Towards a comprehensive river barrier mapping solution to support environmental management

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Abstract
The environmental effects of large dams on river connectivity are well recognized and mapped globally. However, datasets describing distribution and attributes of smaller barriers (e.g. weirs, culverts) are lacking or incomplete for many regions. This has hindered accurate impact assessments for water resource planning, biased understanding of restoration potential, and limited research aiming to understand and mitigate river fragmentation effects. Developing an efficient method to accurately record river barriers, including small ones, has become a priority. We critically review barrier mapping approaches, from field survey to automated detection, showcasing recent approaches to recording, counting and classifying river barriers. We demonstrate how incomplete barrier databases, particularly those lacking many small barriers, provide a flawed basis for water management and ecological restoration planning. We discuss the efficiency and accuracy of alternative barrier mapping approaches, highlight future priorities, and emphasize harmonizing barrier assessment methods to generate reliable, freely-shared information for effective basin-level management.

Main
Fresh waters are among the most threatened ecosystems in the world, as a result of habitat fragmentation, water extraction, pollution, invasive species, overexploitation and climate change[1,2]. Due to their dendritic structure, rivers are particularly vulnerable to infrastructure such as dams, weirs, and sluices (Fig. 1) that act as barriers to the flow of water, sediment, wood, organisms, and energy[3–6]. River fragmentation and flow regime alteration caused by these structures pose major threats to freshwater ecosystems[1,7], contributing to ongoing declines in biodiversity globally[8,9]. Recent estimates reveal that the construction of dams has resulted in connectivity loss for more than two-thirds of global rivers and fragmented the distributional ranges of thousands of fish species and other aquatic organisms[10–12].

The effects of large dams and other river barriers have received considerable attention from scientists and conservation practitioners. However, only more recently have concerns mounted regarding the negative impacts of relatively small barriers. For the purposes of this paper, we distinguish small barriers of several types (see Garcia de Leaniz & O'Hanley[13] for definitions) as being less than 10-m high. These include low-head dams or weirs, which generally allow flow to overtop the crest (widely used to store or divert water for irrigation, hydropower, and flood control among other uses), transport-stream crossings (infrastructure associated with transport routes such as culverts, fords, and bridge aprons), and sluice gates (structures with movable gate(s) through which flow is regulated) that are numerous across the world[7,13–16] (Fig. 1). Despite being smaller in size, these structures disrupt the flow of water, sediments, and wood[4,17,18], decrease water quality[19,20] and modify water temperature regimes[21,22], ultimately compromising ecosystem processes and leading to native biodiversity loss[23–25]. Importantly, small barriers are usually built in greater numbers than large dams due to less restrictive regulations, lower construction budget, and greater cumulative channel length of smaller streams in river networks[26]. For instance, Belletti et al.[16] report that there are at least 1.2 million instream barriers across 36 European countries, among which over 99% are small-sized barriers. Sun et al.[27] recorded more than 13,000 barriers in the Mekong Basin and found that at least 95% of them are smaller barriers. Emerging evidence shows that the combination of numerous small barriers may produce considerable cumulative impacts on freshwater ecosystems[28–32].

There are often major ecological, economic, and social trade-offs associated with river barrier construction[33,34]. River barriers can support a variety of services to society but can also negatively affect human communities by altering the hydromorphology and ecology of riverine ecosystems. Despite large dams inflicting the greatest hydromorphic impacts[35], the relatively larger numbers of smaller barriers can have significant effects on habitat connectivity and movement of organisms[7,16,28]. Many river barriers have been shown to be no longer serving their intended purpose, yet continue to have impacts beyond their operational life[36]. Understanding the extent and nature of these effects and navigating trade-offs associated with new or existing river infrastructure, requires readily-available, open access databases that provide information on the locations and characteristics of existing barriers at an appropriately fine scale[37].

From an ecological perspective, barrier databases have been used in a number of ways. These include evaluating basin-wide river connectivity status[10], selecting suitable river barrier construction sites to minimize biodiversity and habitat loss[38], facilitating application of the 'adaptive management' process towards river barriers[36], guiding ecological connectivity restoration efforts[39–42] and promoting basin-scale conservation planning policies[43,44]. Using advanced analytical tools and a high-resolution barrier database, scientists can support energy and water resource planners to clarify trade-offs between specific objectives (e.g., energy, water storage, flood retention) and environmental or social impacts, to maximize meeting societal needs with minimum negative effects on river ecosystems and humans[28,45,46]. Results from strategic planning also help inform governments when comparing siting alternatives for new dam construction[47] to meet national energy requirements in the future[28].

The past decade has witnessed considerable efforts to compile comprehensive geospatial data on both large (e.g., Global Reservoir and Dam [GRanD][35]; Global River Obstruction Database [GROD][48]; Global Dam Tracker [GDAT][49]; Global Dam Watch [GDW][50]; Global Water Watch [GWW][51]; and The World Register of Dams [ICOLD WRD][52]), and small barriers (e.g., Adaptive Management of Barriers in European Rivers [AMBER] Barrier Atlas[16] and Mekong River Barrier Database [MRBD][27]). Efforts like the Global Dam Watch (www.globaldamwatch.org) seeks to develop a single, globally consistent dam and instream barrier database, build tools to visualize river barrier data to aid policy and decision making, and develop Earth observation techniques to aid mapping of river barriers and their properties[37,50]. This type of integrative global initiative is urgently needed but its progress is partly limited by the generation of accurate, up-to-date, openly accessible barrier inventories for river basins, particularly in the Global South, and especially for small river barriers that often represent dispersal and migration barriers for fish and other organisms. Therefore, the development of accurate, but more efficient, barrier detection methods is a priority. This study seeks to support this need by critically reviewing barrier mapping approaches that have been used, exploring real-world examples of the utility and problems with barrier mapping for environmentally-sensitive river management, and proposing consolidate existing knowledge and technology into a new opportunity towards the development of comprehensive and accessible global databases.

Approaches for river barrier mapping

Integrating existing barrier databases

Integration of reliable existing barrier data, which involves using datasets from energy or water resources management plans, government databases, and web sources to estimate barriers in a region of interest, is one of the commonly used approaches to compile barrier databases (Fig. 2). Lehner et al.[35] developed one of the first global dam databases containing 6,862 geo-located dams compiled from 11 research institutions. Zarfl et al.[33] recorded a total of 3,700 proposed hydropower dams with a capacity of more than 1 MW from locations around the world by combining data from hydropower investments, industry resources, and other relevant sources. Flecker et al.[38] recorded the locations and technical information of 158 existing and 351 proposed dams in the Amazon Basin from governmental reports, energy agency databases, and publications. Detailed databases have also been generated in particular countries, for example, the National Office for Water and Aquatic Environments (Onema), sponsored by the French government, generated the Référentiel national des Obstacles à l'Ecoulement (ROE) database[53]. With input from several hundred contributors, from government departments to local stakeholders, the ROE database includes over 100,000 recorded river barriers of all sizes and types, demonstrating that such efforts are possible at least at a national scale and providing a state-of-art baseline on which to continue building the database for future monitoring and management. At a continental scale, the AMBER Barrier Atlas, a compilation of 630,000 unique barrier records from 120 databases across 36 countries, including 65 local databases, 52 national databases, and four global ones, is considered to be the most comprehensive barrier database in Europe[16]. The Global Dam Watch integrates, harmonizes, and augments several existing global dam datasets (i.e., the GlObal GeOreferenced Database of Dams [GOODD][54], GRanD, and GROD), and contains point locations of 41,145 barriers globally[50].

A drawback of this approach is that the information on barriers is often dispersed across various agencies and reports (in some cases from different countries and languages), making it challenging to access. Due to data-sharing policies or geopolitical circumstances across large transboundary river basins, many regional or local databases are not publicly available[34,55,56], which further increases the difficulties in acquiring available data. Even when there is existing data, there are challenges of duplication and accuracy. When integrating barrier data from different sources, identifying and removing duplicates is one of the most time-consuming steps. During the cleaning process of the AMBER Atlas, a total of 106,393 duplicates were removed, by visually assessing different sources of databases on high-resolution satellite images. Yet, subsequent analyses of barrier distribution from the AMBER dataset had to be carried out on sub-basin areas of the European Catchments and Rivers Network System (ECRINS) rather than on the low-resolution ECRINS river network, as the latter had insufficient spatial resolution[16]. In addition to the removal of barrier duplicates, integrating data from diverse sources requires the maintenance of a consistent level of accuracy across datasets. Disparate inventorying effort and data transparency can result in datasets that differ in terms of the range of sizes and the number of barriers they include. Data harmonization is a time-consuming process, and can be challenging when integrating multiple regional and global datasets. Consequently, merging datasets from different sources and geographic locations can introduce significant bias into data analysis with a national or global scope.

Barrier surveys

River barrier identification and compilation into inventories for environmental management has traditionally relied on a combination of historical records, often in the form of topographical maps, combined with field surveying to ground-truth existing records[57] (Fig. 2b) and identify barriers missing from historical records[26]. Field surveys require traversing the watercourse to identify and record the location of river barriers, and evaluate their physical features (e.g., construction characteristics, height, slope, and width)[26]. This approach involves considerable labor and resources, and often requires land access permission. Site-by-site validation of anthropogenic river structures from existing maps and historical records generates a conservative estimate of barrier numbers and distribution. By contrast, field surveys along river reaches generate independent and much more accurate inventories, often identifying multiple structures unreported on maps and in historical records, although restricted to those reaches surveyed[16,26,58]. Independent field surveys of two river basins in the national river barrier database of England, generated by the former method[59], found that 55% and 78% of recorded anthropogenic river barriers, including eight dams higher than

10 m, were missing in previous inventories[26]. Clearly, detailed surveys in situ have the potential to produce more complete databases, but the accuracy of field surveys may vary according to the methods employed and available resources.

Basin-wide field surveys of instream barriers are not usually feasible due to their high cost and logistical complexity, making this approach particularly challenging to implement in regions with harsh environmental conditions and limited access, such as rivers located in the Asian highlands (e.g., the upper Mekong River Basin) and in tropical forests (e.g., the Amazon River Basin). Until recently, involvement of public stakeholders (e.g. recreationists such as boaters and anglers, environmental associations, citizen scientists) in river barrier detection programs has been rather limited. This is despite the fact that many people have routine interactions with river barriers. This is now changing, even in developing countries. For example, a significant, multi-catchment survey in Myanmar mobilized local people to generate an inventory of river infrastructure[60,61]. In order to harness the power of citizen science, and facilitate barrier database construction, many regions or countries have developed their own mobile applications (e.g., AMBER Barrier Tracker, River Obstacles, Géobs) for citizen scientists to upload information regarding the location and basic attributes of barriers[62]. For instance, since the launch of the AMBER Barrier Tracker app in 2018, it has received more than 10,500 confirmed records of river barriers in 40 European countries[62]. Despite its potential, validating such data still requires considerable effort to remove duplicate records and conduct required verification of barrier attribute fields[16,50].

Visual interpretation with remote sensing

Visual interpretation is a commonly used desk-based assessment approach to identify river barriers[48,63](Fig. 2d). River segments within the study region are visually examined from the source to confluence using high-resolution remotely sensed images (e.g., Google Earth, BirdsEye, World Imagery Basemap), and the location of each potential barrier is manually recorded. Using this approach, Yang et al.[48] identified more than 30,000 river barriers (i.e., the GROD) across 2.1 million kilometers of large rivers (width ≥30 m) globally. Mulligan et al.[54] 2020 recorded more than 38,000 dams across five continents (i.e., the GOODD) by systematically digitizing visible dams from Google Earth's satellite imagery. Sun et al.[32] recorded more than 1,000 unique barriers in the Upper Mekong Basin using visual interpretation, and found that small barriers are the main factors leading to fish habitat fragmentation in that region. Whittemore et al.[64] adopted the citizen science-based approach in barrier mapping, with 13 participants who visually mapped 4,197 river barriers on 108,993 km of rivers from satellite images in the United States.

Although the visual interpretation approach is faster compared to walkover surveys and can be carried out on a large spatial scale, it does not provide fine detailed information such as height and slope of each barrier, so should be applied associated with a walkover survey when possible (Table 1). In addition, this approach relies on the visual interpretation of images that vary in quality and availability across space and time, being quite susceptible to false positives and negatives depending on the images selected. Furthermore, small-sized barriers are difficult to identify, notably in small rivers or rivers with high density of vegetation and canopy cover[27]. Visual interpretation can also be argued to be a subjective process and so requires independent validation on a subset of samples in order to ensure accuracy. Currently, there are no widely accepted standards to guide the use of this method.

Geospatial and geostatistical modeling

Increasing interest in mapping barriers in larger and often data-poor areas will only serve to magnify the utility of geospatial and geostatistical modeling. They are referred to here as approaches that rely solely on existing products from Geographical Information System (GIS) and modeling to predict barrier locations (Fig. 2e). Examples from the literature include the automated interpretation (i.e., machine learning) of data derived from Light Detection and Ranging (LIDAR) Digital Elevation Models[65] and Advanced Space-Borne Thermal Emission and Reflection Radiometer (ASTER)[21] to identify river barriers. These two examples employ binary random forest classification algorithms to predict unmapped barrier locations based on hydrographic (e.g., slope, elevation, stream order) and habitat (e.g., waterbody features) variables[21,65]. Buchanan et al. achieved a detection accuracy of 80–94%, by applying the algorithm to two sub-basins in the Hudson River, USA. However, Parks et al.[66] achieved a lower accuracy of 62–65% when applying a similar algorithm to the River Afan catchment, Wales.

Other common geospatial modeling approaches use intersecting features of the landscape to predict potential barrier locations, which is particularly useful to identify barriers associated with transportation infrastructure such as road-crossings (i.e., intersection of roads and hydrography polylines). Assessments in watersheds of the North American Great Lakes[14], identified 268,818 road crossings, which is 38 times the number of potential barriers in existing databases. Among these road crossings, 1,403 were field assessed and results showed only 1% of structures were fully passable for larger-bodied fish like northern pike (*Esox lucius*), and at least 41% of structures were partially passable[14]. In the Restigouche catchment, Canada, the LiDAR crossing model identified 1,633 potential stream crossings across a 3,200 km^2 area. A total of 242 potential structures were field-verified, with 32% culvert, 19% drainage ditches, 24% bridges, 24% sites with no channel upstream, 3% fords, and 12% of false detection. In northeast Australia[68], within an 18,363 km assessed river network, a total of 3,748 potential barriers comprising 3,228 road and 520 rail intersections were recorded. However, no field validation was conducted by the research team [68]. Despite being useful in certain types of investigation, the outputs from these methods are biased towards modern transport infrastructure and tend to be largely conservative in their recording (Table 1, but see Belletti et al.[16]). Also, road and hydrography data are not always available or not in a sufficient resolution to reliably apply the intersection method. Additionally, although some of the studies mentioned above achieved high accuracy, they do not specifically focus on identifying barriers. For example, the intersection method by Arsenault et al. [67] can identify crossing locations, but it detects many structures that are not actual barriers (e.g., ditches, clear span bridges).

Unlike field assessment and other desk-based approaches, geospatial and geostatistical modeling enables a rapid acquisition of barrier location information, relying solely on GIS products. Such information is gradually becoming more accurate and accessible, such as in open-source GIS products for hydrography (e.g. HydroSHEDS[69]) and road infrastructure. This means that the geospatial and geostatistical approaches can be scaled up and applied over large data-deficient areas of the globe that still lack instream barrier assessments. The drawback is that false positive and false negative outputs are generated, and additional steps must be taken to validate the data and ensure true positives are used for databases. Similar to visual interpretation, geospatial and geostatistical modeling normally does not provide detailed information about each barrier (e.g. type of structure, height), and additional information should be obtained via field surveys or visual inspections[70]. To overcome this limitation, Arsenault et al.[67] estimated elevation drops for culverts via LiDAR DEM; an approach that still made it challenging to estimate elevation values from both ends of the structure.

Automated object detection with deep learning

Object detection recently emerged as an advanced technique based on neural networks to localize and classify river barriers in high-resolution remotely sensed imagery[27,71]. This approach uses convolutional neural networks (CNNs) to extract deep image features (i.e., river barrier features, and water body features immediately upstream and downstream of the barrier) from satellite images and creates detection boxes to flag potential barriers[27,71] (Fig. 2f). In Japan, a CNN-based object detection approach identified 112 dams (with a recall of 91%) from three cities/prefectures, with 39 of them not previously recorded in existing databases [71]. On a larger scale, the object detection approach (with an accuracy of 87%), along with visual validation has been used to identify more than 10,000 previously unreported river barriers including small earth dams, sluice gates, and weirs in the Mekong Basin, the largest transboundary river in Southeast Asia[27].

Similar to modeling approaches, object detection rapidly acquires barrier location information and can classify barriers according to types (but without measured barrier physical attributes such as height) and can be applied over large data-deficient regions. The drawback of this method is that training data from one region can result in poor detection for another region, as has been observed in the Lower Mekong in the previous study[27]. This can be caused by differences in infrastructure design, land cover type, river morphology, and climate. As a result, the false positive and false negative outputs require additional steps for validation (i.e., visual or field-based). Hence, automated detection relies upon the quality of training material as well as the algorithm itself, and also requires adequate independent validation of a subset of images (Table 1).

Under certain circumstances, for example, depending on the river discharge when the remote sensing images were taken, anthropogenic structures associated with the river channel might be submerged completely or fully exposed on a dry riverbed, leading to omission or commission errors[27,72]. The challenge of mapping barriers due to these temporal dynamics is likely more pronounced in regions experiencing large flow extremes (e.g. the Lower Mekong) but can also occur in heavily managed rivers. In this case, small-sized barriers are particularly susceptible to this. Furthermore, to facilitate an efficient deep learning process for object detection, a high-performance graphics processing unit (GPU) is often required[73], which could largely increase the budget for purchasing essential hardware.

Table 1. Strengths and challenges of different barrier mapping approaches.

Approach	Strengths	Challenges
Integrate existing databases	• Cost-effective • Applicable across large spatial extents. • Barrier attributes often available.	• Duplicated records from different sources require removal. • Time-consuming to harmonize data from different sources. • Databases may not be publicly available. • Small barriers are often missing. • Potentially biased datasets when merged from different sources.
Barrier surveys	• Small barrier locations can be recorded. • Detailed physical features of barrier can be attributed. • Higher accuracy. • Can provide the opportunity to collect ecological data	• Time-consuming and labor-intense. • Requires land / river access permission and accessibility. • Financially costly. • Limited spatial coverage.
Visual interpretation	• Relatively time-efficient. • Cost-effective. • Small barriers can be identified when high-resolution satellite images are available.	• Relatively time-consuming and labor-intense at large spatial extents. • Unable to generate detailed barrier attributes. • Independent measures of accuracy needed. • Omission errors occur when river covered with canopy or barriers submerged during high flow events.
Geospatial and geostatistical modeling	• Time-efficient. • Applicable across large spatial scales. • Effective in detecting road crossing type barriers	• Unable to generate detailed barrier attributes. • Curation needed to remove false positives. • Independent measures of

	(intersection approach).	accuracy needed. • Relies on GIS products that may be unavailable or have limited resolution (hydrography, surface reflectance, transportation infrastructure). • Barrier data biased towards modern transport infrastructure (intersection approach).
Automated detection with deep learning	• Time-efficient. • Small barriers can be identified and classified when high-resolution satellite images are available. • Applicable across large spatial scales.	• Unable to generate detailed barrier attributes. • Omission errors occur when river covered with canopy or barriers submerged during high flow events. • Data curation needed to remove false positives. • Independent measures of accuracy needed. • Representative labeled barrier dataset for deep learning is needed. • Expensive to purchase high-resolution imagery data or high-performance server.

Consequences of incomplete barrier databases

Due to the challenges of detecting small river barriers, research and policy attention tend to be focused on the impacts of large-sized barriers. The result is that information on the number and location of small barriers across large catchments is often overlooked in environmental assessments[31]. The omission of small barriers from most existing barrier databases has hindered the accurate assessment of river connectivity[74]. Without having comprehensive databases that include the vast majority of barriers at the catchment scale, it is difficult to accurately prioritize local river restoration efforts such as barrier mitigation and fish passage installation[75]. Ioannidou et al.[74] evaluated habitat gains of using both complete and incomplete barrier databases to facilitate connectivity restoration in Maine (United States) and found that using incomplete barrier data resulted in nearly 50% lower habitat gain than was anticipated.

In recent years, growing studies have assessed the impacts of small-sized river infrastructure on river connectivity, flow regimes, aquatic biota, and other environmental factors across continents. For instance, in the United States, small-sized dams contributed to more than two-thirds of anthropogenically derived river fragmentation and largely altered natural connectivity patterns[7]. In Brazil, small hydropower dams are primary river fragmentation agents, resulting in four times higher losses in river connectivity than large dams[28], and leading to impacts to biological communities[24]. In Australia, small barriers such as farm dams caused flow alteration in headwater streams of the Murray-Darling Basin approximately three to four times more than large dams[31]. In Southeast Asia, the proliferation of small earth dams and sluice gates has resulted in more river fragmentation in the Middle and Lower Mekong Basin than that caused by major dams[27,60]. The cascading effects of multiple small-sized barriers can cause profound negative impacts by preventing migratory species from accessing upstream habitats[39,43,60,76]. They further exert selective effects on morphological, physiological, and behavioural traits in aquatic species, and alter community composition and ecosystem processes[30,77,78].

It is now increasingly recognized that the contribution of small barriers to catchment fragmentation is often underestimated. For instance, the Mekong River Commission regularly reports the number of barriers via access to national irrigation databases from countries across the Lower Mekong Basin[79]. This database is regularly updated but relies on data to be shared by various agencies to remain accurate. For large dams, especially those associated with hydropower, details are very accurately recorded and updated. But data on small-sized barriers is far more variable. The large amount of foreign investment in the region further complicates accuracy. Many international donors, development banks and aid agencies are investing significant amounts into flood mitigation and irrigation programs. In some instances, these are implemented directly with provincial governments and thus are not captured on national database systems. In addition, barriers which are developed at the district-level are often installed and managed at local villages and are not captured in any databases because many are not formally licensed. In summary, despite the challenges, the inclusion of small-sized barriers into barrier databases remains a priority.

Many small river structures are still built without adherence to the appropriate technical support and licensing procedures[15,28]. For instance, inadequate and poorly planned infrastructure associated with roads and agriculture can be widespread in rural and remote areas of Brazil[21,80,81]. Hazardous and obsolete infrastructure, such as small, abandoned impoundments could be identified and prioritized in connectivity restoration efforts[26]. A comprehensive barrier mapping framework is fundamental to support prioritization efforts like this and should guide management plans seeking to mitigate the impacts of small barriers in freshwater ecosystems (Fig. 2).

The establishment of a freely accessible, comprehensive, river barrier database, covering a large area, such as an entire river basin, or multiple river basins, involves several key steps. First, depending on available resources, systematic barrier coordinate collection can be conducted through field surveys, visual interpretation, or automated detection at regional scales. Barrier data from various sources, including regional barrier databases, government reports, and basin management plans, should be integrated into a unified database after duplicate removal and data harmonization. Both of these steps should include small, as well as large, barriers, as it is clear that basin-scale management options are affected by the distribution, size and types of barriers present. Supplementary field surveys may be necessary in certain sub-basins to gather missing physical features of barriers and check the veracity of existing records[14,26]. Ultimately, the comprehensive database should be stored on a free-access server, ensuring open availability to stakeholders, researchers, and policymakers. This database will serve as a critical resource for conducting barrier impact assessments and supporting large-scale basin management. We recommend and support the development of a series of international standards for barrier record data formats, verification and intellectual property use, in order to enable the combination of regional open-access barrier databases into a global database.

Research / management priorities and opportunities

With recent advances in river barrier mapping approaches and increasing scientific attention focusing on small barriers, the time is ripe to advance new data and tools in support of barrier management.

First, we echo recent calls by Global Dam Watch encouraging the production of open access databases that include barriers of all sizes with multiple attributes (size, reservoir area, volume, fish passage structures etc.) and harmonize barrier data in a consistent form to strengthen its utility and relevance for all stakeholders[37,50].

Second, we stress the importance of combining multiple barrier detection approaches to produce more comprehensive and robust barrier mapping products. The combination of methods allow for a more refined quality control of barrier locations and the inclusion of a suite of basic barrier attributes that are relevant for management. (Fig. 2). For instance, automated deep learning detection or visual interpretation could be conducted across large-scale areas to gain an overview of the barrier locations and connectivity status (with the dendritic connectivity index and its variants[82,83]) of the entire basin. Then, field surveys can be conducted at certain sub-basins to gather specific barrier attributes (e.g., height, slope, width), and barrier-mitigation decision-support frameworks[13,84–86] can be applied to support ecological management and restoration actions (Box 1).

Third, we urge further exploration of new automated tools for barrier detection that leverage deep learning. To date, this approach has been employed in only a limited number studies. Considering the rapid development and impressive outcomes of deep learning in other fields like road monitoring[87] and water body extraction[88], there is an untapped potential for deep learning tools in barrier mapping research and management. This can include the development and testing of deep learning algorithms to identify, and categorize barriers in rivers with different landscape topographies (e.g. arid zone, boreal rainforest, tropical rainforest), and associated differing ease of detection, using satellite images[27,72]. Generic barrier identification algorithms need to be tested on datasets from river catchments with "complete" contemporary barrier inventories in order to measure their accuracy and performance variability in different conditions. In addition, to combat the insufficient labeling of river barriers, a globally representative labeled dataset for river infrastructure is also needed in the field of automated detection.

Conclusion

Given the increasing impacts of flow regulation and river habitat fragmentation on the environmental sustainability and biodiversity of rivers globally, there is an urgent need to accelerate the development of comprehensive and open access global barrier databases that are inclusive of smaller infrastructure. Global Dam Watch provides an encouraging step in this direction by offering an effective harmonized and quality-assured repository of accessible information on many river barriers globally[50]. They also provide a mechanism to support the curation of additional barrier data sets. Although information on small-sized river barriers is challenging to generate[16], given the urgency of understanding and forecasting their environmental impacts, researchers should take advantage of all tools now available to collect reliable information on river barriers and share this freely through contributing to Global Dam Watch. Regardless of the difficulty, a comprehensive river barrier database for all river basins is a necessary resource for facilitating effective river basin and water resources management. Knowing the numbers, distribution, and types of barriers across entire catchments can provide fundamental information to river managers to make informed decisions regarding barrier removal or remediation, to support important ecosystem services (fisheries, energy generation, flood control, water storage), and to improve the connectivity of habitat for native aquatic biota ultimately[63].

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ADDITIONAL INFORMATION

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Figure captions

Figure 1. Different types of river barriers: (a) stepped weir (River Leven, UK), (b) ford (River Wear, UK), (c) sluice gates (Qingli River, China), (d) culverts with apron (Sherburnhouse Beck, UK), (e) bridge apron (Lishe River, China), (f) artificial waterfall (Muyang River, China), (g) small hydropower dam (Chapecó River, Brazil), (h) tidal barrage (Sittaung River, Myanmar), (i) large hydropower dam (Skagit River, United States). Functions provided by the barriers illustrated - flow regulation: a, c, g, h, i; transport crossing: b, d, e, h; cultural attraction: f; power generation: g, i; water supply: c, i. All photos were taken by the authors of this manuscript.

Figure 2. Framework for river barrier detection showing relationships among different approaches. 1. Data collections referring the boxes at the top; 2. Data compilation and processing; 3. Dataset integration; 4. Quality control and amendments; 5. Ensuring data to publicly available; and 6. Use in research and management. Different colors indicate different barrier mapping approaches and processes. Dotted-line boxes are optional steps in the barrier detection survey. The lower panel illustrates the evolution of a suite of river barrier detection methods: (b) Initially, river barriers could only be located using field-based surveys. (c) With improved technology, river barriers were recorded in high-resolution images by satellite or drone, for further processing. (d) Desk-based approaches are used to identify river barriers from satellite images and/or existing governmental and independent databases. (e) Geospatial and geostatistical modeling have been adopted to map barriers in larger and often data-deficient regions. (f) Artificial intelligence combined with remote sensing approaches is now accessible to automate barrier detection. All photos were taken by the authors of this manuscript.

Figure 3. Field-validated barriers with the highest potential barrier impact on migratory fish in the Xe Champhone catchment, Lao PDR. An assessment using Google Earth identified 450 potential barriers to fish migration. After removing sites that were subsequently found to be non-barriers, the 25 sites highest ranked as likely migration barriers were field-surveyed. Three of the 25 barriers were large dams (>10 m in height) and the remaining 22 were small barriers, consisting of weirs, regulators, wetland bund walls, and culverts, demonstrating that small barriers are responsible for a high preponderance of habitat disconnection for fish and other aquatic animals. Fish passage has since been restored at one of the sites, Souy Dam, through the installation of a cone fishway (red hexagon on [a]). Map created using ESRI basemap data.

Box

[Box 1. Case study on the practical importance of open access barrier inventories for conservation planning]

An example of the dichotomy between mapping large and small river barriers for better-informed management is illustrated by the Xe Champhone system (Lao PDR, Lower Mekong Basin [LMB]); an internationally important wetland for conservation, listed under the Ramsar Convention. The catchment was subject to a five-stage prioritization process of the likely impacts of barriers, aiming to identify priority sites for fish passage rehabilitation[89]. The five-stage process was based on the the Mekong River Commission Fish-Friendly Irrigation: Guidelines to Prioritising Fish Passage[89], and involves (1) identifying all potential barriers within the catchment using satellite imagery; (2) undertaking a GIS-based assessment to provide an initial ranking for further investigation; (3) field-validating the highest ranked barriers to authenticate the GIS-based results; (4) identifying the highest priority field-validated barriers influencing fisheries productivity; and (5) prioritizing the list of barriers with respect to socio-economic considerations.

All potential fish passage barriers within the Xe Champhone catchment were identified using existing information (e.g., irrigation infrastructure and road crossing spatial layers) where available and by overlaying layers indicating waterways and roads within the catchment. This process identified 450 potential barriers for checking using Google Earth (Fig. 3). After excluding sites that were subsequently found to be non-barriers (e.g. clear span bridges), 25 sites ranked highest as likely barriers to fish migration, were field-surveyed to assess barrier height, design type, hydrology, and water levels (in the rainy season and the dry season), local fish community composition, and the area of inaccessible upstream habitat[89]. Of the 25 field-validated barriers, only three were large dams (>10 m in height) and the remaining 22 were small barriers, consisting of weirs, gated water-regulators, wetland bund walls, and culverts (Fig. 3). Thus, large dams contributed less than 1% of all identified barriers, and focusing on these barriers alone would likely have greatly underestimated the total extent of fragmentation in the catchment. Indeed, the fragmentation (based on dendritic connectivity index [DCI] analysis[60,82]) caused by the three high priority large dams was only about 11% of that caused by all 25 high priority barriers for potamodromous fish ($DCI_{\text{large dams}}$ 96 vs. $DCI_{\text{all barriers}}$ 10).

The practical outcome of this process was the development of a scientifically rigorous prioritized inventory of barriers for fish passage rehabilitation in the catchment. The inventory was presented to a large donor in the region and the local irrigation authorities, for a discussion regarding an Integrated Water Management project, which was seeking to upgrade several dated barriers that required rehabilitation. After reviewing the prioritized barrier inventory, it was agreed by the three parties (us – the researchers, the donor, and the local irrigation authorities) that Souy Dam was an appropriate site to start rehabilitating fish passage in the catchment. Prioritized barrier inventories were similarly developed for several other LMB catchments through this program, resulting in a further 26 high-priority sites being rehabilitated throughout the region.

This case study highlights the importance of developing open-access barrier inventories for conservation planning. The development of open-access databases, which contain the location and impacts of migration barriers, is fundamental for establishing prioritized barrier inventories. However, effective data management would require central coordination, across LMB countries and a commitment to maintain the databases over a longer term. Logistically, such an endeavor is possible, but requires ongoing maintenance to ensure the barrier data are accurate. The implementation of these barrier identification and prioritization programs – using open-access inventories – would enhance river restoration efforts by enabling the true level of river fragmentation to be quantified and recognized.