Gao et al. (2016)
PQ06	Turkey	3	Hydroelectric	Impounded	1956–1960	Kokpinar et al. (2015)
PQ07	China	1	Recreation	Natural lakes	–	Chen et al. (2015)
PQ08	China	1	Irrigation	Impounded	1956	Tang et al. (2014)
PQ09	USA	1	Multipurpose	Impounded	1976	Pope and Odhiambo (2014)
PQ10	Republic of Korea	1	Multipurpose	Impounded	1973	Kim et al. (2014)
PQ11	Tunisia	1	Conservation	Natural lakes	–	Trabelsi et al. (2012)
PQ12	Europe (~60% UK)	207	–	Natural lakes	–	Rose et al. (2011)
PQ13	Pakistan	1	Multipurpose	Impounded	1967	Butt et al. (2011)
PQ14	Australia	1	Water supply	Impounded	1970	Tibby et al. (2010)
PQ15	USA	1	Flood control	Impounded	1953	Dunbar et al. (2010)
PQ16	USA	12	Recreation	Impounded	1939–2000	Renwick et al. (2005)
WS01	Poland	1	Recreation	Impounded	1976	Banasik et al. (2021)
WS02	India	1	Recreation	Natural lakes	–	Singh and Vasudevan (2021)
WS03	USA	1	Hydroelectric	Impounded	1929	Palinkas and Russ (2019)
WS03.1	USA	1	Hydroelectric	Impounded	1929	Langland (2014)
WS03.2	USA	3	Multipurpose	Impounded	1914 1939 1938	McCall et al. (1984)
WS04	Turkey	1	Irrigation	Impounded	1977	Oguz et al. (2019)
WS05	Uganda	1	–	Impounded	2000	Mbatya et al. (2019)
WS06	China	8	Conservation	Natural lakes	–	Chen et al. (2019)
WS07	Morocco	1	–	Impounded	1951	Ahbari et al. (2018)
WS08	USA	1	Multipurpose	Impounded	1972	Odhiambo and Ricker (2012)
WS09	Spain	1	Irrigation	Impounded	1959	Navas et al. (2009)
WS10	Japan	5	Irrigation	Natural lakes	–	Ahn et al. (2009)
WS11	Japan	1	-	Natural lakes	–	Ahn et al. (2006)
WS12	Mexico	1	Conservation	Natural lakes	–	Ruiz-Fernández et al. (2005)
WS13	China	8	-	Natural lakes	–	Xiang et al. (2002)
WS14	Spain	1	Multipurpose	Impounded	1932	Valero-Garcés et al. (1999)

Appendix B

Reservoir dimensions and average climatic conditions

				Reservoir dimensions			
Article code	Number of reservoirs	Avg. precipitation, mm	Climatic zones	Volume, Mm^3	Area, km^2	Water depth, m	Length, km
PQ01	1	800–1000	–	50.63		30	
PQ02	1	2500–3000	Monsoon and trade-wind coastal Mild, humid Wet-dry tropical Temperate rainy	36.7	31.9	31	
PQ03	3	986–1576	Marshy alluvial, deltaic plains	0.068 0.016 0.090	0.063 0.0137 0.0519	1.1 1.2 1.8	
PQ04	14	1000–1600	Cold and dry winters, hot and wet summers	30–5140	11.8–2425	1.2–4.2	
PQ04.1	104	500–3000	Insular and coast mountains		0.06–13.5		
PQ05	1	> 1000	Subtropical southeast monsoon		65.5	15	
PQ06	3	400–1000	Semi-arid Mediterranean Continental	1200 1320 5980		74–78 (dam wall)	18–75
PQ07	1	1004	Subhumid	320	31	34	11.5
PQ08	1	826	–	0.0013		2.5	
PQ09	1	1000	Humid-temperate		1.66		
PQ10	1	1297	–	99	139.8		
PQ11	1	920	Arid		87	1.4–2.5	
PQ12	207	-	Humid-oceanic (majority) humid-continental (underrepresented)		from < 0.5 to > 0.5	from < 5 to > 5	
PQ13	1	1084	Sub-tropical scrub zone	7254			
PQ14	1	–	–	190		63 (dam wall)	
PQ15	1	680	Subtropical steppe cool, dry winters hot, humid summers	0.183			
PQ16	12	–	–		0.0025–2.39		
WS01	1	614	Temperate	0.252	0.141	3.2	0.9
WS02	1	1920	A subtropical monsoon climate				3.65
WS03	1	–	–				
WS03.1	1	–	–	350		33.53 (dam wall)	
WS03.2	3	–	–	0.018/5.57/7.42	0.016/1.70/2.78		
WS04	1	419.6	Semi-arid	0.05487		19.5 (dam wall)	
WS05	1	–	Semi-arid and arid	0.091	0.0289		
WS06	8	1200	Monsoonal climate cold, dry winters hot, wet summers		3–2933	1.9–6.4	
WS07	1	360	–	1507			
WS08	1	1050	Humid-temperate	400	46		27
WS09	1	800–1500	Temperate Atlantic to continental Mediterranean	471		74 (dam wall)	14.7
WS10	5	1227	–		0.01–0.14	0.4–1.8	

Article code	Number of reservoirs	Avg. precipitation, mm	Climatic zones	Reservoir dimensions			
				Volume, Mm^3	Area, km^2	Water depth, m	Length, km
WS11	1	1045	Dry and chilly winters. Cool and humid summers		1.3	2.4–3	
WS12	1	850	Subtropical upland Subhumid and temperate climate	0.05	0.153		
WS13	8	995–1570	–		12.4–2933	1.1–6.39	
WS14	1	500–2000	Wet and cold mountain type with both Atlantic and Mediterranean influence	92	6.92	16.5	

Appendix C

Summary of sedimentation rate trends, measurement methods and values per time interval

Article code	No. reservoirs	Measurement method	Recent rate trend	Causative factors	Time intervals	Sedimentation rate per period			
						cm/year	mg/cm^2/year	10^3 m^3/year	Tonne/year
PQ01	1	Combined methods	Decrease	Soil/sed. manag. + climate change	1974–1999 1999–2014			485.6 72	
PQ02	1	Bathymetry	Decrease	Soil/sed. manag. + climate change	1953–1998 2005–2015			420 210	
PQ03	3	Core chronology	Increase	Land use	Before 1890 1890s–1940s 1940s–2007		18/40/12 (RC) 114/110/21 167/203/81		112/54/63 717/151/111 1055/278/422
PQ04	14	Core chronology	Mixed results	Combined effect	1850–1900 1930–1960 1960–1990s		10–200 (RC) 200–500 300–600		
PQ04.1	104	Core chronology	Increase	Land use + climate change	1900–1952 End of twentieth century		2–20 (RC) 50% > RC		
PQ05	1	Combined methods	Decrease	Climate change	1956–1962 1963–1981 1982–1998 1989–1997 1998–2004 2005–2013	1.143/1.429 1.368/0.526 2.286/2.000 1.778/1.778 1.714/1.714 1.556/0.444			
PQ06	3	Bathymetry	Decrease	Sediment/soil management	1955–1977 1991–2005			~ 13,000 2430–2800	
PQ07	1	Bathymetry	Increase	Land use	1952–1988 1988–2003 2003–2010			500 600 570	
PQ08	1	Core chronology	Decrease	Sediment/soil management	1956–1963 1963–1989 1989–2010	3.79 1.35 1.07			
PQ09	1	Core chronology	Increase	Land use	1976 2009		~ 510/210/190 ~ 780/310/270		

						Sedimentation rate per period			
Article code	No. reservoirs	Measurement method	Recent rate trend	Causative factors	Time intervals	cm/year	mg/cm^2/year	10^3 m^3/year	Tonne/year
PQ10	1	Hydrological calculations	Increase	Land use	1986 1992 2000				267,807 301,477 339,332
PQ11	1	Core chronology	Increase	Land use	1940s 2009		~250 ~670		
PQ12	207	Core chronology	Increase	Land use + Climate change	1850 2000		20–31 (RC) 5–10 times > RC		
PQ13	1	Not available	Mixed results	Not available	1967–2005			Varies between 32,000–46,000	
PQ14	1	Core chronology	Mixed results	Not available	1971–1983 1983–1997 1997–2001	0.92 1.42 1.03			
PQ15	1	Bathymetry	Decrease	Climate change	1953–1960 1960–1965 1965–1971 1971–2007			4.380 1.850 0.385 0.217	
PQ16	12	Bathymetry	Decrease	Sediment/soil management	1957–1961 1961–1971 1971–1987 1987–2001			75.52 57.6 25.6 7.68	
WS01	1	Bathymetry	Decrease	Sediment/soil management	1980–1991 1991–2003 2003–2009 2009–2019			1.33 0.97 0.83 0.74	
WS02	1	Core chronology	Increase	Land use	1910–2019		4–125		
WS03	1	Core chronology	Inconclusive	Not available	1929 –2012		Varies between 900–6300		
WS03.1	1	Bathymetry	Decrease	Trap efficiency decline	1929–1959 1959–1990 1990–2011				3,200,000 1,935,484 1,238,095
WS03.2	3	Combined methods	Increase	Land use	1949/1945/1932 1962/1958/1946 1967/1964/1958 1980/–/1964	0.93/0.9/0.29 1.2/1.3/0.49 1.5/1.6/0.89 2.4/–/1.2		0.228/14.2/13	
WS04	1	Combined methods	Decrease	Sediment/soil management	1981–1987 1987–2006	0.012 0.009		0.707 0.534	
WS05	1	Remote sensing	Mixed results	Not available	2000–2018			Varies between 2.38–4.94	
WS06	8	Core chronology	Decrease	Soil/sed. manag. + climate change	< 1930 1950s/1960s/1970s 1980s–2012		< 200 (RC) 500–2500 90–580		
WS07	1	Bathymetry	Mixed results	Not available	1951–2008			Varies between 1924–18,610	
WS08	1	Core chronology	Increase	Land use	1972 2007		~18/131 ~28/151		

						Sedimentation rate per period			
Article code	No. reservoirs	Measurement method	Recent rate trend	Causative factors	Time intervals	cm/year	mg/cm^2/year	10^3 m^3/year	Tonne/year
WS09	1	Combined methods	Decrease	Soil/sed. manag. + Climate change	1959–1979	15–17.5			
					1979–1988	18–19			
					1988–2000	9			
WS10	5	Core chronology	Increase	Land use	1739–1963		66/7/1/7/24		
					1963–2007		286/225/286/301/176		
WS11	1	Core chronology	Increase	Land use	1694–1739		17		
					1739–1898		14		
					1898–1963		77		
					1963–2004		99		
WS12	1	Core chronology	Increase	Land use	Early 1910s–late 1990s	0.12–0.93	140–490		
WS13	8	Core chronology	Increase	Land use	< 1990		10–180 (RC)		
					1998		150–1000		
WS14	1	Core chronology	Decrease	Soil/Sed. Manag. + Climate change	1932–1950s	1.5			
					1954–1963	15 –24.6			
					1970–1990s	3.7–11.6			

RC: reference or initial conditions

Soil/sed. manag.: soil or sediment management measures

Appendix D

Full information from the selected articles

A data table integrating the full information on categories and sub-categories from the selected articles can be accessed online.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00027-023-00960-0.

Acknowledgements The authors thank the University of the Sunshine Coast (UniSC) for providing the tools and resources necessary to carry out this study. LGR expresses gratitude to the Australian Government for the financial support through the Research Training Program Scholarship.

Author contributions All authors developed the research categories and sub-categories, and agreed on the search strings used to identify the articles in the two databases. LGR: data curation, preparation of the database with metadata, original draft preparation. AM, DK and CR: paper search and selection, data validation, reviewing-editing. HF: study leader, result validation, reviewing-editing.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. LGR received financial support for the submitted work through the Research Training Program.

Data availability The data used in this work have been included as a supplementary material file.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

References

Ahbari A, Stour L, Agoumi A, Oualkacha L (2018) A simple and efficient approach to predict reservoir settling volume: case study of Bin El Ouidane reservoir (Morocco). Arab J Geosci 11(19):591. https://doi.org/10.1007/s12517-018-3959-7

Ahn YS (2018) Recent changes in sedimentation rate in Three Lakes of Ishikari Wetland, Northern Japan Determined by 210Pb Dating. Water Resour 45(5):795–802. https://doi.org/10.1134/S009780781805024X

Ahn YS, Mizugaki S, Nakamura F, Nakamura YJG (2006) Historical change in lake sedimentation in Lake Takkobu, Kushiro Mire, northern Japan over the last 300 years. Geomorphology 78(3–4):321–334

Ahn YS, Nakamura F, Kizuka T, Nakamura YJESP, Landforms (2009) Elevated sedimentation in lake records linked to agricultural activities in the Ishikari River floodplain, northern Japan. Earth Surf Process Landf 34(12):1650–1660

Auel C, Kobayashi S, Takemon Y, Sumi T (2017) Effects of sediment bypass tunnels on grain size distribution and benthic habitats in regulated rivers. Int J River Basin Manage 15(4):433–444. https://doi.org/10.1080/15715124.2017.1360320

Banasik K, Hejduk L, Krajewski A, Wasilewicz M (2021) The intensity of siltation of a small reservoir in Poland and its relationship to environmental changes. CATENA 204:105436. https://doi.org/10.1016/j.catena.2021.105436

Butt MJ, Mahmood R, Waqas A (2011) Sediments deposition due to soil erosion in the watershed region of Mangla Dam. Environ Monit Assess 181(1–4):419–429. https://doi.org/10.1007/s10661-010-1838-0

Chamoun S, Zordan J, De Cesare G, Franca MJ (2016) Measurement of the deposition of fine sediments in a channel bed. Flow Meas Instrum 50:49–56. https://doi.org/10.1016/j.flowmeasinst.2016.06.008

Chen N, Chen M, Li J, He N, Deng M, Iqbal Tanoli J, Cai M (2015) Effects of human activity on erosion, sedimentation and debris flow activity—a case study of the Qionghai Lake watershed, southeastern Tibetan Plateau, China. Holocene 25(6):973–988. https://doi.org/10.1177/0959683615574893

Chen X, Qiao Q, McGowan S, Zeng L, Stevenson MA, Xu L, Cao Y (2019) Determination of geochronology and sedimentation rates of shallow lakes in the middle Yangtze reaches using 210Pb, 137Cs and spheroidal carbonaceous particles. CATENA 174:546–556. https://doi.org/10.1016/j.catena.2018.11.041

Condé RDC, Martinez J-M, Pessotto MA, Villar R, Cochonneau G, Henry R, Nogueira MJRS (2019) Indirect assessment of sedimentation in hydropower dams using MODIS remote sensing images. Remote Sens 11(3):314

Darama Y, Selek Z, Selek B, Mehmet Ali A, Dagdeviren M (2019) Determination of sediment deposition of Hasanlar Dam using bathymetric and remote sensing studies. Nat Hazards 97(1):211–227. https://doi.org/10.1007/s11069-019-03635-y

Dunbar JA, Allen PM, Bennett SJ (2010) Effect of multiyear drought on upland sediment yield and subsequent impacts on flood control reservoir storage. Water Resour Res. https://doi.org/10.1029/2008WR007519

EndNote (2021) Accelerate Your Research. https://endnote.com/. Accessed 28 Jul 2021

Espa P, Batalla RJ, Brignoli ML, Crosa G, Gentili G, Quadroni S (2019) Tackling reservoir siltation by controlled sediment flushing: impact on downstream fauna and related management issues. PLoS ONE 14(6):e0218822–e0218822. https://doi.org/10.1371/journal.pone.0218822

Gao J-Z, Long Y, Zhang X-B, Collins AL, He X-B, Zhang Y-Q, Shi Z-L (2016) Interpreting sedimentation dynamics at Longxi catchment in the Three Gorges Area, China, using Cs-137 activity, particle size and rainfall erosivity. J Mt Sci 13(5):857–869. https://doi.org/10.1007/s11629-015-3637-0

Gopinath G, Ashitha MK, Jayakumar KV (2014) Sedimentation assessment in a multipurpose reservoir in Central Kerala. India Environ Earth Sci 72(11):4441–4449. https://doi.org/10.1007/s12665-014-3344-0

Hsiao-Wen W, Kondolf M, Tullos D, Wei-Cheng K (2018) Sediment management in Taiwan's reservoirs and barriers to implementation. Water 10(8):1034. https://doi.org/10.3390/w10081034

James KL, Randall NP, Haddaway NR (2016) A methodology for systematic mapping in environmental sciences. Environ Evid. https://doi.org/10.1186/s13750-016-0059-6

Kim SM, Jang TI, Kang MS, Im SJ, Park SW (2014) GIS-based lake sediment budget estimation taking into consideration land use change in an urbanizing catchment area. Environ Earth Sci 71(5):2155–2165. https://doi.org/10.1007/s12665-013-2621-7

Kokpinar MA, Altan-Sakarya AB, Kumcu SY, Gogus M (2015) Assessment of sediment yield estimations for large watershed areas: a case study for the Seyhan, Demirköprü and Hirfanli reservoirs in Turkey. Hydrol Sci J 60(12):2189–2203. https://doi.org/10.1080/02626667.2014.959954

Kondolf GM, Gao Y, Annandale GW, Morris GL, Jiang E, Zhang J, Yang CT (2014) Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth Future 2(5):256–280. https://doi.org/10.1002/2013EF000184

Langland MJ (2014) Sediment transport and capacity change in three reservoirs, Lower Susquehanna River Basin, Pennsylvania and Maryland, 1900–2012. US Department of the Interior, US Geological Survey

Lemma H, Frankl A, Dessie M, Poesen J, Adgo E, Nyssen JJG (2020) Consolidated sediment budget of Lake Tana, Ethiopia (2012–2016). Geomorphology 371:107434

Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JP, Moher DJJOCE (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. Ann intern med 62(10):e1–e34

Londero AL, Minella JPG, Deuschle D, Schneider FJA, Boeni M, Merten GH (2018) Impact of broad-based terraces on water and sediment losses in no-till (paired zero-order) catchments in southern Brazil. J Soils Sediments 18(3):1159–1175. https://doi.org/10.1007/s11368-017-1894-y

Mbatya W, Qayoom LAT, Sempewo JI (2019). Assessment of Reservoir Sedimentation Level and Storage Capacity Using Remotely Sensed Data for Namadope Reservoir in Luuka District, Uganda. <Go to ISI>://WOS:000477924400055

McCall P, Robbins J, Matisoff GJCG (1984) 137Cs and 210Pb transport and geochronologies in urbanized reservoirs with rapidly increasing sedimentation rates. Chem Geol 44(1–3):33–65

Moher D, Liberati A, Tetzlaff J, Altman DG, Therapy, P. G. J. P. (2009) Reprint—preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Phys Ther 89(9):873–880

Morris GL (2015) Collection and interpretation of reservoir data to support sustainable use. 10th FICS 5th FIHMC, Reno

Morris GL, Fan J (2010) Reservoir sedimentation handbook. McGraw-Hill Book Co., New York

Navas A, Valero-Garces B, Gaspar L, Machin J (2009) Reconstructing the history of sediment accumulation in the Yesa reservoir: an approach for management of mountain reservoirs. Lake Reserv Manage 25(1):15–27. https://doi.org/10.1080/07438140802714304

Nguyen HH (2019) Modelling effects of land-use and climate changes on catchment streamflow, sediment and nutrient loads by means of alternative and integrated models [phd thesis, The University of Adelaide]

NVivo (2021) Unlock insights in your data with powerful analysis. https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home/. Accessed 21 May 2021

Odhiambo BK, Ricker MC (2012) Spatial and isotopic analysis of watershed soil loss and reservoir sediment accumulation rates in Lake Anna, Virginia, USA. Environ Earth Sci 65(1):373–384. https://doi.org/10.1007/s12665-011-1098-5

Oguz I, Susam T, Kocyigit R, Bicak H, Demirkiran O, Demir S (2019) Estimation of soil erosion and river sediment yield in a Rural Basin of North Anatolia, Turkey. Appl Ecol Environ Res 17(4):7741–7763. https://doi.org/10.15666/aeer/1704_77417763

Palinkas CM, Russ E (2019) Spatial and temporal patterns of sedimentation in an infilling reservoir. CATENA 180:120–131. https://doi.org/10.1016/j.catena.2019.04.024

Petrokofsky G, Pullin AS, Frampton GK, Livoreil BE (2018) Guidelines and Standards for Evidence Synthesis in Environmental Management: Version 5.0

Pickering C, Byrne J (2013) The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. High Educ Res Dev 33(3):534–548. https://doi.org/10.1080/07294360.2013.841651

Pope IC, Odhiambo BK (2014) Soil erosion and sediment fluxes analysis: a watershed study of the Ni Reservoir, Spotsylvania County, VA, USA. Environ Monit Assess 186(3):1719–1733. https://doi.org/10.1007/s10661-013-3488-5

Rahmani V, Kastens JH, deNoyelles F, Jakubauskas ME, Martinko EA, Huggins DH, Blackwood AJ (2018) Examining storage capacity loss and sedimentation rate of large reservoirs in the central US great plains. Water 10(2):190. https://doi.org/10.3390/w10020190

Renwick W, Carlson K, Hayes-Bohanan J (2005) Trends in recent reservoir sedimentation rates in Southwestern Ohio. J Soil Water Conserv 60(2):72–79

Rose NL, Morley D, Appleby PG, Battarbee RW, Alliksaar T, Guilizzoni P, Punning J-M (2011) Sediment accumulation rates in European lakes since AD 1850: trends, reference conditions and exceedence. J Paleolimnol 45(4):447–468. https://doi.org/10.1007/s10933-010-9424-6

Ruiz-Fernández A, Páez-Osuna F, Urrutia-Fucugauchi J, Preda MJC (2005) 210Pb geochronology of sediment accumulation rates in Mexico City Metropolitan Zone as recorded at Espejo de los Lirios lake sediments. CATENA 61(1):31–48

Schiefer E, Petticrew EL, Immell R, Hassan MA, Sonderegger DL (2013) Land use and climate change impacts on lake sedimentation rates in western Canada. Anthropocene 3:61–71. https://doi.org/10.1016/j.ancene.2014.02.006

Shrestha B, Maskey S, Babel MS, van Griensven A, Uhlenbrook SJCC (2018) Sediment related impacts of climate change and reservoir development in the Lower Mekong River Basin: a case study of the Nam Ou Basin, Lao PDR. Clim Change 149(1):13–27

Singh KK, Vasudevan S (2021) Reconstruction of sedimentation rates based on the chronological framework of Lake Pykara, Tamil Nadu, India. Environ Monit Assess 193(7):428. https://doi.org/10.1007/s10661-021-09200-0

Tang X-Y, Zhang X-B, Guan Z, Long Y, Tang Q, Lü Y-J (2014) Historical sediment record of ^sup 137^Cs, [delta]-HCH, and [delta]^sup 13^C reflects the impact of land use on soil erosion. J Mt Sci 11(4):866–874. https://doi.org/10.1007/s11629-013-2945-5

Tibby J, Gell P, Hancock G, Clark M (2010) Complex reservoir sedimentation revealed by an unusual combination of sediment records, Kangaroo Creek Reservoir, South Australia. J Paleolimnol 43(3):535–549. https://doi.org/10.1007/s10933-009-9349-0

Trabelsi Y, Gharbi F, El Ghali A, Oueslati M, Samaali M, Abdelli W, Abril JM (2012) Recent sedimentation rates in Garaet El Ichkeul Lake, NW Tunisia, as affected by the construction of dams and a regulatory sluice. J Soils Sediments 12(5):784–796. https://doi.org/10.1007/s11368-012-0496-y

Valero-Garcés BL, Navas A, Machín J, Walling DJG (1999) Sediment sources and siltation in mountain reservoirs: a case study from the Central Spanish Pyrenees. Geomorphology 28(1–2):23–41

Wisser D, Frolking S, Hagen S, Bierkens MFP (2013) Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs. Water Resour Res 49(9):5732–5739. https://doi.org/10.1002/wrcr.20452

Worldometer (2023) World Population (2020 and historical). https://www.worldometers.info/world-population/world-population-by-year/. Accessed 7 Feb 2023

Xiang L, Lu XX, Higgitt DL, Wang SM (2002) Recent lake sedimentation in the middle and lower Yangtze basin inferred from Cs-137 and Pb-210 measurements. J Asian Earth Sci 21(1):77–86. https://doi.org/10.1016/s1367-9120(02)00015-9

Xu M, Dong X, Yang X, Chen X, Zhang Q, Liu Q, Jeppesen E (2017) Recent sedimentation rates of shallow lakes in the middle and lower reaches of the yangtze river: patterns, controlling factors and implications for lake management. Water 9(8):617. https://doi.org/10.3390/w9080617

Zhang J, Shang Y, Liu J, Fu J, Wei S, Tong L (2020) Causes of variations in sediment yield in the Jinghe river Basin, China. Sci Rep 10(1):18054–18054. https://doi.org/10.1038/s41598-020-74980-3