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PERSPECTIVE

Global Dam Watch: curated data and tools for management and decision making

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Abstract

Dams, reservoirs, and other water management infrastructure provide benefits, but can also have negative impacts. Dam construction and removal affects progress toward the UN sustainable development goals at local to global scales. Yet, globally-consistent information on the location and characteristics of these structures are lacking, with information often highly localised, fragmented, or inaccessible. A freely available, curated, consistent, and regularly updated global database of existing dams and other instream infrastructure is needed along with open access tools to support research, decision-making and management needs. Here we introduce the Global Dam Watch (GDW) initiative (www.globaldamwatch.org) whose objectives are: (a) advancing recent efforts to develop a single, globally consistent dam and instream barrier data product for global-scale analyses (the GDW database); (b) bringing together the increasingly numerous global, regional and local dam and instream barrier datasets in a directory of databases (the GDW directory); (c) building tools for the visualisation of dam and instream barrier data and for analyses in support of policy and decision making (the GDW knowledge-base) and (d) advancing earth observation and geographical information system techniques to map a wider range of instream structures and their properties.

Our focus is on all types of anthropogenic instream barriers, though we have started by prioritizing major reservoir dams and run-of-river barriers, for which more information is available. Our goal is to facilitate national-scale, basin-scale and global-scale mapping, analyses and understanding of all instream barriers, their impacts and their role in sustainable development through the provision of publicly accessible information and tools. We invite input and partnerships across sectors to strengthen GDW's utility and relevance for all, help define database content and knowledge-base tools, and generally expand the reach of GDW as a global hub of impartial academic expertise and policy information regarding dams and other instream barriers.

1. Introduction

Dams, other instream barriers and associated water management infrastructure such as reservoirs (hereafter dams or instream infrastructure) are built to support social and economic development and are one of the most pervasive global geo-engineering works in human history. Damming rivers for hydropower generation, water supply, flood control, navigation and other purposes provides huge social benefits, while also causing destructive inundation, fragmentation, regulation, and other impacts to land and water ecosystems and to societies (Vörösmarty *et al* 2003, Syvitski and Milliman 2007, Richter *et al* 2010, Haddeland *et al* 2014, Kirchherr *et al* 2016, Scherer and Pfister 2016, Latrubesse *et al* 2017, Veldkamp *et al* 2017, Siciliano *et al* 2018, Grill *et al* 2019, Frederikse *et al* 2020). Globally, dam construction (Zarfl *et al* 2015, Winemiller *et al* 2016, Wagner *et al* 2019, Tang *et al* 2019) and removal (Garcia de Leaniz 2008, O'Connor *et al* 2015, Bellmore *et al* 2017, Ding *et al* 2019, Habel *et al* 2020) continue apace; yet neither is adequately monitored nor documented in the public domain (Couto and Olden 2018, Lange *et al* 2019, Schulz and Adams 2019). Dam construction and removal have consequences for managing and tracking progress toward UN sustainable development goals (Szabo *et al* 2016b, Ho and Goethals 2019, Mulligan *et al* 2020a), the Paris climate accord (Hermoso 2017, Matthews and McCartney 2017, Baruch-Mordo *et al* 2019), and the UN convention on diodiversity (Hughes 2017, Zarfl *et al* 2019). With improved and open-access documentation of existing and proposed instream infrastructure (Ansar *et al* 2014, Jeuland 2020), international development aid supporting investment for these structures could be made more effective, efficient, and equitable. There is a need for a freely available, curated (i.e. selected, organized, and verified using expert knowledge), consistent, and regularly updated global database of existing dams and other instream infrastructure and their attributes, to facilitate more transparent decision-making and management (Januchowski-Hartley *et al* 2013, Nazemi and Wheater 2015, Pelayo-Villamil *et al* 2015, Thieme and Tickner 2015, Winemiller *et al* 2016, Grill *et al* 2019, Belletti *et al* 2020, Maavara *et al* 2020). Existing dam inventories vary widely in scope (types of dams and other barriers included), quality (degree of curation), geographical coverage (local to global), consistency of mapping effort between basins and countries, and accessibility (public domain, pay-walled or restricted). Nevertheless, an impressive range of analyses (figure 1) and tools have been produced over the last decade, which could be further accelerated by a concerted effort focused on creating and providing collaborative, open-access dam data and tools. Examples of current open-access tools include the reservoir assessment tool (Biswas *et al* 2021), which provides information on the operation of current and planned large dams, and the Global Reservoirs and Lakes Monitor [G-REALM] (Birkett *et al* 2009), which provides water level information for lakes and reservoirs based on satellite altimetry.

Though there have been concerted efforts to develop comprehensive local and regional dam datasets, these cannot easily be aggregated into a global repository. In particular, data consistency is necessary for global analyses and includes: (a) consistently applied definitions and classifications of dams and instream barriers; (b) a consistent methodology and effort in mapping between countries and basins; and (c) consistently recorded or calculated dam attributes. The few globally consistent datasets that currently exist are known to be highly incomplete, as they miss many smaller dams or important attributes.

Despite the current limitations, the utility of consistent global dam inventories and their potential to advance a broad range of water resource assessments has been showcased in a variety of recent cutting edge studies. For example, Veldkamp *et al* (2017) used the global reservoir and dam database (GRanD; Lehner *et al* 2011) to ascertain that reservoirs alleviated water scarcity for 8.3% of the global population but exacerbated water scarcity for 8.8%, most of whom lived downstream of reservoirs. Frederikse *et al* (2020) used GRanD to gauge how reservoir filling in the 1970s and 1980s slowed sea level rise associated with global warming. Maavara *et al* (2020) combined GRanD and the future hydropower reservoir and dam database (FHReD; Zarfl *et al* 2015) to assess how reservoirs affect the ratio of key nutrients that are transported through rivers to the oceans at the global scale, and how future hydropower development will change those ratios over the coming decades. Gonzalez Sanchez *et al* (2020) used GRanD and the global surface water dataset (GSW; Pekel *et al* 2016) to analyse the gross water lost through evaporation in African hydropower reservoirs, and Grill *et al* (2019) combined GRanD and the global georeferenced database of dams (GOODD; Mulligan *et al* 2009, 2020b) to present a high-resolution river connectivity assessment and identify the world's remaining free-flowing rivers. Barbarossa *et al* (2020) combined GOODD, GranD and FHReD data to examine impacts on geographic range connectivity of freshwater fish globally and Zarfl *et al* (2019) evaluated how future large hydropower dams might impact global freshwater megafauna. Finally, Cooley *et al* (2021) used GOODD to understand human alteration of global surface water storage variability.

Here, we advocate for developing a more comprehensive, freely available and curated global dam database alongside a suite of tools to help grow, manage and convert these data into open-access, actionable national,

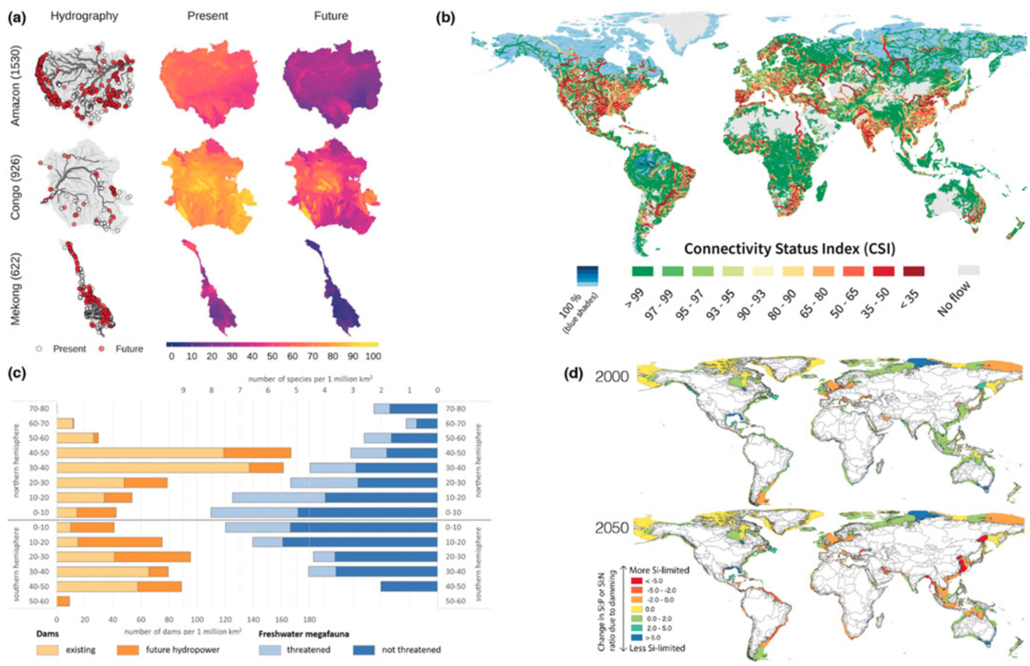

Figure 1. Visual examples of research that uses global dam data. (a) Barbarossa *et al* (2020) integrated data from GRanD, GOODD, and FHReD to assess the effects of existing and future dams on fish migration. Reproduced with permission from Barbarossa *et al* (2020). CC BY 4.0; (b) Grill *et al* (2019) merged data from GRanD and GOODD to quantify connectivity along the world's rivers. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature, Mapping the world's free-flowing rivers, Grill *et al* (2019); (c) Zarfl *et al* (2019) used GRanD and FHReD to highlight overlaps between existing and future dam development and threatened freshwater megafauna. Reproduced from Zarfl *et al* (2019). CC BY 4.0; (d) Maavara *et al* (2020) used GRanD and FHReD to calculate how existing and future dams affect ratios of key nutrients that are delivered from rivers to coastal zones. Maavara *et al* (2020). John Wiley & Sons. ©2020. American Geophysical Union. All Rights Reserved.

basin and global *intelligence* on dams to accelerate sustainable solutions at the water, energy, food and environment nexus. As stewards and custodians for this effort, we hereby introduce the Global Dam Watch (GDW) initiative (www.globaldamwatch.org) with the following goals:

(a) Establishing cross-sector collaborations to expand on previous efforts to develop a single, globally consistent dam and instream barrier database (the GDW database). This could be used as a community standard to further investigate pressing global-scale questions (examples are given in figure 1). This database is currently being compiled, and while the intent is to include all types of dam and instream barriers and to clearly separate the different types, the compilation has started from the largest and thus most widely documented structures. The initial databases to be included in this harmonization effort are available at www.globaldamwatch.org (GOODD, GranD and FHReD) and currently contain 38 660, 7320 and 3700 dams, respectively, which represent medium to large (GOODD), large only (GRanD), and planned dams (FHReD).

(b) Bringing together the increasingly numerous global, regional and local dam and instream barrier datasets in a directory of databases (the GDW directory). The GDW directory currently links to 14 regional databases and 7 global databases.

(c) Building tools for the presentation and assessment of dam and instream barrier data and for analyses in support of policy and decision making (the GDW knowledge-base). The GDW knowledge-base currently includes 121 396 dams under curation and a total of more than 8 million attribute values. A range of tools are available for adding, editing, moving, and connecting dams to hydrological flow networks as well as summarising and visualising dams and their attributes at the national and basin scales.

(d) Advancing earth observation and geographical information system (GIS) techniques to map more of the full range of instream structures and their properties.

2. The challenge of multiple inconsistent and static databases

Existing dam inventories provide a valuable foundation for any researcher who seeks to investigate the effects of dams. The challenge is that the data exist, but vary widely in scope, quality, spatial coverage, temporal scale, and accessibility, and there is little guidance as to which data might be most appropriate for a given research or policy question. This slows research progress and hinders access by decision-makers. Across regions and within countries, there have been some concerted efforts to develop comprehensive local dam datasets. For example, in Europe, Belletti *et al* (2020) collated records for more than 600 000 dams, weirs, and culverts from government databases. The Water Land and Ecosystems—Mekong Dams Observatory (2018) and Stimson Center's Mekong Dam Monitor (2020) provide free data with locations and attributes for hundreds of dams in the six countries that intersect with the Mekong River basin. Government agencies in Brazil (Agência Nacional de Águas 2018), South Africa (list of registered dams), and the United States (National Inventory of Dams) all maintain publicly available national dam databases, which include thousands (in the case of South Africa) to tens of thousands (in the case of Brazil and the US) of records. Academic contributions include Jones *et al* (2019) who provide a comprehensive database for Great Britain, Jones *et al* (2017) for the Volta basin and Speckhann *et al* (2021) for Germany. Built for a particular place and purpose, the criteria for dam inclusion and the associated attributes within regional and country-level databases vary, making them difficult to integrate.

Existing *global* databases have the benefit of more consistent information across regions but tend to be skewed towards larger dams (Garcia de Leaniz *et al* 2019), are only updated sporadically, and often place an emphasis on certain types of instream infrastructure, such as hydropower dams. The focus on large dams for global scale databases makes sense given that these are easiest to detect. At the global scale, the GRanD database includes georeferenced locations and a variety of attributes for over 7000 dams but focuses on dams with large reservoirs (Lehner *et al* 2011). The GOODD database contains more than 38 000 georeferenced dam locations, including medium-sized infrastructure, but lacks associated attributes (such as year of construction, physical attributes of the dam and reservoir, drainage area, or purpose) because the data were manually mapped from satellite imagery (Mulligan *et al* 2009, Mulligan *et al* 2020b). The proprietary ICOLD database (International Commission on Large Dams 2020) includes information on nearly 60 000 dams and has the benefit of regular updates, but it also focuses on large dams, not all dams have been georeferenced, and the data are not open-access. Some recent studies have started to combine parts of these different sources towards a specific objective (for example the georeferenced global dam and reservoir dataset (GeoDAR; Wang *et al* 2021), yet to our knowledge none contains the full suite of available records and attributes. This mix of regional and global data with varied characteristics complicates the decision over which dataset to use in the evaluation of impacts or potential mitigation solutions, and none may be fully adequate for the task. Equally, the complex procedure of combining and cleaning such disparate databases continues to fall on individual end-users, and ultimately leads to duplication of effort while producing a variety of products that are tailored to the individual focus of the users. All together these and other existing datasets provide an inconsistent picture of the world's dams, though they remain useful for analyses within their specific area of application. Given the described shortcomings, we believe that an open-access one-stop-shop for global dam information will accelerate our ability to understand and analyse the world's distribution of dams, their benefits and dis-benefits.

There are millions of small dams and instream barriers around the world (Smith *et al* 2002, Lehner *et al* 2011, Belletti *et al* 2020) that appear in none of the local or global databases. As a result, there is a need for a more comprehensive and consistent inventory to enable quantification of their cumulative benefits, risks and disbenefits for ecosystems and societies (Kibler and Tullos 2013, Fencl *et al* 2015, Athayde *et al* 2019, Jones *et al* 2019, Januchowski-Hartley *et al* 2020) globally, as well as for comparison between countries and basins. Such data have direct implications for several UN sustainable development goals, including those related to infrastructure development (SDG 9), affordable and clean energy (SDG 7), food (SDG 2) and water (SDG 6). Currently, tracking changes in dam construction, operation, and removal is difficult to achieve because of the inconsistency of existing static databases and the difficulty involved in *manually* monitoring such developments over time. However, we believe that these limitations can be overcome through greater coordination and collaboration, coupled with advances in participatory science, remote sensing, and machine learning that could help in inclusion of smaller infrastructure (see Whittemore *et al* 2020). We also see emerging opportunities to represent reservoir dynamics, and to document historical dam construction dates, ownership, hydropower capacity, water withdrawal amounts, and other attributes through growing partnerships and participatory science initiatives fostered through GDW.

3. The Global Dam Watch initiative

The GDW initiative is led by a cooperative network of dam and instream barrier data and tool providers, which works with users across sectors and scales to gather, curate and share high quality, georeferenced data. This initiative will provide: a directory of existing local, regional and global databases; an internationally consistent, free, curated, regularly updated global database of dams and instream barriers; and a suite of tools for analysis of dams and their benefits and impacts. As a first step toward these goals, we are creating a single global database that is scheduled for release in late 2021 which will initially harmonize data from: GRanD (Lehner *et al* 2011), GOODD (Mulligan *et al* 2009, 2020b), FHReD (Zarfl *et al* 2015), the global river obstruction database (Whittmore *et al* 2020), and the GSW dataset developed by the Joint Research Centre of the European Commission (JRC) (Pekel *et al* 2016). Furthermore, our GDW knowledge-base is online at www.globaldamwatch.org and provides tools for managing dam data, visualisation of attributes, various analyses and downloadable data at the national and basin scale, with global extent.

Going forward, GDW aims to curate and maintain a dynamic global-scale dam and instream barrier database (the GDW database) through a combination of geo-wiki approaches (*sensu* Mulligan *et al* 2009, 2020a, 2020b), supervised machine learning techniques and expert systems applied to high and medium resolution satellite imagery, *in situ* and space-borne altimetry level measurements, and relevant emerging methods or technologies. In addition, through the GDW website (www.globaldamwatch.org), we will share links and information on existing regional and country-level databases of dams and freshwater barriers (the GDW directory). The GDW directory will organize these existing resources together in a single searchable online directory to facilitate their discovery and recognition. These databases can offer locations of smaller run-of-river dams, wing dams, partial dams, weirs, locks, as well as other instream structures associated with roads such as culverts, fords, and bridges. Finally, we aim to further develop and provide web-based tools and analyses (the GDW knowledge-base) on dams, their benefits, impacts and environmental challenges. All of these will be supported by enhanced use of earth observation and GIS techniques to map more of the full range of instream structures and their properties.

4. A GDW invitation

The provision of a high quality, globally consistent and current georeferenced global dam database will open significant opportunities for further knowledge generation and applications, as well as more consistent analyses across disciplines and scales. While data contained within version 1 of the GDW database will offer a robust starting point, it will need to evolve over time. Alongside updates which include new dams or dam removals, we envision a broad suite of attributes agreed upon by data developers and users that would increase understanding of the status of dams and potential dam futures. Some of the attributes may include, for example, reservoir extent, level, and storage dynamics, dam purpose, operation rules, construction date, hydropower potential, reservoir evaporative loss, temperature profile, water quality, and sedimentation rates. From these emerging data, we envision analyses and analytical tools that explore interrelations between dam development and other global changes (e.g. population, land use, and climate change) to better understand shifting water dynamics, provision, and vulnerability as well as impacts on local and downstream aquatic and riparian biodiversity, ecosystem health, and ecosystem services (nature's contributions to people). The contribution of dams to local, national and global food, water and energy security will also be better supported with improved data access. We recognize that these goals can only be achieved through collaborative and inclusive effort. Thus, we invite input and partnerships from industry, governments, research institutions, non-governmental organisations, and policy makers to strengthen GDW's utility and relevance to a broad range of communities, help define database content and knowledge-base tools, provide analytical expertise, better understand domain-specific applications, and generally expand the reach of GDW.

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Data availability statement

No new data were created or analysed in this study.

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