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More than one million barriers fragment Europe's rivers

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42 **Summary**

43 **Rivers support some of Earth's richest biodiversity¹ and provide essential**
44 **ecosystem services to society², but they are often impacted by barriers to free-**
45 **flow³. In Europe, attempts to quantify river connectivity have been hampered**
46 **by the absence of a harmonised barrier database. Here we show that there are**
47 **at least 1.2 million instream barriers in 36 European countries (mean density =**
48 **0.74 barriers/km), 68% of which are low-head (<2 m) structures that are**
49 **typically unreported. Standardised walkover surveys along 2,715 km of stream**
50 **length in 147 rivers indicate that existing records underestimate barrier**
51 **numbers by ~61%. The highest barrier densities occur in the heavily modified**
52 **rivers of Central Europe, and the lowest in the most remote, sparsely**
53 **populated alpine areas. Across Europe, the main predictors of barrier density**
54 **are agricultural pressure, density of river-road crossings, extent of surface**
55 **water, and elevation. Relatively unfragmented rivers are still found in the**
56 **Balkans, the Baltic states, and parts of Scandinavia and southern Europe, but**
57 **these require urgent protection from new dam developments. Our findings can**
58 **inform the implementation of the EU Biodiversity Strategy, which aims to**
59 **reconnect 25,000 km of Europe's rivers by 2030, but achieving this will require**
60 **a paradigm shift in river restoration that recognises the widespread impacts**
61 **caused by small barriers.**

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68 **MAIN TEXT**

69 **Broken rivers**

70 Rivers support some of the most biodiverse ecosystems in the world, but also some
71 of the most threatened¹. The defining characteristic of non-ephemeral, natural rivers
72 is that they flow⁴, and the most pervasive telltale of human impacts on rivers is the
73 break in connectivity caused by artificial barriers to free-flow⁵. Without dams, weirs,
74 fords and other instream structures it is difficult to imagine abstracting water,
75 generating hydropower, controlling floods, ferrying goods, or simply crossing
76 waterways. Rivers provide essential services to society, but our use of rivers has
77 nearly always involved fragmenting them⁶. However, assessing river fragmentation
78 has proved challenging⁷ due to the dendritic nature of rivers, the seasonality of the
79 hydrological regime, and the spatio-temporal nature of barrier impacts^{8,9}.

80

81 A critical challenge for quantifying river fragmentation is the lack of information on
82 the abundance and location of all but the largest of dams, especially over spatial
83 scales relevant for river basin management. Global database initiatives and novel
84 developments in remote sensing are making it possible to accurately map the
85 location of large dams, typically those above 10 m to 15 m high^{3,10-12}, but these only
86 represent a small fraction of all instream barriers, typically <1%¹³. Most low-head
87 structures are unreported¹⁴, despite the fact that their cumulative impact on river
88 connectivity is far more substantial^{15,16}. For instance, while only large storage dams
89 can affect the hydrological regime¹⁷, nearly all barriers can affect sediment
90 transport^{18,19}, the movement of aquatic organisms²⁰, and the structure of river
91 communities^{15,21}. Under-reporting of small barriers can vastly underestimate the

92 extent of river fragmentation²². For example, assessments of fragmentation based
93 solely on large dams³ would ignore 99.6% of the barriers present in Great Britain²³.
94 To estimate the true extent of river fragmentation, all barriers need to be considered,
95 large and small.

96

97 With only one third of its rivers having 'good ecological status' according to criteria of
98 the EU Water Framework Directive (WFD)²⁴, Europe probably has more heavily
99 modified rivers than anywhere else in the world^{25,26}, as well as a long legacy of
100 fragmentation, with fish passage legislation dating back to the 7th century²⁷.
101 Strikingly, the extent of river connectivity remains unknown for most European rivers,
102 despite the fact that the concept of river continuity is enshrined in the WFD and
103 inventories of physical barriers are required in River Basin Management Plans
104 (RBMP)²⁸. Yet, there is no comprehensive inventory of stream barriers in Europe,
105 only disparate records that differ in quality and spatial coverage from country to
106 country^{29,30}. Many weirs in Europe, for instance, were built at the turn of the 18th
107 century and sometimes much earlier, and their number and location are
108 consequently poorly known^{31,32}.

109

110 Here we present the first comprehensive estimate of river fragmentation in Europe
111 based on empirical and modelled barrier densities. We collated and harmonised 120
112 regional, national and global barrier datasets, and applied robust exclusion rules to
113 identify unique barrier records. To account for underreporting, we surveyed 147
114 rivers in 26 countries to derive field-corrected barrier densities, and employed
115 random forest regression (a machine learning technique) to estimate the number and
116 location of missing barriers (Extended Data Fig. 1).

117

118 **Barrier abundance, type and distribution**

119 We assembled information on 736,348 instream barriers from 36 countries and
120 identified 629,955 unique barrier records (Fig. 1), after excluding 106,393 duplicates
121 (see Methods). This figure is one order of magnitude higher than previous estimates
122 of longitudinal fragmentation for Europe based only on large dams^{11,12}, but
123 consistent with regional^{31,33,34} and country estimates that considered all barriers²³.
124 Most of the barriers in Europe's rivers are structures built to control and divert water
125 flow, or to raise water levels, such as weirs (30.5%), dams (9.8%), and sluice gates
126 (1.3%), to stabilise river beds, such as ramps and bed sills (31.5%), or to
127 accommodate road crossings, such as culverts (17.6%) and fords (0.3%). In 8.9% of
128 cases, barrier type was not recorded or could not be easily classified into one of our
129 six main types (e.g., gauge stations, spillways, groynes). Height data for 117,371
130 records indicate that 68% of barriers are less than 2 m high and 91% are less than 5
131 m high (mean = 2.77 m, SE = 0.025; median = 1.20 m; Extended Data Fig. 2), which
132 probably explains why so many barriers can be easily missed in surveys and
133 automated procedures, and why low-head structures are under-represented in most
134 barrier inventories.

135

136 **Accounting for barrier underreporting**

137 Barrier inventories in Europe are not homogeneous with respect to barrier types,
138 reach, or completeness (Table 1), as they were compiled for different purposes using
139 different resources. They have different spatial coverage and suffer from strong
140 sampling bias (Fig. 2a,b) that result in under-reporting of small structures. We
141 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 network³⁵, 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 streams³⁶. 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 Europe³⁷, as well as the location of rivers of good ecological status²⁴. 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 reasons⁴⁰, 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 straightening⁴⁵. Loss of connectivity depends mostly on the number and location of barriers, not on their height⁴⁶. 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 connectivity⁴⁶. 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 precision³⁶. More detailed hydrographic maps, available in many countries, are needed for dendritic estimates of longitudinal river connectivity²³ 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 connectivity⁴⁷, 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 development⁴⁸ 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 2030⁵⁰, 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

267 the attention, it is the small barriers that collectively do most of the damage. Small is

268 not beautiful.

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Main References

- 1 Reid, A. J. *et al.* Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol. Rev.* **94**, 849-873 (2019).
- 2 Grizzetti, B. *et al.* Relationship between ecological condition and ecosystem services in European rivers, lakes and coastal waters. *Sci. Tot. Environ.* **671**, 452-465 (2019).
- 3 Grill, G. *et al.* Mapping the world's free-flowing rivers. *Nature* **569**, 215-221 (2019).
- 4 Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. & Cushing, C. E. The river continuum concept. *Can. J. Fish. Aqua. Sci.* **37**, 130-137 (1980).
- 5 Vitousek, P. M., Mooney, H. A., Lubchenco, J. & Melillo, J. M. Human Domination of Earth's Ecosystems. *Science* **277**, 494-499 (1997).
- 6 Carpenter, S. R., Stanley, E. H. & Zanden, M. J. V. State of the world's freshwater ecosystems: physical, chemical, and biological changes. *Ann. Rev. Env. Res.* **36**, 75-99 (2011).
- 7 Fuller, M. R., Doyle, M. W. & Strayer, D. L. Causes and consequences of habitat fragmentation in river networks: River fragmentation. *Ann. N. Y. Acad. Sci.* **1355**, 31-51 (2015).
- 8 Van Looy, K., Tormos, T. & Souchon, Y. Disentangling dam impacts in river networks. *Ecol. Ind.* **37**, 10-20 (2014).
- 9 Kemp, P. & O'Hanley, J. Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. *Fish. Mgmt. Ecol.* **17**, 297-322 (2010).
- 10 Lehner, B. *et al.* High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front. Ecol. Env.* **9**, 494-502 (2011).
- 11 Lehner, B. *et al.* Global Reservoir and Dam Database, version 1 (GRanDv1): Palisades, NY: NASA Socioeconomic Data and Applications Center (2011).
- 12 Mulligan, M., Soesbergen, A. v. & Sáenz, L. GOODD, a global dataset of more than 38,000 georeferenced dams. *Sci. Dat.* **7**, 1-8 (2020).
- 13 Garcia de Leaniz, C., Berkhuysen, A. & Belletti, B. Beware small dams as well as large. *Nature* **570**, 164-164 (2019).
- 14 Mantel, S. K., Rivers-Moore, N. & Ramulifho, P. Small dams need consideration in riverscape conservation assessments: Small dams and riverscape conservation. *Aqua. Cons. Mar. Freshw. Ecosys.* **27**, 748-754 (2017).
- 15 Lucas, M. C., Bubb, D. H., Jang, M.-H., Ha, K. & Masters, J. E. G. Availability of and access to critical habitats in regulated rivers: effects of low-head barriers on threatened lampreys. *Freshw. Biol.* **54**, 621-634 (2009).
- 16 Birnie-Gauvin, K., Aarestrup, K., Riis, T. M. O., Jepsen, N. & Koed, A. Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers, and its implications for management. *Aqua. Cons. Mar. Freshw. Ecosys.* **27**, 1345-1349 (2017).
- 17 Magilligan, F. J., Nislow, K. H. & Renshaw, C. E. in *Treatise on Geomorphology* (ed John F. Shroder) 794-808 (Academic Press, 2013).
- 18 Petts, G. E. & Gurnell, A. M. Dams and geomorphology: Research progress and future directions. *Geomorph.* **71**, 27-47 (2005).
- 19 Bizzi, S. *et al.* On the control of riverbed incision induced by run-of-river power plant. *Wat. Res. Res.* **51**, 5023-5040 (2015).

319 20 Jones, P. E., Consuegra, S., Börger, L., Jones, J. & Garcia de Leaniz, C.
320 Impacts of artificial barriers on the connectivity and dispersal of vascular
321 macrophytes in rivers: A critical review. *Freshw. Biol.* **65**, 1165-1180 (2020).
322 21 Carpenter-Bundhoo, L. *et al.* Effects of a low-head weir on multi-scaled
323 movement and behavior of three riverine fish species. *Sci. Rep.* **10**, 1-14
324 (2020).
325 22 Graf, W. L. Dam nation: A geographic census of American dams and their
326 large-scale hydrologic impacts. *Wat. Res. Res.* **35**, 1305-1311 (1999).
327 23 Jones, J. *et al.* A comprehensive assessment of stream fragmentation in
328 Great Britain. *Sci. Tot. Env.* **673**, 756-762 (2019).
329 24 Grizzetti, B. *et al.* Human pressures and ecological status of European rivers.
330 *Sci. Rep.* **7**, 205 (2017).
331 25 Mauch, C. & Zeller, T. (Eds.) *Rivers in History: Perspectives on Waterways in*
332 *Europe and North America* x + 231 (University of Pittsburgh Press, Pittsburgh
333 2008).
334 26 Petts, G. E., Möller, H. & Roux, A. L. Historical Change of Large Alluvial
335 Rivers: Western Europe. 355 (John Wiley and Sons Ltd., Chichester, 1989).
336 27 Kemp, P. S. in *Freshwater Fisheries Ecology* (ed J. F. Craig) 717-769
337 (Wiley, 2015).
338 28 European Environment Agency. European Waters - Assessment of status
339 and pressures 2018. 85 (European Environment Agency, Luxembourg, 2018).
340 29 Garcia de Leaniz, C. *et al.* in *From Sea to Source v2 Protection and*
341 *Restoration of Fish Migration in Rivers Worldwide* (eds K. Brink *et al.*) 142-
342 145 (World Fish Migration Foundation., 2018).
343 30 Pistocchi, A. *et al.* Assessment of the effectiveness of reported Water
344 Framework Directive Programmes of Measures. Part II – development of a
345 system of Europe-wide Pressure Indicators. Report No. EUR 28412 EN, (Joint
346 Research Centre, 2017).
347 31 Garcia de Leaniz, C. Weir removal in salmonid streams: implications,
348 challenges and practicalities. *Hydrobiologia* **609**, 83-96 (2008).
349 32 Downward, S. & Skinner, K. Working rivers: the geomorphological legacy of
350 English freshwater mills. *Area* **37**, 138-147 (2005).
351 33 Sun, J., Galib, S. M. & Lucas, M. C. Are national barrier inventories fit for
352 stream connectivity restoration needs? A test of two catchments. *Wat.*
353 *Environ.J.* **n/a** (2020).
354 34 Atkinson, S. *et al.* An inspection-based assessment of obstacles to salmon,
355 trout, eel and lamprey migration and river channel connectivity in Ireland. *Sci.*
356 *Tot. Env.* **719**, 137215 (2020).
357 35 European Environment Agency. *European Catchments and Rivers Network*
358 *System (ECRINS)*, 2012).
359 36 Kristensen, P. & Globevnik, L. European small water bodies. *Biol. Env.: Proc.*
360 *R. Ir. Acad.* **114B**, 281-287 (2014).
361 37 Ferreira, T., Globevnik, L. & Schinegger, R. in *Multiple Stressors in River*
362 *Ecosystems* 139-155 (Elsevier, 2019).
363 38 Schwarz, U. Hydropower Pressure on European Rivers. 36 (WWF, 2019).
364 39 Schiemer, F. *et al.* The Vjosa River corridor: a model of natural hydro-
365 morphodynamics and a hotspot of highly threatened ecosystems of European
366 significance. *Land. Ecol.* (2020).
367 40 Duflo, E. & Pande, R. Dams. *Quart. J. Econ.* **122**, 601-646 (2007).

368 41 Grill, G., Ouellet Dallaire, C., Fluet Chouinard, E., Sindorf, N. & Lehner, B.
369 Development of new indicators to evaluate river fragmentation and flow
370 regulation at large scales: A case study for the Mekong River Basin. *Ecol. Ind.*
371 **45**, 148-159 (2014).

372 42 Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L. & Tockner, K. A global
373 boom in hydropower dam construction. *Aqua. Sci.* **77**, 161-170 (2015).

374 43 Tilt, B., Braun, Y. & He, D. Social impacts of large dam projects: A
375 comparison of international case studies and implications for best practice. *J.*
376 *Env.Mgmt.* **90**, S249-S257 (2009).

377 44 Schmitt, R. J. P., Bizzi, S., Castelletti, A. & Kondolf, G. M. Improved trade-offs
378 of hydropower and sand connectivity by strategic dam planning in the
379 Mekong. *Nature Sust.* **1**, 96-104 (2018).

380 45 Weibel, D. & Peter, A. Effectiveness of different types of block ramps for fish
381 upstream movement. *Aquat. Sci.* **75**, 251-260 (2013).

382 46 Cote, D., Kehler, D. G., Bourne, C. & Wiersma, Y. F. A new measure of
383 longitudinal connectivity for stream networks. *Land. Ecol.* **24**, 101-113 (2009).

384 47 Tickner, D. *et al.* Bending the curve of global freshwater biodiversity loss: an
385 emergency recovery plan. *BioSci.* (2020).

386 48 Bódis, K., Monforti, F. & Szabó, S. Could Europe have more mini hydro sites?
387 A suitability analysis based on continentally harmonized geographical and
388 hydrological data. *Renew. Sust. En. Rev.* **37**, 794-808 (2014).

389 49 Hušek, H., Žganec, K. & Pusch, M. T. A review of hydropower dams in
390 Southeast Europe – distribution, trends and availability of monitoring data
391 using the example of a multinational Danube catchment subarea. *Renew.*
392 *Sust. En. Rev.* **117** (2020).

393 50 European Union. Bringing nature back into our lives. EU 2030 Biodiversity
394 Strategy. (European Commission, Brussels, 2020).

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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 Agency³⁵.

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 Agency³⁵.

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.

METHODS

Overview

The connectivity of most rivers in Europe is unknown²⁸. 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 km². As there is no agreed definition of ‘barrier’ in relation to river connectivity⁵¹, 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 ones⁵². 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 km² (SE = 0.24) derived from the European Catchment and Rivers Network System database (ECRINS³⁵). 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 networks³⁶, 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 m²³. 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 3.10⁵⁴. We used bootstrapping⁵⁵ 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 algorithm⁵³ (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 previously²³. 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 order⁵⁶ 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 constraints⁵². 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 4.0.0⁵⁷. 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 package⁵⁸ 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

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

where N_a is the number of barriers recorded in the barrier atlas and N_f 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-crossings⁵⁹, small weirs with water mills in headwaters³², and storage dams with nearby cities, agriculture and hydropower⁶⁰. Similarly, the location of barriers is also determined by topography, geology and climate⁷.

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 water⁶¹); population density (No./km²)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/km²)^{35,63}, and number of road crossings in the river network divided by catchment area (No./km²)⁶⁴.

We used a data-driven, nonparametric Random Forest Regressor⁶⁵ 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 importance⁶⁵, 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 km²; 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 km², which corresponds to 593.5 km² 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 older³². 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/km²; Extended Data Fig. 4a) and then transformed into linear river density (barrier/km; Fig. 2c).

The average model validation error was 0.09 barrier/km² (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 km² (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.

Methods References

- 51 Wohl, E. Connectivity in rivers. *Prog. Phys. Geo. Earth. Env.* **41**, 345-362 (2017).
- 52 Belletti, B. *et al.* Datasets for the AMBER Barrier Atlas of Europe. Table S1. Details of test rivers showing number of barriers present in current inventories (Atlas) and those encountered in the field. Table S3. Barrier Database sources. figshare <https://doi.org/10.6084/m9.figshare.12629051> (2020).
- 53 Jones, J. *et al.* Quantifying river fragmentation from local to continental scales: data management and modelling methods. *Authorea (pre-print)* doi: [10.22541/au.159612917.72148332](https://doi.org/10.22541/au.159612917.72148332) (2020).
- 54 QGIS Geographic Information System (Open Source Geospatial Foundation Project, 2010).
- 55 Chao, A., Wang, Y. T. & Jost, L. Entropy and the species accumulation curve: a novel entropy estimator via discovery rates of new species. *Meth. Ecol. Evol.* **4**, 1091-1100 (2013).
- 56 Strahler, A. N. Quantitative analysis of watershed geomorphology. *Trans. Am. Geophys. Un.* **38**, 913-920 (1957).
- 57 R: A language and environment for statistical computing. Version 4.0.0 (2020-04-24) v. 4.0.0 (2020-04-24) (R Foundation for Statistical Computing, Vienna, Austria., 2020).
- 58 Signorell, A., K. Aho, A. Alfons, N. Anderegg, T. Aragon, and A. Arppe. DescTools: Tools for descriptive statistics. R package version 0.99.37. v. 0.99.37 (2020).
- 59 Januchowski-Hartley, S. R. *et al.* Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. *Front. Ecol. Env.* **11**, 211-217 (2013).
- 60 Schmutz, S. & Moog, O. in *Riverine Ecosystem Management Aquatic Ecology Series* 111-127 (Springer, Cham, 2018).
- 61 European Environment Agency. *CORINE Land Cover (CLC), Version 20*, 2012).
- 62 European Commission. *Global Human Settlement - GHS Population Grid*, 2015).
- 63 European Environment Agency. *EU-DEM v1.1 — Copernicus Land Monitoring Service*, 2016).
- 64 Meijer, J. R., Huijbregts, M. A. J., Schotten, K. C. G. J. & Schipper, A. M. Global patterns of current and future road infrastructure. *Env. Res. Lett.* **13**, 064006 (2018).
- 65 Louppe, G., Wehenkel, L., Suter, A. & Geurts, P. in *Advances in Neural Information Processing Systems*. (eds C.J.C. Burges *et al.*) 431-439 (Neural Information Processing Systems Foundation, Inc.).

668 66 Anon. *National Inventory of Dams*, <http://nid.usace.army.mil/> (2018).
 669 67 Yoshimura, C., Omura, T., Furumai, H. & Tockner, K. Present state of rivers
 670 and streams in Japan. *Riv. Res. Appl.* **21**, 93-112 (2005).
 671 68 Anon. *Table of Major Rivers in Japan*,
 672 <https://www.mlit.go.jp/river/basic_info/english/admin.html> (2020).
 673 69 Anon. *Brazil Dams Safety Report*. (Global Dam Watch)
 674 <<http://globaldamwatch.org/data/>> (2020).
 675 70 World Commission on Dams. *Dams and Development: A New Framework for*
 676 *Decision Making*. (Earthscan Publications Ltd., 2000).
 677 71 International Rivers. The True Cost of Hydropower in China. 8 (2014).
 678 72 Yang, X. *et al.* Our fragmented rivers - mapping human-made river
 679 obstructions around the globe. *Am. Geophys. Un. (AGU) Fall Meeting*.
 680 <<https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/564635>> (2019)
 681 73 Anon. *Hydrology and Water Resources Information System for India*,
 682 <http://117.252.14.242/rbis/India_Information/rivers.htm> (2020).
 683 74 Lehner, B., Verdin, K. & Jarvis, A. New global hydrography derived from
 684 spaceborne elevation data. *Eos, Trans. Am. Geophys. Un.* **89**, 93-94 (2008).
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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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765

766 **Additional information**

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

769

770 **EXTENDED DATA TABLES**

771

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

775

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

778

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

781

782

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

784

785

786 **Extended Data Table 5.** Sensitivity analysis for barrier density modelling. RMSE:

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

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790

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/km²; No. of sub-

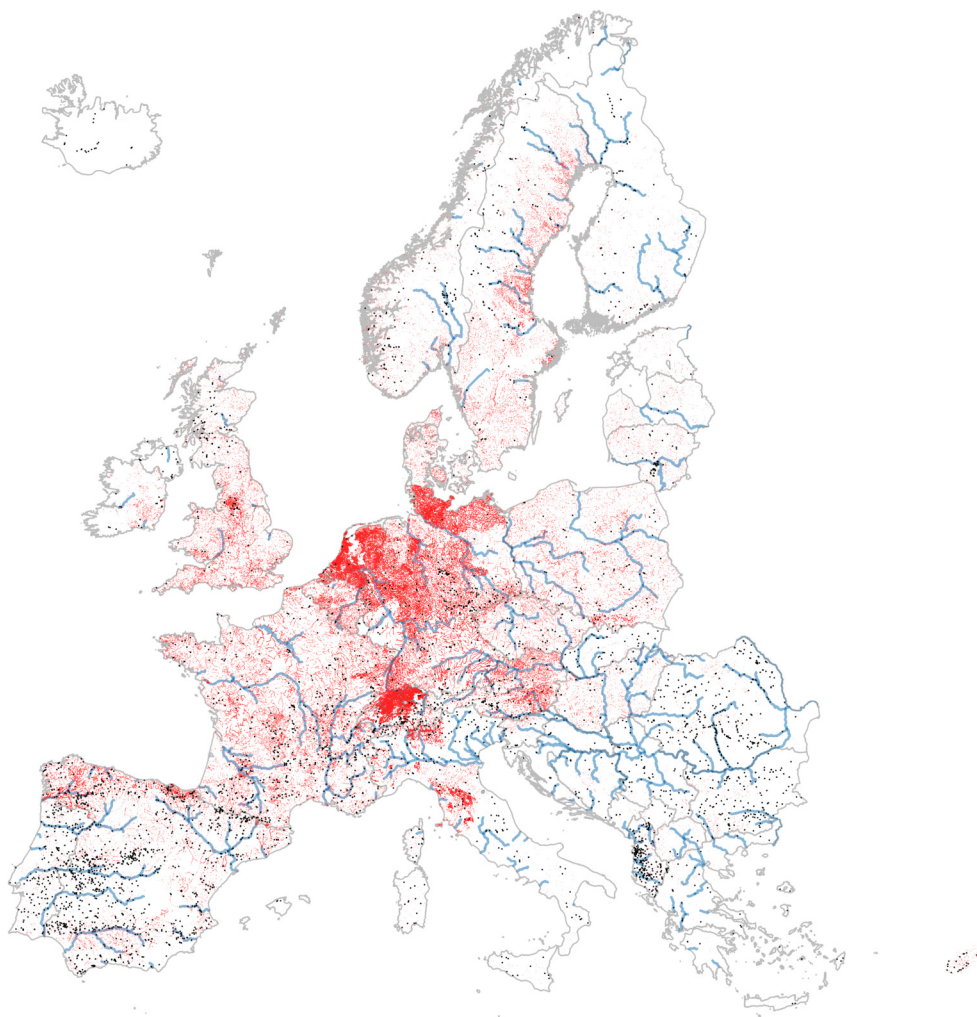
catchments = 8,467); **(b)** agricultural pressure (proportion of agricultural area, Corine Land Cover 2 – level 1); **(c)** road crossing density (No./km²); **(d)** mean altitude (m.a.s.l.); **(e)** extent of surface water (proportion of area occupied by surface water, Corine Land Cover 5 – level 1). **(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 database⁶⁴.

Extended Data Fig. 5. Performance of the barrier density model. The maps show the distribution of modelling residuals (predicted-observed in barrier density – barriers/km²) 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 Agency³⁵.

Atlas barriers

- Global databases
- Other databases
- River network
- Country boundaries

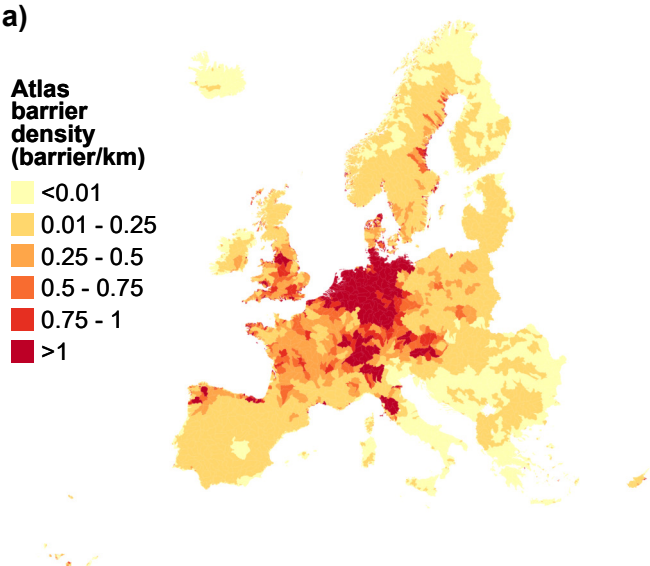
0 500 1,000 km



a)

**Atlas
barrier
density
(barrier/km)**

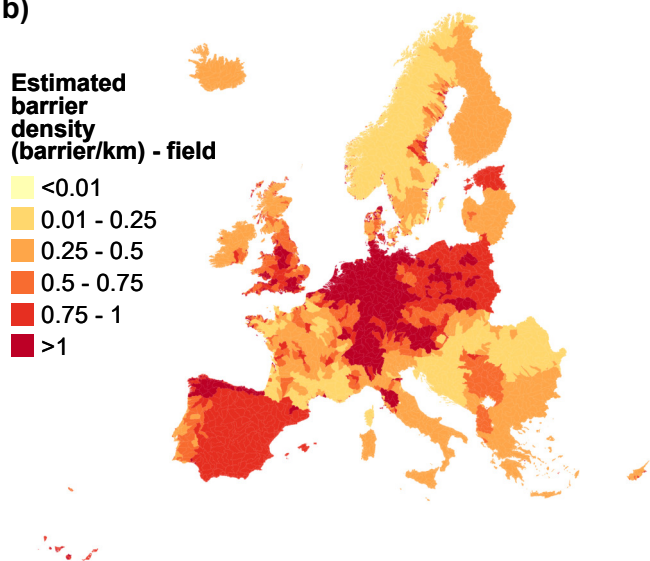
<0.01
0.01 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
>1



b)

**Estimated
barrier
density
(barrier/km) - field**

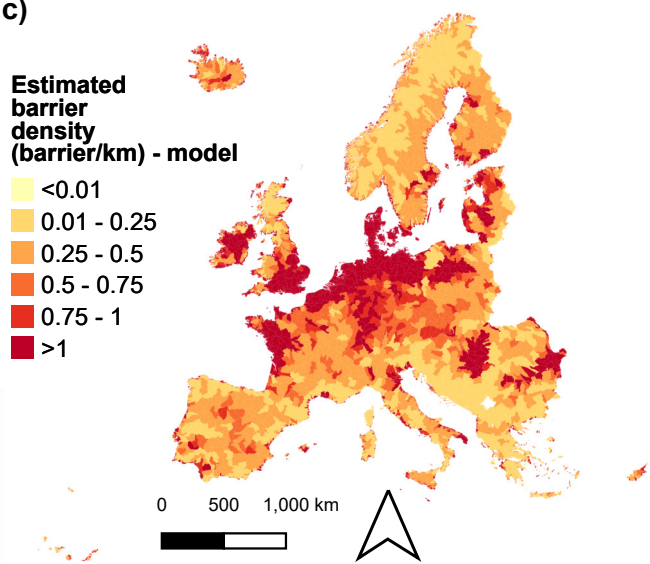
<0.01
0.01 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
>1



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



