More than one million barriers fragment Europe's rivers

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Summary

Rivers support some of Earth's richest biodiversity[1] and provide essential ecosystem services to society[2], but they are often impacted by barriers to free-flow[3]. In Europe, attempts to quantify river connectivity have been hampered by the absence of a harmonised barrier database. Here we show that there are at least 1.2 million instream barriers in 36 European countries (mean density = 0.74 barriers/km), 68% of which are low-head (<2 m) structures that are typically unreported. Standardised walkover surveys along 2,715 km of stream length in 147 rivers indicate that existing records underestimate barrier numbers by ~61%. The highest barrier densities occur in the heavily modified rivers of Central Europe, and the lowest in the most remote, sparsely populated alpine areas. Across Europe, the main predictors of barrier density are agricultural pressure, density of river-road crossings, extent of surface water, and elevation. Relatively unfragmented rivers are still found in the Balkans, the Baltic states, and parts of Scandinavia and 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 widespread impacts caused by small barriers.

MAIN TEXT

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 non-ephemeral, natural rivers is that they flow[4], and the most pervasive telltale of human impacts on rivers is the break in connectivity caused by artificial barriers to free-flow[5]. 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[6]. However, assessing river fragmentation has proved challenging[7] due to the dendritic nature of rivers, the seasonality of the hydrological regime, and the spatio-temporal nature of barrier impacts[8,9].

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[3,10-12], but these only represent a small fraction of all instream barriers, typically <1%[13]. Most low-head structures are unreported[14], despite the fact that their cumulative impact on river connectivity is far more substantial[15,16]. For instance, while only large storage dams can affect the hydrological regime[17], nearly all barriers can affect sediment transport[18,19], the movement of aquatic organisms[20], and the structure of river communities[15,21]. Under-reporting of small barriers can vastly underestimate the extent of river fragmentation[22]. For example, assessments of fragmentation based solely on large dams[3] would ignore 99.6% of the barriers present in Great Britain[23]. 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)[24], Europe probably has more heavily modified rivers than anywhere else in the world[25,26], as well as a long legacy of fragmentation, with fish passage legislation dating back to the 7th century[27]. 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)[28]. 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[29,30]. 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[31,32].

Here we present the first comprehensive estimate of river fragmentation in Europe based on empirical and modelled barrier densities. We collated and harmonised 120 regional, national and global barrier 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 random forest regression (a machine learning technique) to estimate the number and location of missing barriers (Extended Data Fig. 1).

Barrier abundance, types, and distribution

We assembled information on 736,348 instream barriers from 36 countries and identified 629,955 unique barrier records (Fig. 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[11,12], but consistent with regional[31,33,34] and country estimates that considered all barriers[23]. Most of the barriers in Europe's rivers 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 117,371 records indicate that 68% of barriers are less than 2 m high and 91% are less than 5 m high (mean = 2.77 m, SE = 0.025; median = 1.20 m; Extended Data Fig. 2), which probably explains why so many barriers can be easily missed in surveys and automated procedures, and why low-head structures are under-represented in most barrier inventories.

Accounting for barrier underreporting

Barrier inventories in Europe are not homogeneous with respect to barrier types, reach, or completeness (Table 1), as they were compiled for different purposes using different resources. They have different spatial coverage and suffer from strong sampling bias (Fig. 2a,b) that result in under-reporting of small structures. We adopted two complementary strategies to account for barrier under-reporting and derive more realistic barrier densities (Extended Data Fig. 1): ground-truthing of existing barrier records via walkover field surveys in matched river reaches (a bottom-up strategy; Fig.

2b; Extended Data Fig. 3), and barrier modelling at sub-catchment level using random forest regression (a top-down strategy; Fig. 2c).

Our study indicates that there are more barriers than existing databases would suggest. We found 1,583 barriers in 2,715 km of walkway river surveys across Europe, 960 of which (61%) were absent from current barrier inventories (Extended Data Table 1). None of the 147 surveyed rivers were free of artificial barriers (although some of the contiguous test-reaches were). The number of barriers recorded in the field was on average 2.5 times higher than in existing inventories.

Extent of river fragmentation in Europe

Field-corrected barrier densities indicate that there are on average 0.74 barriers per km of river length, 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 1,213,874 barriers across Europe using a conservative estimate of 1.65M km for the river network[35], 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[36]. Our barrier density estimates are higher than those reported anywhere (Extended Data Table 2), possibly making Europe the most fragmented river landscape in the world.

On the other hand, modelling of barrier density predicted 0.60 barriers/km (SE = 0.24; Fig. 2c, Extended Data Fig. 4a) or 991,341 barriers across Europe, which is within 20% of the field-corrected estimate. Thus, both approaches provided congruent results and suggest that fragmentation estimates based on existing barrier records underestimate true barrier numbers by 36 to 48% according to modelling and field survey results, respectively. This is largely due to the presence of many small structures (Extended Data Fig. 2) that tend to be under-reported in barrier inventories (Fig. 3a,b).

Correlates of barrier abundance

The highest barrier densities are found in Central Europe and correspond with densely populated areas, intense use of water, and high road density (Fig. 2b,c); in contrast, the lowest barrier densities tend to 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[37], as well as the location of rivers of good ecological status[24]. Although no catchment in Europe is free of artificial barriers, there are still relatively unfragmented rivers in the Balkans, the headwaters of the Baltic States, and parts of Scandinavia and Southern Europe. Worryingly, these are also the areas where many of the new hydropower dams are being planned[38,39], which threatens their biodiversity and good ecological status and 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[40], but also because these create large reservoirs that are easier to detect remotely[41,42], generate social conflict[40,43], and there is the implicit assumption that large dams are primarily responsible for the loss of longitudinal connectivity[22,44]. However, our study shows that dams greater than 15 m high are rare (<1.0%) and that most barriers to free-flow are small structures that are difficult to detect and are poorly mapped (Fig. 2a, Fig. 3a). For example, in Switzerland fragmentation is mostly caused by ~100,000 small bed sills built to compensate for bed incision caused by channel straightening[45]. Loss of connectivity depends mostly on the number and location of barriers, not on their height[46]. 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. A concerted global effort is required to map low-head structures and complement existing dam databases. 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[46]. 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[23,34]. 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 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. Importantly, 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 (Log Likelihood Ratio = 97.94, df = 5, $P < 0.001$; Fig. 3a), particularly fords, culverts and sluice gates (LRT = 44.70, df = 5, $P < 0.001$; Fig. 3b), and these are structures that should be targeted in future surveys. Likewise, the completeness of current inventories differs widely from country to country (Fig. 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 can 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 the required precision[36]. More detailed hydrographic maps, available in many countries, are needed for dendritic estimates of longitudinal river connectivity[23] and for detailed barrier mitigation planning. Having a more consistent high resolution hydrographic network across Europe (i.e. improving on ECRINS) must be viewed as a priority for large scale assessments and for more effective restoration of connectivity.

Secondly, to reconnect rivers, information is needed on the current use and legal status of barriers, as many are 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[31,32]. Given the current impetus on barrier removal and restoration of river connectivity[47], 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 also need to be halted, and this may require a critical reappraisal of the sustainability and promotion of micro-hydro development[48] 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[38,49], and the new EU Biodiversity Strategy’s target of reconnecting at least 25,000 km of Europe’s rivers by 2030[50], our results can serve as a baseline against which future gains or losses in connectivity can be gauged. Estimates of fragmentation can also be incorporated into pan-European assessments of river ‘ecological status’ and inform the level of funding required to achieve desired connectivity targets.

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.

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TABLES

Table 1. Number of unique barrier records in Europe (AMBER Barrier Atlas) and corrected barrier abundance estimates derived from field surveys.

Country	ECRINS river network (km)	Number of each barrier type									Atlas barrier density (No km^{-1})	Corr. barrier density (No km^{-1})	Corr. No. barriers
		dam	weir	sluice	culvert	ford	ramp	other	unknown	total			
Albania (AL)	16,717	210							308	518	0.03	0.51	8,607
Andorra (AD)	273	43	267							310	1.14	1.49	407
Austria (AT)	41,429	19,379	2,208		4		5	5,811		27,407	0.66	1.04	43,189
Belgium (BE)	8,018	1,504	1,388	254	1,993		4	1,394	205	6,742	0.84	1.19	9,580
Bosnia-Herzegovina	25,295	20	1					11	182	214	0.01	0.20	5,150
Bulgaria (BG)	42,050	187							549	736	0.02	0.42	17,800
Croatia (HR)	21,985	25							88	113	0.01	0.04	889
Cyprus (CY)	2,811	119		1				165		285	0.10	0.46	1,280
Czech Republic (CZ)	26,788	2,210	1,934				7	1,331		5,482	0.20	0.78	20,846
Denmark (DK)	6,723	333	380	19	186		863	305	980	3,066	0.46	0.62	4,176
Estonia (EE)	9,981	187								187	0.02	0.80	7,939
Finland (FI)	87,703	96						733		829	0.01	0.36	31,876
France (FR)	183,373	8,744	36,855	346	5,915	357	4,512	1,579	3,652	61,960	0.34	0.35	63,932
Germany (DE)	104,142	4,250	19,236	530	72,795	337	76,895	4,944	9	178,996	1.72	2.16	224,658
Greece (GR)	61,994	143							75	218	0.00	0.36	22,508
Hungary (HU)	21,483	781	1,048	875				79		2,783	0.13	0.15	3,124
Iceland (IS)	16,367	32								32	0.00	0.36	5,826
Ireland (IE)	19,503	32	389	30	390	34	554	87	16	1,532	0.08	0.43	8,436
Italy (IT)	134,868	1,406	20,428		5	586	7,849	1,760	5	32,039	0.24	0.49	65,756
Latvia (LV)	16,589	601							1	602	0.04	0.39	6,474
Lithuania (LT)	17,218	125							1,132	1,257	0.07	0.45	7,800
Luxembourg (LU)	960	6	7		3		15	5		36	0.04	0.39	376
Montenegro (ME)	7,621	5							33	38	0.00	0.00	38
Netherlands (NL)	3,220	15	55,762	328	11		30	6,440		62,586	19.44	19.44	62,610
North Macedonia (MK)	12,876	7							166	173	0.01	0.37	4,731
Norway (NO)	107,079	3,977	1		1		1			3,980	0.04	0.08	9,045
Poland (PL)	80,401	1,071	10,742	2,707	1,339		44		268	16,171	0.20	0.96	77,530
Portugal (PT)	31,451	725	117				1		354	1,197	0.04	0.51	16,095
Romania (RO)	78,829	305	6	3				302	175	791	0.01	0.23	18,095
Serbia (RS)	25,376	73	3						197	273	0.01	0.59	14,901
Slovakia (SK)	20,412	147	4					1		152	0.01	0.36	7,378
Slovenia (SI)	9,891	23	1						669	693	0.07	0.13	1,321
Spain (ES)	187,809	5,131	17,005	10	135	104	2,725	1,429	3,343	29,882	0.16	0.91	171,203
Sweden (SE)	128,357	7,628	2,483		8,013		1,033		338	19,495	0.15	0.24	31,068
Switzerland (CH)	21,178	415	4,599	93	19,888	722	103,961	670	15,113	145,461	6.87	8.11	171,693
United Kingdom (UK)	68,719	1,566	17,539	2,915	266	61	92	1,280		23,719	0.35	0.70	48,293
Total	**1,649,489**	**61,521**	**192,403**	**8,111**	**110,944**	**2,201**	**198,591**	**28,326**	**27,858**	**629,955**	**0.38**	**0.74**	**1,213,87**
												Sum	**1,194,62**

FIGURE LEGENDS

Fig. 1. Artificial instream barriers in Europe (AMBER Barrier Atlas). The map shows the distribution of 629,955 unique barrier records compiled from 120 local, regional, and national databases after duplicate exclusion. Red dots represent the new barrier records assembled in this study, whereas black dots represent large dams (>15m in height) from existing global databases. The full georeferenced data can be downloaded from *figshare* https://doi.org/10.6084/m9.figshare.12629051. Country and sub-basin boundaries were sourced from the European Environment Agency[35].

Fig. 2. Extent of river fragmentation in Europe. The map shows the barrier density (barrier/km) in ECRINS sub-catchments (n= 8,467) across Europe based on (a) existing barrier records (AMBER Barrier Atlas), (b) ground-truthed barrier abundance (bottom-up approach), and (c) barrier modelling via random forest regression (top-down approach). Country and sub-basin boundaries were sourced from the European Environment Agency[35].

Fig. 3. Extent of barrier under-reporting. The figures show the estimated under-reporting error (% of barriers that are missing from current inventories) for barriers of (a) different height (m), (b) different types, and (c) in different countries. Values are colour-coded depending on whether the reporting error is above (blue) or below (light yellow) the median error (dotted line). Country codes are given in Table 1.

Fig. 1

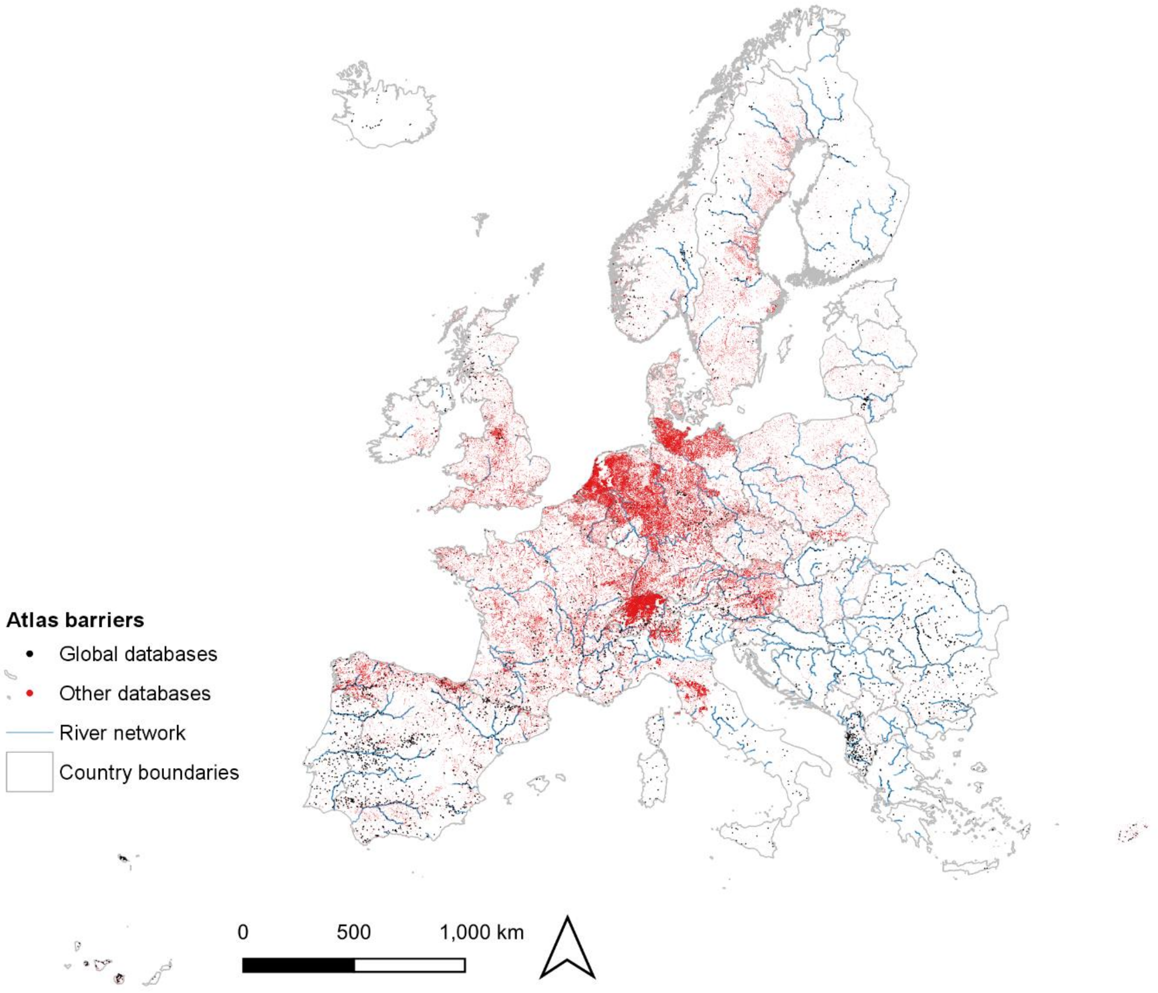
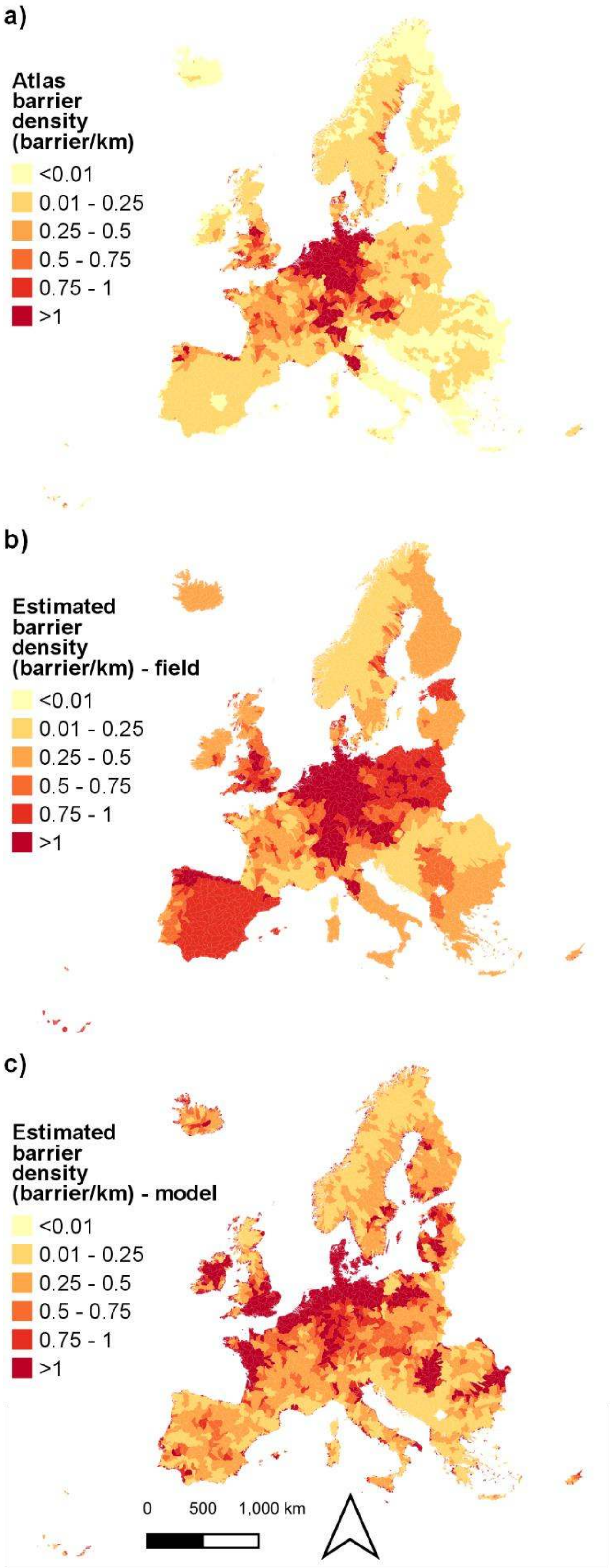
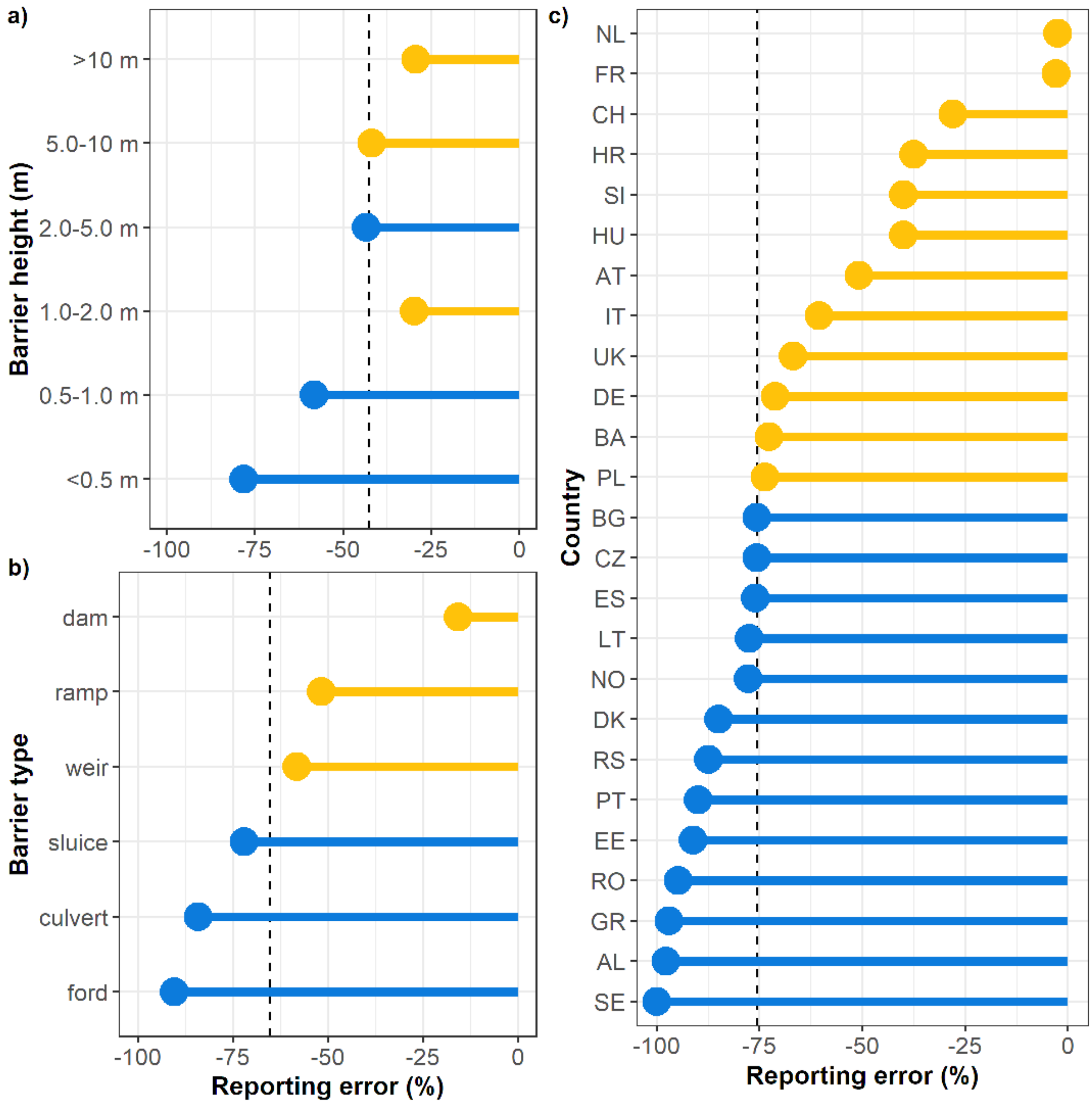

Atlas barriers
Global databases
Other databases
River network
Country boundaries
0
500
1,000 km

Fig. 2



a)
Atlas barrier density (barrier/km)
<0.01
0.01 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
>1
b)
Estimated barrier density (barrier/km) - field
<0.01
0.01 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
>1
c)
Estimated barrier density (barrier/km) - model
<0.01
0.01 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
>1
0 500 1,000 km

Fig. 3


a)
>10 m
5.0-10 m
2.0-5.0 m
1.0-2.0 m
0.5-1.0 m
<0.5 m
Barrier height (m)
-100
-75
-50
-25
0
b)
dam
ramp
weir
sluice
culvert
ford
Barrier type
-100
-75
-50
-25
0
Reporting error (%)
c)
NL
FR
CH
HR
SI
HU
AT
IT
UK
DE
BA
PL
BG
CZ
ES
LT
NO
DK
RS
PT
EE
RO
GR
AL
SE
Country
-100
-75
-50
-25
0
Reporting error (%)

METHODS

Overview

The connectivity of most rivers in Europe is unknown[28]. 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 (barriers/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 ~5.02 million km^2. As there is no agreed definition of 'barrier' in relation to river connectivity[51], 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 (Extended Data Fig. 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 random forest regression. This allowed us to identify nearly 630,000 unique barrier records (Fig. 1, 2a), and to estimate the extent of longitudinal fragmentation in Europe from field-corrected (Fig. 2b) and modelled barrier densities Fig. 2c).

Building the European Atlas of artificial instream barriers

We collected and cross-referenced barrier records from 120 databases from 36 countries, including 65 local and regional databases, 52 national databases and four global ones[52]. After quality checking, we harmonised records into a single relational database (the AMBER Barrier Atlas) and removed duplicates (see below). We classified over 1,000 different barrier types into six main functional groups that capture variation in barrier size and use[23,53]: dam, weir, sluice, ramp/bed sill, ford, and culvert, plus 'other' (e.g., groynes, spillways) and 'unknown' (Table 1). 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 compare them to ground-truthed values.

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[35]). 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[36], it is the only consistent river network that can currently be used for global comparisons across Europe. The consequences of underestimating river length for estimates of river fragmentation are difficult to predict. Underestimating river length can overestimate river fragmentation if the observed number of barriers is in reality distributed over a longer river network, but it can also underestimate it if undetected barriers are more likely to occur in poorly mapped first order streams.

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 [23]. 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[54]. We used bootstrapping[55] 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[53] (Extended Data Table 3).

Ground-truthing barrier records through walkway river surveys

To ground-truth barrier density estimates, we surveyed 147 rivers across 26 countries, totalling 2,715 km or 0.16% of the river network (Extended Data Table 1, Extended Data Fig. 3) using a method described previously[23]. We used expert judgement to choose 2-6 test rivers per country that were broadly representative of the river types found in Europe in terms of altitude, slope, stream order[56] and, depending on accessibility, biogeography and land use. Surveyed reaches were mostly single-thread (>80%) and spanned Strahler stream orders 1 to 8, although most were order

3-5 (62%). At each river, we surveyed a contiguous 20 km reach at low flow conditions (~Q80-Q95) during the spring of 2017 and the summers of 2018 and 2019, except in Denmark and Scotland where we surveyed multiple 5-10 km reaches due to logistic constraints[52]. For each barrier we encountered we recorded its coordinates, type, height class, status (abandoned or in use), and span width (full or partial river width).

The influence of survey length on barrier discovery rate was determined via bootstrapping[23,53] using R version 4.0.0[57]. This showed an asymptotic relationship in most cases indicating that a 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 random forest regression (see below).

Field-derived correction factors were applied in each country to adjust existing barrier records and derive more realistic barrier densities (Fig. 2b; 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 the 26 surveyed countries. We employed the Likelihood Ratio Test (two-tailed) implemented in the *DescTools* R 4.0 package[58] to assess the level of under-reporting, comparing the frequencies of barrier types and barrier height classes in existing databases and in walkover river surveys. Barrier reporting error (e) was calculated as

$$\boldsymbol{e = \frac{Na - Nf}{Nf} * 100}$$

where Na is the number of barriers recorded in the barrier atlas and Nf the number of barriers detected in the field in the same test reaches.

Modelling barrier density through random forest regression

We employed random forest regression 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[59], small weirs with water mills in headwaters[32], and storage dams with nearby cities, agriculture and hydropower[60]. Similarly, the location of barriers is also determined by topography, geology and climate[7].

For each ECRINS sub-catchment we extracted information on 11 variables (Extended Data Table 4): land cover (Corine level 1: %urban, agricultural, natural, wetlands and water[61]); population density (No./km^2)[62]; 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; km/km^2)[35,63], and number of road crossings in the river network divided by catchment area (No./km^2)[64].

We used a data-driven, nonparametric Random Forest Regressor[65] 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[65], 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 5) using an *ad-hoc* graph theory algorithm in R 4.0 according to a criterion of minimum aggregation area from upstream to downstream direction. This step was used to reduce the influence of unaccounted local factors (e.g. existence of canals for navigation, or pipes and aqueducts for water diversion) operating at finer spatial scales than the predictors.

Comparisons of model performance at different sub-catchment sizes (Extended Data Table 5) 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 from field-corrected values 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[32]. A temporal mismatch may thus occur between drivers that governed barrier construction in the past and the current landscape.

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 (barrier/km^2; Extended Data Fig. 4a) and then transformed into linear river density (barrier/km; Fig. 2c).

The average model validation error was 0.09 barrier/km^2 (0.24 barrier/km; Extended Data Fig. 5). 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 Fig. 5) 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 were not adequately captured in our study. Inclusion in future models of barrier age, or proxies for barrier age - perhaps obtained from consideration of barrier type, height and location, may improve model performance.

Despite model limitations, modeled barrier densities for sub-catchment aggregations of 3,000 km^2 (Fig. 2c) were broadly consistent with field-corrected barrier densities (Fig. 2b) and identified the same broad patterns of river fragmentation across

Europe, especially in data-poor areas (e.g., the Danube and the Balkans). The most important predictors of barrier density were agricultural land cover, road crossing density, proportion of area covered by surface water, and altitude which together accounted for 0.63 in the Mean Decrease Impurity index (Extended Data Fig. 4f). Higher barrier densities correspond to areas with intense agricultural pressure (e.g., central Europe), and the lower densities to more remote, alpine areas (e.g. parts of Scandinavia).

Data availability

Data for the AMBER Barrier Atlas (Fig. 1), observed barrier densities (Fig. 2a), ground-truthed barrier densities (Fig. 2b) and modelled barrier densities (Fig. 2c) are freely available at https://amber.international/european-barrier-atlas/ as well as in figshare https://doi.org/10.6084/m9.figshare.12629051 under a CC-BY-4.0 license. Data for ground-truthed surveyed reaches (Extended Table 1, Extended Data Fig. 3) are also available at https://doi.org/10.6084/m9.figshare.12629051 under a CC-BY-4.0 license.

Code availability

The Python code used for modelling of barrier abundance, with links to GIS files for visualization, is available under a GNU General Public License at https://github.com/AMBER-data/atlas-model. Protocols used for barrier database management, duplicate exclusion and processing were done manually in SQL and QGIS using *ad-hoc* procedures and are not deposited in a repository.

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Author contributions

B.B., S.B. W.v.d.B and C.G.L. designed the study. B.B., S.B., G.S. and W.v.d.B. led the work and organised the collection of barrier data; B.B., S.B., L.B., A.C., & C.G.L. carried out the analysis; C.G.L. and B.B. wrote the initial drafts of the manuscript with essential input from S.B., L.B, J.J., A.C., S.C. and W.v.d.B.; G.S. and J.J. designed and curated the barrier database; K.M.W. helped secured unpublished barrier records from German Länder; B.B., P.F.G., R.O.A., S.R. and G.S. cleaned existing barrier inventories; walkover river surveys were conducted/organised by G.S. and P.M. (Portugal, France); E.D., E.G.V, C.R., S.F. and G.L. (Spain); B.B. and S.B. (Italy, Lithuania); J.J. and P.E.J. (Wales); K.A., K.B and N.J. (Denmark), J.B. and J.K. (Ireland), M.C. and M.P (Balkans, Danube, Estonia, Germany, Scandinavia); T.F., C.T.S. (Germany); P.K., A.V., J.K., M.C.L., S.V. and J.S.T. (England); E.V. and L.M. (Scotland); P.P., M.L. and M.Z. (Poland); H.W. and A.B. (The Netherlands); G.G., J.R., L.W., M.B. & P.G.. advised on the development of the Atlas and the policy implications. All co-authors critically revised and approved the edited manuscript.

Competing interests

The authors declare no competing interests.

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Additional information

Results of walkover surveys in test rivers (Table S1), and barrier database sources (Table S3) are available at figshare https://doi.org/10.6084/m9.figshare.12629051

EXTENDED DATA TABLES

Extended Data Table 1. Results of river walkaway surveys used to ground-truth barrier records. NA: number of barriers present in the Atlas; NF: number of barriers encountered in the field.

Country	ECRINS (km)	No. rivers surveyed	Length surveyed (km)	% ECRINS surveyed	NA	NF	Bootstrapped Correction Factor		
							L95CI	Median	U95CI
Albania	16,717	4	93.0	0.56	1	46	0.387	0.484	0.581
Austria	41,429	5	83.9	0.20	31	63	0.274	0.381	0.488
Bosnia-Herzegovina	25,295	2	40.6	0.16	3	11	0.073	0.195	0.317
Bulgaria	42,050	3	69.5	0.17	9	37	0.290	0.406	0.522
Croatia	21,985	4	85.4	0.39	5	8	0.000	0.035	0.082
Czech Republic	26,788	5	135.8	0.51	25	103	0.493	0.574	0.654
Denmark	6,723	18	102.7	1.53	3	20	0.097	0.165	0.243
Estonia	9,981	5	94.3	0.95	7	80	0.691	0.777	0.862
France	183,373	6	93.0	0.05	33	34	0.000	0.011	0.032
Germany	104,142	6	130.1	0.12	23	80	0.354	0.438	0.523
Greece	61,994	5	89.2	0.14	1	33	0.258	0.360	0.461
Hungary	21,483	6	125.8	0.59	3	5	0.000	0.016	0.040
Italy	134,868	5	104.0	0.08	17	43	0.173	0.250	0.337
Lithuania	17,218	5	100.0	0.58	11	49	0.290	0.380	0.480
Montenegro	7,621	1	21.6	0.28	0	0	0.000	0.000	0.000
Netherlands	3,220	5	132.2	4.11	38	39	0.000	0.008	0.023
Norway	107,079	5	148.1	0.14	2	9	0.014	0.047	0.081
Poland	80,401	6	114.1	0.14	31	118	0.684	0.763	0.842
Portugal	31,451	5	95.2	0.30	5	50	0.379	0.474	0.579
Romania	78,829	4	81.8	0.10	1	19	0.134	0.220	0.317
Serbia	25,376	5	84.9	0.33	7	56	0.471	0.576	0.682
Slovenia	9,891	3	63.2	0.64	6	10	0.016	0.063	0.127
Spain	187,809	5	101.0	0.05	24	100	0.663	0.752	0.832
Sweden	128,357	5	121.8	0.09	0	11	0.041	0.090	0.148
Switzerland	21,178	5	88.1	0.42	281	390	1.148	1.239	1.330
United Kingdom	68,719	19	315.9	0.46	56	169	0.307	0.358	0.411
Total	1,463,977	147	2,715.4	0.19	623	1,583	0.335	0.354	0.372

Extended Data Table 2. Comparisons of barrier densities (barriers/km) in Europe and in other parts of the world using a common river network (HydroSHEDS).

Location	River network* (km)	Barrier Height (m)	No. barriers	Density (barriers/km)	Reference
Europe	1,471,840	All barriers	1,213,874	0.825	This study
		>2 m	157,691	0.107	This study
USA	2,381,096	>1.83 m	90,580	0.038	[66]
Japan	126,045	>15 m	2,675	0.021	[67-68]
Brazil	2,498,090	Small to Large	24,097	0.010	[69]
China	2,410,700	>15 m	22,104	0.009	[70]
		Small to Large	86,000	0.036	[71]
India	879,738	Large	4,657	0.005	[72-73]

*HydroSHEDS river network[74]

Extended Data Table 3. Incidence of barrier duplicates and duplicate exclusion criteria (*databases already collated and cleaned)

Country	No. barriers		% barriers excluded	Exclusion radius (m)	Algorithm (80% or optimised)
	Before duplicate exclusion	After duplicate exclusion			
Albania	1,230	1,209	1.7	332	80%
Andorra	316	310	1.9	178	Optimised
Austria	27,605	27,407	0.7	261	Optimised
Belgium	7,105	6,742	5.1	583	80%
Bosnia-Herzegovina	883	214	75.8	492	80%
Bulgaria	1,730	736	57.5	510	Optimised
Croatia	459	113	75.4	504	80%
Cyprus	524	285	45.6	279	Optimised
Czech Republic	5,698	5,482	3.8	347	80%
Denmark	3,073	3,064	0.3	29	80%
Estonia	193	187	3.1	13	Optimised
Finland	929	829	10.8	371	Optimised
France*	63,478	61,960	2.4	-	-
Germany	246,072	179,005	27.3	366	80%
Greece	1,065	214	79.9	356	80%
Hungary	2,835	2,783	1.8	306	80%
Iceland	104	32	69.2	935	80%
Ireland	1,826	1,532	16.1	204	80%
Italy	32,846	32,039	2.5	439	80%
Latvia	657	602	8.4	575	Optimised
Lithuania	1,311	1,257	4.1	58	Optimised
Luxembourg	38	36	5.3	677	Optimised
Montenegro	218	38	82.6	576	80%
Netherlands	63,438	62,588	1.3	18	Optimised
North Macedonia	524	173	67.0	442	80%
Norway	4,254	3,980	6.4	825	Optimised
Poland	16,658	16,171	2.9	283	80%
Portugal*	1,562	1,197	23.4	-	-
Romania	904	791	12.5	649	80%
Serbia	1,986	273	86.3	527	Optimised
Slovakia	169	152	10.1	732	80%
Slovenia	1,117	693	38.0	455	Optimised
Spain*	32,044	29,882	6.7	-	-
Sweden	19,497	19,466	0.2	366	80%
Switzerland	171,511	145,461	15.2	121	80%
United Kingdom*	23,719	23,719	0.0	-	-

Extended Data Table 4. Variables used to model barrier density.

Variable ID	Variable	Description	Resolution (m)	Data source	Owner	URL
1	elev	mean elevation (m) - weighted by catchment area	25	EU-DEM v1.1 -Copernicus Land Monitoring Service	EEA	https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1
2	slop	mean slope (digital number; high number = low slope) - weighted by catchment area	25	EU-DEM v1.0 and Derived Products	EEA	https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1-0-and-derived-products/slope
3	popd	population density (No./km^2)	250	Global Human Settlement - GHS POPULATION GRID	EC	https://ghsl.jrc.ec.europa.eu/ghs_pop.php
4	clc1	proportion of CLC level 1 - type 1 (urban areas)	100	CORINE Land Cover (CLC), Version 20	EEA	https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012
5	clc2	proportion of CLC level 1 - type 2 (agricultural areas)	100	CORINE Land Cover (CLC), Version 20	EEA	https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012
6	clc3	proportion of CLC level 1 - type 3 (forested/natural areas)	100	CORINE Land Cover (CLC), Version 20	EEA	https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012
7	clc4	proportion of CLC level 1 - type 4 (wetlands)	100	CORINE Land Cover (CLC), Version 20	EEA	https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012
8	clc5	proportion of CLC level 1 - type 5 (surface water)	100	CORINE Land Cover (CLC), Version 20	EEA	https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012
9	LenD	drainage density (km/km^2)	100	European catchments and Rivers network system (ECRINS)	EEA	https://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network
10	denr	dendritic ratio (total river length/No. rivers)	100	European catchments and Rivers network system (ECRINS)	EEA	https://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network
11	roadD	density of river-road crossing (No./km^2)	NA	GRIP global roads database	GLOBIO	https://www.globio.info/download-grip-dataset

Extended Data Table 5. Sensitivity analysis for barrier density modelling.

RMSE: Root Mean Squared Error; MAE: Mean Absolute Error.

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	0.99M

EXTENDED DATA FIGURE LEGENDS

Extended Data Fig. 1. Approach used to estimate river fragmentation in Europe. To correct for under-reporting and derive more accurate estimates of barrier density we used a four-step approach: (1) compilation of georeferenced barrier records from local, regional and national barrier databases (the AMBER Barrier Atlas), (2) data cleaning and removal of duplicate records, (3) ground-truthing barrier densities from walkover river surveys, and (4) statistical barrier modelling via random forest regression.

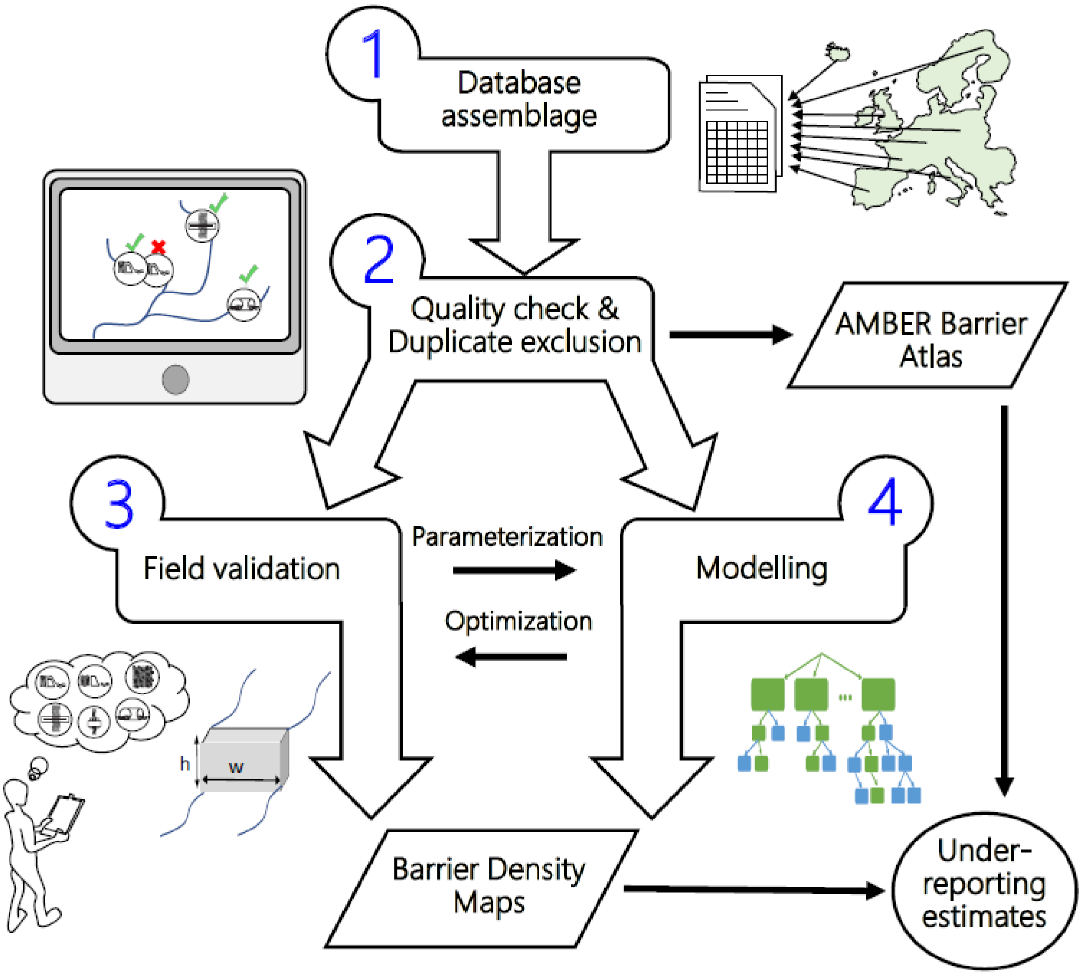
Extended Data Fig. 2. Cumulative height distribution of artificial barriers found in European rivers. The figure shows (log10 scale) that most barriers (68% of n = 117,371 built structures equal or greater than 10 cm in height) are low head structures (such as fords, culverts, and sluice gates) smaller than 2 m in height; these are ubiquitous but typically unreported in existing barrier inventories.

Extended Data Fig. 3. Location of test reaches used to ground-truth the AMBER Barrier Atlas during walkover surveys. We walked 147 test reaches totalling 2,715 km that were representative of river types found in Europe in terms of altitude, slope, stream order, biogeography and land use. River network and country sub-basin boundaries sourced from European Environment Agency [35].

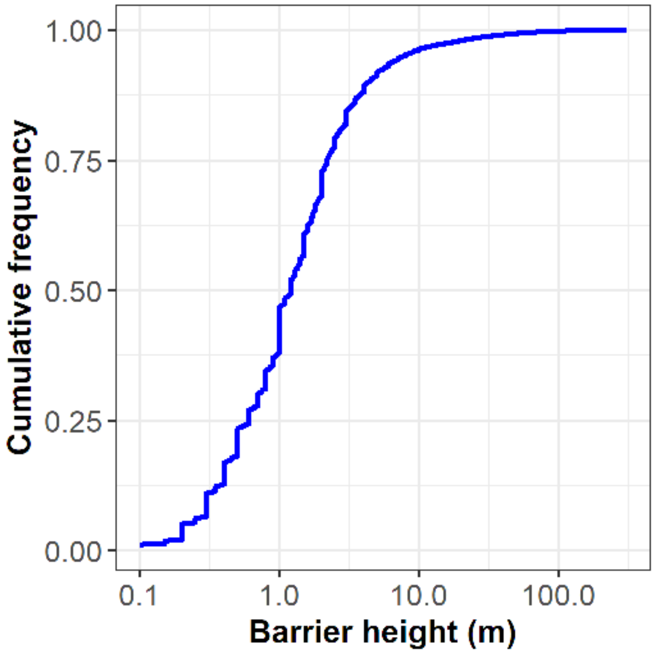
Extended Data Fig. 4. Variation in areal barrier density and main drivers of barrier abundance modelled by random forest regression. The maps show **(a)** the predicted barrier density at ECRINS sub-catchments (barriers/km^2; No. of sub-catchments = 8,467); **(b)** agricultural pressure (proportion of agricultural area, Corine Land Cover 2 – level 1); **(c)** road crossing density (No./km^2); **(d)** mean altitude (m.a.s.l.); **(e)** extent of surface water (proportion of area occupied by surface water, Corine Land Cover 5 – level 1). **(f)** shows the relative weight (Mean Decrease Impurity, MDI) of the 11 predictors used to model barrier density (detailed in Extended Data Table 4). Country and sub-basin boundaries, CORINE Land Cover and mean altitude sourced from European Environment Agency[35,61,63]; Road density sourced from the GRIP database[64].

Extended Data Fig. 5. Performance of the barrier density model. The maps show the distribution of modelling residuals (predicted-observed in barrier density – barriers/km^2) for **(a)** the model calibration dataset (No. of sub-catchments = 2,306), and **(b)** the whole AMBER Barrier Atlas dataset (No. of sub-catchments = 8,467). Country and sub-basin boundaries sourced from European Environment Agency[35].

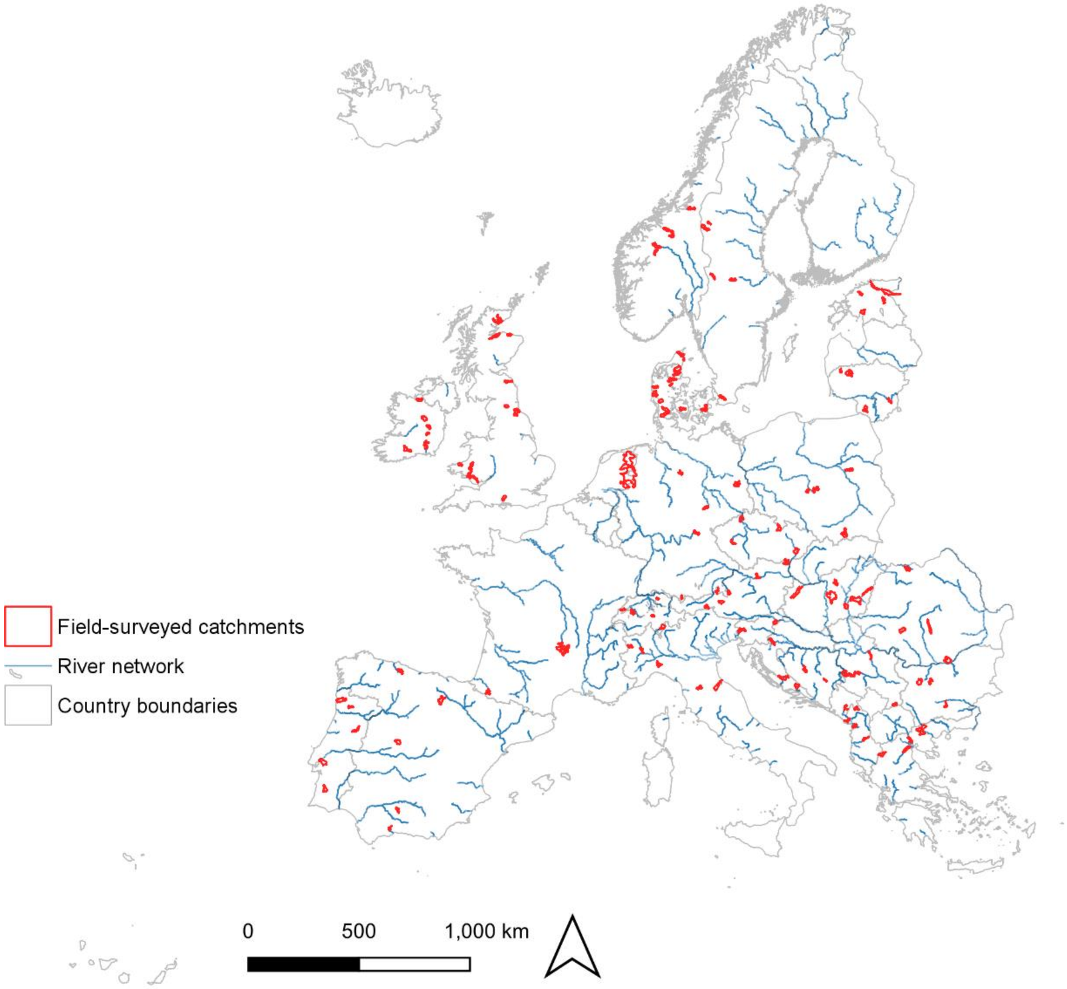
Extended Data Fig. 1



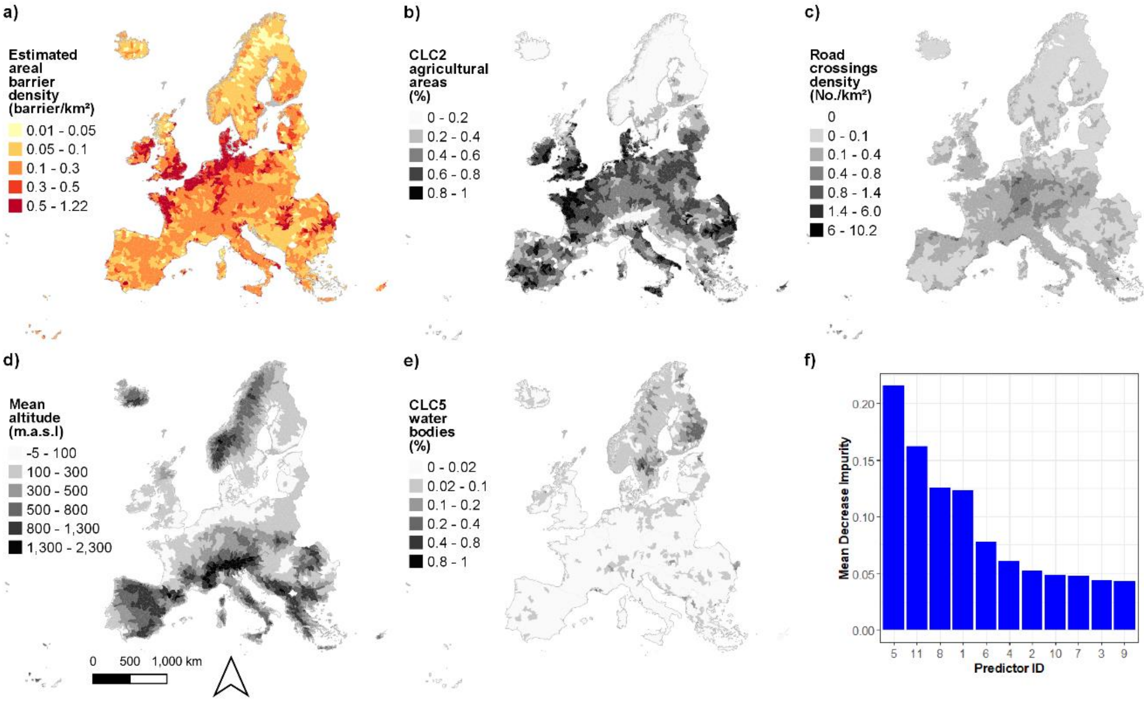
Extended Data Fig. 2



Extended Data Fig. 3

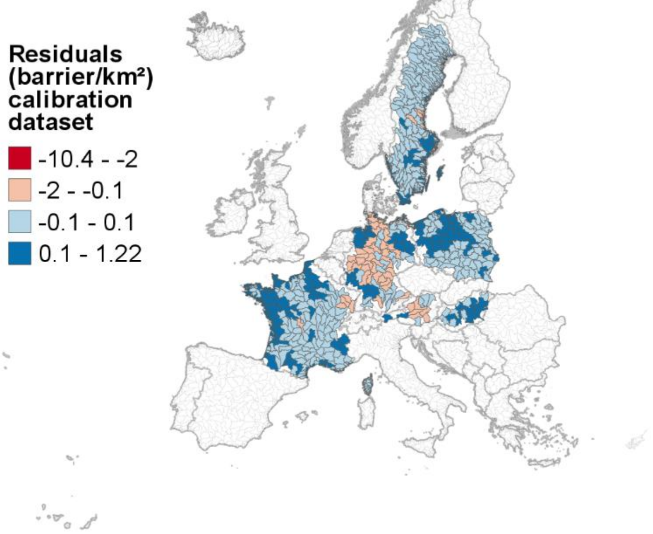


Extended Data Fig. 4



Extended Data Fig. 5

a)



b)