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A systematic review and meta-analysis on downstream Dam-Induced river channel adjustment

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ABSTRACT

This is the first study on the effects of the dam on channel morphology the downstream of dam on a global scale with a systematic review and meta-analysis approach. This study was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Therefore, the SCOPUS and Web of Science databases were searched using the Boolean operators 'AND' and 'OR' combined with keywords related to the subject area. All of the papers were in English and published up to 2023. Ultimately, 76 papers were evaluated for systematic review (qualitative analysis) and only 6 papers for meta-analysis (quantitative analysis). Results showed that the number of published papers has increased over time. In terms of channel adjustment, channel width decreased in the post-dam period, with narrowing and incision dominating in the downstream reaches. Meta-analysis showed that the dam has a moderately negative effect on channel width. Understanding these changes on a global scale can increase awareness of the impacts of dams on channel adjustment and their consequences.

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1. Introduction

River channel morphology changes in response to alterations in the hydrological regime and sediment load due to the natural processes (climate changes, volcanic eruptions, large floods, and fires) and human intervention (Khaleghi and Surian, 2019). The most common direct human intervention on channel morphology is dam construction. Dams are one of the oldest man-made infrastructures, built for foods control, irrigation, water supply, electricity generation, and navigation. According to Mulligan et al. (2020), dams and impoundments have been constructed from thousands of years up to now, but most large dams have been built in the last 60 years. Current estimates suggest there are around 58,000 large dams worldwide (https://www.icold-cigb.org/GB/world_register/general_synthesis.asp).

Asia, Africa, Europe, and the Americas have large dams along major river basins with Asia, North America and South America accounting for 27%, 23% and 21% the global dam count, respectively (Zhang and Gu, 2023). Dam construction has increased global surface water coverage over the past three decades, especially in developing countries in Asia and South America (Zhang and Gu, 2023). Dam can redistribute sediment and water, causing significant changes in the river morphology (Gordon and Meentemeyer, 2006; Takahashi and Nakamura, 2011; Ma et al., 2012; Smith et al., 2016). These changes lead to social and environmental effects, such as reduced floods (Petts, 1983; Kondolf and Swanson, 1993), damage to structures (Kale and Ataol, 2021) decreased groundwater resources (Williams and Wolman, 1984), and a reduction in native species.

Therefore, a better understanding of channel adjustments due to dams worldwide and in different regions is crucial for river management. Assessments and studies of rivers channel adjustments due to dams are less common than those focused on effects of dams on water and sediment, ecology, or human needs (Han et al., 2018). There is no comprehensive view on morphological change in pre- and post-dam periods globally. This paper prepares a systematic review of what is known about the impacts of dams on downstream channel morphology worldwide. The goals of the review are to quantitatively assess the number of published papers on the morphological impacts of dams on rivers and identify the main knowledge gaps to help set a research agenda to improve understanding of dam impacts on rivers channel morphology. The review was conducted using the SCOPUS and Web of Science databases to analyze published papers and understand the spatial and temporal patterns of dam impacts on the nature and magnitude of channel morphology in rivers worldwide. As part of the review, a meta-analysis was carried out to evaluate the effect of dams on channel morphology. The question addressed is what types of channel adjustments have occurred downstream of dams. The review helps to understand the magnitude of channel adjustment in various rivers and downstream sections globally for future river management and to reduce the economic losses and development challenges in the lower reaches.

2. Material and Methods

This study was carried out based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). A systematic review was conducted to obtain information from a large number of scientific papers, identify trends and patterns in published literature, understand key aspects of the published papers on effect of dams on channel morphology, and finally identify knowledge gaps. In this review, we analyzed peer-reviewed papers published on the effect of dams on downstream channel morphology worldwide. The literature search was carried out using the Web of Science and SCOPUS database. The primary search used Boolean operators 'AND' and 'OR' combined with keywords related to the subject area, such as "channel morphology", "dam", "hydrology" etc. to filter the identified papers. Combined keywords search in abstracts, keywords, and article titles were applied. Papers with unrelated keywords, duplicate articles, and papers without full text were excluded from the review. The search included only articles in English with no time limitation. Meta-analyses were done using random effects model. Pooled summary estimates for the respective log-transformed measures of association were computed and presented in forest plots. The standardized difference in means was calculated as effect sizes for the statistical analysis. Effect size metrics such as Cohen's d were employed in this study. To evaluate the risk of publication bias on the findings of meta-analysis performed using CMA, funnel plot techniques were used. The funnel plot and Egger's test were used for the statistical assessments of publication bias. All statistical analysis and plots were performed using CMA (Comprehensive Meta-analysis) 4 software.

3. Results and discussion

In the first step, a literature search was conducted using the SCOPUS database. The search results were 165 related articles on the study topic. An additional search using the Web of Science yielded 110 published articles. Forty articles were duplicates between the SCOPUS and Web of Science database searches. Additionally, 62 unrelated articles were removed, and then, after screening the title and abstracts of the articles, we select 114 related papers on dams and channel morphology. Finally, papers with unrelated indexed keywords and papers in other languages were removed. Ultimately, 76 relevant full-text articles were included in the systematic review. Among these articles, only 6 records were suitable for meta-analysis (Fig. 1). The studies investigated the impacts of dam on spatio-temporal changes in river morphology. We found that 76 case studies included in this review examined the effects of dams on downstream channel morphology over several decades (before and after dam construction). Fig. 2. shows the number of the publications from 1974 to 2023, with an increasing trend. In terms of channel changes, most of the studies (56%) reported incision, and 28% reported narrowing. Only 9 and 7% reported aggradation and widening, respectively (Fig. 3).

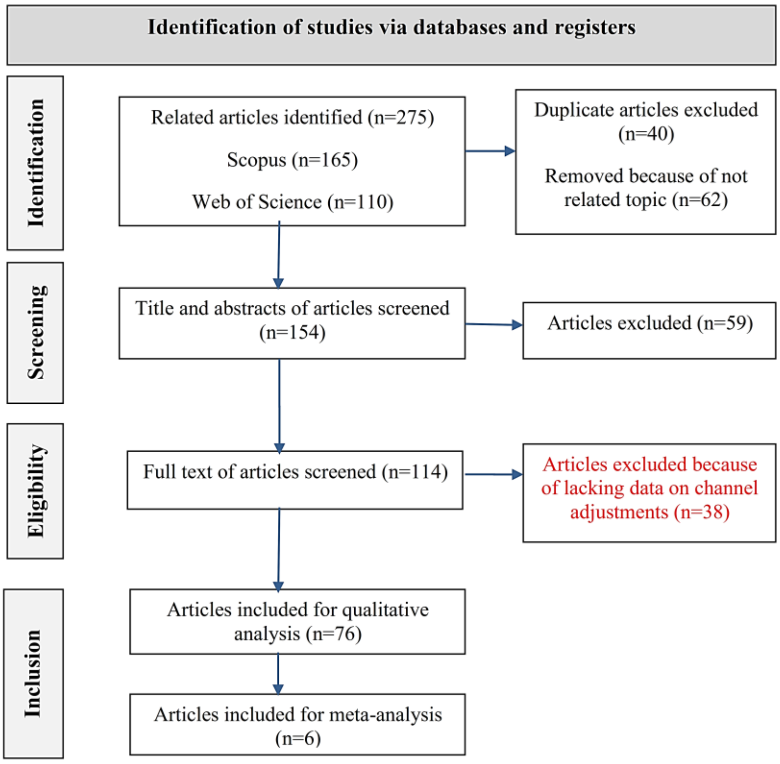

Fig. 1. PRISMA flow diagram for the process of articles selection.

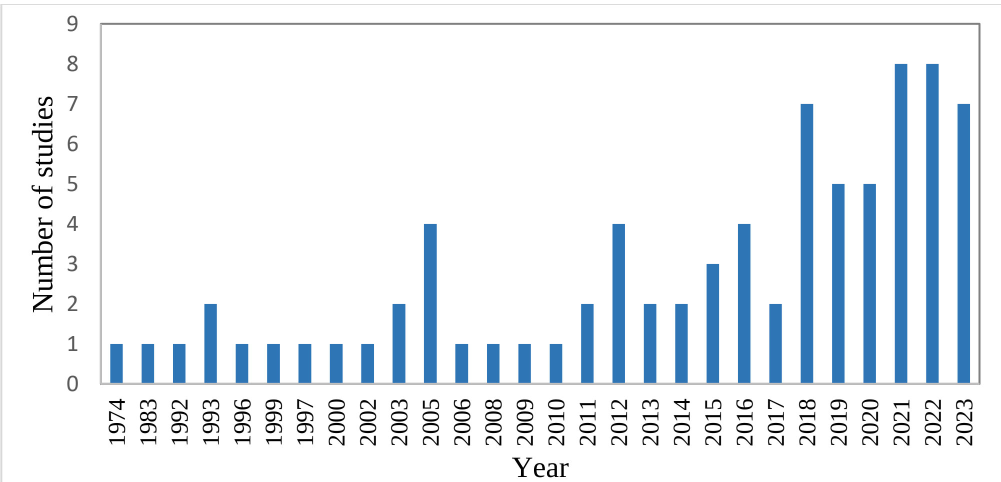

Fig. 2. Number of 76 related publications based on year (Table S1).

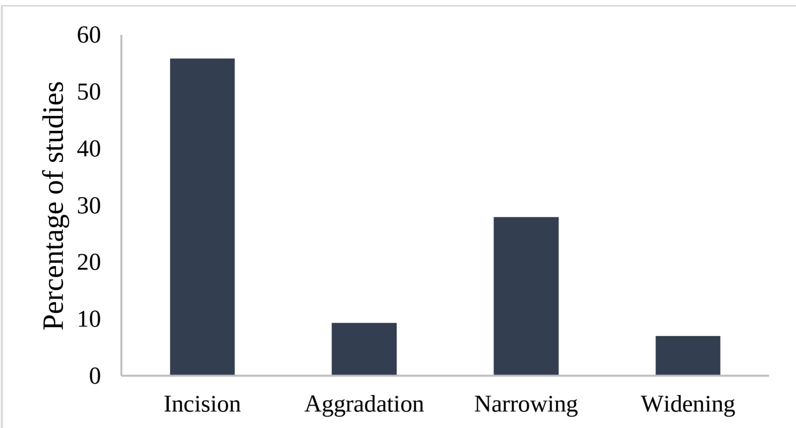

Fig. 3. Dam-induced downstream channel adjustment reported in the reviewed case studies.

Table 1 illustrates the six case studies included in the meta-analysis. These studies were conducted in Asia (3), America (2) and Europe (1). The effect of dams on downstream channel width was reported in these studies based on historical gauged data, remote sensing materials and channel cross-sections records.

Table 1. Summary of the studies included for meta-analysis.

NO.	Reference	River	Dam	Location and Time of Changes	Morphological changes
1	Zhou et al. 2021	Yangtze	Three Gorges Dam	China, mountain and alluvial plain (~30 km), 2002 to 201	Narrowing; incision
2	Liu et al. 2021	Lower Yellow River	Xiaolangdi	China, alluvial plain (786 km), 1965 to 2015	Narrowing; aggradation; decreasing width–depth ratio; large migration of the river channel; shrinkage of the channel
3	Phillips et al. 2005	Lower Trinity	Livingston Dam	Texas, alluvial plain and coastal plain (175 km), 1995–2003	Incision; widening; bank erosion; lateral channel migration; coarsening of channel sediment and a decrease in channel slope.
4	Lyons and Pucherelli, 1992	Green	Flaming Gorge Dam	USA, alluvial plain and mountain plain (162 km), 1952 to 1987	Narrowing; decreasing channel surface area
5	Surian, 1999	Pieve	Pieve di Cadore	Italy; mountain and alluvial plain (~220 km), 1900s-1991	Narrowing (more than 50%); decrease of braiding index; incision (up to 2 – 3 m); changes in channel pattern (from braided to wandering)
6	Ashouri et al. 2015	Ahar Chai	Sattarkhan	Iran; mountain plain (U: 33.6 Km; D:43.9 Km); 1990 to 2009	Narrowing (27%); incision (42.4%)

The statistical assessments of publication bias were carried out using the funnel plot and Egger's test. The funnel plot shows the present of potential publication bias. The funnel plot is a plot of a measure of study size (standard error) on the vertical axis as a function of effect size (Std difference in mean) on the horizontal axis (Fig. 4), in the absence of publication bias we would expect the studies to be distributed symmetrically about the combined effect size. By contrast, in the presence of bias, we would expect that the bottom of the plot would show a higher concentration of studies on one side of the mean than the other. The Egger's regression test result B= −4.08, 95% confidence interval (−9.92, 1.82) with t=1.92 and df=4. The 1-tailed p-value is 0.06, and the 2-tailed p-value is 0.12. The non-significant interception indicated the absence of publication bias. Finally, publication bias for the difference in mean width of the six studies is not significant in 95% confidence level.

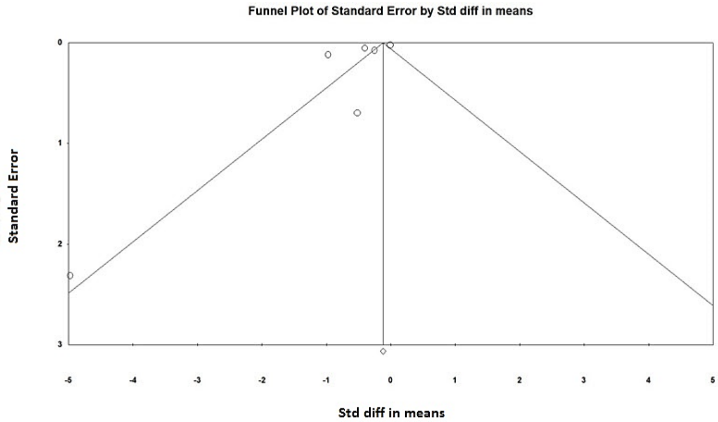

Fig. 4. Funnel plot of difference in means of width for the observed studies.

The effect size index is standardized difference in means (d). The random-effects model was employed for the analysis. The results of meta-analysis showed that the mean effect size is -0.421 with a 95% confidence interval of -0.743 to -0.099. The mean effect size in the universe of comparable studies could fall anywhere in this interval. The Z-value tests the null hypothesis that the mean effect size is zero. The Z-value is -2.564 with p = 0.010. The null hypothesis is rejected and concluded that in the universe of populations comparable to those in the analysis, the mean effect size is not precisely zero. The Standard difference in means of width and weight of each study at the 95 % confidence level is represented in Figure 5. The middle square and line segment show the average score and confidence interval in each study, respectively. The diamond shape shows the average score of all studies (Fig. 5).

Study, Pub Year	Std diff in means	Z-Value	p-Value	95% CI	Weight
Zhou 2021	-0.008	-0.308	0.758	[-0.059; 0.043]	24.90%
Liu 2021	-0.249	-3.170	0.002	[-0.404; -0.095]	23.69%
SURIAN 1999	-0.403	-7.243	0.000	[-0.511; -0.294]	24.36%
Phillips 2005	-0.517	-0.738	0.461	[-1.889; 0.856]	4.51%
Ashouri 2015	-0.972	-8.012	0.000	[-1.210; -0.734]	22.04
LYONS 1992	-4.971	-2.148	0.032	[-9.507; -0.435]	0.49%
Random	-0.421	-2.564	0.010	[-0.743; -0.099]	100%

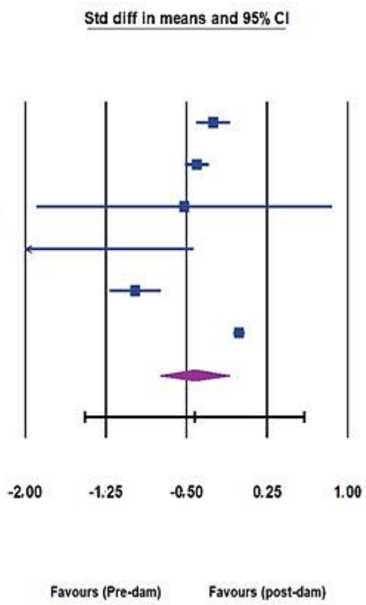

Fig. 5. Forest plot for the standard difference in mean channel width and weight of each study based on random model.

The question addressed was what types of channel adjustments have occurred downstream of dams. Given that data about dam-induced channel adjustments are neither homogeneous nor complete for all rivers, the analysis of the extracted data showed that narrowing and incision of channels have dominated in the downstream reaches of dams. Meta-analysis represented those dams have negative effects on channel width (narrowing). These findings agree with Khaleghi and Surian (2019), who reported that narrowing and incision due to the dams have been observed in studied Iranian rivers and in some studies around the world (Surian and Rinaldi, 2003; Lu et al., 2007; Korpak, 2007; Wyzga, 2008). According to the meta-analysis results, dams have effect on channel width in downstream. This effect is negative, implying that channel width has decreased (narrowing). These decreasing can cause some ecological and management challenges. Finally, although channel changes have environmental and ecosystem effects, such effects have not been broadly evaluated in the existing studies. However, only some of the reviewed papers have addressed ecological and management consequences of channel adjustments downstream of dams.

4. Conclusion

This work presents the first systematic review about the effect of dams on downstream channel adjustments on a global scale. This study showed that although there are many large dams worldwide with significant morphological effects on river channels, only some studies have evaluated their downstream morphological adjustments. Although the number of studies is increasing over time, this is insufficient compared to the numbers of dams worldwide. However, dams have effect on downstream channel morphology, so that incision and narrowing of channel in downstream reaches are dominant. Recognizing these changes on a global scale can enhance awareness of the effects of dams on river channel adjustment and their consequences.

These findings are crucial for river management, regulation, and navigational safety, and they have significant implications for estimating geomorphic changes in response to upstream damming, potentially informing better river management and ecological assessment in other similar alluvial rivers.

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