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, Sicilian 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 (Hermo 2017, Matthews and McCartney 2017, Baruch-Mordo et al 2019), and the UN convention on biodiversity (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 Wheeler 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 (consists 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,
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, 7,320 and 3,700 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, Fencil 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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References

Agência Nacional de Águas 2018 Relatório de Segurança de Barragens 2017 (Brasilia Agência Nacional de Águas)
Amsar A, Flyvbjerg B, Budzier A and Lunn D 2014 Should we build more large dams? The actual costs of hydropower megaproject development Energy Policy 69 43–56
Athayde S, Duarte C G, Gallardo A L C F, Moretto E M, Sangoi L A, DiBo A P A, Siqueira-Gay J and Sánchez L E 2019 Improving policies and instruments to address cumulative impacts of small hydropower in the Amazon Energy Policy 132 265–71
Barborosa V, Schmitz R J P, Huijbregts M A J, Zarf C, King H and Schipper A M 2020 Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide Proc. Natl Acad. Sci. 117 201912776
Baruch-Mordo S, Kiesecker J, Kennedy C M, Oakleaf J R and Opperman J J 2019 From Paris to practice: sustainable implementation of renewable energy goals Environ. Res. Lett. 14 024013
Belletti B et al 2020 More than one million barriers fragment Europe’s rivers Nature 588 436–41
Birkett C M, Reynolds C, Beckley B and Dooms B 2009 From research to operations: the USDA global reservoir and Lake monitor Coastal Altimetry 6 S Vignudelli, A G Kostianoy, P Cipollini and J Benveniste (Berlin: Springer) ch 2
Biswas N, Hossain F, Bonnema M, Lee H and Chishite F 2021 Towards a global reservoir assessment tool for predicting hydrologic impacts and operating patterns of existing and planned reservoirs Environ. Model. Software 140 105043
Cooley S W, Ryan J C and Smith L C 2021 Human alteration of global surface water storage variability Nature 591 78–81
Couto T B and Olden J D 2018 Global proliferation of small hydroelectric plants—science and policy Front. Ecol. Environ. 16 91–100
Ding L, Chen L, Ding C and Tao J 2019 Global trends in dam removal and related research: a systematic review based on associated datasets and bibliometric analysis Chin. Geogr. Sci. 29 1–12
Fend J S, Matter M E, Costigan K H and Daniels M D 2015 How big of an effect do small dams have? Using geomorphological footprints to quantify spatial impact of low-head dams and identify patterns of across-dam variation PlaS One 10 1–22
Frederikse T et al 2020 The causes of sea-level rise since 1900 Nature 584 393–7
Garcia de Leaniz C 2008 Weir removal in salmonid streams: implications, challenges and practicalities Hydrobiologia 609 83–96
Garcia de Leaniz C, Berkhuyzen A and Belletti B 2019 Beware small dams, they can do damage, too Nature 570 164
Gonzalez Sanchez R, Seliger R, Fahl F, De Felice L, Ouarda T B M J and Farinosi F 2020 Freshwater use of the energy sector in Africa Appl. Energy 270 115171
Grill G et al 2019 Mapping the world’s free-flowing rivers Nature 569 215–21
Habel M, Meckkin K, Podgorska K, Saunes M, Babitski Z, Chalov S, Absalon D, Podgórski Z and Obołówski K 2020 Dam and reservoir removal projects: a mix of social-ecological trends and cost-cutting attitudes Sci. Rep. 10 19210
Haddeland I et al 2014 Global water resources affected by human interventions and climate change Proc. Natl Acad. Sci. 111 3251–6
Hermoso V 2017 Freshwater ecosystems could become the biggest losers of the Paris Agreement Global Change Biol. 23 3433–6
Ho L T and Goethals P L M 2019 Opportunities and challenges for the sustainability of lakes and reservoirs in relation to the sustainable development goals (SDGs) Water 11 1462
Hughes A C 2017 Understanding the drivers of Southeast Asian biodiversity loss Ecosphere 8 e01624
International Commission on Large Dams 2020 Large dams 2020 General synthesis methods Int. Comm. Large Dams. http://icold-cigb.net/_gb/world_register/general_synthesis.asp (accessed 10 November 2017)
Januchowski-Hartley S R, Mclntyre P B, Diebel M, Doran P J, Infante D M, Joseph C and Allan J D 2013 Restoring aquatic ecosystem services and evidence of environmental and ecological responses Ecol. Solut. Evol. 1 e12026
Jeuland M 2020 The economics of dams Oxf. Rev. Econ. Pol. 36 45–68
Jones J et al 2019 A comprehensive assessment of stream fragmentation in Great Britain Sci. Total Environ. 673 756–62
Jones S K, Bremer A K, DeClerck F A, Smedley D, Ortega Pieck A and Mulligan M 2017 Big data and multiple methods for mapping small reservoirs: comparing accuracies in agricultural landscapes Remote Sens. 9 1307
Kibler K and Instruments to address cumulative impacts of small hydropower in the Amazon Energy Policy 132 265–71
Kirchherr J, Pohlner H and Charles K J 2016 Cleaning up the big muddy: a meta-synthesis of the research on the social impact of dams Environ. Impact Assess. Rev. 60 115–25
Lange K et al 2019 Small hydropower goes unchecked Front. Ecol. Environ. 17 256–8
Larubresse E M et al 2017 Damming the rivers of the Amazon basin Nature 546 563–9
Lehner B et al 2011 High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management Front. Ecol. Environ. 9 494–502
Maavara T, Akbarzadeh Z and van Cappellen P 2020 Global dam-driven changes to riverine N:P:Si ratios delivered to the coastal ocean Geophys. Res. Lett. 47 1–9
Matthews N and McCartney M 2018 Opportunities for building resilience and lessons for navigating risks: dams and the water energy food nexus Environ. Prog. Sustain. Energy 37 56–61
Mulligan M, Saenz-Cruz L, van Soesbergen A, Smith V T and Zurita I 2009 Global dams database and geowiki. Version 1. http://geodata.policysupport.org/dams
Mulligan M, van Soesbergen A, Hole D G, Brooks T M, Burke S and Hutton J 2020a Mapping nature’s contribution to SDG 6 and implications for other SDGs at policy relevant scales Remote Sens. Environ. 239 111671
Mulligan M, van Soesbergen A and Sáenz L 2020b GOODD, a global dataset of more than 38,000 georeferenced dams Sci. Data 7 1
Mulligan M 2015b Trading off agriculture with nature’s other benefits, spatially Impact of Climate Change on Water Resources in Agriculture ed C A Zolin and R de A R Rodrigues (Boca Raton, FL: CRC Press) pp 184–204
National Inventory of Dams US Army Corps of Engineers: Federal Emergency Management Agency, Washington, DC https:// nid.sec.usace.army.mil/
Nazemi A and Wheater H S 2015 On inclusion of water resource management in Earth system models: II. Representation of water supply and allocation and opportunities for improved modeling Hydrol. Earth Syst. Sci. 19 63–90
O’Connor J E, Duda J J and Grant G E 2015 1000 dams down and counting Science 348 496–7
Pekel J-F, Cottam A, Gorelick N and Belward A S 2016 High-resolution mapping of global surface water and its long-term changes Nature 540 418–22
Pelayo-Villamil P et al 2015 Global diversity patterns of freshwater fishes—potential victims of their own success Divers. Distrib. 21 345–56
Richter B D, Postel S, Revenga C, Scudder T, Lehner B, Churchill A and Chow M 2010 Lost in development’s shadow: the downstream human consequences of dams Water Altern. 3 14–42
Ryan Bellmore J, Duda J J, Craig L S, Greene S L, Torgersen C E, Collins M J and Vittum K 2017 Status and trends of dam removal research in the United States Wiley Interdiscip. Rev. Water 4 e1164
Scherer L and Pfister S 2016 Hydropower’s biogenic carbon footprint PLoS One 11 e0161947
Schulz C and Adams W M 2019 Debating dams: the world commission on dams 20 years on Wiley Interdiscip. Rev. Water 6 1–19
Siciliano G, Urban F, Tan-Mullins M and Mohan G 2018 Large dams, energy justice and the divergence between international, national and local developmental needs and priorities in the global south Energy Res. Soc. Sci. 41 199–209
Smith S V, Renwick W H, Bartley J D and Buddemeer R W 2002 Distribution and significance of small, artificial water bodies across the United States landscape Sci. Total Environ. 299 21–36
Speckhann G A, Kreibich H and Merz B 2021 Inventory of dams in Germany Earth Syst. Sci. Data 13 731–40
Stimson Center’s Mekong Dam Monitor 2020 Stimson Center’s South East Asia program https://stimson.org/project/me-kong-dam-monitor/ (accessed 13 January 2021)
Syvitski J P M and Milliman J D 2007 Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean J. Geol. 115 1–19
Szabo S et al 2016b Making SDGs work for climate change hotspots Environment 58 24–33
Tang S, Chen J, Sun P, Li Y, Yu P and Chen E 2019 Current and future hydropower development in Southeast Asia countries (Malaysia, Indonesia, Thailand and Myanmar) Energy Pol. 129 239–49
Thieme M and Tickner D 2015 Data, data everywhere: providing big data on dams and their impact on freshwater systems WWF Stories https://worldwildlife.org/stories/data-data-everywhere (accessed 5 January 2021)
Veldkamp T I E et al 2017 Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century Nat. Commun. 8 15697
Vörösmarty C J, Meybeck M, Fekete B, Sharma K, Green P and Syvitski J P M 2003 Anthropogenic sediment retention: major global impact from registered river impoundments Global Planet. Change 39 169–90
Wagner B, Hauer C and Habersack H 2019 Current hydropower developments in Europe Curr. Opin. Environ. Sustain. 37 41–9
Wang J et al 2021 GeoDAR: georeferenced global dam and reservoir dataset for bridging attributes and geolocations Earth Syst. Sci. Data Discuss. 1–52
Water Land and Ecosystems-Mekong 2018 Greater Mekong Dams Observatory https://wle-mekong.cgiar.org/changes/our-research/greater-mekong-dams-observatory/ (accessed 13 January 2021)
Whittemore A et al 2020 A participatory science approach to expanding instream infrastructure inventories Earth’s Future 8 e2020EF001558
Winemiller K O et al 2016 Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong Science 351 128–9
Zarfl C, Berlekamp J, He F, Jähnig S C, Darwall W and Tockner K 2019 Future large hydropower dams impact global freshwater megafauna Sci. Rep. 9 1–10
Zarfl C, Lumsdon A E, Berlekamp J, Tydecks I and Tockner K 2015 A global boom in hydropower dam construction Aquat. Sci. 77 161–70