Biodiversity responses of implementing environmental flows in regulated rivers: A systematic review protocol

Project group

External scientific project members:

Roland Jansson (Chair), Professor, Department of Ecology and Environmental Science, Umeå University, roland.jansson@umu.se

Peter Carlson, Researcher, Department of Aquatic Sciences and Assessment, Division of Ecology and Biodiversity, Swedish University of Agricultural Sciences, peter.carlson@slu.se

Saija Koljonen, Senior Research Scientist, Finnish Environment Institute, saija.koljonen@syke.fi

Birgitta Malm Renöfält, Staff scientist, Department of Ecology and Environmental Science, Umeå University, birgitta.malm-renofalt@umu.se

Formas project members:

Josefin Thorslund (Project Manager), josefin.thorslund@formas.se

Arvid Bring (Deputy Project Manager)

Tom Liffen (Analyst)

Sten Anttila (Analyst)

Matilda Svensson (Information Specialist)

Summary

Freshwater ecosystems, though rich in biodiversity, are heavily degraded by human activities, particularly through dams and flow regulation, which disrupts natural flow regimes. A restoration measure designed to support biodiversity in freshwater ecosystems affected by human activities, particularly by dams, is environmental flows (or e-flows). Environmental flows are designed to mimic natural water flow patterns to some degree, thereby supporting ecosystem health. While individual studies have documented the impacts of environmental flows on biodiversity, comprehensive knowledge of their overall effectiveness in improving native biodiversity remains limited. This review seeks to synthesize evidence on how environmental flows affect biodiversity in rivers regulated by dams, to guide better river restoration decisions and implementations.

To conduct the review, we will systematically search for literature, using bibliographic databases, search engines and specialist websites (if deemed relevant). The references will be screened for relevance according to a predefined set of eligibility criteria. The criteria will be tested and clarified iteratively, until consistency in interpretations is achieved. Thereafter, the literature will be screened in two stages, first based on title and abstract and then by screening full-texts. Full-text screening will be performed with blinded decisions by two independent reviewers. Each relevant study will go through quality assessment, based on a set of predefined criteria. A narrative synthesis will be provided, and quantitative syntheses based on meta-analyses will be performed, if sufficient data is available. Identified relevant knowledge gaps will be highlighted and discussed.

Background

Freshwater ecosystems harbour high biodiversity in relation to the area they occupy but are among the ecosystem types most degraded by human use (Haase et al., 2023). A key driver of ecological integrity in rivers is the flow regime, which shapes the species composition, community structure, and ecological processes of riverine habitats (Poff et al., 1997; Palmer and Ruhi 2019). Deviations from natural flow regimes caused by human interventions have been consistently linked to declines in biodiversity (Jansson et al., 2000; Haxton & Findlay, 2008; Poff et al., 2010). Worldwide, river systems are increasingly regulated, primarily by the construction of dams, which disrupt the natural hydrological and sediment dynamics (Nilsson et al., 2005; Grill et al., 2019). The ecological consequences of damming are profound, including habitat fragmentation, altered flow patterns, and reductions in species richness. Many freshwater species are now at risk of extinction due to these changes (Dudgeon et al., 2006; Reid et al., 2019).

To mitigate negative impacts of hydropower dams on ecosystems, several environmental restoration or rehabilitation measures of hydropower dams are now being implemented. Restoration measures range from complete dam removal, which allows the river to return closer to its natural state, to targeted interventions such as the construction of fish passage systems. These include fish ladders and bypass channels, which allow migratory species to bypass dams and reach e.g., their spawning grounds (Silva et al., 2018; Shry et al. 2024). Another approach is sediment management, which seeks to restore natural sediment transport by flushing accumulated sediments downstream to improve habitat conditions (Kondolf et al., 2014).

Although dam removal is often considered one of the most effective restoration measures for biodiversity recovery, it is not always feasible or desirable, especially when considering the socio-economic importance of hydropower. To reduce the negative effects on biodiversity and still retain the services provided by dams, implementation of environmental flows (or e-flows) has become a primary mitigation strategy (Tharme 2003; Owusu et al., 2020). Environmental flows aim to restore critical components of the natural flow regime, mimicking key hydrological characteristics such as seasonal flow variation and peak-flow events that support the health and resilience of aquatic and riparian communities (Richter, 2010; Gebreegziabher et al., 2023).

Previous research has highlighted the importance of flow-ecology relationships, demonstrating that changes in flow regimes can significantly alter ecosystem structure and function (Davies et al., 2014; Palmer & Ruhi, 2019). Individual studies have also provided evidence for the benefits of implementing environmental flows in restoring biodiversity (Richter et al., 2006; Poff & Zimmerman, 2010; Cheng et al., 2023). However, despite these insights, a comprehensive understanding of the overall impact and effectiveness of environmental flows on biodiversity—particularly in terms of effect sizes and variability across contexts—is still lacking.

Objectives

The purpose of this systematic review is to support river restoration decisions by synthesizing and critically evaluating the available evidence on how biodiversity responds to the implementation of environmental flows in watercourses regulated by dams. By identifying trends, gaps, and variations in these responses—based on factors such as taxonomic groups, geographic regions, and specific flow modifications—this study aims to provide insights for improving the design and implementation of environmental flow strategies. Such decisions can be related to the efficacy of environmental flows in producing beneficial effects on biodiversity in areas affected by the dam, both in upstream and downstream areas. Ultimately, the findings of this review will contribute to advancing efforts restore and mitigate freshwater ecosystems affected by dams.

Review question

The primary question that this systematic review aims to address is:

- *How does biodiversity respond to implementation of environmental flows in regulated rivers?*

We also aim to address the following secondary questions, if possible with regards to data availability:

- *Do responses differ depending on taxonomic group?*
- *Which type of environmental flow practices have the strongest impacts on biodiversity?*

Definitions of the review question components

The PICO (Population/Intervention/Comparator/Outcome) framework for systematic reviews is used to make an evidence-based evaluation of interventions/actions that modify aspects of river flow, with the aim of improving aspects of the biodiversity of native species. Environmental flows can be achieved in multiple ways, but two major strategies can be discerned: (1) Limiting alterations from the natural flow baseline to maintain biodiversity and ecological integrity, or (2) designing flows to achieve some specific ecological and ecosystem service outcome (Acreman et al. 2014). Both these aspects are considered here, if the aim is to enhance the conditions for native species (thus excluding introduced and invasive ones) that have been negatively affected by dam operations. The components of the PICO framework are:

Population: rivers or river basins regulated by one or multiple dams of all sizes, modifying some aspect of the flow regime.

Intervention: environmental flow implementation(s), i.e. modification of flows below the dam(s) with the intention to improve ecological conditions (brining it closer to some unimpacted state)..

Comparator: the same area before the flow intervention, or a separate but similar site with no environmental flow implementation.

Outcome: biodiversity responses, assessed using a variety of biodiversity metrics (e.g. species composition, native species richness, abundance, density). The question components are defined in more detail under the “Study selection criteria” section below.

Study selection criteria

Papers will be considered relevant to our review if they present empirical data on biodiversity responses to changes in flow regime. This means that reviews and pure modelling studies will not be included, unless they include primary data used for calibration. The changes in flow must be associated with the dam operation, with the intention to improve ecological conditions, known as environmental flows.

For a study to be eligible and included, the following criteria must be met:

Relevant population(s)

River/river basin with dam(s) of all sizes, with dams built at lake outlets or in streams. In a first step, we include all sites globally and we do not put any restrictions on the size of basins or climate of the study sites. However, we will not include studies that consider dams with no capacity at all to regulate flows (e.g., weirs, road culverts), constructed experimental facilities unless they are connected to the stream network, natural dams (e.g., beaver dams), or dams that are built to mimic natural dams (e.g., beaver dam analogues).

Relevant intervention(s)

Eligible interventions must encompass flow adaptations/modifications, with the intention to improve ecological conditions, known as environmental flows. The changes in flow must be associated with the dam operation, but not include dam construction, dam closure or complete removal of dams (since this has been covered in other systematic reviews). We consider a range of environmental flows, including changes related to magnitude, frequency, duration, timing (seasonality), rate of change of flow, or surrogate thereof (e.g., water velocity or depth), so that it becomes closer to the natural conditions of the river. This could relate to changes to minimum flows (variable or not), limited zero-flow events, seasonal flow variations, diversions of flow into passages, attraction flows, or hydropeaking mitigation. We also consider studies that address a combination of restoration interventions, if environmental flows are one of these. Natural experiments are included if they are formulated and evaluated as environmental flow interventions. E-flows designed to reduce non-native species (or native species if the population needs to be decreased) are also included, if the species has increased due to human interventions.

Changes to flows that are not associated with a dam or dam operations, or studies that evaluate the impact of existing flow regimes without any mention of these variations being intended to improve ecological conditions, are not included. Also, we do not consider studies looking at impacts of flow regulation, such as hydropeaking with no attempt at mitigation.

Relevant comparator(s)

For a study to have an eligible comparator, it must consider the same area before the flow intervention (BA study design), or a separate but similar site with no intervention (i.e. no

attempt to implement environmental flows, or less intervention, but similar in other factors determining presence or absence of organisms; CI study design), or a combination of both (BACI study design). Studies that compare the influence of environmental flows with an unaffected system (i.e. no dam) will be excluded.

There is no limit in the length of time that studies may investigate changing flows and their impact on ecological conditions. Studies that investigate short periods of time, or single events, are included. Studies that measure a single point in time with no comparison to another site are excluded.

Relevant outcome(s)

Eligible outcomes must include biological responses, or changes to physical conditions with clear links to biological responses (such as measured changes in habitat conditions that can be linked to responses in biota). This for instance includes changes in species composition, native species richness, abundance, biodiversity indices, functional diversity of species, density of key species (e.g., salmon, trout, eel), biomass and yield. Studies that measure changes in invasive species may also be included, if the intervention aimed at reducing such species. We also do not consider changes to genetic variability, unless the study also addresses changes in the abundance or population status of species.

Study design

In addition to the PICO components, we also consider the following study design criteria. Eligible study designs include Control-Impact (CI) studies, Before-After (BA) studies or Before-After Control-Impact (BACI) studies. We only include empirical studies, except for modelling studies that include empirical data (e.g., for calibration) fulfilling the criteria. Review and methodological studies are not considered. Studies written in Swedish, English, Finnish, Norwegian, Danish, German and French are included.

Potential effect modifiers and reasons for heterogeneity

There are multiple sources of heterogeneity that could impact recorded effects (so called effect modifiers). It is therefore important to record and test the impact of various effect modifiers across study sites, in addition to the intervention, to be able to investigate potential reasons for heterogeneity in the results. For all articles included from the full-text assessment, we will record information on factors of potential heterogeneity, if the information is available. We will also consider using external data sources (e.g. GIS-datasets) to systematically extract relevant information at the catchment scale, using study information/coordinates. Some examples of variables that we will consider are:

- **Land use change:** Past and current land use practices, such as agriculture, deforestation, or urbanization, as well as previous alterations to the river can modify the effects of the flow restoration measure, through altering the river's hydrology, sediment flow, and nutrient inputs. If the dam or the river's physical structure has been significantly altered (through erosion, sedimentation, or artificial structures), e-flows may also have less effect since the natural river environment no longer supports the ecosystem’s original functions.

- **Climate change or extreme weather events**: Changes in precipitation patterns and temperature due to variations in climate across regions or due to climate change or extreme weather events during e-flow implementation can affect water availability. For instance, in hotter, drier regions, higher evaporation rates may reduce the effectiveness of e-flows, especially if the water is intended to reach downstream ecosystems. In colder or temperate regions, e-flows might more easily meet ecological needs with lower water losses due to evaporation.

- **Type of biome or ecoregion**: Species in different biomes are adapted to varying water availability and flow conditions of that ecosystem. Local characteristics (including water quality and sediment dynamics) of the studied catchment can thus influence the net-effect of a similar e-flow implementation in different regions with varying biomes.

Stakeholder engagement and relevance for Swedish conditions

In Sweden, a comprehensive effort is currently underway to adapt hydropower dams by imposing modern environmental conditions, according to a national plan. This is because many smaller dams were built a long time ago and have not been tested against today's environmental legislation (including the EU's Water Framework Directive 2000/60/EG). For many hydropower plants, it may be necessary to modify the dams in various ways to improve conditions for the aquatic environment, or to completely remove some smaller installations. In connection with these investigations, it is important to have knowledge about the potential effects of different measures on biodiversity.

During the design of the project, consultations (including workshops and dialogues) have been held with several stakeholders, primarily government agencies with a mandate that involves biodiversity or permits for dam operation, including the Swedish Agency for Marine and Water Management, the Water District Authorities, and regional County Administrative Boards who oversee dam restoration projects. Additional consultation has been held with representatives from dam owners and hydropower companies. Stakeholders have also been invited to comment on the protocol before publication and will be invited to comment on the results of the review before publication.

The results of the systematic review and the recommendations arising from them are expected to be useful for the Swedish Agency for Marine and Water Management and the County Administrative Boards in assessing the possible biological effects of environmental flows. Results are also expected to be significant to the owners of the affected power plants/dams, as they decide on possible restoration measures related to permit applications for modifications of dams or dam operations. Furthermore, the issue is expected to be of interest to citizens and local communities, including local associations, as well as recreational fishers and environmental organizations.

Methods

Literature search

Searches for relevant literature will mainly be made using bibliographic databases and web-based search engines. The selected search platforms will also encompass grey literature, in the form of for instance dissertations and various reports (governmental or consultant). Searches at organizational websites will however not be included as a main search strategy, but used to complement the original search, if deemed necessary. Relevant organizational websites will then be identified by the external scientific project group members (hereafter referred to as the expert group).

Bibliographic databases include the Web of Science Core Collections, Scopus, CAB Abstracts and ProQuest Natural Science Collection. All databases are accessed through Formas Institutional subscription. The searches will be conducted in the fields “title”, “abstracts” and “keywords” for the bibliographic databases, using English search terms. There will be no restrictions regarding language, publication dates or publication types. The searches in the search engines will be done using the “advanced search” option. No filters will be used, except in the BASE and DiVA portal, where only theses and reports will be searched for.

The format of the search strings will be adapted to match the specific syntax of each database, search engine and website. The search strings we will use in the search engines and websites will be simplified compared to the one used in the bibliographic databases. In the bibliographic databases, three substrings will be used and combined with the Boolean operator AND. Within the substrings the Boolean operator OR is used.

For web-based search engines, we will do a Google Scholar Search in Publish or Perish. The first 500 search results for each search string will be screened for relevance. SwePub, DivA Portal and BASE will also be used to locate various academic documents on the web. SwePub contains references to articles, conference papers and dissertations published at Swedish universities and authorities. DiVA contains references to articles, conference papers and dissertations published at Swedish universities and authorities. BASE is a search engine especially for academic web resources. An updated search will be considered depending on the relevance in time (e.g. searching for additional literature over the last year, if possible). Information about each search strings, as well as fields and filters, can be found in Additional file 1, as well as in searchRxiv (Jansson et al., 2024).

Comprehensiveness of the search

A list of 11 benchmark studies (Additional file 1) was used during the development of the search strings and to test the comprehensiveness of the search. If any of the titles had been missed, the search strings were adapted to include the missed studies. The process was iterative and new search terms were added after consulting with experts.

Screening strategy

The reference management software EndNote 20 will be used to collect all search results and to remove duplicates. Duplicates will be removed using the de-duplication method (Bramer et

al., 2017). We will also use DedupEndNote (version 1.0.1 20240114) and Rayyan (Ouzzani et al., 2016) to track duplicates from the search results.

Publications will be screened for their relevance and eligibility at two stages: 1) title and abstract, and 2) full-text. Abstract screening will be done in Rayyan. Consistency checking of abstract screening has been performed in several iterations. First, a subset of articles (n = 300) was double-screened by members of the review team in pairs to refine the PICO criteria. In a second step, a new set of articles (n = 300) was double-screened to ensure that the criteria were consistently applied among all reviewers. In this round, agreement was very high (conflicts for 15 articles out of 300, or 5%). This level of conflict was deemed acceptable and is in line with requirements in most other systematic reviews in the environmental field (above c. 80%).

At the abstract screening stage, articles will be classified into three categories: (1) include, (2) exclude, and (3) probably exclude. Articles in category (3) will then be separately discussed, or screened by another author, to minimize the risk of erroneously excluding any articles. Due to the expected large volume of abstracts, articles excluded at the title and abstract stage will not be coded with a reason for exclusion.

For full-text screening, we will use the Covidence software (Covidence.org). The publications that have passed the first screening step will be divided amongst the reviewer team. All articles that have passed from the first stage will be screened in full text independently by two authors, and any disagreements will be resolved through discussion. If the pair of reviewers cannot agree, disagreements will be resolved through discussion with additional review team members or the full project group. If reviewers are uncertain about whether to include a publication, it will be included, at every stage of screening. Articles excluded at the full-text screening stage will be provided in an appendix, with recorded reasons for exclusion.

Meta-data extraction

Metadata will be extracted to an Excel spreadsheet that is common to all reviewers. Where applicable, the coding will be locked to fixed alternatives to improve clarity in the extraction process. For other columns, coding instructions will guide how to extract and enter values. Before commencement of data extraction, a pilot extraction will be performed on several of the included studies. Methods and results from the pilot extraction will be discussed with the entire review team. The articles included for data extraction will then be allocated between several reviewers. At least 10 % of the articles allocated to each reviewer will be double checked by another reviewer, to ensure consistency.

We will record data related to bibliographic data, study design, study population, intervention details, comparison information, outcomes and potential effect modifiers. Relevant bibliographic data such as title of article, author, publication year will also be included in the spreadsheet. Furthermore, information about where and when the study was conducted will be recorded. Study coordinates will be entered directly as reported. When no coordinates are presented, included maps will be used to identify locations. If both coordinates and maps are missing, place/river names and descriptions will be used to determine an approximate location. If repeated measurements have been carried out, the data for all reported time points will be recorded, if they are possible to separate. Continuous time series will be extracted if possible, but may be averaged to relevant time steps. In cases where outcome data are reported only in

graphics, we will use WebPlotDigitizer (or AI-tools, see below) to extract data. All outcome data used in the meta-analysis will be available in an Additional file.

Usage of AI-tools for meta-data extraction

Artificial intelligence (AI) tools can enhance the efficiency and consistency of metadata extraction and analysis in systematic reviews (refs). Elicit is an example of a research automation tool that utilizes AI to speed up literature review and data synthesis (ref). For this project, we will do a pilot meta-data extraction, using this tool, to assist in the extraction of metadata from included studies. Elicit uses generative AI and large language models (LLMs) to identify and extract relevant information from uploaded article pdfs. Elicit allows the user to specify meta-data fields, give specific instructions on which data to search for and specify which outputs format to report in. A significant advantage of this tool is the possibility to easily verify the extracted information (links to the text in the pdf where the extracted data is based on), as well as the possibility to extract meta-data from tabulated text and from graphics.

We will define key metadata fields in advance and Elicit will help to populate these fields by summarizing and categorizing the relevant information. The data will then be exported as a csv file and checked against manually extracted meta-data, to ensure consistency and test accuracy of the tool.

Study validity assessment

Each study will be assessed on the risk of bias. The purpose of the study validity assessment is to reduce the risk that the conclusions of the review are misleading. We aim to assess each study's internal and external validity from a set of criteria (such as selection bias and performance bias), to be developed according to the needs of the project. The responses for each study will be recorded in a data sheet and presented with justifications.

To ensure consistency in judgements, all team members will first do an assessment of a subset of 5 % of the included articles (or at least 20 studies), and decisions will be discussed among all authors. For each study, the study validity assessment will then be carried out by team members individually, with decisions double checked by another reviewer. If the expert is the author or co-author of a given article, the assessment of that study will be allocated to another member of the team. In the event of disagreement, this is discussed among the review pair. If there is still disagreement, additional experts are involved until consensus is reached. The results of the critical appraisal are included as a figure or table in the systematic review.

Synthesis methods

Results from the meta-data extraction that are relevant for answering our review question will be presented in a narrative synthesis. Where appropriate, data will also be compiled in quantitative meta-analyses. Quantitative meta-analyses (including weightings where possible) will be carried out on data from studies performed in an equivalent way, whereas the narrative syntheses will be used in cases where mergers cannot be carried out, for example where the outcome variable differs significantly between the studies.

Descriptive statistics of key variables, including those that may cause heterogeneity in study findings, will also be presented. Provided enough data, we will consider the potential effect modifiers and critical appraisal criteria as covariates in a meta-regression analysis.

We will also perform sensitivity analyses, in cases where experts deem this necessary. For example, meta-analyses may be performed with and without results from studies with a high risk of bias, to see if the overall result is affected. If possible, summary effects will be complemented by effects evaluated for separate groups, such as species groups, dam types and/or sizes, or different dam and/or river environments.

Knowledge gaps are defined based on the specific information needs of Swedish stakeholders. A knowledge gap may be due to a lack of results of relevance to stakeholders or that existing results are methodologically too substandard to be of value to stakeholders.

Conclusions and evidence grading

Conclusions will be based on results from the meta-analyses and narrative syntheses. These conclusions will be evidence-graded, i.e. we will describe how much confidence we have in the conclusions based on shortcomings in the reliability of the studies, transferability to the Swedish context and consistency between studies. The stronger the evidence, the less likely it is that reported results will be affected by new research findings in the foreseeable future. The evidence grading will have the following levels:

- **Strong scientific evidence**
  Based on studies with high or medium reliability without, or with minor debilitating factors in an overall assessment.
- **Moderately strong scientific evidence**
  Based on studies with high or medium reliability with moderately debilitating factors in an overall assessment.
- **Limited scientific evidence**
  Based on studies with high or medium reliability with severely debilitating factors in an overall assessment.
- **Insufficient scientific evidence**
  When studies are lacking, available studies have low reliability or where studies of similar reliability show contradictory results, the scientific evidence is indicated as insufficient.

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Additional File 1.

Information about the search strings used for the included databases and search engines

Database: Web of Science Core Collection (1970-)

No	**Search string**
1	TS=((dam OR dams OR hydroelectric OR hydropower OR impound* OR reservoir OR river* OR stream* OR "water basin" OR watercourse OR watershed) AND (implement* OR management OR recover OR regulat* OR restor*))
2	TS=("altered flow" OR "altered flows" OR "base flow" OR "base flows" OR baseflow* OR "dynamic flow" OR "dynamic flows" OR "eflow" OR "eflows" OR "e-flow" OR "e-flows" OR "ecological flow" OR "ecological flows" OR "environmental flow" OR "environmental flows" OR "flood flow" OR "flood flows" OR "flow adjustment" OR "flow adjustments" OR "flow alteration" OR "flow alterations" OR "flow variability" OR "flow variation*" OR "functional flow" OR "functional flows" OR "hydrological flow" OR "hydrological flows" OR "instream flow" OR "instream flows" OR "mini flow" OR "mini flows" OR "minimum flow" OR "minimum flows" OR "natural flow" OR "natural flows" OR "seasonal flow" OR "seasonal flows" OR streamflow* OR "stream flow" OR "stream flows")
3	TS=(abundance* OR "aquatic plant" OR "aquatic plants" OR "aquatic vegetation" OR assemblage* OR alga* OR beetle* OR biodiversity OR "biological diversity" OR "biological variability" OR "eel" OR "eels" OR "endangered species" OR evenness OR extinct* OR fauna OR "fish" OR "fishes" OR "floodplain vegetation" OR "functional diversity" OR geomorphology OR "habitat" OR "habitats" OR heterogenity OR hydromorphology OR invertebrate* OR macroinvertebrate* OR macrophyte* OR mesohabitat* OR microhabitat* OR microinvertebrate* OR "rare species" OR rarity OR richness OR riparian OR salmon* OR sediment* OR "species diversity" OR "species interaction" OR "species interactions" OR threatened OR trout)
	Combination of search strings
4	1 AND 2 AND 3
* = Represents any group of characters, including no character " " = Searches for an exact phrase TS = Topic Search (search the Title, Abstract, Author Keywords and Keywords Plus within every record)	

Database: Scopus

No	**Search string**
1	TITLE-ABS-KEY((dam OR dams OR hydroelectric OR hydropower OR impound* OR reservoir OR river* OR stream* OR {water basin} OR watercourse OR watershed) AND (implement* OR management OR recover OR regulat* OR restor*))
2	TITLE-ABS-KEY({altered flow} OR {altered flows} OR {base flow} OR {base flows} OR baseflow* OR {dynamic flow} OR {dynamic flows} OR {eflow} OR {eflows} OR {e-flow} OR {e-flows} OR {ecological flow} OR {ecological flows} OR {environmental flow} OR {environmental flows} OR {flood flow} OR {flood flows} OR {flow adjustment} OR {flow adjustments} OR {flow alteration} OR {flow alterations} OR {flow variability} OR {flow variation*} OR {functional flow} OR {functional flows} OR {hydrological flow} OR {hydrological flows} OR {instream flow} OR {instream flows} OR {mini flow} OR {mini flows} OR {minimum flow} OR {minimum flows} OR {natural flow} OR {natural flows} OR {seasonal flow} OR {seasonal flows} OR streamflow* OR {stream flow} OR {stream flows})
3	TITLE-ABS-KEY(abundance* OR {aquatic plant} OR {aquatic plants} OR {aquatic vegetation} OR assemblage* OR alga* OR beetle* OR biodiversity OR {biological diversity} OR {biological variability} OR {eel} OR {eels} OR {endangered species} OR evenness OR extinct* OR fauna OR {fish} OR {fishes} OR {floodplain vegetation} OR {functional diversity} OR geomorphology OR {habitat} OR {habitats} OR heterogenity OR hydromorphology OR invertebrate* OR macroinvertebrate* OR macrophyte* OR mesohabitat* OR microhabitat* OR microinvertebrate* OR {rare species} OR rarity OR richness OR riparian OR salmon* OR sediment* OR {species diversity} OR {species interaction} OR {species interactions} OR threatened OR trout)
	Combination of search strings
4	1 AND 2 AND 3
* = Represents any group of characters, including no character { } = Searches for an exact phrase TITLE-ABS-KEY = Title or Abstract or Keywords	

Database: ProQuest Natural Science Collection

No	**Search string**
1	ti,ab,if((dam OR dams OR hydroelectric OR hydropower OR impound* OR reservoir OR river* OR stream* OR "water basin" OR watercourse OR watershed) AND (implement* OR management OR recover OR regulat* OR restor*))
2	ti,ab,if("altered flow" OR "altered flows" OR "base flow" OR "base flows" OR baseflow* OR "dynamic flow" OR "dynamic flows" OR "eflow" OR "eflows" OR "e-flow" OR "e-flows" OR "ecological flow" OR "ecological flows" OR "environmental flow" OR "environmental flows" OR "flood flow" OR "flood flows" OR "flow adjustment" OR "flow adjustments" OR "flow alteration" OR "flow alterations" OR "flow variability" OR "flow variation*" OR "functional flow" OR "functional flows" OR "hydrological flow" OR "hydrological flows" OR "instream flow" OR "instream flows" OR "mini flow" OR "mini flows" OR "minimum flow" OR "minimum flows" OR "natural flow" OR "natural flows" OR "seasonal flow" OR "seasonal flows" OR streamflow* OR "stream flow" OR "stream flows")
3	ti,ab,if(abundance* OR "aquatic plant" OR "aquatic plants" OR "aquatic vegetation" OR assemblage* OR alga* OR beetle* OR biodiversity OR "biological diversity" OR "biological variability" OR "eel" OR "eels" OR "endangered species" OR evenness OR extinct* OR fauna OR "fish" OR "fishes" OR "floodplain vegetation" OR "functional diversity" OR geomorphology OR "habitat" OR "habitats" OR heterogenity OR hydromorphology OR invertebrate* OR macroinvertebrate* OR macrophyte* OR mesohabitat* OR microhabitat* OR microinvertebrate* OR "rare species" OR rarity OR richness OR riparian OR salmon* OR sediment* OR "species diversity" OR "species interaction" OR "species interactions" OR threatened OR trout)
	Limitis: Dissertations & Theses, Reports
	Combination of search strings
4	1 AND 2 AND 3
* = Represents any group of characters, including no character " " = Searches for an exact phrase ti,ab,if = Title or Abstract or Keywords/identifiers	

Database: CAB Abstracts (1973-)

No	**Search string**
1	((dam OR dams OR hydroelectric OR hydropower OR impound* OR reservoir OR river* OR stream* OR "water basin" OR watercourse OR watershed) AND (implement* OR management OR recover OR regulat* OR restor*)).ti,ab,hw.
2	("altered flow" OR "altered flows" OR "base flow" OR "base flows" OR baseflow* OR "dynamic flow" OR "dynamic flows" OR "eflow" OR "eflows" OR "e-flow" OR "e-flows" OR "ecological flow" OR "ecological flows" OR "environmental flow" OR "environmental flows" OR "flood flow" OR "flood flows" OR "flow adjustment" OR "flow adjustments" OR "flow alteration" OR "flow alterations" OR "flow variability" OR "flow variation*" OR "functional flow" OR "functional flows" OR "hydrological flow" OR "hydrological flows" OR "instream flow" OR "instream flows" OR "mini flow" OR "mini flows" OR "minimum flow" OR "minimum flows" OR "natural flow" OR "natural flows" OR "seasonal flow" OR "seasonal flows" OR streamflow* OR "stream flow" OR "stream flows").ti,ab,hw.
3	(abundance* OR "aquatic plant" OR "aquatic plants" OR "aquatic vegetation" OR assemblage* OR alga* OR beetle* OR biodiversity OR "biological diversity" OR "biological variability" OR "eel" OR "eels" OR "endangered species" OR evenness OR extinct* OR fauna OR "fish" OR "fishes" OR "floodplain vegetation" OR "functional diversity" OR geomorphology OR "habitat" OR "habitats" OR heterogenity OR hydromorphology OR invertebrate* OR macroinvertebrate* OR macrophyte* OR mesohabitat* OR microhabitat* OR microinvertebrate* OR "rare species" OR rarity OR richness OR riparian OR salmon* OR sediment* OR "species diversity" OR "species interaction" OR "species interactions" OR threatened OR trout).ti,ab,hw.
	Combination of search strings
4	1 AND 2 AND 3
* = Represents any group of characters, including no character .ti,ab,hw. = Title or Abstract or Heading words	

Search engine: Google Scholar

The first 500 results for every search will be exported from Google Scholar using Publish or Perish version 6 software: Harzing, A.W. (2007) Publish or Perish, available from https://harzing.com/resources/publish-or-perish

Language	Search string
English	Any of the words: "environmental flow" "ecological flow" "e-flow" ”minimum flow*”
	All of the words: Biodiversity dam*
	Any of the words: "environmental flow" "ecological flow" "e-flow" ”minimum flow*”
	All of the words: Biodiversity hydropower*
	Any of the words: "environmental flow" "ecological flow" "e-flow" ”minimum flow*”
	All of the words: Biodiversity hydroelectric*
	-
	Any of the words: "environmental flow" "ecological flow" "e-flow" ”minimum flow*”
	All of the words: Dam management*

Database: SwePub

Search string
Biodiversity AND ("environmental flow" OR "ecological flow" OR "e-flow")
Hydropower* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Hydroelectric* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Management* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Dam* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Limits: None

Database: DiVA

Search string
Biodiversity AND ("environmental flow" OR "ecological flow" OR "e-flow")
Hydropower* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Hydroelectric* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Management* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Dam* AND ("environmental flow" OR "ecological flow" OR "e-flow")
Limits: Student thesis

Database: BASE

Search string
(Biodiversity AND dam*) AND ("environmental flow" OR "ecological flow" OR "e-flow")
(Biodiversity AND hydropower*) AND ("environmental flow" OR "ecological flow" OR "e-flow")
(Biodiversity AND hydroelectric*) AND ("environmental flow" OR "ecological flow" OR "e-flow")
(Dam AND management*) AND ("environmental flow" OR "ecological flow" OR "e-flow")
Limitis: Thesis, reports, english

Search fields and filters used for databases and Web-based search engines

Bibliographic databases	Search Fields	Publisher and URL	"Subdatabases"	Search Filters
Web of Science Core Collection	Topic (title, abstract and author keywords)	Clarivate Analytics, https://clarivate.com/products/web-of-science/	Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index- Science (CPCI-S), Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH) and Emerging Sources Citation Index (ESCI)	x
Scopus	Title, abstract and keywords (keywords = Author keywords + vocabulary terms from EMBASE, MedLine and Compendex	Elsevier, https://www.scopus.com/	x	x

ProQuest Natural Science Collection	ti,ab,if (title, abstract and and Keywords/identifiers)	ProQuest, https://www.proquest.com/	Aquatic Sciences and Fisheries Abstracts (AFSA)	Document type: Thesis and reports
CAB Abstracts	ti,ab,hw.(title, abstract, heading words (heading words = Subject Heading, Organism Descriptor, Broad Term, Geographic Location, Identifiers)	Ovid, https://ovidsp.ovid.com/	x	x

Web-based search engines	**Search Fields**	**Publisher and URL**	**"Subdatabases"**	**Search Filters**
Google Scholar	Advanced Search, Free text	Google: https://scholar.google.com/		x
Diva Portal	Advanced Search, Free text	Uppsala University, https://www.diva-portal.org/		Document type: Student thesis
SwePub	Advanced Search, Free text	National Library of Sweden, https://swepub.kb.se/		x
BASE	Advanced Search, Free text	Bielefeld University, https://base-search.net/		Document type: Thesis, reports

Information on the 11 benchmark studies that was used during the development of the search strings and to test the comprehensiveness of the search

Title	Link	Retrieved
Long-term Trends in Abundance and Size of Sport Fishes in the Flathead River, Montana, Following Changes in Hydroelectric Dam Operations	https://doi.org/10.3955/046.092.0203	Yes
Hydro-power production and fish habitat suitability: Assessing impact and effectiveness of ecological flows at regional scale	https://doi.org/10.1016/j.advwatres.2018.04.002	Yes
Flow restoration and the impacts of multiple stressors on fish communities in regulated rivers	https://doi.org/10.1111/1365-2664.13413	Yes
Restoring native fish assemblages to a regulated California stream using the natural flow regime concept	https://doi.org/10.1890/11-0480.1	Yes
Effects of environmental flows in a restored floodplain system on the community composition of fish, macroinvertebrates and macrophytes	https://doi.org/10.1016/j.ecoleng.2019.04.003	Yes
Streamside herbaceous vegetation response to hydrologic restoration on the San Pedro River, Arizona	https://doi.org/10.1002/eco.62	Yes
Large-scale environmental flow results in mixed outcomes with short-term benefits for a semi-arid floodplain plant community	https://doi.org/10.1111/fwb.13191	Yes
Effects of hydropeaking on benthic invertebrate community composition in two central Norwegian rivers	https://doi.org/10.1002/rra.3241	Yes
Effects of hydropeaking on drift, stranding and community composition of macroinvertebrates	http://dx.doi.org/10.22541/au.163898017.70213878/v1	Yes
Long-term Macrobentos Responses to Environmental Flows and Water Quality improvement along River Jarama	https://doi.org/10.1016/j.ecohyd.2022.12.009	Yes
Effects of re-braiding measures on hydromorphology, floodplain vegetation, ground beetles and benthic invertebrates in mountain rivers	https://doi.org/10.1111/j.1365-2664.2009.01611.x	No