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Authors	Belletti, Barbara;Garcia de Leaniz, Carlos;Jones, Joshua;Bizzi, Simone;Börger, Luca;Segura, Gilles;Castelletti, Andrea;van de Bund, Wouter;Aarestrup, Kim;Barry, James;Belka, Kamila;Berkhuysen, Arjan;Birnie-Gauvin, Kim;Bussettini, Martina;Carolli, Mauro;Consuegra, Sofia;Dopico, Eduardo;Feierfeil, Tim;Fernández, Sara;Fernandez Garrido, Pao;Garcia-Vazquez, Eva;Garrido, Sara;Giannico, Guillermo;Gough, Peter;Jepsen, Niels;Jones, Peter E.;Kemp, Paul;Kerr, Jim;King, James;Łapińska, Małgorzata;Lázaro, Gloria;Lucas, Martyn C.;Marcello, Lucio;Martin, Patrick;McGinnity, Philip;O'Hanley, Jesse;del Amo, Rosa Olivo;Parasiewicz, Piotr;Pusch, Martin;Rincon, Gonzalo;Rodriguez, Cesar;Royte, Joshua;Schneider, Claus Till;Tummers, Jeroen S.;Vallesi, Sergio;Vowles, Andrew;Verspoor, Eric;Wanningen, Herman;Wantzen, Karl M.;Wildman, Laura;Zalewski, Maciej
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More than one million barriers fragment Europe's rivers

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3 Barbara Belletti^{1†}, Carlos Garcia de Leaniz^{*2}, Joshua Jones², Simone Bizzi³,
4 Luca Börger², Gilles Segura⁴, Andrea Castelletti¹, Wouter van de Bund^{*5}, Kim
5 Aarestrup⁶, James Barry⁷, Kamila Belka⁸, Arjan Berkhuisen⁹, Kim Birnie-Gauvin⁶,
6 Martina Bussetini¹⁰, Mauro Carolli¹¹, Sofia Consuegra², Eduardo Dopico¹²,
7 Tim Feierfeil¹³, Sara Fernández¹², Pao Fernandez Garrido⁹, Eva Garcia-Vazquez¹²,
8 Sara Garrido¹⁴, Guillermo Giannico¹⁵, Peter Gough⁹, Niels Jepsen⁶, Peter E. Jones²,
9 Paul Kemp¹⁶, Jim Kerr¹⁶, James King⁷, Małgorzata Łapińska⁸, Gloria Lázaro¹⁴,
10 Martyn C. Lucas¹⁷, Lucio Marcello¹⁸, Patrick Martin¹⁹, Phillip McGinnity²⁰, Jesse
11 O'Hanley²¹, Rosa Olivo del Amo^{9†}, Piotr Parasiewicz²², Martin Pusch¹¹, Gonzalo
12 Rincon²³, Cesar Rodriguez¹⁴, Joshua Royte²⁴, Claus Till Schneider²⁵, Jeroen S.
13 Tummers¹⁷, Sergio Vallesi²⁶, Andrew Vowles¹⁶, Eric Verspoor¹⁸, Herman Wanningen⁹,
14 Karl M. Wantzen²⁷, Laura Wildman²⁸ & Maciej Zalewski⁸

15

16 ¹Polytechnic University of Milan (Italy), ²Swansea University (UK), ³University of
17 Padua (Italy), ⁴IS Environnement (France), ⁵European Commission Joint Research
18 Centre (Italy), ⁶Technical University of Denmark (Denmark), ⁷Inland Fisheries Ireland
19 (Ireland), ⁸European Regional Centre for Ecohydrology of the Polish Academy of
20 Sciences (Poland), ⁹World Fish Migration Foundation (Netherlands), ¹⁰Italian
21 National Institute for Environmental Protection and Research (Italy), ¹¹IGB Leibniz-
22 Institute of Freshwater Ecology and Inland Fisheries (Germany), ¹²University of
23 Oviedo (Spain), ¹³IBK- Ingenieur-Büro Kötter GmbH (Germany), ¹⁴AEMS-Rios con
24 Vida (Spain), ¹⁵Oregon State University (USA), ¹⁶University of Southampton (UK),
25 ¹⁷Durham University (UK), ¹⁸University of Highlands & Islands (UK), ¹⁹Conservatoire

26 National du Saumon Sauvage (France), ²⁰University College Cork (Ireland),
27 ²¹University of Kent (UK), ²²Stanisław Sakowicz Inland Fisheries Institute (Poland),
28 ²³Polytechnic University of Madrid (Spain), ²⁴The Nature Conservancy (USA),
29 ²⁵Innogy SE (Germany), ²⁶Hydronexus (Italy), ²⁷University of Tours (France),
30 ²⁸Princeton Hydro (USA)

31

32 †present affiliation: CNRS UMR5600-EVS, University of Lyon (France)

33 ¶present affiliation: University of Murcia (Spain)

34

35 *Corresponding authors:

36 c.garciadeleaniz@swansea.ac.uk

37 wouter.van-de-bund@ec.europa.eu

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40 **Summary**

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

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66 **MAIN TEXT**

67 **Broken rivers**

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

78

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

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

94

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

106

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

114

115 **Barrier abundance, types, and distribution**

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

131

132 **Accounting for barrier underreporting**

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

140 2b; Extended Data Fig. 3), and barrier modelling at sub-catchment level using random
141 forest regression (a top-down strategy; Fig. 2c).

142

143 Our study indicates that there are more barriers than existing databases would
144 suggest. We found 1,583 barriers in 2,715 km of walkway river surveys across Europe,
145 960 of which (61%) were absent from current barrier inventories (Extended Data Table
146 1). None of the 147 surveyed rivers were free of artificial barriers (although some of
147 the contiguous test-reaches were). The number of barriers recorded in the field was
148 on average 2.5 times higher than in existing inventories.

149

150 **Extent of river fragmentation in Europe**

151 Field-corrected barrier densities indicate that there are on average 0.74 barriers per
152 km of river length, ranging from 0.005 barriers/km for Montenegro to 19.44 barriers/km
153 for the Netherlands (Table 1) with a median distance between adjacent barriers for all
154 countries of 108 m (SE = 44). This equates to 1,213,874 barriers across Europe using
155 a conservative estimate of 1.65M km for the river network³⁵, but could be as high as
156 3.7M barriers if we consider a 5M km river network, a figure that better takes into
157 account the abundance of first and second order streams³⁶. Our barrier density
158 estimates are higher than those reported anywhere (Extended Data Table 2), possibly
159 making Europe the most fragmented river landscape in the world.

160

161 On the other hand, modelling of barrier density predicted 0.60 barriers/km (SE =
162 0.24; Fig. 2c, Extended Data Fig. 4a) or 991,341 barriers across Europe, which is
163 within 20% of the field-corrected estimate. Thus, both approaches provided
164 congruent results and suggest that fragmentation estimates based on existing barrier

165 records underestimate true barrier numbers by 36 to 48% according to modelling
166 and field survey results, respectively. This is largely due to the presence of many
167 small structures (Extended Data Fig. 2) that tend to be under-reported in barrier
168 inventories (Fig. 3a,b).

169

170 **Correlates of barrier abundance**

171 The highest barrier densities are found in Central Europe and correspond with densely
172 populated areas, intense use of water, and high road density (Fig. 2b,c); in contrast,
173 the lowest barrier densities tend to occur in the most remote, sparsely populated alpine
174 areas (e.g., Scandinavia, Iceland and Scotland). This pattern of river fragmentation
175 largely mirrors the distribution of other anthropic pressures in Europe³⁷, as well as the
176 location of rivers of good ecological status²⁴. Although no catchment in Europe is free
177 of artificial barriers, there are still relatively unfragmented rivers in the Balkans, the
178 headwaters of the Baltic States, and parts of Scandinavia and Southern Europe.
179 Worryingly, these are also the areas where many of the new hydropower dams are
180 being planned^{38,39}, which threatens their biodiversity and good ecological status and
181 may be contrary to the precautionary principle that guides the WFD.

182

183 **A call for action on small barriers**

184 Views on global patterns of river fragmentation have been dominated by consideration
185 of large dams (>15 m) due to safety and economic reasons⁴⁰, but also because these
186 create large reservoirs that are easier to detect remotely^{41,42}, generate social
187 conflict^{40,43}, and there is the implicit assumption that large dams are primarily
188 responsible for the loss of longitudinal connectivity^{22,44}. However, our study shows that
189 dams greater than 15 m high are rare (<1.0%) and that most barriers to free-flow are

190 small structures that are difficult to detect and are poorly mapped (Fig. 2a, Fig. 3a).
191 For example, in Switzerland fragmentation is mostly caused by ~100,000 small bed
192 sills built to compensate for bed incision caused by channel straightening⁴⁵. Loss of
193 connectivity depends mostly on the number and location of barriers, not on their
194 height⁴⁶. As many of these barriers are small, old and obsolete, they provide
195 unprecedented opportunities for restoring connectivity, which our study can help
196 inform.

197
198 Firstly, to restore connectivity efficiently, we call for better mapping and monitoring of
199 barriers, particularly small ones, as they are the most abundant and the main cause
200 of fragmentation. A concerted global effort is required to map low-head structures and
201 complement existing dam databases. Although barrier density is only a crude measure
202 of fragmentation, the number and location of barriers serves as the basis for most
203 metrics of river connectivity⁴⁶. In this sense, our work highlights the merits, but also
204 the limitations, of modelling fragmentation, and suggests that there is no substitute for
205 a 'boots on the ground' approach for estimating barrier numbers and location^{23,34}. It
206 also exposes the inadequacies of current barrier inventories, and emphasizes the
207 need for complete, harmonized barrier databases in order to select the river
208 catchments that offer the best prospects for restoration of connectivity.

209
210 With nearly 630,000 records, the AMBER Barrier Atlas represents the most
211 comprehensive barrier inventory available anywhere, but is far from being complete.
212 A staggering 0.6M barriers are probably missing from current inventories. Importantly,
213 our study can help optimise future mapping efforts, and fill data gaps where
214 information is lacking. For example, our field surveys indicate that existing records

215 grossly underestimate the abundance of small barriers (Log Likelihood Ratio = 97.94,
216 $df = 5$, $P < 0.001$; Fig. 3a), particularly fords, culverts and sluice gates (LRT = 44.70,
217 $df = 5$, $P < 0.001$; Fig. 3b), and these are structures that should be targeted in future
218 surveys. Likewise, the completeness of current inventories differs widely from country
219 to country (Fig. 3c). Barrier underreporting appears to be very high across the Danube
220 and the Balkans (76-98% underreporting), but also in Estonia (91%), Greece (97%),
221 and particularly in Sweden regarding low-head structures (100%). Thus, although our
222 barrier inventory is inevitably incomplete, we can determine where most of the
223 information is missing. At present, the results of our study cannot be used to manage
224 barriers at the catchment scale because although the coordinates of the barriers we
225 mapped are essentially accurate, the underlying European digital river map (ECRINS)
226 lacks the required precision³⁶. More detailed hydrographic maps, available in many
227 countries, are needed for dendritic estimates of longitudinal river connectivity²³ and for
228 detailed barrier mitigation planning. Having a more consistent high resolution
229 hydrographic network across Europe (i.e. improving on ECRINS) must be viewed as
230 a priority for large scale assessments and for more effective restoration of connectivity.

231

232 Secondly, to reconnect rivers, information is needed on the current use and legal
233 status of barriers, as many are no longer in use and could be removed. In some parts
234 of Europe, for example, many weirs were built to service former water mills, which
235 have subsequently been abandoned^{31,32}. Given the current impetus on barrier removal
236 and restoration of river connectivity⁴⁷, it would make sense to start with obsolete and
237 small (<5 m) structures, which constitute the majority of barriers in Europe. Removing
238 small barriers will likely be easier and cheaper than removing larger infrastructures,
239 and probably also better accepted by local stakeholders, whose support is essential

240 for restoring river connectivity. However, removing old barriers will not increase
241 connectivity if more barriers are built elsewhere. Current rates of fragmentation also
242 need to be halted, and this may require a critical reappraisal of the sustainability and
243 promotion of micro-hydro development⁴⁸ against the alternative of enhancing the
244 efficiency of existing dams.

245

246 Finally, we call for an evidence-based approach to restoring river connectivity, and
247 the use of ‘what if’ predictive modelling for assessing the cost and benefits of
248 different restoration strategies under various barrier mitigation scenarios. Given the
249 threat of further fragmentation posed by new dams in Europe^{38,49}, and the new EU
250 Biodiversity Strategy’s target of reconnecting at least 25,000 km of Europe’s rivers
251 by 2030⁵⁰, our results can serve as a baseline against which future gains or losses in
252 connectivity can be gauged. Estimates of fragmentation can also be incorporated
253 into pan-European assessments of river ‘ecological status’ and inform the level of
254 funding required to achieve desired connectivity targets.

255

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

262

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388

389 TABLES

390

391 Table 1. Number of unique barrier records in Europe (AMBER Barrier Atlas)

392 and corrected barrier abundance estimates derived from field surveys.

393

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

394

395

396 **FIGURE LEGENDS**

397

398 **Fig. 1. Artificial instream barriers in Europe (AMBER Barrier Atlas).** The map

399 shows the distribution of 629,955 unique barrier records compiled from 120 local,

400 regional, and national databases after duplicate exclusion. Red dots represent the

401 new barrier records assembled in this study, whereas black dots represent large

402 dams (>15m in height) from existing global databases. The full georeferenced data

403 can be downloaded from *figshare* <https://doi.org/10.6084/m9.figshare.12629051>.

404 Country and sub-basin boundaries were sourced from the European Environment

405 Agency³⁵.

406

407 **Fig. 2. Extent of river fragmentation in Europe.** The map shows the barrier

408 density (barrier/km) in ECRINS sub-catchments (n= 8,467) across Europe based on

409 (a) existing barrier records (AMBER Barrier Atlas), (b) ground-truthed barrier

410 abundance (bottom-up approach), and (c) barrier modelling via random forest

411 regression (top-down approach). Country and sub-basin boundaries were sourced

412 from the European Environment Agency³⁵.

413

414 **Fig. 3. Extent of barrier under-reporting.** The figures show the estimated under-

415 reporting error (% of barriers that are missing from current inventories) for barriers of

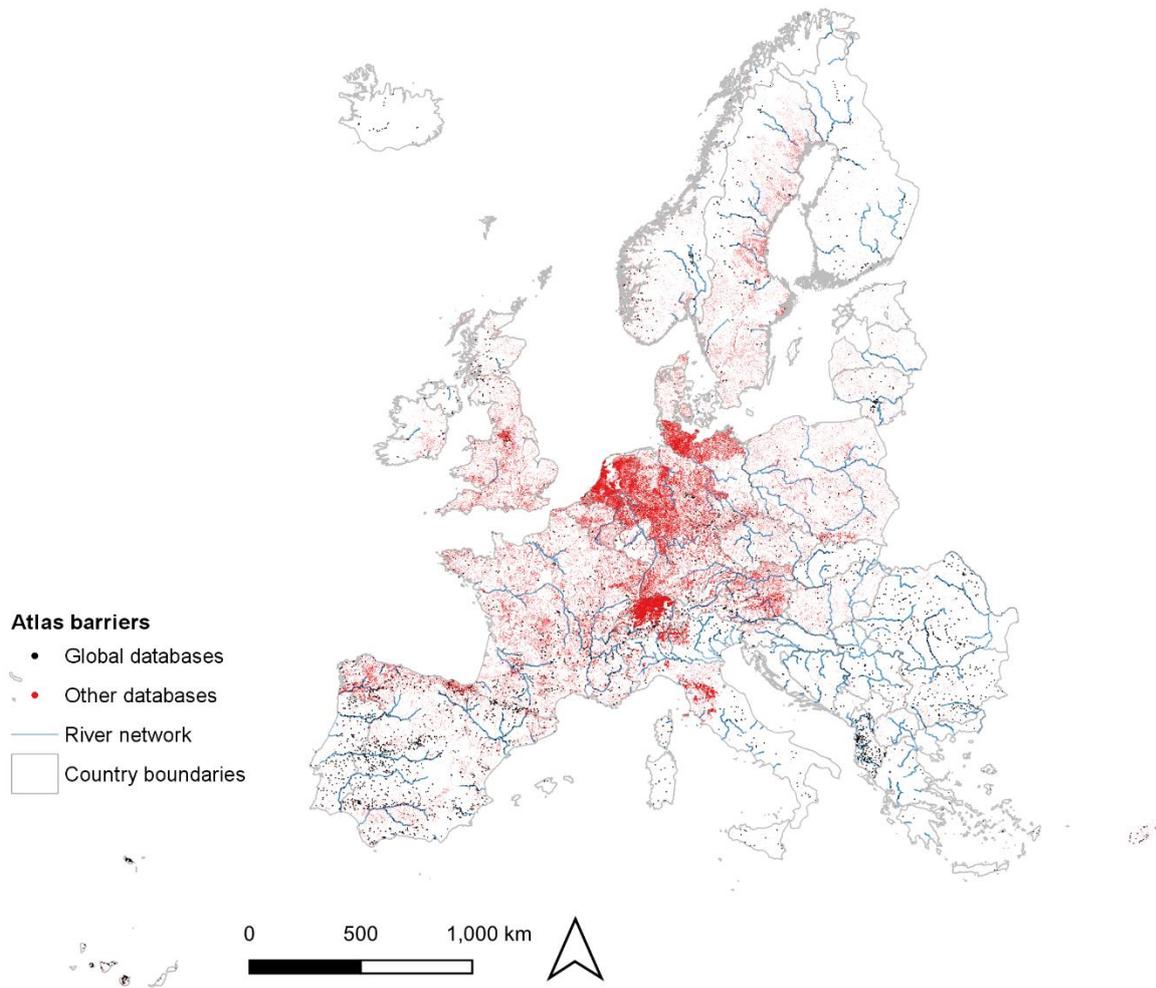
416 (a) different height (m), (b) different types, and (c) in different countries. Values are

417 colour-coded depending on whether the reporting error is above (blue) or below (light

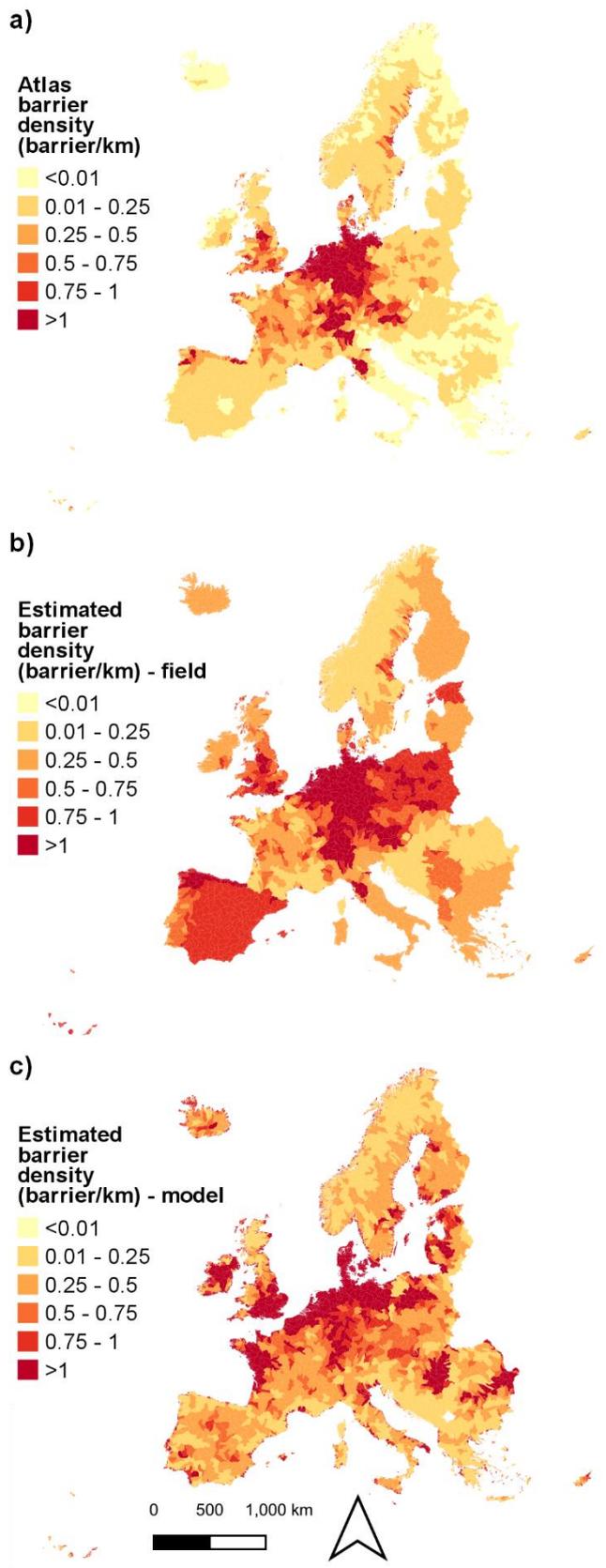
418 yellow) the median error (dotted line). Country codes are given in Table 1.

419

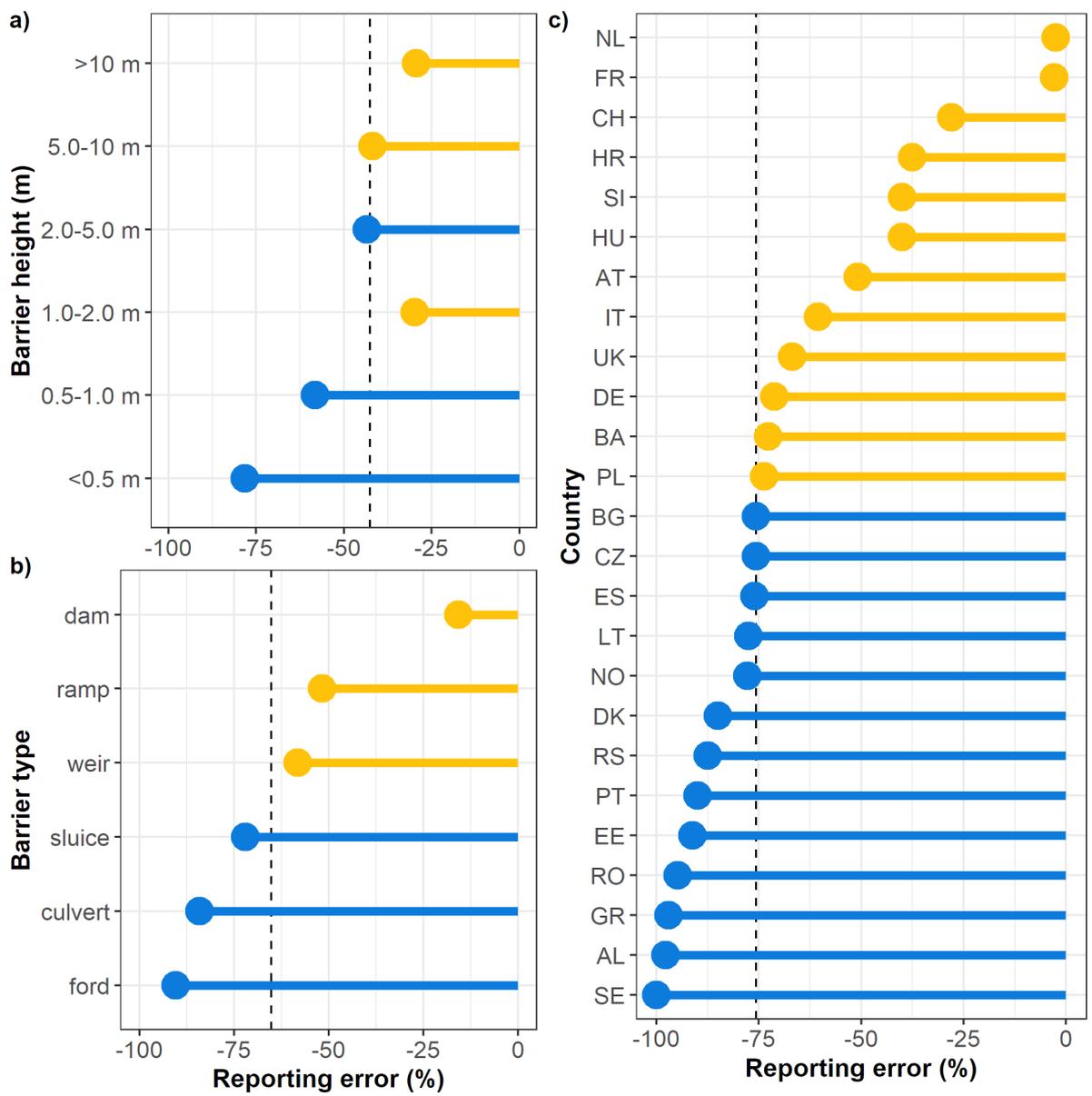
420 **Fig. 1**
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422
423



425 **Fig. 3**



426

427 **METHODS**

428

429 **Overview**

430 The connectivity of most rivers in Europe is unknown²⁸. To fill this gap, we quantified
431 the abundance of artificial barriers across Europe as part of the EC-funded Horizon
432 2020 project 'Adaptive Management of Barriers in European Rivers' (AMBER;
433 www.amber.international). We estimated barrier densities (barriers/km) in 36
434 European countries including all 26 member states of the European Union (EU), the
435 United Kingdom, three members of the Economic European Area (Switzerland,
436 Iceland and Norway) and seven countries geographically located within Europe
437 (Albania, Andorra, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, and
438 Serbia) covering an area of ~5.02 million km². As there is no agreed definition of
439 'barrier' in relation to river connectivity⁵¹, for the purposes of our work we defined an
440 artificial longitudinal barrier as "any built structure that interrupts or modifies the flow
441 of water, the transport of sediments, or the movement of organisms and can cause
442 longitudinal discontinuity".

443

444 To estimate barrier densities we used a four-step approach (Extended Data Fig. 1)
445 consisting of (1) compiling a georeferenced atlas of barrier records from local,
446 regional and national barrier databases (the AMBER Atlas), (2) cleaning and
447 removing duplicate records, (3) ground-truthing barrier densities with field surveys,
448 and (4) modelling fragmentation at the pan-European scale via random forest
449 regression. This allowed us to identify nearly 630,000 unique barrier records (Fig. 1,
450 2a), and to estimate the extent of longitudinal fragmentation in Europe from field-
451 corrected (Fig. 2b) and modelled barrier densities Fig. 2c).

452

453 **Building the European Atlas of artificial instream barriers**

454 We collected and cross-referenced barrier records from 120 databases from 36
455 countries, including 65 local and regional databases, 52 national databases and four
456 global ones⁵². After quality checking, we harmonised records into a single relational
457 database (the AMBER Barrier Atlas) and removed duplicates (see below). We
458 classified over 1,000 different barrier types into six main functional groups that
459 capture variation in barrier size and use^{23,53}: dam, weir, sluice, ramp/bed sill, ford,
460 and culvert, plus 'other' (e.g., groynes, spillways) and 'unknown' (Table 1). We
461 included country, river name, geographical coordinates, and barrier height if known,
462 as well as database source. These attributes were available in most databases and
463 provided the information required to allow us to estimate barrier densities and
464 compare them to ground-truthed values.

465

466 To map barriers consistently across Europe we used 86,381 functional sub-
467 catchments with an average area of 58.2 km² (SE = 0.24) derived from the European
468 Catchment and Rivers Network System database (ECRINS³⁵). This database and
469 the associated river network are derived from a 100 m resolution digital elevation
470 model (DEM) and covers 1.65 million km of river length across the study area.

471 Although ECRINS may underestimate river length by up to 74% compared to more
472 detailed river networks³⁶, it is the only consistent river network that can currently be
473 used for global comparisons across Europe. The consequences of underestimating
474 river length for estimates of river fragmentation are difficult to predict.

475 Underestimating river length can overestimate river fragmentation if the observed
476 number of barriers is in reality distributed over a longer river network, but it can also

477 underestimate it if undetected barriers are more likely to occur in poorly mapped first
478 order streams.

479

480 **Excluding duplicated barrier records**

481 We chose a maximum Euclidean distance of 1,000 m between neighbouring barriers
482 within the same ECRINS sub-catchment to investigate potential duplicates; we had
483 previously determined for a smaller database that few or no duplicates may be
484 expected beyond 500 m²³. To derive exclusion distances, three people working
485 independently assessed up to 200 potential random duplicates per country, or all
486 potential duplicates if the number was less than 200. Each person visually assessed
487 25% of duplicate records using Google and Bing satellite imagery, and all assessed
488 a common subsample comprising 25% of the records. The distance between each
489 potential duplicate was measured in QGIS 3.10⁵⁴. We used bootstrapping⁵⁵ to
490 calculate a mean and 95% CI distance that excluded 80% of potential duplicates and
491 showed 80% or better agreement between the three people working on the common
492 subsamples using an optimised algorithm⁵³ (Extended Data Table 3).

493

494 **Ground-truthing barrier records through walkway river surveys**

495 To ground-truth barrier density estimates, we surveyed 147 rivers across 26 countries,
496 totalling 2,715 km or 0.16% of the river network (Extended Data Table 1, Extended
497 Data Fig. 3) using a method described previously²³. We used expert judgement to
498 choose 2-6 test rivers per country that were broadly representative of the river types
499 found in Europe in terms of altitude, slope, stream order⁵⁶ and, depending on
500 accessibility, biogeography and land use. Surveyed reaches were mostly single-
501 thread (>80%) and spanned Strahler stream orders 1 to 8, although most were order

502 3-5 (62%). At each river, we surveyed a contiguous 20 km reach at low flow conditions
503 (~Q80-Q95) during the spring of 2017 and the summers of 2018 and 2019, except in
504 Denmark and Scotland where we surveyed multiple 5-10 km reaches due to logistic
505 constraints⁵². For each barrier we encountered we recorded its coordinates, type,
506 height class, status (abandoned or in use), and span width (full or partial river width).

507

508 The influence of survey length on barrier discovery rate was determined via
509 bootstrapping^{23,53} using R version 4.0.0⁵⁷. This showed an asymptotic relationship in
510 most cases indicating that a sufficient river length had been sampled to derive robust
511 correction factors for barrier density in each country, as well as a single correction
512 factor across all countries (Extended Data Table 1). These results were used to
513 inform the choice of calibration datasets for modelling barrier numbers using random
514 forest regression (see below).

515

516 Field-derived correction factors were applied in each country to adjust existing
517 barrier records and derive more realistic barrier densities (Fig. 2b; Table 1). To
518 obtain corrected barrier densities for the 10 countries that had not been surveyed in
519 the field we applied a mean correction factor of 0.35 barriers/km, derived from the 26
520 surveyed countries. We employed the Likelihood Ratio Test (two-tailed) implemented
521 in the *DescTools* R 4.0 package⁵⁸ to assess the level of under-reporting, comparing
522 the frequencies of barrier types and barrier height classes in existing databases and
523 in walkover river surveys. Barrier reporting error (e) was calculated as

524
$$e = \frac{Na - Nf}{Nf} * 100$$

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

527 **Modelling barrier density through random forest regression**

528 We employed random forest regression to model barrier densities based on
529 anthropic and environmental predictors that were expected to be associated with
530 breaks in river connectivity. For example, culverts tend to be associated with road-
531 crossings⁵⁹, small weirs with water mills in headwaters³², and storage dams with
532 nearby cities, agriculture and hydropower⁶⁰. Similarly, the location of barriers is also
533 determined by topography, geology and climate⁷.

534

535 For each ECRINS sub-catchment we extracted information on 11 variables
536 (Extended Data Table 4): land cover (Corine level 1: %urban, agricultural, natural,
537 wetlands and water⁶¹); population density (No./km²)⁶²; mean elevation (m) and slope
538 both scaled by catchment area, dendricity (i.e., river length/No. river segments;
539 km/No.), drainage density (i.e., river length/catchment area; km/km²)^{35,63}, and
540 number of road crossings in the river network divided by catchment area (No./km²)⁶⁴.

541

542 We used a data-driven, nonparametric Random Forest Regressor⁶⁵ developed using
543 the *scikit-learn* library in Python. The advantages of this modelling approach are that
544 it does not make any assumptions on the relation between predictors and the
545 dependent variable, or about the distribution, correlation or linearity of predictors. We
546 used *k*-fold (*k* = 5) for cross validation and the Mean Decrease Impurity (MDI) index
547 to estimate variable importance⁶⁵, based on the number of tree nodes that included
548 each predictor, normalized by the number of samples. After some tests, the original
549 ECRINS sub-catchments (n= 30,176; mean area = 60.90 km²; SE=0.41) were
550 aggregated into increasing larger ones (Extended Data Table 5) using an *ad-hoc*
551 graph theory algorithm in R 4.0 according to a criterion of minimum aggregation area

552 from upstream to downstream direction. This step was used to reduce the influence
553 of unaccounted local factors (e.g. existence of canals for navigation, or pipes and
554 aqueducts for water diversion) operating at finer spatial scales than the predictors.

555

556 Comparisons of model performance at different sub-catchment sizes (Extended Data
557 Table 5) indicated poor model performance at the original ECRINS sub-catchment
558 scale. Best model performance (explained variance = 0.4) was reached when the
559 minimum aggregation area was 3,000 km², which corresponds to 593.5 km² on
560 average at the pan-European scale (SE = 12.6). The predicted number of barriers
561 was broadly consistent with expectations from field-corrected values and did not vary
562 much between different models. The relatively high amount of unexplained variance
563 may be due to the coarse resolution of our predictors, but also likely to the omission
564 of key predictors of barrier density, for example unaccounted variation in barrier use,
565 or possibly in barrier age. Instream barriers in Europe vary widely in age, and many
566 are over 50 years or even much older³². A temporal mismatch may thus occur
567 between drivers that governed barrier construction in the past and the current
568 landscape.

569

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

577

578 As per above, we used the ECRINS sub-catchment as our spatial modelling unit.
579 This allowed us to make use of all barrier records and avoid errors that would have
580 resulted from snapping accurate barrier locations to the less precise, low resolution
581 ECRINS river network. For these reasons, we modelled areal barrier density
582 (barrier/km²; Extended Data Fig. 4a) and then transformed into linear river density
583 (barrier/km; Fig. 2c).

584

585 The average model validation error was 0.09 barrier/km² (0.24 barrier/km; Extended
586 Data Fig. 5). The model tended to overestimate the number of barriers in small sub-
587 catchments, as well as in flat areas of France and Poland, and underestimate the
588 highest barrier densities, possibly due to superimposition of barriers of different types
589 and ages. Inspection of model residuals (Extended Data Fig. 5) showed that the
590 model was able to account for barrier under-reporting across large areas, including
591 southern Europe, the Danube basin, the Baltic area, and Ireland. However, in
592 general, the model underestimated the extent of river fragmentation in Europe, most
593 likely because densities of low-head barriers are determined by local drivers
594 operating at finer spatial scales that were not adequately captured in our study.
595 Inclusion in future models of barrier age, or proxies for barrier age - perhaps
596 obtained from consideration of barrier type, height and location, may improve model
597 performance.

598

599 Despite model limitations, modeled barrier densities for sub-catchment aggregations
600 of 3,000 km² (Fig. 2c) were broadly consistent with field-corrected barrier densities
601 (Fig. 2b) and identified the same broad patterns of river fragmentation across

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

609

610 **Data availability**

611 Data for the AMBER Barrier Atlas (Fig. 1), observed barrier densities (Fig. 2a),
612 ground-truthed barrier densities (Fig. 2b) and modelled barrier densities (Fig. 2c) are
613 freely available at <https://amber.international/european-barrier-atlas/> as well as in
614 figshare <https://doi.org/10.6084/m9.figshare.12629051> under a CC-BY-4.0 license.
615 Data for ground-truthed surveyed reaches (Extended Table 1, Extended Data Fig. 3)
616 are also available at <https://doi.org/10.6084/m9.figshare.12629051> under a CC-BY-
617 4.0 license.

618

619 **Code availability**

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

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Methods References

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688
689

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697 Medi Ambient, Agricultura i Sostenibilitat. Govern d'Andorra (Andorra);
698 Bundesministerium für Nachhaltigkeit und Tourismus (Austria); Service Public de
699 Wallonie, Secrétariat Général (Belgium); Vlaamse Milieumaatschappij (Belgium);
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701 Association (Bulgaria); The Cyprus Conservation Foundation, Terra Cypria (Cyprus);
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703 Agency (Denmark); Keskkonnaministeerium (Estonia); Suomen ympäristökeskus
704 (Finland); Office national de l'eau et des milieux aquatiques, ONEMA (France);
705 Landesanstalt für Umwelt Baden-Württemberg (Germany); Bayerisches Landesamt
706 für Umwelt (Germany); Senatsverwaltung für Umwelt, Verkehr und Klimaschutz
707 Berlin (Germany); Landesamt für Umwelt Brandenburg (Germany); Der Senator für
708 Umwelt, Bau und Verkehr Bremen (Germany); Amt für Umweltschutz Hamburg
709 (Germany); Hessisches Landesamt für Naturschutz, Umwelt und Geologie
710 (Germany); Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-
711 Vorpommern (Germany); Ministerium für Umwelt, Energie, Bauen und Klimaschutz
712 Niedersachsen (Germany); Landesamt für Natur, Umwelt und Verbraucherschutz
713 Nordrhein-Westfalen (Germany); Landesamt für Umwelt Rheinland-Pfalz (Germany);
714 Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (Germany);

715 Landesbetrieb für Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt
716 (Germany); Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes
717 Schleswig-Holstein (Germany); Thüringer Landesamt für Umwelt und Geology
718 (Germany); Bundesanstalt für Gewässerkunde (Germany); Greek Committee on
719 Large Dams (Greece); WWF Greece; Országos Vízügyi Főigazgatóság (Hungary);
720 Marine and Freshwater Research Institute (Iceland); Inland Fisheries Ireland
721 (Ireland); Registro Italiano Dighe (Italy); Regione Emilia-Romagna, Lombardia,
722 Piemonte, Toscana (Italy), Latvijas Vides, ģeoloģijas un meteoroloģijas centrs
723 (Latvia); Aplinkos apsaugos agentūra (Lithuania); Ministère du Développement
724 durable et des Infrastructures (Luxembourg); Ministarstvo poljoprivrede i ruralnog
725 razvoja (Montenegro); PDOK (The Netherlands); VISpas (The Netherlands); Norges
726 vassdrags- og energidirektorat (Norway); Gospodarstwo Wody Polskie, National
727 Water Management Board (Poland); Stanisław Sakowicz Inland Fisheries Institute
728 (Poland); Universidade de Lisboa, Centro de Estudos Florestais (Portugal); Agência
729 Portuguesa do Ambiente (Portugal); Ministerul Apelor și Pădurilor (Romania); WWF
730 Danube-Carpathian (Romania); Ministerstvo životného prostredia (Slovakia);
731 Confederación Hidrográfica del Júcar (Spain); Confederación Hidrográfica del
732 Cantábrico (Spain); Confederación Hidrográfica del Duero (Spain); Confederación
733 Hidrográfica del Tajo (Spain); Confederación Hidrográfica del Guadiana (Spain);
734 Confederación Hidrográfica del Ebro (Spain); Uraren Euskal Agentzia (Spain);
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736 Segura (Spain); Universidad de Murcia (Spain); Universidad de Córdoba (Spain);
737 Universidad de Cantabria (Spain); Ministerio para la Transición Ecológica y el Reto
738 Demográfico (Spain); Agència Catalana de l'Aigua (Spain); SUDOANG (Spain); LST
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745

746 **Author contributions**

747 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
748 the work and organised the collection of barrier data; B.B., S.B., L.B., A.C., & C.G.L.
749 carried out the analysis; C.G.L. and B.B. wrote the initial drafts of the manuscript with
750 essential input from S.B., L.B, J.J., A.C., S.C. and W.v.d.B.; G.S. and J.J. designed
751 and curated the barrier database; K.M.W. helped secured unpublished barrier
752 records from German Länder; B.B., P.F.G., R.O.A., S.R. and G.S. cleaned existing
753 barrier inventories; walkover river surveys were conducted/organised by G.S. and
754 P.M. (Portugal, France); E.D., E.G.V, C.R., S.F. and G.L. (Spain); B.B. and S.B.
755 (Italy, Lithuania); J.J. and P.E.J. (Wales); K.A., K.B and N.J. (Denmark), J.B. and
756 J.K. (Ireland), M.C. and M.P (Balkans, Danube, Estonia, Germany, Scandinavia);
757 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
758 L.M. (Scotland); P.P., M.L. and M.Z. (Poland); H.W. and A.B. (The Netherlands);
759 G.G., J.R., L.W., M.B. & P.G.. advised on the development of the Atlas and the
760 policy implications. All co-authors critically revised and approved the edited
761 manuscript.

762

763 **Competing interests**

764 The authors declare no competing interests.

765 **Corresponding author**

766 Correspondence and requests for materials should be addressed to C. Garcia de
767 Leaniz or W. van de Bund.

768

769 **Additional information**

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

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776 **EXTENDED DATA TABLES**

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778 **Extended Data Table 1. Results of river walkaway surveys used to ground-**779 **truth barrier records. NA: number of barriers present in the Atlas; NF: number**780 **of barriers encountered in the field.**

781

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

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

787

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

788

789 *HydroSHEDS river network⁷⁴

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793 **Extended Data Table 3. Incidence of barrier duplicates and duplicate exclusion**794 **criteria (*databases already collated and cleaned)**

795

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	-	-

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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

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

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

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Model	No. catchments	Mean catchment area (km²)	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

807

808 **EXTENDED DATA FIGURE LEGENDS**

809

810 **Extended Data Fig. 1. Approach used to estimate river fragmentation in Europe.**

811 To correct for under-reporting and derive more accurate estimates of barrier density
812 we used a four-step approach: (1) compilation of georeferenced barrier records from
813 local, regional and national barrier databases (the AMBER Barrier Atlas), (2) data
814 cleaning and removal of duplicate records, (3) ground-truthing barrier densities from
815 walkover river surveys, and (4) statistical barrier modelling via random forest
816 regression.

817

818 **Extended Data Fig. 2. Cumulative height distribution of artificial barriers found**

819 **in European rivers.** The figure shows (log₁₀ scale) that most barriers (68% of n =
820 117,371 built structures equal or greater than 10 cm in height) are low head
821 structures (such as fords, culverts, and sluice gates) smaller than 2 m in height;
822 these are ubiquitous but typically unreported in existing barrier inventories.

823

824 **Extended Data Fig. 3. Location of test reaches used to ground-truth the**

825 **AMBER Barrier Atlas during walkover surveys.** We walked 147 test reaches
826 totalling 2,715 km that were representative of river types found in Europe in terms of
827 altitude, slope, stream order, biogeography and land use. River network and country
828 sub-basin boundaries sourced from European Environment Agency ³⁵.

829

830 **Extended Data Fig. 4. Variation in areal barrier density and main drivers of**

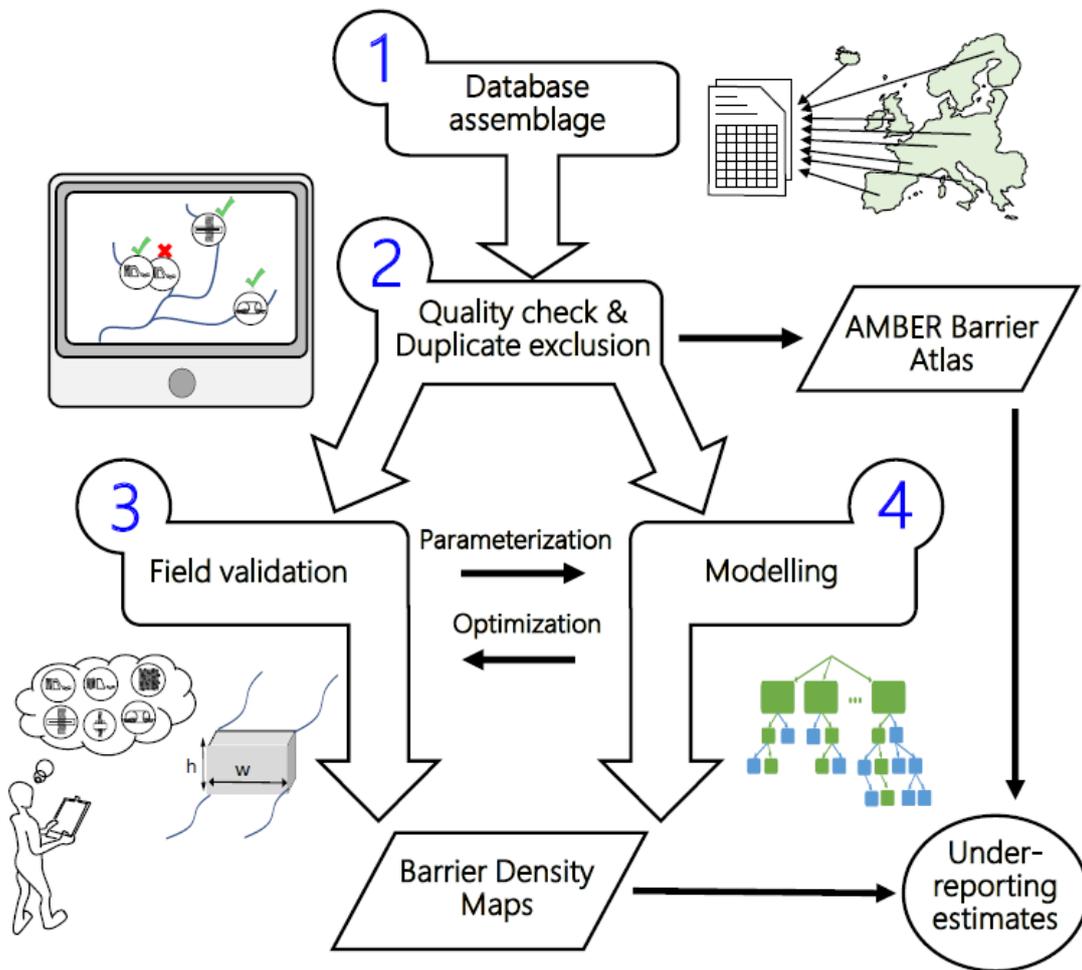
831 **barrier abundance modelled by random forest regression.** The maps show (a)
832 the predicted barrier density at ECRINS sub-catchments (barriers/km²; No. of sub-

833 catchments = 8,467); **(b)** agricultural pressure (proportion of agricultural area, Corine
834 Land Cover 2 – level 1); **(c)** road crossing density (No./km²); **(d)** mean altitude
835 (m.a.s.l.); **(e)** extent of surface water (proportion of area occupied by surface water,
836 Corine Land Cover 5 – level 1). **(f)** shows the relative weight (Mean Decrease
837 Impurity, MDI) of the 11 predictors used to model barrier density (detailed in
838 Extended Data Table 4). Country and sub-basin boundaries, CORINE Land Cover
839 and mean altitude sourced from European Environment Agency^{35,61,63}; Road density
840 sourced from the GRIP database⁶⁴.

841

842 **Extended Data Fig. 5. Performance of the barrier density model.** The maps show
843 the distribution of modelling residuals (predicted-observed in barrier density –
844 barriers/km²) for **(a)** the model calibration dataset (No. of sub-catchments = 2,306),
845 and **(b)** the whole AMBER Barrier Atlas dataset (No. of sub-catchments = 8,467).
846 Country and sub-basin boundaries sourced from European Environment Agency³⁵.

847

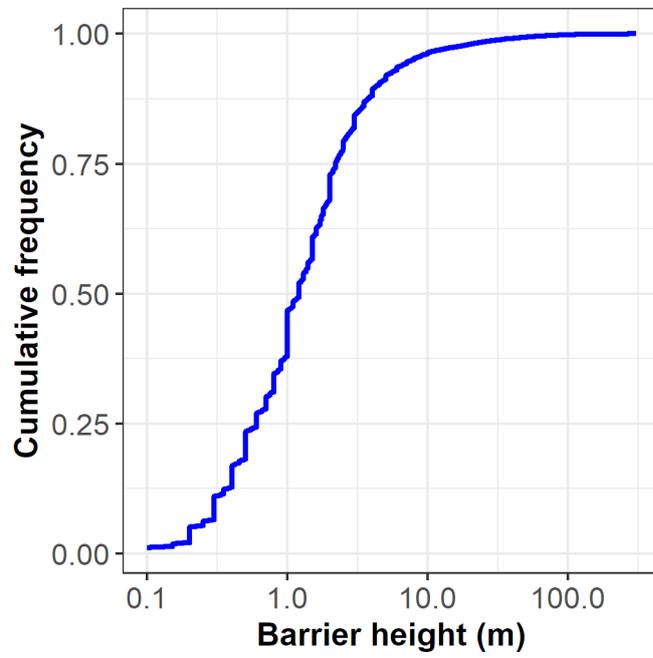


850 **Extended Data Fig. 2**

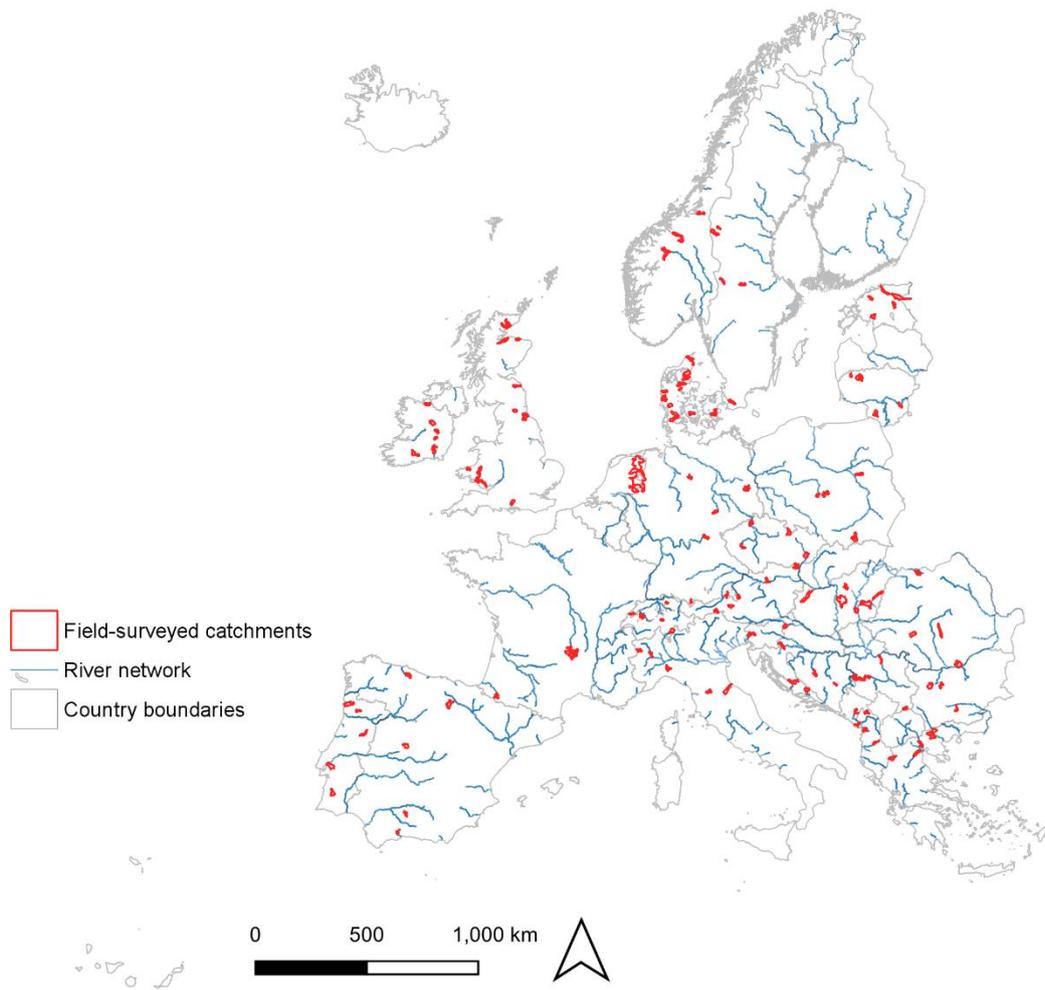
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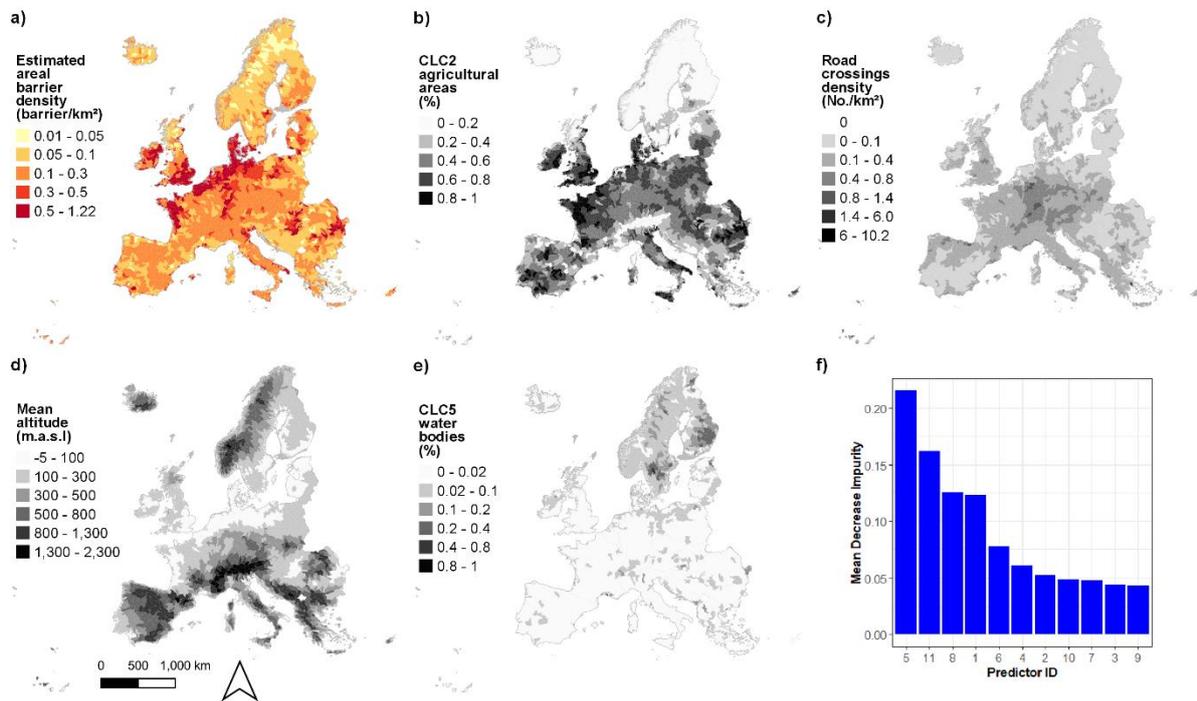
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856 **Extended Data Fig. 4**

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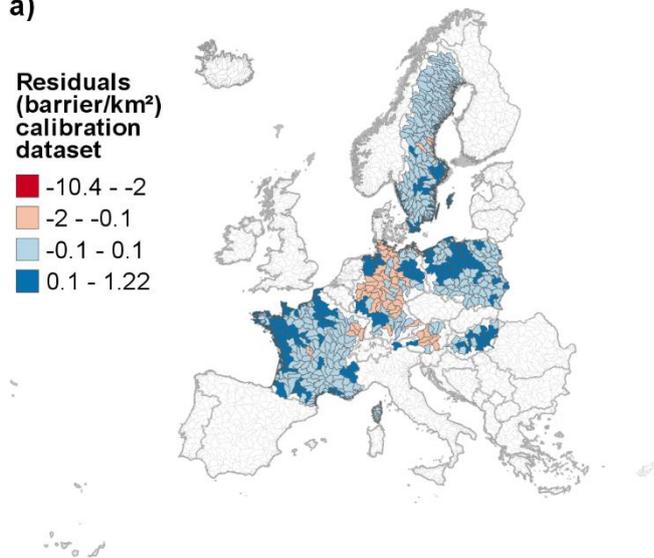
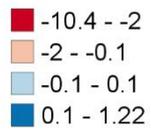
865

866

Extended Data Fig. 5

a)

Residuals
(barrier/km²)
calibration
dataset



b)

Residuals
(barrier/km²)
Atlas

