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Re-operating dams for environmental flows: From recommendation to practice

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Abstract
Dam construction and operation are known to alter the hydrology of rivers and degrade riverine ecosystems. In recent decades, the call to reverse these negative impacts by re-operating dams has become stronger. Dams can support riverine ecosystems by releasing environmental flows (e-flows). Unfortunately, despite the development of numerous methodologies to determine e-flows and optimise dam releases, actual implementation has not followed suit. Integrating e-flow requirements in the design of new dams is relatively easier than changing operations of existing dams; however, re-operating existing dams is essential to restore ecosystems and ecosystem services that have already been affected by the construction and operation of dams. This study provides insights into how e-flows evolve from recommendation to practice through a systematic literature review on practical experiences to integrate e-flows in dam operations. Sixty-nine cases of successful dam re-operation have been identified, ranging from the well-documented case of the Glen Canyon Dam in the United States to less known cases such as the Katse Dam in Lesotho. We find that the most important factors that facilitate the successful implementation of e-flows are the existence of e-flows legislation or policy, the development of a research base in the form of an environmental impact study, and then flow experimentation. Illustrations of the important role of collaboration between various stakeholders and set timelines for implementation of recommendations are also given. These insights will inform how existing dams can be re-operated and governed more equitably and sustainably for both humans and the environment.

KEYWORDS
dam operation, e-flows implementation, environmental flows, flow restoration

1 | BACKGROUND

The origins of many ancient societies and modern-day cities can be traced to rivers and other freshwater bodies. These water bodies not only provided water for drinking and agriculture but served as vital transportation, trade and communication links (Konishi, 2000). River regulation, in the form of dams, locks and weirs supported many of these uses, becoming more and more sophisticated over the years as demand for water increased. Modification to natural river systems, however, comes with some unintended consequences (Petts, 1999; Poff et al., 1997; WCD, 2000). In particular, large dams are now recognised as one of the major stressors on freshwater ecosystems because they create large stagnant water bodies and disrupt the natural dynamic flow regime of rivers (Poff et al., 1997). This natural flow regime plays a key role in shaping riverine habitats and biotic communities, triggering life-history strategies of aquatic species, maintaining lateral and longitudinal connectivity, and controlling exotic species invasion in rivers (Bunn & Arthington, 2002).

The provision of flows for the environment, e-flows, is a means to mitigate the negative impacts of river regulation and protect or restore the benefits of naturally flowing rivers. The increasing importance of providing e-flows is reflected in the fact that in some countries and states, e-flows are enshrined in law. For instance, the 1998 Water Act of South Africa recognises aquatic ecosystems as having a right to water, and in Colorado in the United States, Senate Bill 73-97 instituted the 'In-stream Flow and Natural Lake Level' water rights in 1973 (King & Brown, 2006; Shupe, 1988). Despite adopting e-flows in their laws, implementing environmental flow releases in accordance with the law is challenging (Bischoff-Mattson & Lynch, 2016; King & Brown, 2006; Smith, Browning, & Osting, 2011).

Integrating e-flow requirements into the design of new dams is relatively easier than changing operations of existing dams; however re-operating existing dams is essential to restore ecosystems and ecosystem services that have already been affected by the construction and operation of dams (Mul et al., 2017; Richter & Thomas, 2007). Unfortunately, while the theories and concepts for e-flows estimation abound, actual implementation is minimal (Arthington et al., 2018; Horne et al., 2016; Tharme, 2003; Warner, Bach, & Hickey, 2014). In this respect, there are questions yet to be addressed on how e-flows are integrated into dam operation policy and practice; and on why some efforts at e-flow implementation have failed. The physical and institutional setting of each river basin and dam is unique; however, in cases where there have been re-operation or at least an attempt at re-operation, there are common themes that can be identified as keys to success or barriers to implementation (Patten, Harpman, Voita, & Randle, 2001; Richter, Warner, Meyer, & Lutz, 2006; Warner et al., 2014). This study provides insights into how e-flows evolve from recommendation to practice through a systematic literature review on practical experiences to integrate e-flows into dam operations.

2 | RESEARCH APPROACH—LITERATURE REVIEW

This review analyses the process of how e-flows are incorporated in reservoir operations. Thus the focus is on the inputs, activities, drivers and barriers to operational changes for the release of e-flows from dams (Thissen & Twaalfhoven, 2001). The study does not look at the impacts of dam releases on downstream ecology as this has been the focus of several papers already (see Gillespie, Desmet, Kay, Tillotson, & Brown, 2015; Olden et al., 2014; Thompson, King, Kingsford, Mac Nally, & Poff, 2018).

2.1 | Systematic journal database search

The methodology for the systematic literature review is adapted from the guidelines by the Centre for Evidence-Based Conservation (Collaboration for Environmental Evidence, 2013). The search string was made up of three parts: the target population: dams; the intervention type: re-operation; and then the topic: environmental flows. Variants of each were also included (see Table S1). The term river restoration was not included as it is too broad and encompasses physical and geomorphological interventions in rivers that do not necessarily involve e-flow releases from dams.

The publication databases used were selected based on accessibility and the relevance of the journals curated to the subject matter of this review. The databases selected are Scopus, ISI Web of Science, Google Scholar, JSTOR, Worldcat.org and SciELO.

2.2 | Article selection and exclusion criteria

Studies were initially selected based on the presence of one term in all three categories of the search terms in the title or abstract. The selected papers were then retained if they included at least a case study or documentation of (a) A process of change or continuous modification in the operation and/or operation rules of a dam to implement e-flows; (b) A process of development or modification of dam operation rules and/or policies to implement e-flows.

Exclusion criteria included studies which only test or model dam re-operation outcomes without actual implementation. The selected papers included cases documented before November 2018 when the database search was completed.

2.3 | Data synthesis and framework of analysis

To develop an understanding of the process of re-operation, a logic model of the process was developed from the data gathered from the cases of dam re-operation (Figure 1). The basic form of a logic model captures the inputs, activities, outputs, outcomes and impacts of a project. This study focused on the first three components where the last of these, '*output*' is defined for successful re-operation projects as a modification to the flow releases from the dam to meet e-flow requirements (Figure 1). Borrowing from the classification by Thissen and Twaalfhoven (2001), '*inputs*' refer to the products informing recommendations for e-flows while '*activities*' relate to the process and organisation of dam re-operation to fulfil the recommendations.

It is acknowledged that reviewing the outcomes and impacts of dam re-operation are important for understanding the entire life cycle of dam re-operation; however, the research objective of this study was to generate insights on how dam re-operation occurs, that is, the steps resulting in dam re-operation and not the results of dam re-operation.

2.3.1 | Article organisation

The selected papers were stored and tagged in the Mendeley reference-managing software (v. 1.19.3) and then classified according to the framework of analysis in Figure 1 (Owusu, Mul, van der Zaag, &

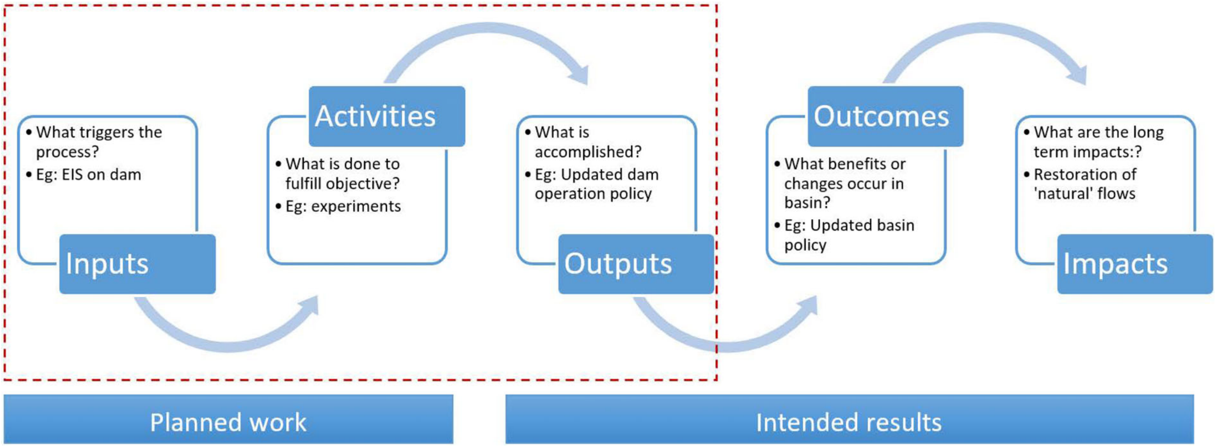
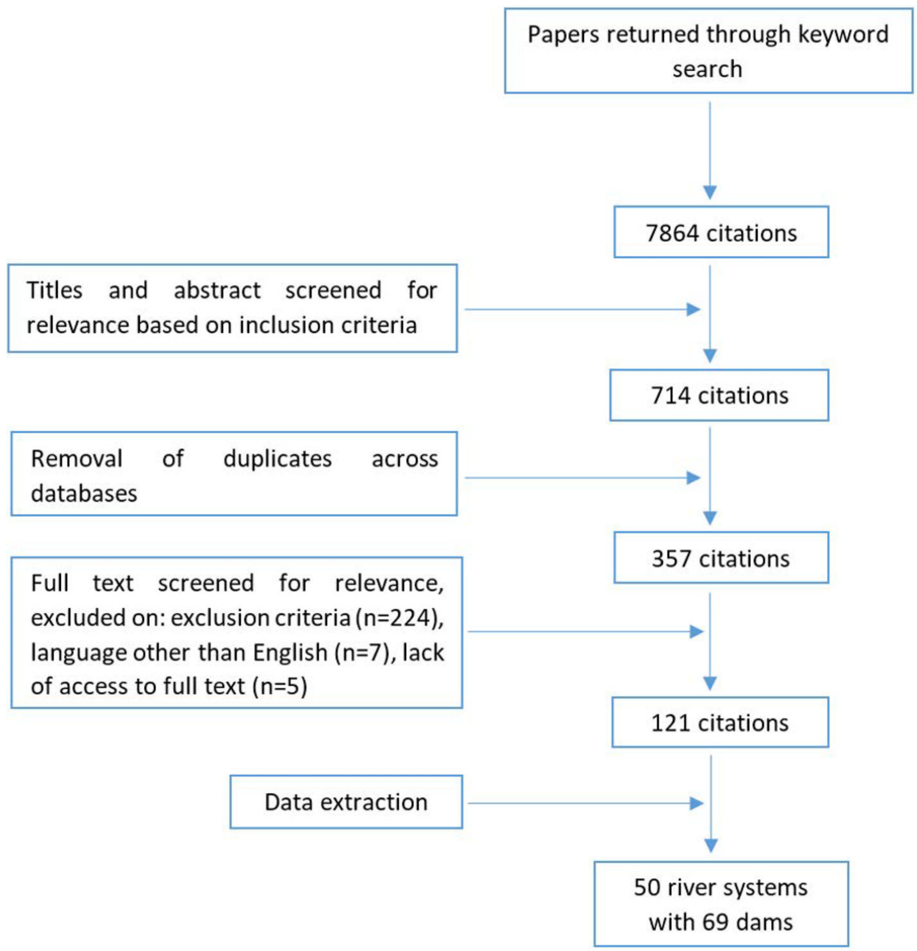


FIGURE 1 Framework of analysis for developing conceptual framework of dam re-operation with examples of events at each stage. The red box highlights the section of focus in this study

FIGURE 2 Results of database search on dams re-operated for e-flows implementation



Slinger, 2019). The final sets of parameters and tags, which can be found in Table S2, were informed by the descriptions used in the studies. Frequency statistics of the tags associated with the parameters were calculated to determine the characteristics of documented cases of dam re-operation.

2.3.2 | Kappa assessment of classification

Cross-checking of the systematic classification was carried out for consistency using Kappa analysis, which compares the amount of agreement with what would be expected by chance alone

(Collaboration for Environmental Evidence, 2013; Smeeton, 1985). In this method, 20% of the selected papers are reclassified by an external reviewer and a minimum agreement level of 50% must be achieved (Collaboration for Environmental Evidence, 2013) while an agreement level of 80% and above shows that the review results can be replicated independently (Filoso, Bezerra, Weiss, & Palmer, 2017). An agreement of 61% was achieved in this study.

3 | RESULTS

After the keyword search in the six databases, a total of 121 papers were retained for data extraction (Figure 2). These revealed 50 river systems with 69 dams, which have been re-operated for e-flows implementation (see Figure 3a for the location of these dams). Re-operation of the Glen Canyon Dam on the Colorado River was the most documented program with 54 papers reporting on the adaptive management program for this dam.

3.1 | Patterns in dam re-operation

3.1.1 | Location of re-operated dams

The locations where dams have been re-operated generally correspond to the locations where large-scale flow experiments have occurred, as found by Olden et al. (2014) (Figure 3a).

The documented cases of dam re-operation begin in 1983 with the Derby and Stampede dams on the Truckee River in the United States (Rood et al., 2003; Figure 3b). The most recent documented cases of dam re-operation occurred in 2014 with the Espinasses, La Saulce, Escale and the Cadarache dams on the Durance River in France as well as the Morelos dam upstream of the Colorado Delta in United States (Bêche, Loire, Barillier, Archambaud, & Morel, 2015; Kendy et al., 2017; Loire et al., 2018; Pitt & Kendy, 2017; Ramírez-Hernández, Rodríguez-Burgueño, Kendy, Salcedo-Peredia, & Lomeli, 2017; Shafroth et al., 2017).

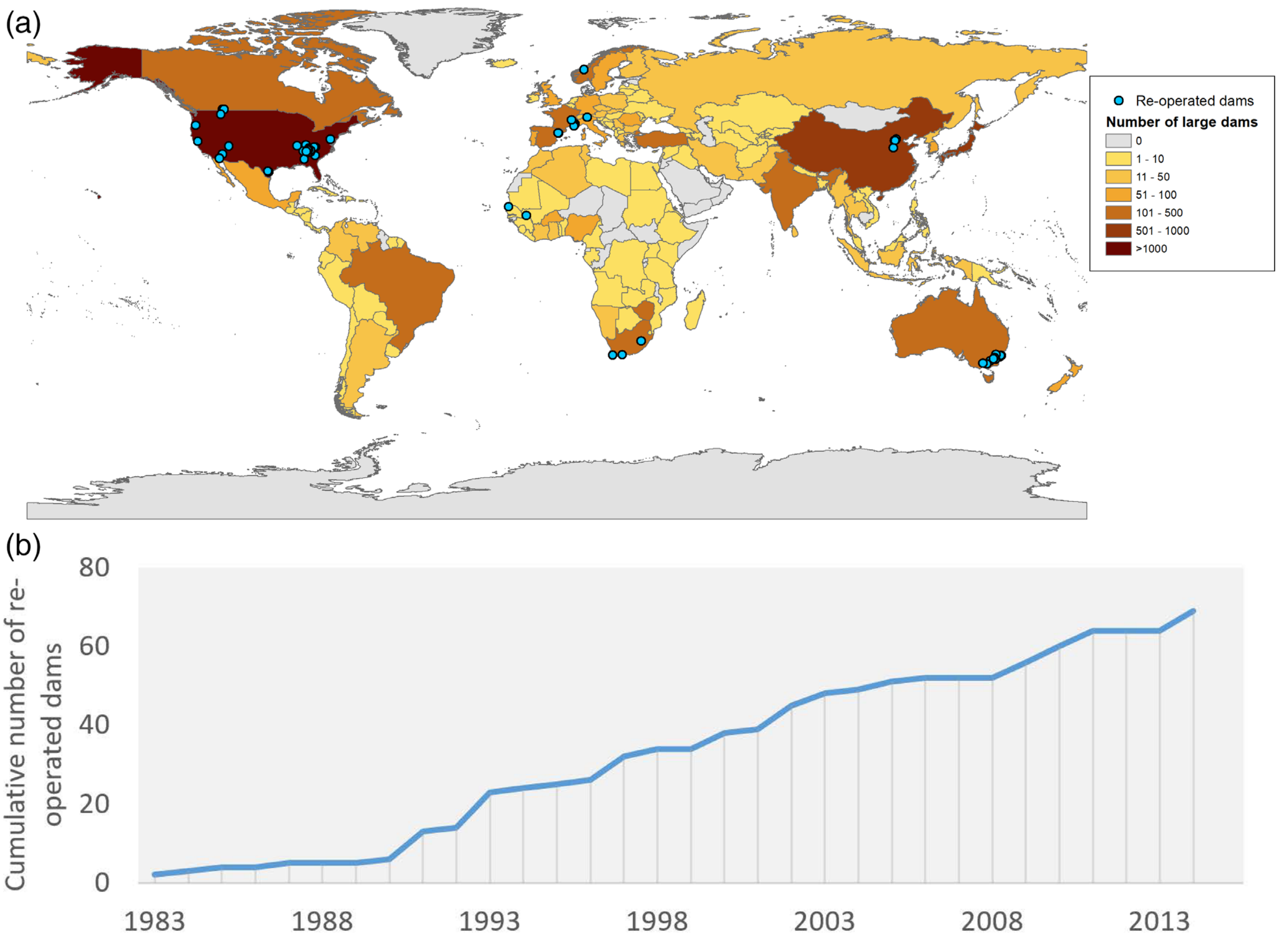


FIGURE 3 (a) Locations of re-operated dams mentioned in the papers (n = 69). Shading at the country level represents the number of large dams (≥0.1 km^3), as found in the Global Reservoir and Dam Database (GRanD, n = 6,862; Lehner et al., 2011). (b) Cumulative number of re-operated dams over time

3.1.2 | What are the inputs in dam re-operation?

Legislation is found to be the main trigger (input) in dam re-operation, followed by environmental impact studies (EIS) or e-flow studies (Figure 4). It is worthy to note that legislation can have different forms; Figure 5 shows the breakdown of the type of legislation that triggered dam re-operation. The majority of implemented cases have local or basin level legislation for e-flows objectives in place. It is hypothesized that this is because such policies for water management and dam operation are framed with local interests in mind and thus more easily implemented. In contrast, it is more difficult to reconcile large-scale decisions and directives, as found in international legislation such as the Water Framework Directive of Europe with local interests in dam operation (Acreman & Ferguson, 2010). The one case where a change in dam level operation policy led to actual dam re-operation was at Seli'š Ksanka Qlispe' Dam (formerly Kerr Dam) on the Flathead River in the United States. Here, the Federal Energy Regulatory Commission (FERC) changed the status of the dam from a load-following and power-peaking status to a baseload status, thus creating room for the provision of e-flows (Barfoot, Evarts, & Lukacs, 2018). It is worth noting that for many cases, there may have been overlapping international, national and local level policies that have fed into each other and led to dam re-operation. It was, however, not possible to identify these overlaps completely and consistently with certainty based on the papers in this study.

For 36 dams, either an EIS of the dam on downstream ecology or an e-flow study to determine e-flow requirements was carried out. The New South Wales (NSW) local government in Australia, for instance, conducted studies on the water needs for Sydney as well as requirements for irrigation and e-flows, leading to re-operation of eight dams (Growns, 2016; Growns & Reinfelds, 2014).

The growing number of requests for a review of the operations of dams in the Tennessee Valley was an input to the provision of e-flows at 16 dams (Bednarek & Hart, 2005; Higgins & Brock, 1999; Schulte & Harshbarger, 1997). For other locations, a more contentious route was taken with lawsuits regarding the operations of four dams being filed. This included two dams on the Neuces River in Texas, USA. Although there was a law in place for this river system when the Wesley Seal and Choke Canyon dams were built, the requirement to supply water to the estuary was not fulfilled until shellfish declined and a shrimper organisation filed a complaint with the Texas Water Commission in 1989 (Montagna, Hill, & Moulton, 2009; Smith et al., 2011). Again for the Putah Diversion Dam in California, USA, a drought which caused a river stretch of 32 km downstream of the dam to completely dry up resulted in a lawsuit being filed and won by the local area council against the irrigation and water supply agencies (Kiernan, Moyle, Crain, & Crain, 2012).

Observations in the aftermath of natural hydrological events such as the 'Millennium Drought' from 2000 to 2010 in the Murray–Darling Basin and a two-year drought in the Ebro basin in Spain also initiated a collaboration to determine e-flows by water managers (Banks & Docker, 2014; Gómez, Delacámara, Pérez-Blanco, & Rodríguez, 2015). Likewise, natural floods in the Grand Canyon in 1983 led to an emergency release which showcased how much the Glen Canyon Dam had altered the downstream ecology as in the aftermath, backwater reaches critical for native fish had been restored, eroded areas had been replenished with sand, and non-native vegetation had declined (Collier, Webb, & Andrews, 1997). Much in the same manner, planned upgrades or maintenance also provided the opportunity for experimentation as in the case of the River Spöl in Switzerland, or the review of existing dam operations at the Glen Canyon and the Seli'š Ksanka Qlispe' dams in the United States (Barfoot et al., 2018; Patten et al., 2001; Scheurer & Molinari, 2003).

3.1.3 | What activities are carried out to re-operate dams?

The majority of the activities undertaken in dam re-operation are flow experiments (Figure 6), with the most frequent of these being the

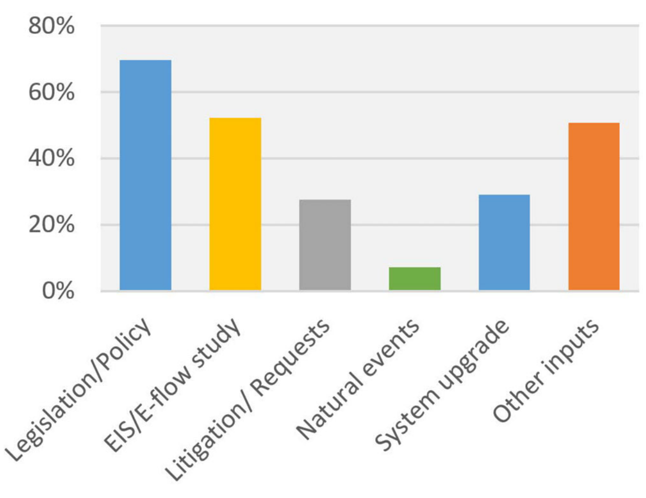


FIGURE 4 Frequency distribution of inputs to dam re-operation across documented cases (n = 69)

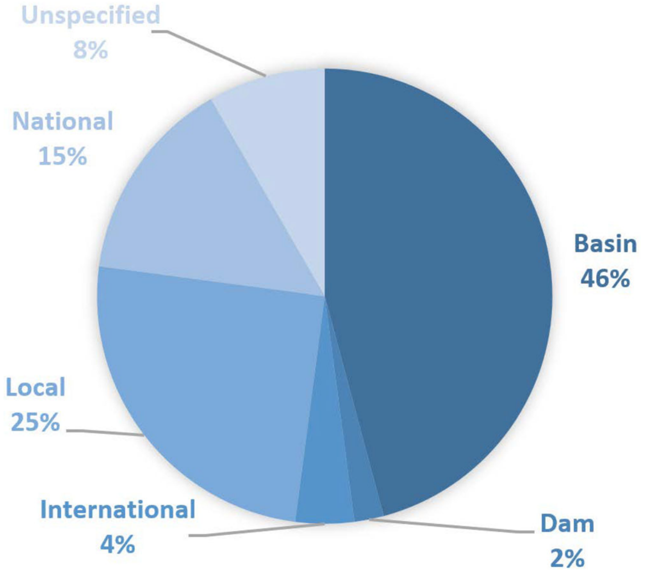


FIGURE 5 Legislation/policy level in cases where legislation was an input in dam re-operation (n = 48)

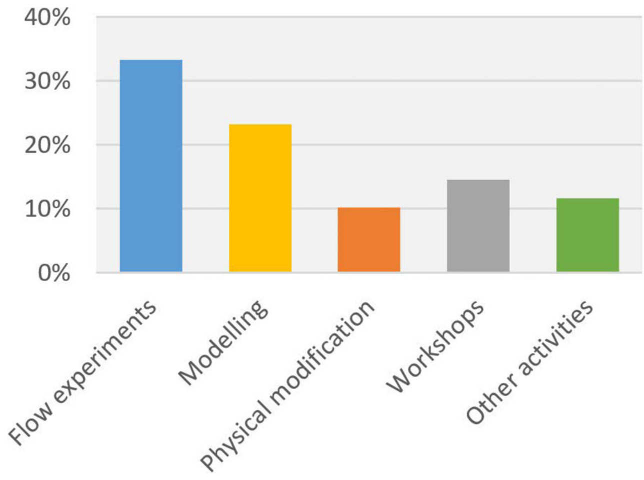


FIGURE 6 Activities in dam re-operation (n = 69)

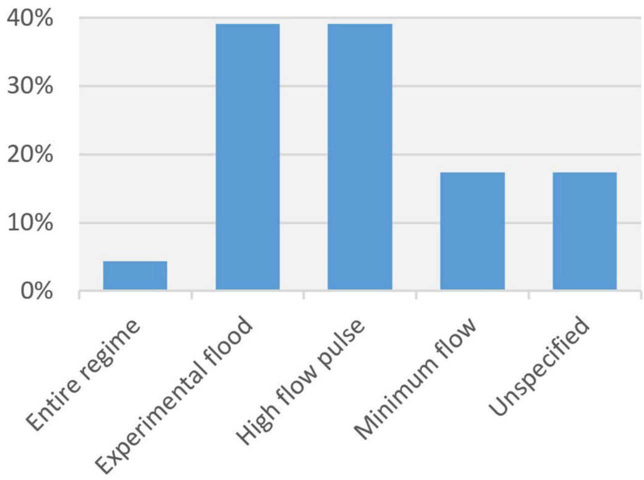


FIGURE 7 Manipulation in flow experiments (n = 23)

release of experimental floods and high flow pulses (Figure 7). This corresponds with the findings of Olden et al. (2014), who found that these were the most frequent flow experiments. Note that in this current study, these flow categories, namely, experimental floods and high flow pulses, were kept separate and categorized according to the descriptions of the authors reporting on the flow experiments since these flow categories have different ecosystem influences as described by Mathews and Richter (2007). The median number of flow experiments of this subset of re-operated dams was four, and the median number of years between the first and most recent experiments as of November 2018 was 3 years.

Physical modifications to dams occurred at seven dams, including four dams: Avon, Cataract, Cordeaux and Nepean Dams in NSW, Australia, for which new release outlets were added in 2008 (Growns, 2016; Growns & Reinfelds, 2014). On the other hand, for some cases such as the Katse Dam in Lesotho and the Glen Canyon Dam in the United States, the recommended e-flows, particularly for

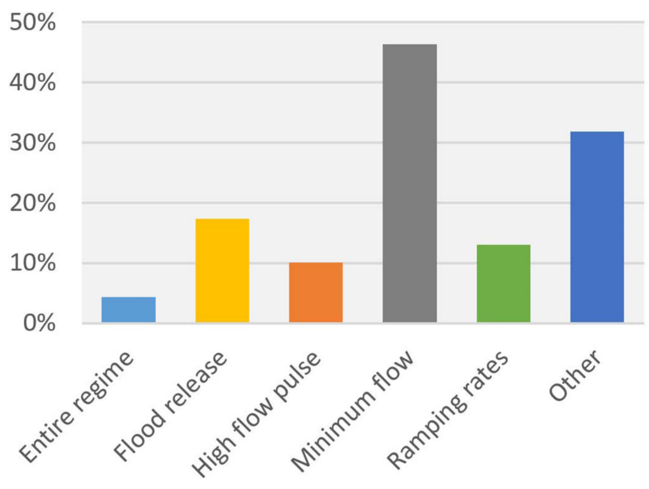


FIGURE 8 Implemented flow change in dam re-operation (n = 69)

larger floods, were rather reduced to fit the existing physical infrastructure (Brown & King, 2012; Rice, 2013).

3.1.4 | Which approach is taken in re-operating dams to implement e-flows?

Thirty-two dams were re-operated to provide minimum flows (Figure 8). In contrast to the activities stage (Figure 7), high flow experiments and experimental floods were less frequently implemented. Flow changes falling into the 'Other' category included bulk water allocations for e-flows or the establishment of transparency and translucency rules for dams such that low flows are allowed to pass through completely based on a transparency threshold while a percentage of flows above this threshold, translucency flows, are allowed to pass through to maintain flow regime dynamics (Growns & Reinfelds, 2014).

The approaches to dam re-operation were categorised into three based on Warner et al. (2014). One approach is Adaptive Management, where prescribed dam releases for e-flows, are essentially treated as flow experiments for scientific validation of hypothesis regarding flow components. These releases are thus monitored and continuously refined. An example of this is the case of the Glen Canyon Dam on the Colorado River in the United States (Rice, 2013). The second approach is Blanket Operation, where broad changes in dam operations are made based on available management and ecological information. The large-scale implementation of minimum flow and increase in floods from the Katse Dam on the Malibamat'so River in Lesotho is an example of this (Arthington, Rall, Kennard, & Pusey, 2003; Brown & King, 2012; Hirji & Panella, 2003). The third approach, Episodic Implementation, is an opportunistic approach to dam re-operation driven by prevailing hydrological conditions that allow for modifications to dam operations. The ad hoc releases to the Baiyandian Lake from Angezhuang Reservoir and three other dams in China since 1997 fall into this category (Yang & Yang, 2014).

Blanket operational changes to dam operations to provide e-flows were made at 44 dams (64%), while 12 dams were adaptively managed. For 13 dams, episodic implementation was practiced.

3.1.5 | Enabling factors in dam re-operation for e-flows

In the documented cases of dam re-operation, certain factors stand out as important to successful and timely implementation. These factors include: minimal impact on existing water uses, the importance of setting implementation timelines and collaboration and will be illustrated with examples in this section.

The common misunderstanding that implementing e-flows will certainly conflict with existing dam operation objectives is refuted in at least six cases. For instance, for the Green River Dam in Kentucky, USA, traditional objectives of flood protection were maintained, and in addition, water quality, recreation and storage for water supply were enhanced with the implementation of e-flows (Warner et al., 2014). In the case of the River Spöl in Switzerland, the water required for test releases was available, and overall there was no loss in power generation or revenue for the dam operator (Robinson et al., 2004; Scheurer, 2014). Again in implementing Minute 319 that governed the Colorado Delta pulse flow, a policy of 'no harm to existing water users' was the overarching constraint, and this was met (Pitt & Kendy, 2017). Furthermore, at Diama Dam in the Senegal River Basin, artificial floods for inundating the Diawling Park required only 1% of flows routinely released in average years, and new dry season floods used only 10% of dry season releases from the dam (Duvail & Hamerlynck, 2003). Another example of how dam re-operation impacted minimally on existing water uses is found in the case of the Glen Canyon Dam in the United States, where the cost of the 1996 flood was estimated at $3.8 million in lost power generation and other additional costs. This is against the $80 million annual value of rafting and associated tourism, which depends on the presence of sand bars, which were meant to be replenished by the floods (Andrews & Pizzi, 2000). Finally, flushing flows on the Ebro since 2003 were seen to effectively remove macrophytes while yielding positive results for the hydropower company by the prevention of clogging of water intakes (Gómez et al., 2015). The average cost of two flushing flows was pegged at €76,000 in autumn and € 33,000 in spring- only 0.16% of the mean annual revenue of the hydropower company (Gómez et al., 2015).

The benefit of having clear timelines or implementation plans for flow experiments is also clear. For example in the Sustainable Rivers Project, out of thirty-six dams selected as demonstration sites for e-flow studies, there was a lack of momentum to transition from flow experiments to actual change in dam operations after twelve years at all but one: the Green River Dam, Kentucky where 3 years for flow tests was set (Warner et al., 2014). For the River Spöl as well, where artificial floods have been incorporated into the operations of the Ova Spin Dam, an initial 3-year period was set for flow experiments (Robinson et al., 2004; Scheurer & Molinari, 2003). Again in the case of the pulse flow to the Colorado Delta, scientists and dam operators had approximately 2 years to submit a delivery design for the pulse flow for approval by a joint Mexican and American water commission, after which the pulse hydrograph could not be changed (Pitt & Kendy, 2017).

In many of the cases where the operations of dams have been successfully changed to allow for e-flows, the collaboration between dam operators, governing institutions, scientists and other stakeholders was a key factor in successful dam re-operation (Duvail & Hamerlynck, 2003; Pitt & Kendy, 2017; Richter et al., 2006; Scheurer & Molinari, 2003; Warner et al., 2014). The numbers involved in some cases were huge, as in the case of the Blue Ridge Dam and 16 other dams in the Tennessee Valley in the United States, where almost 1,200 people attended the meetings to review the EIS on the dams and provided 627 written and 196 verbal responses (Higgins & Brock, 1999). Marzolf, Jackson, and Randle (1999) also stress how collaboration between the agencies in charge of various aspects of the Colorado River and Glen Canyon dam led to the 1996 controlled flood. In the case of the Sustainable Rivers Project in the United States, Richter et al. (2006) point out that the involvement of stakeholder agencies in the e-flow recommendation process makes them supportive of its implementation.

4 | DISCUSSION

Irrespective of the dam database used, the documented cases of dam re-operation identified in this study make up a small fraction of existing dams-compared to the GRanD database, they make up approximately 1%. Furthermore, in line with recommendations by Olden et al. (2014) in the case of flow experiments, there is the need to expand and document cases of dam re-operation in countries beyond the United States, Australia and Western Europe. It is encouraging nonetheless that the countries where methodologies for determining e-flows were pioneered in the 1970s and 1980s are now at the forefront in their implementation, thus becoming examples for other countries to follow (Tharme, 2003).

This review confirms that there is no single combination of inputs and activities that will guarantee actual dam re-operation for e-flows. Two alternative models have been suggested in the literature: the analytical or traditional science model and the opportunistic or political model. On the one hand, the analytical approach to problems seeks to use research and analysis to solve problems (Mayer, van Daalen, & Bots, 2018). In this approach, there is intelligence, design, choice and implementation over a series of iterations (Simon, 1977). The re-operation of the Ova Spin and Punt dal Gall Da dams on the River Spöl follows this model, starting with the identification of the problem of deteriorating downstream conditions. This led to an EIS of the dams in the 1990s followed by experimentation from 2000 to 2001 and then adaptive management of the dams. On the other hand, there are political models for decision making such as the Garbage Can Model (Cohen, March, & Olsen, 1972) or Kingdon's Streams model where opportunism is the underlying paradigm (Cohen et al., 1972; Enserink et al., 2010; Vreugdenhil, Slinger, Thissen, & Ker Rault, 2010). The case of the Mequinenza and Ribarroja dams on the Ebro basin fall within this category since it was a drought and macrophyte bloom which triggered dam re-operation (Banks & Docker, 2014; Gómez et al., 2015). In some cases, dam re-operation does not fall neatly into either category and has elements of both models. For instance, for the Blue Ridge Dam on the Taccoa River in the United States, over twenty years of studies, pilot projects and tests had been undertaken when growing public requests for a review of dam operations triggered another round of intelligence, design, choice and implementation finally culminating in blanket re-operation (Bednarek & Hart, 2005; Higgins & Brock, 1999; Schulte & Harshbarger, 1997).

As the most common input to e-flow implementation, legislation provides the legal backing for dam operations to be changed. Even in cases where these laws are mostly overlooked, they provide the basis for challenges to be made against those in charge of the operation of dams. This was the case in dam re-operation in two cases in the United States following drought events. Thus drafting these laws causes changes to be made, however reluctantly, by those in charge of dam operations. Existing legislation may also explain why blanket re-operation was most prevalent in the documented cases of re-operation since dam operators and other stakeholders are mandated by law to provide e-flows and thus go ahead in following the letter of the law. The downside to this approach is that it provides no established avenue for monitoring and further improvements on dam operations for the environment.

Experimentation, which was the most frequent activity in dam re-operation, along with the adaptive management approach and even the episodic implementation approach to dam re-operation, provides the opportunity to test out proposed solutions. This is because it is usually unclear which dam releases will provide the desired results. As observed by Richter et al. (2006), stakeholders were reluctant to provide quantitative flow targets for the Thurmond Dam on the Savannah River until they were reminded of how these proposed flows would be considered approximations to be refined through adaptive management. Rice (2013) proposes that this hesitancy is in line with a re-enchantment with nature, which has come about due to the realization of the uncertainty, complexity and vibrancy of ecological processes. Therefore, now it is acknowledged that an action at a dam cannot be predicted with certainty to have a specific result downstream. In a number of cases, timelines for re-operating dams have served to overcome the hesitancy in e-flow implementation. Timelines force a decision to be made between business-as-usual, which is leading to deteriorating habitats in many cases, and implementation of some changes to dam operations based on best available data on river ecosystems. In contrast to this hesitancy in dam re-operation, the era of dam building in the mid-20th century was characterised by an attitude of confidence in man's mastery over and disenchantment with nature (Rice, 2013).

5 | CONCLUSION

Re-operation of dams may be considered a 'wicked' (Rittel & Webber, 1973), 'messy' (Ackoff, 1974) or 'unstructured' problem due to the multiple stakeholders involved as well as the numerous problem definitions, solutions and conflicts (Enserink et al., 2010; Weber & Khademian, 2008). The documented cases of dam re-operation thus shed light on how this problem has been successfully tackled. These documented cases of dam re-operation show that there is no one sure way to dam re-operation and that analytical, political as well as mixed approaches have been equally successful. This review, however, highlighted that the inputs and activities most commonly found in cases of successful re-operation are legislation and flow experiments. The establishment of minimum flows downstream of dams remains the most commonly implemented flow change. The review also revealed that e-flows are not always in conflict with traditional water uses for which dams have been built.

This study adopted a systematic literature review and logic model framework approach to identify and analyse cases where the operations of dams had been changed to implement e-flows. This provides a comprehensive overview of dam re-operation worldwide, however, the cases identified are limited to those found in the scientific and grey literature that are curated in English in the six scientific databases selected. As such, it is acknowledged that there will certainly be more cases of dam re-operation to be found in government documents and in other languages across different countries. It is also acknowledged that in less extensively documented dam re-operation cases, there is some ambiguity in deducing the timeline of events to determine if a specific event was an input or activity in the process of dam re-operation. It is therefore recommended that detailed studies of these cases be undertaken to record the process of re-operation for these dams accurately.

Finally, it may be the case that for some dams, the process of re-operation to implement e-flows has stalled despite some of the same inputs, activities and even opportunities being present. It remains unclear why this is the case. Some of the documented cases of successful dam re-operation touch on hurdles that were overcome in the process, and the activities carried out hint at an effort to overcome certain limitations—for instance, physical modifications to the dam are carried out to allow for larger flow discharges to be released. It is recommended that future research look at cases that have stalled as these will highlight the obstacles encountered in re-operating of dams, thereby balancing out the narrative and better informing stakeholders on the process of dam re-operation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the 4TU.Centre for Research Data repository at https://doi.org/10.4121/uuid:5824e7a3-4ca1-469c-b014-595a19f0ff6d. This dataset has been updated and is available as supplementary material to this paper.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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