Broken rivers: ground-truthing the world's most fragmented rivers

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June 30, 2020

Abstract

Rivers support some of Earth's richest biodiversity and provide essential ecosystem services to society, but only if they flow. In Europe, attempts to quantify river connectivity have been hampered by the absence of a harmonised barrier database. We assembled ~630,000 unique barrier records from 36 European countries and surveyed 2,715 km of 147 rivers to reveal a ~61% underestimation of barrier numbers. We estimate there are at least 1.2 million instream barriers (mean density = 0.74 barriers/km), 72% of which are low-head (<2m) structures, making Europe the world's most fragmented river landscape. The highest barrier densities occur in the heavily modified rivers of Central Europe, and the lowest in the most remote, sparsely populated alpine areas. Barrier density was predicted by agricultural pressure, road density, extent of surface water, and elevation. Relatively unfragmented rivers are still found in the Balkans, Scandinavia, the Baltic states, and parts of southern Europe, but these require urgent protection from new dam developments. Our findings can inform the implementation of the EU Biodiversity Strategy, which aims to reconnect 25,000 km of Europe's rivers by 2030, but achieving this will require a paradigm shift in river restoration that recognises the impacts caused by small barriers.

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Summary

Rivers support some of Earth's richest biodiversity and provide essential ecosystem services to society, but only if they flow. In Europe, attempts to quantify river connectivity have been hampered by the absence of a harmonised barrier database. We assembled ~630,000 unique barrier records from 36 European countries and surveyed 2,715 km of 147 rivers to reveal a ~61% underestimation of barrier numbers. We estimate there are at least 1.2 million instream barriers (mean density = 0.74 barriers/km), 72% of which are low-head (<2m) structures, making Europe the world's most fragmented river landscape. The highest barrier densities occur in the heavily modified rivers of Central Europe, and the lowest in the most remote, sparsely populated alpine areas. Barrier density was predicted by agricultural pressure, road density, extent of surface water, and elevation. Relatively unfragmented rivers are still found in the Balkans, Scandinavia, the Baltic states, and parts of southern Europe, but these require urgent protection from new dam developments. Our findings can inform the implementation of the EU Biodiversity Strategy, which aims to reconnect 25,000 km of Europe's rivers by 2030, but achieving this will require a paradigm shift in river restoration that recognises the impacts caused by small barriers.

Broken rivers

Rivers support some of the most biodiverse ecosystems in the world, but also some of the most threatened[1]. The defining characteristic of natural rivers is that they flow[2], and the most pervasive telltale of human impacts on rivers is the break in connectivity caused by artificial barriers to free-flow[3]. Without dams, weirs, fords and other instream structures it is difficult to imagine abstracting water, generating hydropower, controlling floods, ferrying goods, or simply crossing waterways. Rivers provide essential services to society, but our use of rivers has nearly always involved fragmenting them[4].

Fragmentation caused by artificial barriers can have multiple impacts on river ecosystem functioning. Barriers can modify flow patterns[5], change the chemistry and temperature of the water[6], disrupt the transport of nutrients and sediments[7], and alter the structure of riverine habitats and the biological communities that live in them[8,9]. However, assessing river fragmentation has proved challenging[10] due to the dendritic nature of rivers, the seasonality of the hydrological regime, and the spatio-temporal nature of barrier impacts[11,12].

A critical challenge for quantifying river fragmentation is the lack of information on the abundance and location of all but the largest of dams, especially over spatial scales relevant for river basin management. Global database initiatives and novel developments in remote sensing are making it possible to accurately map the location of large dams, typically those above 10 m to 15 m high[13-16], but these only represent a small fraction of all instream barriers, typically <1%[17]. Most low-head structures are unreported[18], despite the fact that their cumulative impact on river connectivity is far more substantial[19,20]. For instance, while only large storage dams can affect the hydrological regime[21], nearly all barriers can affect sediment transport[22,23], the movement of aquatic organisms[24], and the structure of river communities[19,25]. Under-reporting of small barriers vastly underestimates the extent of river fragmentation. For example, assessments of fragmentation based solely on large dams[13] would ignore 99.6% of the barriers present in Britain[26]. To estimate the true extent of river fragmentation, all barriers need to be considered, large and small.

With only one third of its rivers having 'good ecological status' according to criteria of the EU Water Framework Directive (WFD)[27], Europe probably has more heavily modified rivers than anywhere else in the world[28,29], as well as a long legacy of fragmentation, with fish passage legislation dating back to the 7th century[9]. Strikingly, the extent of river connectivity remains unknown for most European rivers, despite the fact that the concept of river continuity is enshrined in the WFD and inventories of physical barriers are required in River Basin Management Plans (RBMP)[30]. Yet, there is no comprehensive inventory of stream barriers in Europe, only disparate records that differ in quality and spatial coverage from country to country[31,32]. Many weirs in Europe, for instance, were built at the turn of the 18th century and sometimes much earlier, and their number and location are consequently poorly known[33,34].

Here we present the first comprehensive estimates of river fragmentation in Europe based on empirical and modelled barrier densities. We collated and harmonised information on 736,348 instream barriers from 120 regional, national and global datasets, and applied robust exclusion rules to identify unique barrier records. To account for underreporting, we surveyed 147 rivers in 26 countries to derive field-corrected barrier densities and employed a machine learning algorithm to estimate the number and location of missing barriers. Our results indicate that patterns of river fragmentation largely reflect the distribution of other anthropogenic pressures on rivers, and highlight the need for a concerted global effort to map low-head structures and complement existing large dam databases.

Barrier density, typology and distribution

We identified 629,955 unique artificial barriers in 36 countries (**Figure 1**), after excluding 106,393 duplicates (see Methods). This figure is one order of magnitude higher than previous estimates of longitudinal fragmentation for Europe based only on large dams[15,16], but consistent with regional[33,35,36] and country estimates that considered all barriers[26]. We combined over 1,000 different barrier types into six main functional categories that capture variation in barrier use and size[26] (**Table 1**). Most barriers are structures built to control and divert water flow, or to raise water levels, such as weirs (30.5%), dams (9.8%), and sluice gates (1.3%), to stabilise river beds, such as ramps and bed sills (31.5%), or to accommodate road crossings, such as culverts (17.6%) and fords (0.3%). In 8.9% of cases, barrier type was not recorded or could not be easily classified into one of our six main types (e.g., gauge stations, spillways, groynes). Height data for 119,227 records indicate that 72.5% of barriers are less than 2 m high and 91.4% are less than 5 m high (mean = 2.77 m, SE = 0.258; median = 1.20 m; **Extended Figure 1**), which probably explains why so many barriers are easily missed, and why low-head structures are vastly under-represented in most barrier inventories.

Accounting for barrier underreporting

Barrier inventories in Europe are not homogeneous (**Table 1**), and because they were compiled for different purposes and have different spatial coverage (**Figure 2A**), suffer from strong sampling bias and result in under-reporting of small structures. We adopted two complementary strategies to account for barrier under-reporting and derive more realistic barrier densities: ground-truthing of existing barrier records via walkover field surveys in matched river reaches across Europe (a bottom-up strategy), and barrier modelling at sub-catchment level using machine learning (a top-down strategy;**Box 1**).

To ground-truth barrier density estimates, we surveyed contiguous ~20 km reaches in 147 rivers across 26 countries, totalling 2,715 km or 0.16% of the river network (**Extended Data Table 1; Extended Data Figure 2**) using a method described previously[26]. Surveyed reaches were mostly single thread (>80%) and spanned Strahler stream orders 1 to 8, although most were order 3-5 (62%). In total, we encountered 1,583 barriers, of which 960 were new records for the study reaches compared to inventories held by regional or national water managers (**Suppl. Material Table S1**). None of the 147 surveyed rivers were free of artificial barriers (although some of the contiguous 20 km test-reaches were, see Methods). The number of barriers recorded in the field was on average 2.5 times higher than those in existing inventories. Field-corrected barrier densities indicate that there are on average 0.74 barriers per km of stream across Europe, ranging from 0.005 barriers/km for Montenegro to 19.44 barriers/km for the Netherlands (**Table 1**) with a median distance between adjacent barriers for all countries of 108 m (SE = 44). This equates to 1.2M barriers using a conservative estimate of 1.65M km for the river network[37], but could be as high as 3.7M barriers if we consider a 5M km river network, a figure that better takes into account the abundance of first and second order streams[38]. On the other hand, our modelling of barrier density predicted 0.60 barriers/km (SE = 0.24; **Extended Data Figure 3**), or nearly 1M barriers, which is within 20% of the field-corrected estimate. The best model of barrier density across Europe included agricultural pressure, road density, proportion of area covered by surface water and elevation as main predictors (**Extended Data Figure 4** ; model performance equals 40% of explained variance).

Regardless of the method used to correct for underreporting, the highest barrier densities are found in central Europe and correspond with densely populated areas, intense use of water, and high road density (**Figure 2B,C; Extended Data Figure 5**); in contrast, the lowest barrier densities generally occur in the most remote, sparsely populated alpine areas (e.g., Scandinavia, Iceland and Scotland). This pattern of river fragmentation largely mirrors the distribution of other anthropic pressures in Europe[39], as well as the location of rivers of good ecological status[27]. Although no catchment in Europe is free of artificial barriers, there are still relatively unfragmented rivers in the Balkans, Scandinavia, the headwaters of the Baltic States, and parts of Southern Europe. Worryingly, these are also the areas where most new hydropower dams are being planned[40,41], which may be contrary to the precautionary principle that guides the WFD.

A call for action on small barriers

Views on global patterns of river fragmentation have been dominated by consideration of large dams (>15 m) due to safety and economic reasons[42], but also because these create large reservoirs that are easier to detect remotely[43,44], they can generate social conflict[42,45], and there is an implicit assumption that large dams are primarily responsible for the loss of longitudinal connectivity[46]. However, our study shows that dams >15 m are rare (2.8%) and that most barriers to free-flow are small structures that are difficult to detect and poorly mapped (**Figure 1**). For example, in Switzerland fragmentation is mostly caused by ~100,000 small bed sills built in recent years to compensate for bed incision caused by channel straightening[47]. Loss of connectivity depends mostly on the number and location of barriers, not on their height[48].

By ground-truthing existing barrier records with extensive walkover surveys, we estimate there are at least 1.2M barriers in Europe's rivers, resulting in an overall barrier density of 0.74 barriers/km, of which 0.096 barriers/km correspond to structures greater than 2 m in height. Such density is significantly higher than barrier density estimates for USA, China, Brazil or Japan (**Suppl. Material Table S2**), possibly making Europe the most fragmented river landscape in the world. However, as many of these barriers are small, old and obsolete, they provide unprecedented opportunities for restoring connectivity which our study can help inform.

Firstly, to restore connectivity efficiently, we call for better mapping and monitoring of barriers, particularly small ones, as they are the most abundant and the main cause of fragmentation. Although barrier density is only a crude measure of fragmentation, the number and location of barriers serves as the basis for most metrics of river connectivity[48]. In this sense, our work highlights the merits, but also the limitations, of modelling fragmentation, and suggests that there is no substitute for a "boots on the ground" approach for estimating barrier numbers and location[26,36]. It also exposes the inadequacies of current barrier inventories, and emphasizes the need for complete, harmonized barrier databases in order to select the river catchments that offer the best prospects for restoration of connectivity.

With nearly 630,000 records, the AMBER Barrier Atlas (https://amber.international/european-barrier-atlas/) represents the most comprehensive barrier inventory available anywhere, but is far from being complete. A staggering 0.6M barriers are probably missing from current inventories. However, our study can help optimise future mapping efforts, and fill data gaps where information is lacking. For example, our field surveys indicate that existing records grossly underestimate the abundance of small barriers less than 0.5 m in height (Log likelihood ratio = 668.12, df = 6, $P<0.001$;**Figure 3A**), particularly ramps and river bed sills (LRT = 733.08, df = 7, $P <0.001$; **Figure 3B**), and these are structures that should be targeted in future surveys. Likewise, the completeness of current inventories differs widely from country to country (**Figure 3C**). Barrier underreporting appears to be very high across the Danube and the Balkans (76-98% underreporting), but also in Estonia (91%), Greece (97%), and particularly in Sweden regarding low-head structures (100%). Thus, although our barrier inventory is inevitably incomplete, we are able to determine where most of the information is missing. At present, the results of our study cannot be used to manage barriers at the catchment scale because although the coordinates of the barriers we mapped are essentially accurate, the underlying European digital river map (ECRINS) lacks precision [38]. More detailed hydrographic maps, available in many countries, are needed for dendric estimates of longitudinal river connectivity[26] and for detailed barrier mitigation planning.

Secondly, to reconnect rivers, information is needed on current use and legal status of barriers, as many are likely to be no longer in use and could be removed. In some parts of Europe, for example, many weirs were built to service former water mills, which have subsequently been abandoned[33,34]. Given the current impetus on barrier removal and restoration of river connectivity[49], it would make sense to start with obsolete and small (<5 m) structures, which constitute the majority of barriers in Europe. Removing small barriers will likely be easier and cheaper than removing larger infrastructures, and probably also better accepted by local stakeholders, whose support is essential for restoring river connectivity. However, removing old barriers will not increase connectivity if more barriers are built elsewhere. Current rates of fragmentation need to be halted, and this may require a critical reappraisal of the sustainability and promotion of micro-hydro development[52] against the alternative of enhancing the efficiency of existing dams.

Finally, we call for an evidence-based approach to restoring river connectivity, and the use of 'what if' predictive modelling for assessing the cost and benefits of different restoration strategies under various barrier mitigation scenarios. Given the threat of further fragmentation posed by new dams in Europe[40,50], and the new EU Biodiversity Strategy's target of reconnecting at least 25,000 km of Europe's rivers by 2030[51], our results can serve as a baseline against which future gains or losses in connectivity can be gauged. They can also be used for estimating the level of funding required to achieve desired connectivity targets, and incorporated into pan-European assessments of river "ecological status".

More generally, our analysis indicates that fragmentation caused by a myriad of low-head barriers greatly exceeds that caused by large dams, a problem not unique to Europe and likely widespread elsewhere. A global effort is hence required to map small barriers across the world's rivers. To avoid death by a thousand cuts, a paradigm shift is necessary: to recognise that while large dams may draw most of the attention, it is the small barriers that collectively do most of the damage. Small is not beautiful.

METHODS

Overview

The connectivity of most rivers in Europe is unknown[30]. To fill this gap, we quantified the abundance of artificial barriers across Europe as part of the EC-funded Horizon 2020 project 'Adaptive Management of Barriers in European Rivers' (AMBER; www.amber.international). We estimated barrier densities (No./km) in 36 European countries including all 26 member states of the European Union (EU), the United Kingdom, three members of the Economic European Area (Switzerland, Iceland and Norway) and seven countries geographically located within Europe (Albania, Andorra, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, and Serbia) covering an area of 5.025 million km^2. As there is no agreed definition of "barrier" in relation to river connectivity [52], for the purposes of our work we defined an artificial longitudinal barrier as "any built structure that interrupts or modifies the flow of water, the transport of sediments, or the movement of organisms and can cause longitudinal discontinuity".

To estimate barrier densities we used a four-step approach (**Box 1**) consisting of (1) compiling a georeferenced atlas of barrier records from local, regional and national barrier databases (the AMBER Atlas), (2) cleaning and removing duplicate records, (3) ground-truthing barrier densities with field surveys, and (4) modelling fragmentation at the pan-European scale via machine learning. This allowed us to identify nearly 630,000 unique barrier records (**Figure 1**), and to estimate the extent of longitudinal fragmentation in Europe from field-corrected (**Figure 2B**) and modelled barrier densities**Figure 2C**).

To map barriers consistently across Europe we used 86,381 functional sub-catchments with an average area of 58.2 km^2 (SE = 0.24) derived from the European Catchment and Rivers Network System database (ECRINS[37]). This database and the associated river network are derived from a 100 m resolution digital elevation model (DEM) and covers 1.65 million km of river length across the study area. Although ECRINS may underestimate river length by up to 74% compared to more detailed river networks [38], it is the only consistent river network that can currently be used for global comparisons across Europe.

Building the European Atlas of artificial instream barriers

We collected and cross-referenced barrier records from 120 databases from 36 countries (**Extended Data Figure 6**), including 65 local and regional databases, 52 national databases and four global ones. After quality checking, we harmonised records into a single relational database and removed duplicates (see below). We classified barriers into six main types that capture most of the variation in barrier size and use [26]: dam, weir, sluice, ramp/bed sill, ford, and culvert, plus 'other' (e.g., groynes, spillways) and 'unknown'. We included country, river name, geographical coordinates, and barrier height if known, as well as database source. These attributes were available in most databases and provided the information required to allow us to estimate barrier densities and compared them to ground-truthed values.

Excluding duplicated barrier records

We chose a maximum Euclidean distance of 1,000 m between neighbouring barriers within the same ECRINS sub-catchment to investigate potential duplicates; we had previously determined for a smaller database that few or no duplicates may be expected beyond 500 m [26]. To derive exclusion distances, three people working independently assessed up to 200 potential random duplicates per country, or all potential duplicates if the number was less than 200. Each person visually assessed 25% of duplicate records using Google and Bing satellite imagery, and all assessed a common subsample comprising 25% of the records. The distance between each potential duplicate was measured in QGIS 3.10 [53]. We used bootstrapping[54] to calculate a mean and 95% CI distance that excluded 80% of potential duplicates and showed 80% or better agreement between the three people working on the common subsamples using an optimised algorithm[55] (**Extended Data Table 2**).

Ground-truthing barrier records through field surveys

We ground-truthed barrier records through field surveys in 26 countries to estimate the level of barrier under-reporting as described in Belletti, et al. [56] and Jones, et al.[26]. Briefly, we chose 2-6 test rivers per country, and surveyed a contiguous 20 km reach in each test river at low flow conditions (~Q80-Q95) during the spring of 2017 and the summers of 2018 and 2019. In Denmark and Scotland we surveyed multiple 5-10 km stretches instead of 20 km due to logistic constraints. In total we surveyed 2,715 km of 147 test rivers (~100 km in most countries), which are broadly representative of the river types found in Europe in terms of altitude, slope, stream order and, where possible, land-use (**Extended Data Figure 2, Supplementary Material Table S1**). At each river reach, we recorded barrier location, barrier type, height class, barrier use (abandoned or in use), and barrier span width (full or partial river width). The influence of survey length on barrier discovery rate was determined via bootstrapping [26]using R version 4.0.0 [57]. This showed an asymptotic relationship in all cases indicating that sufficient river length had been sampled to derive robust correction factors for barrier density in each country, as well as a single correction factor across all countries (**Extended Data Table 1**). These results were used to inform the choice of calibration datasets for modelling barrier numbers using machine learning (see below).

Modelling barrier density through machine learning

We employed machine learning to model barrier densities based on anthropic and environmental predictors that were expected to be associated with breaks in river connectivity. For example, culverts tend to be associated with road-crossings [58], small weirs with water mills in headwaters [34], and storage dams with nearby cities, agriculture and hydropower [59]. Similarly, the location of barriers is also determined by topography, geology and climate [10].

For each ECRINS sub-catchment we extracted information on 11 variables (**Extended Data Table 3**): land-cover (Corine level 1: %urban, agricultural, natural, wetlands and water; [60], population density (No./km^2; [61], mean elevation (m) and slope both scaled by catchment area, dendricity (i.e., river length/No. river segments; km/No.), drainage density (i.e., river length/catchment area; l/km^2;[37,62], and number of road crossings in the river network divided by catchment area (n/km^2).[63]

For model training, we selected barrier records from six countries (Austria, France, Hungary, Poland, Sweden and Germany) that fulfilled five criteria: (1) together, they had relatively low levels of barrier under-reporting (mean correction factor = 0.28); (2) were representative of different geographical areas; (3) showed wide variation in ground-truthed barrier densities; (4) there was a national barrier database (or detailed regional ones) built with a broad purpose (for example, the EU WFD) that covered all barrier types; and (5) at least five rivers where surveyed in the field.

As per above, we used the ECRINS sub-catchment as our spatial modelling unit. This allowed us to make use of all barrier records and avoid errors that would have resulted from snapping accurate barrier locations to the less precise, low resolution ECRINS river network. For these reasons, we modelled areal barrier density (No./km^2) and then transformed into linear river density (No./km) (**Extended Data Figure 3** ; **Figure 2C**).

We used a data-driven, nonparametric Random Forest Regressor[64] developed using the *scikit-learn*library in Python. The advantages of this modelling approach are that it does not make any assumptions on the relation between predictors and the dependent variable, or about the distribution, correlation or linearity of predictors. We used k-fold (k=5) for cross validation and the Mean Decrease Impurity (MDI) index to estimate variable importance[64], based on the number of tree nodes that included each predictor, normalized by the number of samples. After some tests, the original ECRINS sub-catchments (n= 30,176; mean area = 60.90 km^2; SE=0.41) were aggregated into increasing larger ones (**Extended Data Table 4**) using an *ad-hoc* graph theory algorithm in R4.0 [57] according to a criterion of minimum aggregation area from upstream to downstream direction. This step was used to reduce the influence of confounding local factors, unrelated to the predictors.

Comparisons of model performance at different sub-catchment sizes (**Extended Data Table 4**) indicated poor model performance at the original ECRINS sub-catchment scale. Best model performance (explained variance = 0.4) was reached when the minimum aggregation area was 3,000 km^2, which corresponds to 593.5 km^{2}on average at the pan-European scale (SE = 12.6). The predicted number of barriers was broadly consistent with expectations (see below) and did not vary much between different models. The relatively high amount of unexplained variance may be due to the coarse resolution of our predictors, but also likely to the omission of key predictors of barrier density, for example unaccounted variation in barrier use, or possibly in barrier age. Instream barriers in Europe vary widely in age, and many are over 50 years or even much older [34]. A temporal mismatch may thus occur between drivers that governed barrier construction in the past and the current landscape.

Average model validation error was 0.09 barrier/km^2(0.24 barrier/km; **Extended Data Figure 7**). The model tended to overestimate the number of barriers in small sub-catchments, as well as in flat areas of France and Poland, and underestimate the highest barrier densities, possibly due to superimposition of barriers of different types and ages. Inspection of model residuals (**Extended Data Figure 7**) showed that the model was able to account for barrier under-reporting across large areas, including southern Europe, the Danube basin, the Baltic area, and Ireland. However, in general, the model underestimated the extent of river fragmentation in Europe, most likely because densities of low-head barriers are determined by local drivers operating at finer spatial scales that are not adequately captured by our study.

Despite model limitations, modeled barrier densities for sub-catchment aggregations of 3,000 km^2 were broadly consistent with field-corrected barrier densities and identified the same broad patterns of river fragmentation across Europe, especially in data-poor areas (e.g., the Danube and the Balkans; **Figure 2A, 2C**). The most important predictors of barrier density were agricultural landcover, road density, proportion of area covered by surface water, and altitude which together accounted for 0.63 in the Mean Decrease Impurity index (**Extended Data Figures 4-5**). Higher barrier densities correspond to areas with intense agricultural pressure (e.g., central Europe), and the lower densities to the more remote, alpine areas (e.g., in Scandinavia).

Mapping more realistic barrier densities

Field-derived correction factors were applied in each country to adjust existing barrier records and derive more realistic barrier densities (**Figures 2A,B** ; **Table 1**). To obtain corrected barrier densities for the 10 countries that had not been surveyed in the field we applied a mean correction factor of 0.35 barriers/km, derived from surveyed countries. This yielded a mean barrier density of 0.74 barriers/km and 1,213,874 barriers across Europe (**Table 1**). Modelling yielded a mean barrier density of 0.60 barriers/km and 991,341 barriers, which is within 20% of the results obtained by the field validation. Thus, both approaches gave congruent results and suggest that fragmentation estimates based on existing barrier records underestimate true barrier numbers by 57 to 93% according to modelling and field survey results, respectively. This is largely due to the presence of many small structures (**Extended Data Figure 1)** that are labour intensive to map and are under-reported in barrier inventories (**Figure 3A,B**).

Our barrier density estimates provide a more realistic overview of the true extent of river fragmentation in Europe, and indicate that there are more barriers than existing databases would suggest. They can also be used to predict the range of barrier densities that may be expected in data poor areas, and help direct future barrier mapping efforts to places where information is most needed, or where gaps in data are most obvious.

Author contributions

B.B., S.B. W.v.W and C.G.L. designed the study. B.B., S.B., G.S. and W.v.W. led the work and organized the collection of data. B.B., S.B., J.J., L.B., A.C., G.S. & C.G.L. carried out the analysis. B.B. and C.G.L. wrote the initial drafts of the manuscript with input from S.B., A.C., L.B., J.J. and W.v.W. G.S. and J.J. designed and curated the barrier database. P.F.G. and R.O.A. collated existing barrier inventories. All co-authors critically revised the edited manuscript.

Acknowledgements

This study was funded by the EC Horizon 2020 Research & Innovation Programme, AMBER - Adaptive Management of Barriers in European Rivers Project, grant agreement No. 689682 led by C.G.L. We are grateful to all the people who facilitated barrier data from local, regional and national inventories listed in Table S3.

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Table 1. Number of unique barrier records in the AMBER Barrier Atlas by barrier type and country, and corrected abundance estimates obtained by applying bootstrapped correction factors on the level of underreporting inferred from field surveys (see Methods).

Country	ECRINS river network (km)	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Atlas barrier density (No/km)	C b d (
		Dam	Weir	Sluice	Culvert	Ford	Ramp	Other	NA	Total		
Albania (AL)	16,717	210							308	518	0.03	0
Andorra (AD)	273	43	267							310	1.14	1
Austria (AT)	41,429	19,380	2,208		4		3	5,812		27,407	0.66	1
Belgium (BE)	8,018	1,504	1,388	254	1,993		4	1,394	205	6,742	0.84	1
Bosnia-Herzegovina (BA)	25,295	20	1					11	182	214	0.01	0
Bulgaria (BG)	42,050	187							549	736	0.02	0
Croatia (HR)	21,985	25							88	113	0.01	0
Cyprus (CY)	2,811	119		1				165		285	0.10	0
Czech Republic (CZ)	26,788	2,210	1,934				7	1,331		5,482	0.20	0
Denmark (DK)	6,723	333	380	19	186		863	305	980	3,066	0.46	0
Estonia (EE)	9,981	187								187	0.02	0
Finland (FI)	87,703	96						733		829	0.01	0
France (FR)	183,373	8,744	36,855	346	5,915	357	4,512	1,579	3,652	61,960	0.34	0
Germany (DE)	104,142	4,250	19,236	530	72,795	337	76,895	4,944	9	178,996	1.72	2
Greece (GR)	61,994	143							75	218	0.00	0

Country	ECRINS river network (km)	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Atlas barrier density (No/km)	C b d (
Hungary (HU)	21,483	781	1,048	875				79		2,783	0.13	0
Iceland (IS)	16,367	32								32	0.00	0
Ireland (IE)	19,503	32	389	30	390	34	554	87	16	1,532	0.08	0
Italy (IT)	134,868	1,417	20,427			586	7,846	1,763		32,039	0.24	0
Latvia (LV)	16,589	601							1	602	0.04	0
Lithuania (LT)	17,218	125							1,132	1,257	0.07	0
Luxembourg (LU)	960	6	7		3		15	5		36	0.04	0
Montenegro (ME)	7,621	5							33	38	0.00	0
Netherlands (NL)	3,220	15	55,762	328	11		30	6,440		62,586	19.44	1
North Macedonia (MK)	12,876	7							166	173	0.01	0
Norway (NO)	107,079	3,977	1		1		1			3,980	0.04	0
Poland (PL)	80,401	1,071	10,742	2707	1,339		44		268	16,171	0.20	0
Portugal (PT)	31,451	725	117				1		354	1,197	0.04	0
Romania (RO)	78,829	305	6	3				302	175	791	0.01	0
Serbia (RS)	25,376	73	3						197	273	0.01	0
Slovakia (SK)	20,412	147	4					1		152	0.01	0
Slovenia (SI)	9,891	23	1						669	693	0.07	0
Spain (ES)	187,809	5,131	17,005	10	135	104	2,725	1,429	3,343	29,882	0.16	0
Sweden (SE)	128,357	7,628	2,483		8,013		1,033		338	19,495	0.15	0
Switzerland (CH)	21,178	415	4,599	93	19,888	722	103,961	670	15,113	145,461	6.87	8

Country	ECRINS river net-work (km)	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Number of each Barrier Type	Atlas barrier density (No/km)	C b d (
United King-dom (UK)	68,719	1,566	17,539	2915	266	61	92	1,280		23,719	0.35	0
Total	**1,649,489**	**61,533**	**192,402**	**8,111**	**110,939**	**2,201**	**198,586**	**28,330**	**27,853**	**629,955**	**0.38**	**0 S**

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Box 1. Four-step approach used to estimate barrier densities: (1) compilation of georeferenced barrier records from local, regional and national barrier databases (the AMBER Atlas), (2) data cleaning and removal of duplicate records, (3) ground-truthing barrier densities with field surveys, and (4) modelling fragmentation via machine learning.

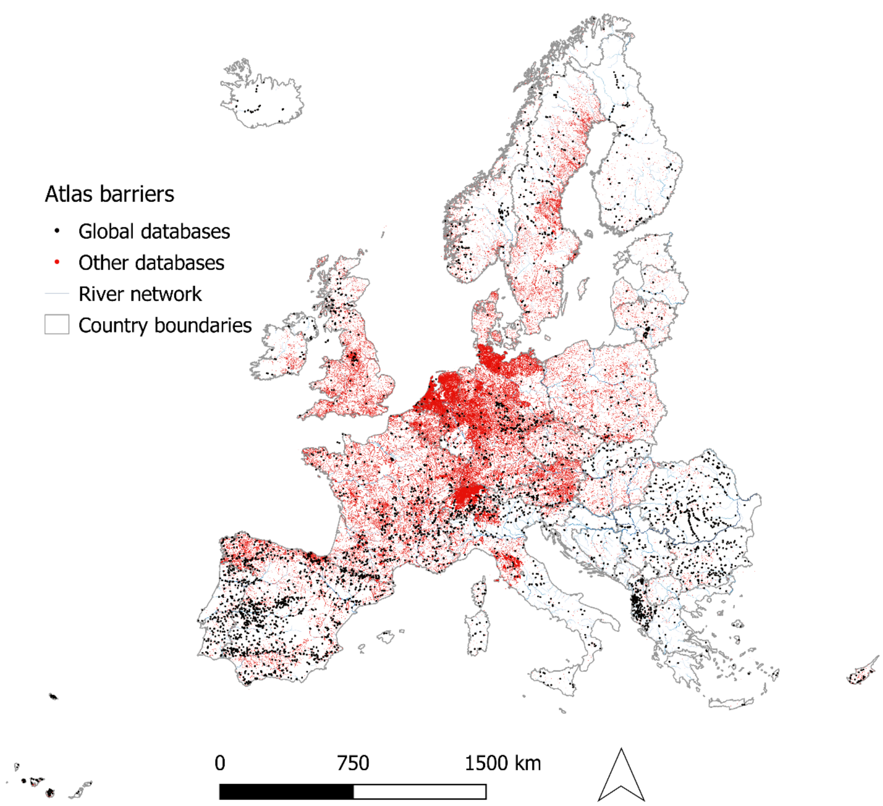

Figure 1. Distribution of 629,955 unique artificial barriers in Europe compiled from 120 local, regional, and national databases. Red dots represent new records, whereas black dots represent large dams (>15m in

height) from existing global scale databases (additional information in Methods **Extended Data Table 1**).

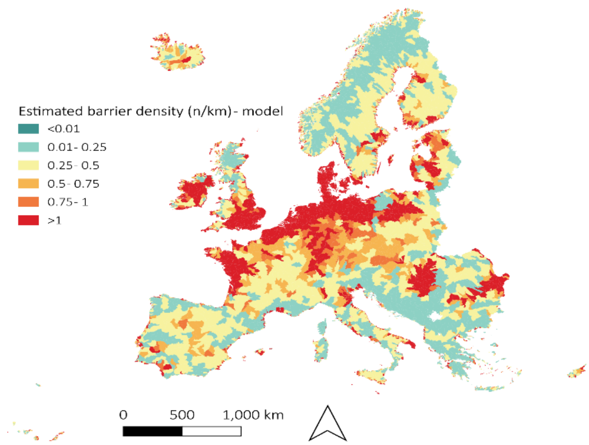

Figure 2. Estimates of barrier density (No./km) for ECRINS sub-catchments across Europe based on (A) Existing barrier records (AMBER Atlas), (B) field-derived correction factors (bottom-up approach), and (C) machine learning (top-down approach).

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Figure 3. Barrier under-reporting error (% frequency in the atlas - % frequency in the field) for (A) barrier height, (B) barrier type, and (C) country. Values are colour-coded depending on the sign of the residuals (A,B) or whether they are above (red) or below (green) the median barrier error across countries (dotted line, C). Country codes are given in Table 1.

Extended Data Table 1. Summary of the ground-truthing field work by country, showing extent of the national river network (ECRINS, km), number of rivers surveyed, length surveyed (km), percentage of the national river network surveyed, number of barriers present in the Atlas (NI), number of barriers encountered in the field (NF) and median bootstrapped correction factor to account for under-reporting with 95% confidence intervals.

Country	ECRINS (km)	No. rivers surveyed	Length surveyed (km)	% ECRINS surveyed	NI	NF	Bootstrapped Correction factor	Bootstrapped Correction factor	Bo Co fac
							L95CI	Median	U9
Albania	16,717	4	93.0	0.56	1	46	0.387	0.484	0.5
Austria	41,429	5	83.9	0.20	31	63	0.274	0.381	0.4
Bosnia-Herzegovina	25,295	2	40.6	0.16	3	11	0.073	0.195	0.3
Bulgaria	42,050	3	69.5	0.17	9	37	0.290	0.406	0.5
Croatia	21,985	4	85.4	0.39	5	8	0.000	0.035	0.0
Czech Republic	26,788	5	135.8	0.51	25	103	0.493	0.574	0.6

Country	ECRINS (km)	No. rivers surveyed	Length surveyed (km)	% ECRINS surveyed	NI	NF	Bootstrapped Correction factor	Bootstrapped Correction factor	Bo Co fac
Denmark	6,723	18	102.7	1.53	3	20	0.097	0.165	0.2
Estonia	9,981	5	94.3	0.95	7	80	0.691	0.777	0.8
France	183,373	6	93.0	0.05	33	34	0.000	0.011	0.0
Germany	104,142	6	130.1	0.12	23	80	0.354	0.438	0.5
Greece	61,994	5	89.2	0.14	1	33	0.258	0.360	0.4
Hungary	21,483	6	125.8	0.59	3	5	0.000	0.016	0.0
Italy	134,868	5	104.0	0.08	17	43	0.173	0.250	0.3
Lithuania	17,218	5	100.0	0.58	11	49	0.290	0.380	0.4
Montenegro	7,621	1	21.6	0.28	0	0	0.000	0.000	0.0
Netherlands	3,220	5	132.2	4.11	38	39	0.000	0.008	0.0
Norway	107,079	5	148.1	0.14	2	9	0.014	0.047	0.0
Poland	80,401	6	114.1	0.14	31	118	0.684	0.763	0.8
Portugal	31,451	5	95.2	0.30	5	50	0.379	0.474	0.5
Romania	78,829	4	81.8	0.10	1	19	0.134	0.220	0.3
Serbia	25,376	5	84.9	0.33	7	56	0.471	0.576	0.6
Slovenia	9,891	3	63.2	0.64	6	10	0.016	0.063	0.1
Spain	187,809	5	101.0	0.05	24	100	0.663	0.752	0.8
Sweden	128,357	5	121.8	0.09	0	11	0.041	0.090	0.1
Switzerland	21,178	5	88.1	0.42	281	390	1.148	1.239	1.3
United Kingdom	68,719	19	315.9	0.46	56	169	0.307	0.358	0.4
Total	1,463,977	147	2,715.4	0.19	623	1,583	0.335	0.354	0.3

Extended Data Table 2 . Incidence of barrier duplicates and duplicate exclusion criteria applied to different countries (*databases already collated and cleaned)

Country	No. barriers	No. barriers	% barriers excluded	Exclusion radius (m)	Algorithm (80% or optimised)
	Before duplicate exclusion	After duplicate exclusion			
Albania	1230	1209	1.7	332	80%
Andorra	316	310	1.9	178	Optimized
Austria	27605	27407	0.7	261	Optimized
Belgium	7105	6742	5.1	583	80%
Bosnia-Herzegovina	883	214	75.8	492	80%
Bulgaria	1730	736	57.5	510	Optimized
Croatia	459	113	75.4	504	80%
Cyprus	524	285	45.6	279	Optimized
Czech Republic	5698	5482	3.8	347	80%
Denmark	3073	3064	0.3	29	80%
Estonia	193	187	3.1	13	Optimized
Finland	929	829	10.8	371	Optimized
France*	63478	61960	2.4	-	-
Germany	246072	179005	27.3	366	80%

Country	No. barriers	No. barriers	% barriers excluded	Exclusion radius (m)	Algorithm (80% or optimised)
Greece	1065	214	79.9	356	80%
Hungary	2835	2783	1.8	306	80%
Iceland	104	32	69.2	935	80%
Ireland	1826	1532	16.1	204	80%
Italy	32846	32039	2.5	439	80%
Latvia	657	602	8.4	575	Optimized
Lithuania	1311	1257	4.1	58	Optimized
Luxembourg	38	36	5.3	677	Optimized
Montenegro	218	38	82.6	576	80%
Netherlands	63438	62588	1.3	18	Optimized
North Macedonia	524	173	67.0	442	80%
Norway	4254	3980	6.4	825	Optimized
Poland	16658	16171	2.9	283	80%
Portugal*	1562	1197	23.4	-	-
Romania	904	791	12.5	649	80%
Serbia	1986	273	86.3	527	Optimized
Slovakia	169	152	10.1	732	80%
Slovenia	1117	693	38.0	455	Optimized
Spain*	32044	29882	6.7	-	-
Sweden	19497	19466	0.2	366	80%
Switzerland	171511	145461	15.2	121	80%
United Kingdom*	23719	23719	0.0	-	-

Extended Data Table 3. Variables used to model areal barrier density.

Variable ID	**Variable**	**Description**	**Data s**
1	elev	mean elevation (m) - weighted by catchment area	EU-DE
2	slop	mean slope (digital number; high number = low slope) - weighted by catchment area	EU-DE
3	popd	population density (N/km^2)	Global
4	clc1	proportion of CLC level 1 - type 1 (urban areas)	CORIN
5	clc2	proportion of CLC level 1 - type 2 (agricultural areas)	CORIN
6	clc3	proportion of CLC level 1 - type 3 (forested/natural areas)	CORIN
7	clc4	proportion of CLC level 1 - type 4 (wetlands)	CORIN
8	clc5	proportion of CLC level 1 - type 5 (surface water)	CORIN
9	LenD	drainage density (km/km^2)	Europea
10	denr	dendritic ratio (total river length/N rivers)	Europea
11	roadD	density of road crossing (n/km^2)	GRIP g

Extended Data Table 4. Sensitivity analysis of model results of barrier density with different catchment areas. Model performance (means of 5-fold cross validation) is given by the explained variance, Root Mean Squared Error (RMSE), and mean Absolute Error (MAE). The estimated number of modelled barriers is also shown. The model with the highest explained variance and lowest RMSE (model 3000) was chosen to produce**Fig. 2C** and **Extended Data Figs. 3-5.**

Model	No. catchments	Mean catchment area (km^2)	Exp. var.	RMSE	MAE	Predicted No. of barriers
ECRINS	30,176	60.90 (SE=0.41)	-0.158654	0.59	0.23	1.43M
600	4,273	497.28 (SE=5.15)	0.369610	0.05	0.10	1.09M
1200	3,062	716.06 (SE=12.36)	0.386606	0.04	0.09	1.03M
2500	1,597	981.03 (SE=32.60)	0.170263	0.06	0.12	1.11M
3000	2,306	1001.53 (SE=30.77)	0.405141	0.04	0.09	991,341

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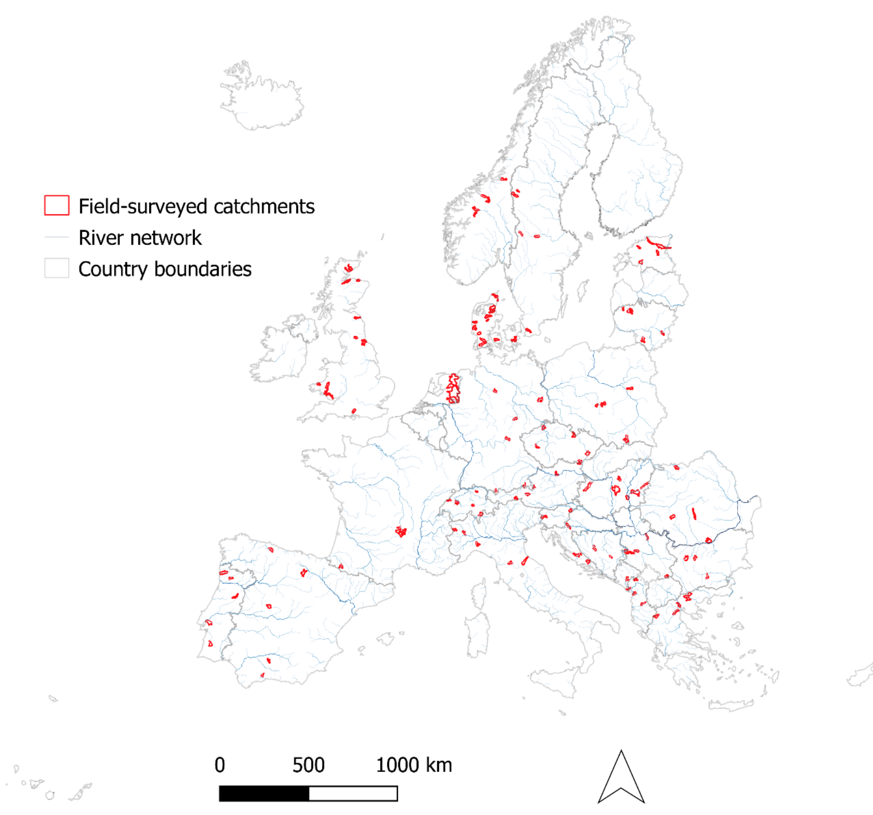
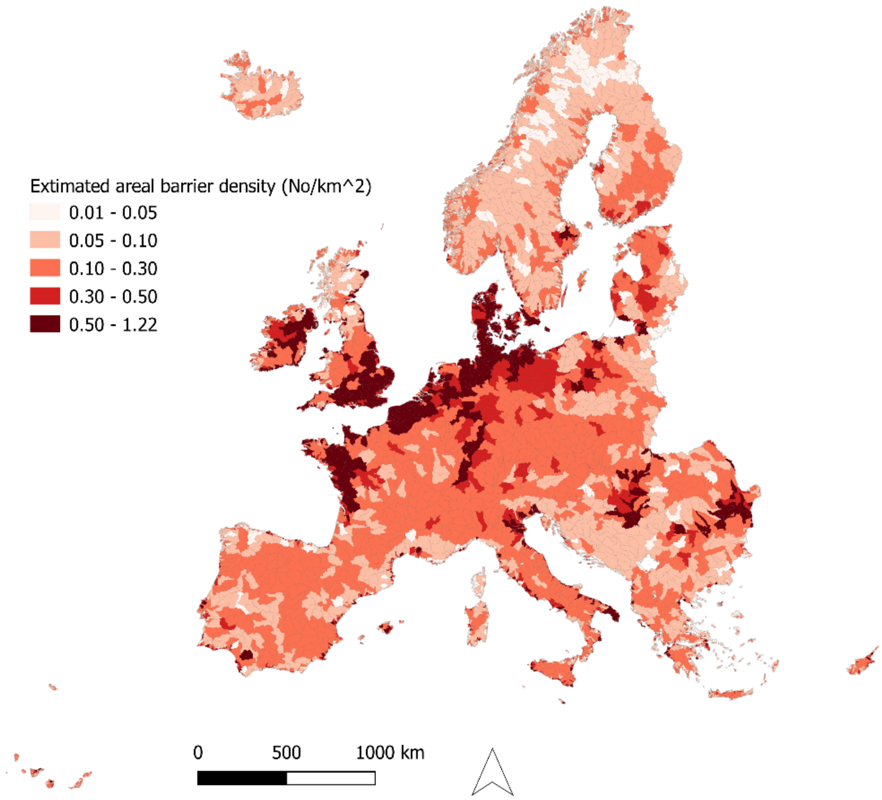
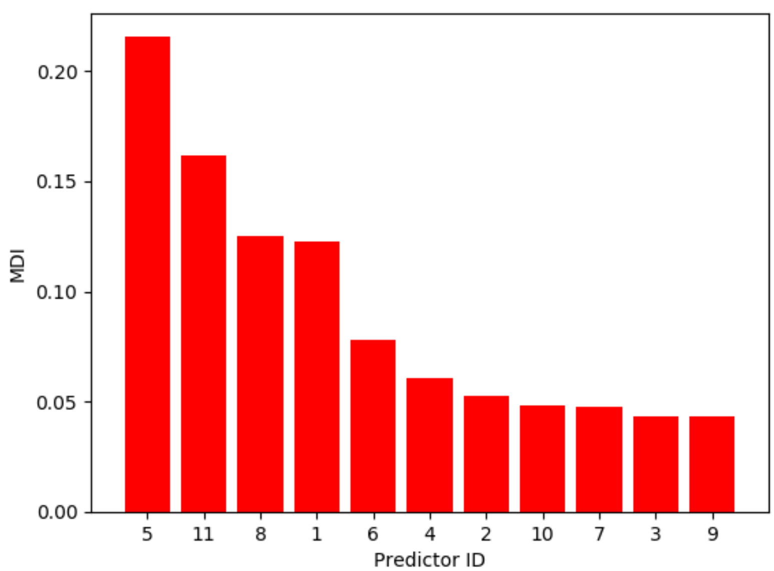
Extended Data Figure 1. Cumulative height distribution (log10 scale, m) of artificial barriers more than 10 cm in height found in European rivers (n = 117,372).



Extended Data Figure 2. Location of the 147 test reaches totalling 2,715 km used to ground-truth the AMBER Barrier Atlas (details in **Extended Table 2** and **Supplementary Material Table S2**).



Extended Data Figure 3. Predicted areal barrier density (n/km^2) derived from machine learning modelling.

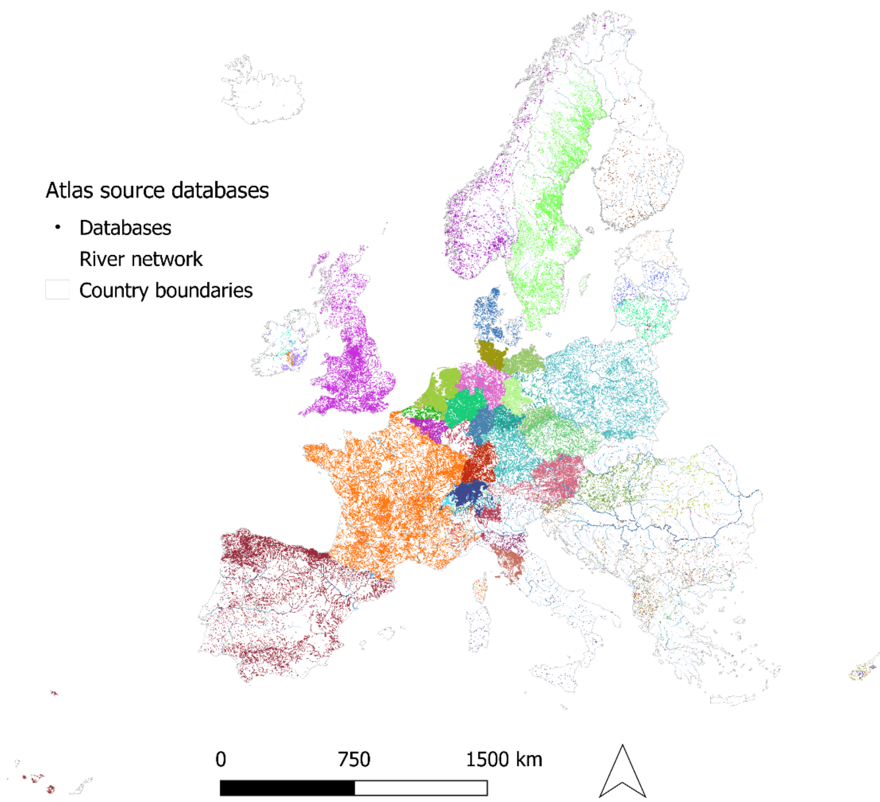


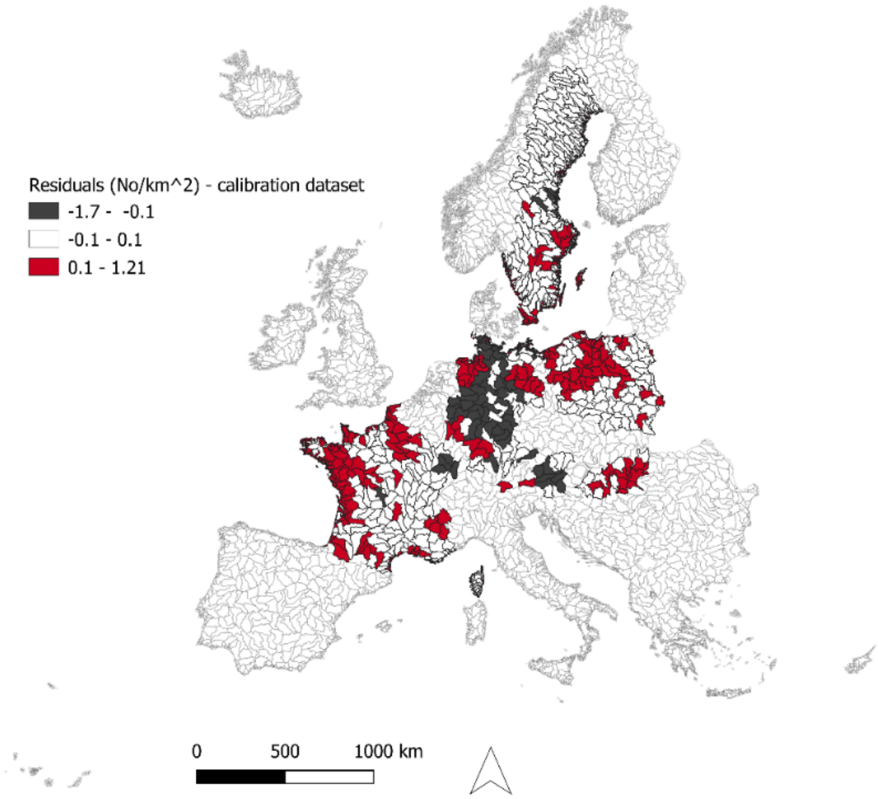
Extended Data Figure 4. Relative weight (Mean Decrease Impurity, MDI) of the 11 predictors used to model barrier density (variable details are given in **Extended Data Table 3**).

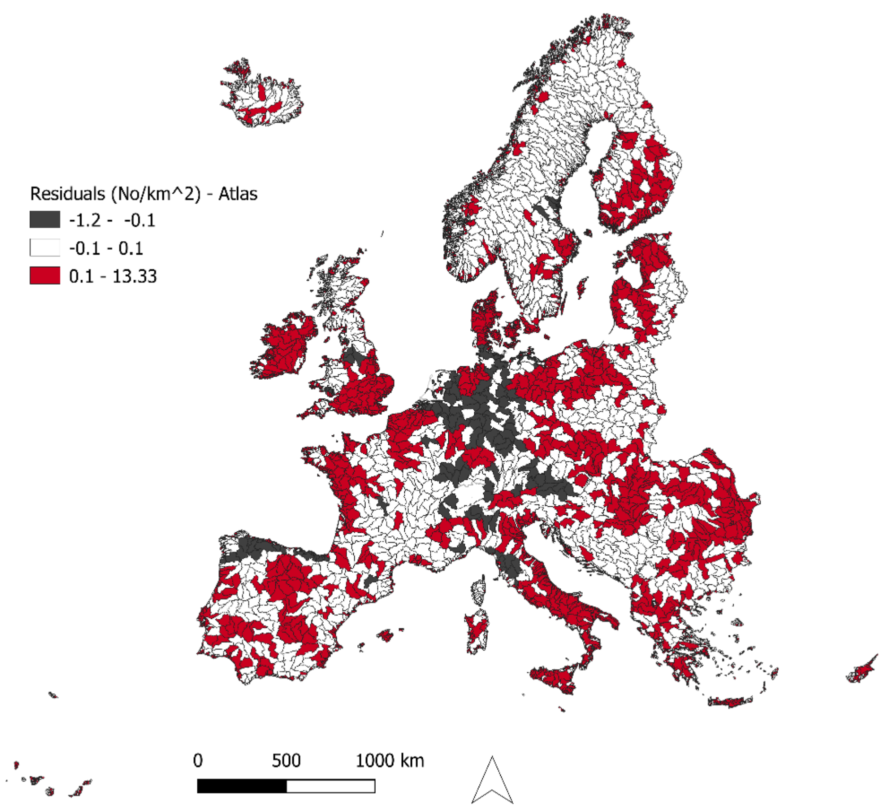
Hosted file

`image11.emf` available at https://authorea.com/users/295565/articles/464013-broken-rivers-ground-truthing-the-world-s-most-fragmented-rivers

Extended Data Figure 5. Main predictors of barrier areal density: (A) proportion of agricultural area (Corine Land Cover 2 – level 1); (B) road density (km/km^2); (C) mean altitude (m.a.s.l.); (D) proportion of area occupied by surface water (Corine Land Cover 5 – level 1). For details see **Extended Data Table 3** .




Residuals (No/km^2) - calibration dataset
-1.7 - -0.1
-0.1 - 0.1
0.1 - 1.21
0
500
1000 km


Residuals (No/km^2) - Atlas
-1.2 - -0.1
-0.1 - 0.1
0.1 - 13.33
0
500
1000 km

Extended Data Figure 6. Spatial coverage of the 120 barrier databases used to assemble the AMBER Barrier Atlas (see**Supplementary Material Table S1** for database sources).

Extended Data Figure 7. Distribution of modelling residuals (predicted-observed) for

(A) the validation dataset, and (B) the whole Atlas dataset.

Table S1. Details of test rivers showing number of barriers present in current inventories (Atlas) and those encountered in the field

Test River	X-Coordinates	Y-Coordinates	Country	Date	Surveyed Length (km)	No of barriers in Atlas									No of barriers encountered in the field								
						Dam	Weir	Sluice	Culvert	Ford	Ramp	Other/NA	Total	Density (No/km)	Dam	Weir	Sluice	Culvert	Ford	Ramp	Other/NA	Total	Density (No./km)
Buna	19.44	42.0	Albania	2018	20.62								0	0							13	13	0.63
Fani	19.79	41.75	Albania	2018	23.96								0	0			1		1		6	8	0.33
Shkumbini	20.2	41.15	Albania	2018	27.37								0	0			1				18	19	0.69
Valbona	19.98	42.43	Albania	2018	21.08	1							1	0.05	2	2					2	6	0.28

Table S2. Comparisons of barrier densities in Europe and in other parts of the world

Location	River Length (km)	Barrier height	No. barriers	Density (No/km)	Reference
Europe	1649488.98	All barriers	1213874	0.74	This study (bootstrapped value)
Europe	1649488.98	>2 m	157691.15	0.1	This study (95 CI = 0.08 – 0.11)
USA	1979770	>1.83 m	90580	0.05	NID http://nid.usace.army.mil/
Japan	122870	>15 m	2675	0.02	Yoshimura et al 2005. River Res. App. 21, 93-112. ; https://www.mlit.go.jp/river/basic_-info/english/admin.html
Brazil	2493760	>15 m	24097	0.01	Brazil Dams Safety Report (Global Dam Watch)
China	2438890	>15 m	22104	0.01	World Commision on Dams https://www.internationalrivers.org/resources/dams-and-development-a-new-framework-for-decision-making-3939

Table 7: Table S2. Global barrier density comparisonstable

Table S3. Barrier Database sources.

Country	Code	Name	Surname	Institution
Albania	AL			
Andorra	AD	Alain	GRIOCHE	Ministry of the Environment, Agriculture and Sustainability. Government of Andorra (Ministeri de Medi Ambient, Agricultura i Sostenibilitat. Govern d'Andorra)
Austria	AT	Veronika	Koller-Kreimel	Austrian Federal Ministry of Sustainability and Tourism (Bundesministerium für Nachhaltigkeit und Tourismus)
Austria	AT	Helena	Mühlmann	Austrian Federal Ministry of Sustainability and Tourism (Bundesministerium für Nachhaltigkeit und Tourismus)
Belgium	BE	Séverine	GASPAR	Public Service of Wallonia - General Secretariat (Service public de Wallonie- Secrétariat général)
Belgium	BE	Maarten	Van Aert	Flanders Environment Agency (Vlaamse Milieumaatschappij)
Bosnia-Herzegovina	BA	Ana	Sudar	Agency for watershed of the Adriatic sea (Agencija za vodno područje Jadranskog mora)
Bulgaria	BG	Ivan	Pandakov	Balkanka association
Bulgaria	BG	Pencho	Pandakov	Balkanka association
Bulgaria	BG	Dimiter	Koumanov	Balkanka association
Croatia	HR			
Cyprus	CY	Christos	Hadjistyllis	Ministry of Agriculture, Rural Development and Environment
Cyprus	CY	Lefkios	Sergides;	The Cyprus Conservation Foundation, Terra Cypria (Τμήμα Αναπτύξεως Υδάτων)
Cyprus	CY	Athina	Papatheodoulou	The Cyprus Conservation Foundation, Terra Cypria (Τμήμα Αναπτύξεως Υδάτων)
Czech Republic	CZ	Hošek	Zdeněk	Ministry of Agriculture of the Czech Republic (Ministerstvo Zemědělství)
Czech Republic	CZ	Jiří	Chrpa	Ministry of Agriculture of the Czech Republic (Ministerstvo Zemědělství)
Denmark	DK	Peter	Kaarup	Danish Environmental Protection Agency
Estonia	EE	Olav	Ojala	Ministry of the Environment (Keskkonnaministeerium)
Finland	FI	Jukka	Jormola	Finnish Environment Insitute
France	FR	Karl	Kreutzenberger	Référentiel des Obstacles à l'Écoulement
Germany	DE			
Greece	GR			Greek Committee on Large Dams (λληνική Επιτροπή Μεγάλων Φραγμάτων (ΕΕΜΦ))
Greece	GR	Thanos	Giannakakis	WWF Greece
Hungary	HU	Szilvia	David	National Directorate of Water Management (Országos Vízügyi Főigazgatóság)
Iceland	IS	Sigurdur	Mar einarsson	Marine and Freshwater Research Institute
Ireland	IE	James	Barry	Inland Fisheries Ireland
Italy	IT	Giovanni	Marchionna	Italian Dams Register (Registro Italiano Dighe)
Latvia	LV			
Lithuania	LT	Gintautas	Sabas	Environmental Protection Agency (Aplinkos apsaugos agentūra)
Luxembourg	LU	Carole	Molitor	Ministry of Sustainable Development and Infrastructure (Ministère du Développement durable et des Infrastructures)
Montenegro	ME	Momčilo	Blagojević	Ministry of Agriculture and Rural Development (Ministarstvo poljoprivrede i ruralnog razvoja)
Netherlands	NL			
North Macedonia	MK			