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Title	More than one million barriers fragment Europe's rivers
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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Supplementary information

More than one million barriers fragment Europe's rivers

In the format provided by the authors and unedited

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Peer Review File

Manuscript Title: More than one million barriers fragment Europe's rivers

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referee #1 (Remarks to the Author):

Review on "Broken rivers: ground-truthing the world's most fragmented rivers" (B. Belletti et al.)

The manuscript by Belletti et al. deals with the identification of the location of small barriers in European rivers by comparing data compilation results from existing databases with an exemplary field survey followed by a statistical model approach.
Key results: The key results and outstanding features of this work are:
(1) unique compilation and harmonization of barrier location data from 36 European countries,
(2) large consorted field survey on barrier identification in 147 rivers to quantify barrier underreporting
(3) estimation of actual barrier numbers (based on the results of the underreporting) with a statistical approach (Random Forest Regression).
With this analysis, the authors convincingly underline the role of small barriers in European rivers and the necessity to invest in data collection/compilation to provide a sound base for river management.
Validity: The title of the manuscript could be more specific and related to small barriers in European rivers instead of to "the world's most fragmented rivers" since 1) it might induce the idea that the article focusses on a global scale, and 2) the term fragmentation can be very general (it might also include vertical and latitudinal dimensions as in Grill et al. 2019), not only longitudinal as considered here). To me, one of the core messages would be that the large number of compiled barrier data in European rivers is even a lot larger when underrepresentation in the available data is taken into account. Thus, I could imagine a title like: "Broken rivers: an integrated approach to map a million small barriers that fragment European rivers."
In general, the text is very well written. For some parts, I suggest small reformulations and restructurings, partly simply to avoid repetitions. 1) I do not agree that rivers do only provide ecosystem services if they are flowing. There is a very large share of intermediate/ephemeral rivers, that naturally cease flowing for specific periods and, still, have a huge ecological meaning and function, also when they dry up. I thus suggest reformulating these statements (e.g. l. 37). 2) Partly, sections take up detailed results later in the manuscript that either already have been mentioned in or are better related to an earlier section. This includes: ll. 185-188 that should be shifted to page 6 and could drop mentioning the number of barriers (1.2M) twice. Same is true for ll.214-217 that better relates to the details of the study on underrepresentation. In the abstract, the method sentence also disturbs the flow of the results presented (ll. 44-45: "Barrier density was predicted…") and should be shifted further to the top showing that the methodology consists of two basic steps, data compilation and estimation of barrier data.
Originality and significance: The study and its results are both, original and significant to the scientific community and, going beyond, also to water managers. The efforts that have been put into achieving a high quality database on small barriers in Europe, e.g. by excluding duplicates, is unique. This is also reflected in the additional and expensive field study that checked 147 rivers for barriers by on-site visits. These two approaches combined, finally allowed to estimate actual barrier numbers to overcome the underreporting of barrier numbers due to missing data. This corrected database is of high significance to the scientific community, to existing databases on large dams and to river managers who have to decide which measures might be the most effective in fulfilling the requirements in the WFD.

Data & methodology: In general, the methodology is clearly described in the methods section and complemented with details to follow the field and modelling approach. For clarity reasons, I suggest starting with the details of the model itself (Random Forest Regressions), before going into parameters involved, details of the training set etc.. Machine Learning is a very broad toolbox when talking about statistical approaches. I would even avoid this term and directly be specific about what has been done. Could results and methods also be disentangled a little more?
The presentation of the data in the figures is in general very well done. A few details could be improved:
• When talking about density, the representation would be nice to be consistent, e.g. n/km, No./km, barrier/km are used throughout the text.
• Figure 2: The maps, especially the legend might be too small in dependence of the final printing format.
Appropriate use of statistics and treatment of uncertainties: The uncertainties in underlying data and in the modelling approaches have been considered by combining several calculations based on different model assumptions and reflected in the Extended Data Table 4. Statistical analysis, e.g. with Random Forests, is well-described and seems to be reasonable. Potential errors in the database are quantified by crosschecking with barrier counts from a field survey in 147 rivers in Europe. The bias in scale, e.g. different rivers orders in dependence of the mapping resolution, is carefully discussed.
Conclusions: The conclusion section is not explicitly written but covered in the section "Mapping more realistic barrier densities. It is very short, and it mainly repeats the results from the text above although it also indicated some interesting relevance of the derived database on small dams and the related modelling approach to estimate barrier density, e.g. in so far not investigated river (sections).
Suggested improvements: Besides my suggestions above I have small details on the text listed here:
l. 37, 55: "…but only if they flow…", "….of natural rivers is that they flow…." ◊ see comment above, I do not agree since there are many ephemeral streams and rivers that do not continuously flow.
l. 99: "…information on 736.348 instream barriers…" – I see the point, but I would not mention the number here (too early since it is a result, even though an intermediate one). The number is well explained in ll. 109 ff. – I would leave it like that.
l. 128: "Barrier inventories …are not homogeneous" – towards which aspect/characteristic? Maybe delete this part of the sentence
l. 143: "None of the…rivers WAS free…"
l. 299: "…and compare them to ground-truthed values
l. 326: "land use"
l. 330: "indicating that a sufficient…
l. 345: '"land cover"
l. 346: "…(No./km2)
l. 391: "The average model…"
Table 1:"Number of each barrier type";
Box 1: "(4) statistical barrier modelling via Random Forrests"
Figure 2: (A) "existing barrier…"
Extended Data Table 1: "showing the extent of …"; "Bootstrapped Correction Factor"
Extended Data Figure 2: Maybe it is due to my screen and printer but the river network and country boundaries are hard to see. Same is true for
Extended Data Figure 5: And legends might be toooooo small.
References: The reference list is appropriately reflecting the topic of the thesis.
Clarity and context: The abstract and the manuscript in general are clearly written, besides comments and suggestions above;

Referee #2 (Remarks to the Author):

A-B) This paper effectively scales up from previous studies that have highlighted the same under-reporting associated with barrier size, but failed to highlight those (ie, go back as far as Graf 1999). The relationship between barriers and anthropogenic activity has also been established many times (ie, Vorosmarty et al. 2010) but was presented as a novel result. Still, this study represents (to my knowledge) the first broad-scale ground-truthing of barrier distribution, which unto itself is a valuable contribution to the field.

It's noteworthy that while georeferenced, the barriers included in the study are not aligned with any hydrography, precluding analyses that consider routing or other dendritic aspects of hydrology. This is surely a next step that would increase the dataset's value dramatically. Barrier density at aggregated scales is a useful metric for guiding continued data collection and coarse management plans, but lacks in meaningful hydro-ecological applications. This is my main hesitation in recommending publication.

C) The overall approach, data quality and methodology are solid. It was frustrating to see just ten nations omitted from the ground-truthing for logistical reasons, especially with such high rates of under-reporting (ie, Finland). Figures 1-3 are excellent.

D) While not a statistician, I found the selected methods appropriate and robust. The sensitivity analysis related to catchment area was helpful.

E) What the authors conclude - that small(er) barriers are consistently under-reported across Europe - is valid and consistent with their work and the work of others. Their use of both bottom-up and top-down approaches adds to the robustness.

F) Suggestions: 1) Box 1 confuses readers as to the genesis and role of the AMBER dataset. 2) Finland jumps out as a nation with significant under-reporting that was not included in the ground-truthing. Given the somewhat unique landscape in Finland (expansive low-elevation networks of connected lakes), I wanted to read about this example in the discussion. 3) How does the use of underestimated (up to 74%) ECRINS river lengths affect results? 4) While lines 77-79 on page 3 list fragmenting impacts of small barriers, more than one sentence about the influence of barrier size on ecological impact is warranted to justify a study dedicated to the accurate inventorying of size-classified barriers; 5) Line 86 - use of "probably" is weak.

G) As mentioned above, the paper needs to cite previous studies that have established the same patterns, both for credibility and also to guide the authors toward a better focus on the novelties of this study.

H) Clarity and context are all good.

Summary: The data compilation, validation and modeling are all impressive, and will be of even greater value once linked to digital hydrographies. So the study increases our knowledge of the degree to which different EU nations are obstructed by barriers, but at a scale that is relatively meaningless for scientific and management action. This leaves me undecided on whether to recommend publication.

Referee #3 (Remarks to the Author):

The authors present an impressive database of river barriers in Europe which addresses an important data gap. There is a clear policy relevance for this information as restoring river connectivity is becoming increasingly part of policy agendas on biodiversity in Europe and elsewhere.

This is essentially a European database paper but it highlights an important global issue, that small

barriers cause much greater river fragmentation than the well-studied larger barriers.

I think it has the potential to become a very important paper. However, in order to achieve its full potential a number of issues need to be clarified or fixed.

Firstly, I find the title slightly misleading. While the authors show these rivers are likely to be among the most fragmented in the world, this study only focuses on Europe and equivalent studies for other world regions do not exist. It also implies that this is a global study which it isn't. This is repeated in L42 "making Europe the world's most fragmented river landscape" which is based on the authors estimate but cannot be confirmed with any currently available data. In line 189 referring to this estimate the authors do add that this density is "possibly making Europe the most fragmented river landscape in the world" but it would be good to add this cautious note earlier on.

L36-37: "Rivers support some of Earth's richest biodiversity and provide essential ecosystem services to society, but only if they flow" This is a bit ambiguous as intermittent and ephemeral streams (IRES) also promote local and regional biodiversity during the dry phase. See e.g. Steward et al., 2012.

L46-48: "Relatively unfragmented rivers are still found in the Balkans, Scandinavia, the Baltic states, and parts of southern Europe, but these require urgent protection from new dam developments" It is not clear to the reader why these require urgent protection. Is it simply because they are relatively unfragmented or are these rivers particularly important for e.g. biodiversity. There is no further mention of protection in the manuscript to clarify this.

L320: "Briefly, we chose 2-6 test rivers per country". What criteria, if any were used to decide on these test rivers?

L385-388: "The relatively high amount of unexplained variance may be due to the coarse resolution of our predictors, but also likely to the omission of key predictors of barrier density, for example unaccounted variation in barrier use, or possibly in barrier age. Instream barriers in Europe vary widely in age, and many are over 50 years or even much older"

The authors correctly note the high amount of unexplained variance in the model and explain this may be due to the coarse resolution of predictors. It would be helpful to add the resolution of the predictors used as this is not clear from Extended data table 3. The authors also note the omission of key predictors of barrier density as well as the temporal mismatch between drivers that governed barrier construction in the past and the current landscape. This raises the question whether the approach of using recent human influence datasets as predictors is a suitable approach to estimate densities. At least 9 of the 11 predictor variables used in the model will have changed considerably in the past 50 years.

L375-376: "This step was used to reduce the influence of confounding local factors, unrelated to the predictors" It would be good to elaborate on what these confounding local factors are that influence the model estimates.

Table 1: I am a bit confused about the categories. L113-119 mention there are six main categories as well as types that cannot be classified. I expected these to be in the 'other' category in Table 1 but there is also a NA category which in some cases has a lot of records but it's not clear what the NA category represents.

Minor issues:
Line 82 Great Britain
Line 122. "easily missed" in what sense? With automated procedures or in surveys?
Line 139. Perhaps add Strahler reference (Strahler, 1957).
Line 160. Central or central. Line 43 uses capital

Line 345 Corine reference needed
Line 376 what confounding local factors influence the model estimates?
Extended data figure 6. What do the different colours represent? This is not clear from the legend or the caption

References:
Steward AL, von Schiller D, Tockner K, Marshall JC, Bunn SE. When the river runs dry: Human and ecological values of dry riverbeds. Frontiers in Ecology and the Environment. 2012;10:202–209.

Strahler, A. N., 1957. Quantitative analysis of watershed geomorphology. Transactions of the American Geophysical Union 38: 913–920.

Author Rebuttals to Initial Comments: (please note that the authors have quoted the reviewers in black text and responded in blue text)

Referees' comments:

Referee #1 (Remarks to the Author):

Review on “Broken rivers: ground-truthing the world’s most fragmented rivers” (B. Belletti et al.)

The manuscript by Belletti et al. deals with the identification of the location of small barriers in European rivers by comparing data compilation results from existing databases with an exemplary field survey followed by a statistical model approach.

Key results: The key results and outstanding features of this work are:
(1) unique compilation and harmonization of barrier location data from 36 European countries,
(2) large consorted field survey on barrier identification in 147 rivers to quantify barrier underreporting
(3) estimation of actual barrier numbers (based on the results of the underreporting) with a statistical approach (Random Forest Regression).
With this analysis, the authors convincingly underline the role of small barriers in European rivers and the necessity to invest in data collection/compilation to provide a sound base for river management.
Validity: The title of the manuscript could be more specific and related to small barriers in European rivers instead of to “the world’s most fragmented rivers” since 1) it might induce the idea that the article focusses on a global scale, and 2) the term fragmentation can be very general (it might also include vertical and latitudinal dimensions as in Grill et al. 2019), not only longitudinal as considered here). To me, one of the core messages would be that the large number of compiled barrier data in European rivers is even a lot larger when underrepresentation in the available data is taken into account. Thus, I could imagine a title like: “Broken rivers: an integrated approach to map a million small barriers that fragment European rivers.”

We like the title suggested by referee #1 but unfortunately it has 99 characters and a colon (as in our original title). We are only allowed 75 characters and no punctuation marks, so we have settled for ‘More than one million barriers fragment Europe’s rivers’ which we feel reflects our findings well.

In general, the text is very well written. For some parts, I suggest small reformulations and restructurings, partly simply to avoid repetitions.

Thank you. We have followed all the advice and avoided repetitions.

1) I do not agree that rivers do only provide ecosystem services if they are flowing. There is a very large share of intermediate/ephemeral rivers, that naturally cease flowing for specific periods and, still, have a huge ecological meaning and function, also when they dry up. I thus suggest reformulating these statements (e.g. l. 37).

We see your point and have deleted it.

2) Partly, sections take up detailed results later in the manuscript that either already have been mentioned in or are better related to an earlier section. This includes: ll. 185-188 that should be shifted to page 6 and could drop mentioning the number of barriers (1.2M) twice. Same is true for ll.214-217 that better relates to the details of the study on underrepresentation.

We agree. We have restructured the flow of information, added some subheadings for clarity, and avoided mentioning 1.2M barriers twice. We have reworded L185-188 and moved it to a new subsection (Extent of river fragmentation in Europe). We feel we should leave L214-217 where it was as it helps us make the point that information on the extent barrier underreporting can help optimise future mapping efforts.

In the abstract, the method sentence also disturbs the flow of the results presented (ll. 44-45: "Barrier density was predicted…") and should be shifted further to the top showing that the methodology consists of two basic steps, data compilation and estimation of barrier data.

OK. We have largely reworded the summary paragraph in accordance to the journal requirements.

Originality and significance: The study and its results are both, original and significant to the scientific community and, going beyond, also to water managers. The efforts that have been put into achieving a high quality database on small barriers in Europe, e.g. by excluding duplicates, is unique. This is also reflected in the additional and expensive field study that checked 147 rivers for barriers by on-site visits. These two approaches combined, finally allowed to estimate actual barrier numbers to overcome the underreporting of barrier numbers due to missing data. This corrected database is of high significance to the scientific community, to existing databases on large dams and to river managers who have to decide which measures might be the most effective in fulfilling the requirements in the WFD.

We are grateful for the encouraging and positive comments of the referee.

Data & methodology: In general, the methodology is clearly described in the methods section and complemented with details to follow the field and modelling approach. For clarity reasons, I suggest starting with the details of the model itself (Random Forest Regressions), before going into parameters involved, details of the training set etc..

We agree. We have rearranged the information on Methods and started with details of the model itself under a new subheading 'Modelling barrier density through random forest regression'

Machine Learning is a very broad toolbox when talking about statistical approaches. I would even avoid this term and directly be specific about what has been done.

Yes we agree. We have replaced by 'random forest regression' throughout.

Could results and methods also be disentangled a little more?

Yes, we have moved L420-428 to results, rearranged the methods and streamlined the text to avoid repetitions.

The presentation of the data in the figures is in general very well done. A few details could be improved:

• When talking about density, the representation would be nice to be consistent, e.g. n/km, No./km, barrier/km are used throughout the text.

We now use barrier/km or barrier/km^2 throughout.

• Figure 2: The maps, especially the legend might be too small in dependence of the final printing format.

We have redone all the legends in all the maps with larger font size (point size 5 or larger as per instructions)

Appropriate use of statistics and treatment of uncertainties: The uncertainties in underlying data and in the modelling approaches have been considered by combining several calculations based on different model assumptions and reflected in the Extended Data Table 4. Statistical analysis, e.g. with Random Forests, is well-described and seems to be reasonable. Potential errors in the database are quantified by crosschecking with barrier counts from a field survey in 147 rivers in Europe. The bias in scale, e.g. different rivers orders in dependence of the mapping resolution, is carefully discussed.

We are glad the referee found our statistical analysis sound; we put a lot of effort into it.

Conclusions: The conclusion section is not explicitly written but covered in the section "Mapping more realistic barrier densities. It is very short, and it mainly repeats the results from the text above although it also indicated some interesting relevance of the derived database on small dams and the related modelling approach to estimate barrier density, e.g. in so far not investigated river (sections).

We have moved this information from methods to the main text. Our conclusions are under the subheading 'A call for action on small barriers', in accordance also with your suggestions.

Suggested improvements: Besides my suggestions above I have small details on the text listed here:

l. 37, 55: "…but only if they flow…", "….of natural rivers is that they flow…." □ see comment above, I do not agree since there are many ephemeral streams and rivers that do not continuously flow.

We have removed this from the summary and qualified it in L68 by writing 'non-ephemeral'.

l. 99: "…information on 736.348 instream barriers…" – I see the point, but I would not mention the number here (too early since it is a result, even though an intermediate one). The number is well explained in ll. 109 ff. – I would leave it like that.

We agree and have deleted it from that part of the MS.

l. 128: "Barrier inventories …are not homogeneous" – towards which aspect/characteristic? Maybe delete this part of the sentence

We have reworded and clarified this as follows: 'Barrier inventories in Europe are not homogeneous with respect to barrier types, reach, or completeness (Table 1), as they were compiled for different purposes using different resources'

l. 143: "None of the…rivers WAS free…"

We respectfully disagree here (if we may). Both 'were' and 'was' are correct after 'none', to our best knowledge. For example, see:
https://www.onlinegrammar.com.au/top-10-grammar-myths-none-always-takes-a-singular-verb/
https://www.dictionary.com/e/none/
https://data.grammarbook.com/blog/singular-vs-plural/none-were-vs-none-was/
https://www.latimes.com/socal/glendale-news-press/opinion/tn-gnp-0429-a-word-please-none-is-or-none-are-both-work-story.html

….but we have to use the plural 'were' here to maintain parallelism (i.e. notional concord) with 'some' in the rest of the sentence ('some of the contiguous test-reaches *were*').

l. 299: "…and compare them to ground-truthed values

Corrected

l. 326: "land use"

Corrected

l. 330: “indicating that a sufficient…

Corrected

l. 345: ‘”land cover”

Corrected

l. 346: “…(No./km2)

Corrected

l. 391: “The average model…”

Corrected

Table 1:”Number of each barrier type”;

Corrected

Box 1: “(4) statistical barrier modelling via Random Forrests”

Figure legend changed as indicated

Figure 2: (A) “existing barrier…”

Corrected

Extended Data Table 1: “showing the extent of …”; “Bootstrapped Correction Factor”

Corrected

Extended Data Figure 2: Maybe it is due to my screen and printer but the river network and country boundaries are hard to see. Same is true for
Extended Data Figure 5: And legends might be toooooo small.

Corrected – thanks for highlighting this. All figures legends have been redone with a larger font size (size 5).

References: The reference list is appropriately reflecting the topic of the thesis.
Clarity and context: The abstract and the manuscript in general are clearly written, besides comments and suggestions above;

We thank the reviewer for the constructive and positive comments and suggested improvements. The MS is now improved.

Referee #2 (Remarks to the Author):

A-B) This paper effectively scales up from previous studies that have highlighted the same under-reporting associated with barrier size, but failed to highlight those (ie, go back as far as Graf 1999). The relationship between barriers and anthropogenic activity has also been established many times (ie, Vorosmarty et al. 2010) but was presented as a novel result. Still, this study represents (to my knowledge) the first broad-scale ground-truthing of barrier distribution, which unto itself is a valuable contribution to the field.

We are glad the reviewer found our study a valuable contribution to the field but we respectfully disagree that we have failed to highlight previous studies. As the reviewer acknowledges, our study represents ‘the first broad-scale ground-truthing of barrier distribution’ and it is this unique ground-truthing aspect that allows us to reveal the extent of under-reporting (how else can one do it?). We

have read Graf (1999) carefully (and cite in the text now – thanks for the suggestion). This is what he wrote:

'There are likely to be a substantial number of dams that are smaller than those included in the National Inventory of Dams, but they are not likely to store large amounts of water or sediment compared to the larger structures. Data presented below show that although small structures are numerous, their cumulative storage pales in comparison with the cumulative storage of large dams. ***In any case, there is no accurate accounting for dams that are smaller than those considered in this analysis***.'

We agree that many studies have highlighted a relation between barriers and anthropogenic activity, and we cite many such studies. What is novel in our study is that we consider all longitudinal instream barriers, large and small, and that we explicitly correct for under-reporting errors. None of the previous large scale studies have done that, and they only considered large dams. Our study shows that considering only large dams underestimates the true extent of river fragmentation, and we put - for the first time - a figure to it.

It's noteworthy that while georeferenced, the barriers included in the study are not aligned with any hydrography, precluding analyses that consider routing or other dendritic aspects of hydrology. This is surely a next step that would increase the dataset's value dramatically. Barrier density at aggregated scales is a useful metric for guiding continued data collection and coarse management plans, but lacks in meaningful hydro-ecological applications. This is my main hesitation in recommending publication.

We agree with the reviewer (and make this point in the text) that our study does not currently permit a detailed dendritic analysis of river connectivity across Europe (what study does?). That was never the intention. But we respectfully disagree that our barrier records are not aligned with any hydrography, or preclude such analysis, as we provide fully georeferenced data of all the ~630,000 *known* barrier records (including names of the water body). Moreover, we also have a good idea where the 0.6M *missing* barriers are likely to be, but of course we don't know the coordinates of those, only the sub-basins they are probably in. This, surely, must be an improvement over only considering *known* barrier records, or to restrict the analysis to just large dams. In our view, what precludes a comparative dendritic analysis of river connectivity at the pan-European scale is not simply the 0.6M missing barriers, but the lack of an accurate map of the river network (to align the barriers to). We used the ECRINS river network because it is the best there is. ECRINS underestimates true river length by up 74% but other global river networks, such as HydroSHEDS, are even worse (ECRINS = 1,649,489 km; HydroSHEDS = 1,471,840 km). Our barrier records are essentially accurate and, in some countries reasonably complete (Fig. 3c). In places where good local river maps exist, detailed dendritic analysis is already possible, it is just not possible to do this everywhere across Europe for the time being.

C) The overall approach, data quality and methodology are solid. It was frustrating to see just ten nations omitted from the ground-truthing for logistical reasons, especially with such high rates of under-reporting (ie, Finland). Figures 1-3 are excellent.

Thank you for the positive evaluation. Regarding ground-truthing, we covered 36 countries and were able to ground truth barrier records for 26 of them (72%) by walking over 2,700 km of river length – a unique effort. Our bootstrapping estimates show this provides good coverage. Of course, we would have liked to have covered the other 10 countries and this is something that we would encourage others to do; it was just not possible for us to do more. Please note we did not ground-truth Finland (as you also note below).

D) While not a statistician, I found the selected methods appropriate and robust. The sensitivity analysis related to catchment area was helpful.

We are glad – thank you.

E) What the authors conclude - that small(er) barriers are consistently under-reported across Europe - is valid and consistent with their work and the work of others. Their use of both bottom-up and top-down approaches adds to the robustness.

Thank you.

F) Suggestions: 1) Box 1 confuses readers as to the genesis and role of the AMBER dataset.

We have moved Box 1 to Extended Data Fig. 1 and reworded and simplified the legend so that is clearer to understand what was done. We trust this is satisfactory.

2) Finland jumps out as a nation with significant under-reporting that was not included in the ground-truthing. Given the somewhat unique landscape in Finland (expansive low-elevation networks of connected lakes), I wanted to read about this example in the discussion.

We did not ground-truth Finland, and provide no measure of under-reporting for it (i.e. it is absent from ED Table 1 and Fig. 3). We used a mean correction factor of 0.35 for the 10 counties like Finland that were not ground-truthed. We trust this is better explained now in the revised Methods (L515-517):

'*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'*

3) How does the use of underestimated (up to 74%) ECRINS river lengths affect results?

We have expanded this in the revised Methods (L470-477):

Although ECRINS may underestimate river length by up to 74% compared to more detailed river networks[36], it is the only consistent river network that can currently be used for global comparisons across Europe. The consequences of underestimating river length for estimates of river fragmentation are difficult to predict. Underestimating river length can overestimate river fragmentation if the observed number of barriers is in reality distributed over a longer river network, but it can also underestimate it if undetected barriers are more likely to occur in poorly mapped first order streams.

4) While lines 77-79 on page 3 list fragmenting impacts of small barriers, more than one sentence about the influence of barrier size on ecological impact is warranted to justify a study dedicated to the accurate inventorying of size-classified barriers;

We address the impacts of small barriers in L83-92 and L191-196 and cite 8 studies that explicitly address low-head structures:

Garcia de Leaniz, C., Berkhuysen, A. & Belletti, B. Beware small dams as well as large. Nature 570, 164-164 (2019).
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).
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).
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).
Carpenter-Bundhoo, L. et al. Effects of a low-head weir on multi-scaled movement and behavior of three riverine fish species. Sci. Rep. 10, 1-14 (2020).
Garcia de Leaniz, C. Weir removal in salmonid streams: implications, challenges and practicalities. Hydrobiologia 609, 83-96 (2008).
Weibel, D. & Peter, A. Effectiveness of different types of block ramps for fish upstream movement. Aquat. Sci. 75, 251-260 (2013).
Bódis, K., Monforti, F. & Szabó, S. Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data. Renew. Sust. En. Rev. 37, 794-808 (2014).

We trust this is adequate and commensurate with Nature's strict page limits.

5) Line 86 - use of "probably" is weak.

We agree but it is difficult to be more assertive.

G) As mentioned above, the paper needs to cite previous studies that have established the same patterns, both for credibility and also to guide the authors toward a better focus on the novelties of this study.

We have shortened the first part of the main text that dealt with well known barrier impacts (L62-66) to better frame the paper and to focus on the most novel aspects of our work. Although the literature on barrier impacts and broad patterns of river fragmentation is large, we cite 50 references (the maximum allowed) that we feel cover the most recent global studies well (i.e. Reid et al 2019; Grill, et al. 2019; Carpenter et al 2011; Fuller et al 2015; Van Looy et al 2014; Lehner et al. 2011; Grizzetti et al. 2017; Zarfl et al 2015; Tickner et al. 2020), as well as some of the most influential, early papers (Vannote et al 1980; Vitousek et al 1997; Graf 1999). We also cover three recent studies that adopted our ground-truthing approach to barrier mapping, albeit at smaller spatial scales (Jones et al 2019; Sun et al 2020; Atkinson et al. 2020). We trust this is adequate within the space limits.

H) Clarity and context are all good.

Thank you.

Summary: The data compilation, validation and modeling are all impressive, and will be of even greater value once linked to digital hydrographies. So the study increases our knowledge of the degree to which different EU nations are obstructed by barriers, but at a scale that is relatively meaningless for scientific and management action. This leaves me undecided on whether to recommend publication.

We are grateful to the referee for his/her constructive comments and hope that the changes made to the MS have improved it sufficiently so that he/she is no longer undecided.

Referee #3 (Remarks to the Author):

The authors present an impressive database of river barriers in Europe which addresses an important data gap. There is a clear policy relevance for this information as restoring river connectivity is becoming increasingly part of policy agendas on biodiversity in Europe and elsewhere.

This is essentially a European database paper but it highlights an important global issue, that small barriers cause much greater river fragmentation than the well-studied larger barriers.

I think it has the potential to become a very important paper. However, in order to achieve its full potential a number of issues need to be clarified or fixed.

We are grateful for the encouraging comments and constructive feedback. We have clarified/fixed all flagged issues.

Firstly, I find the title slightly misleading. While the authors show these rivers are likely to be among the most fragmented in the world, this study only focuses on Europe and equivalent studies for other world regions do not exist. It also implies that this is a global study which it isn't. This is repeated in L42 "making Europe the world's most fragmented river landscape" which is based on the authors estimate but cannot be confirmed with any currently available data. In line 189 referring to this estimate the authors do add that this density is "possibly making Europe the most fragmented river landscape in the world" but it would be good to add this cautious note earlier on.

We agree, this has been removed from the title (which we changed following also guidance from the Editor) and left the comment as a cautious note in the text.

L36-37: "Rivers support some of Earth's richest biodiversity and provide essential ecosystem services to society, but only if they flow" This is a bit ambiguous as intermittent and ephemeral streams (IRES) also promote local and regional biodiversity during the dry phase. See e.g. Steward et al., 2012.

We agree, and following also a similar comment by reviewer 1, this has been deleted from the summary and reworded as 'non-ephemeral' natural rivers elsewhere (L68)

L46-48: "Relatively unfragmented rivers are still found in the Balkans, Scandinavia, the Baltic states, and parts of southern Europe, but these require urgent protection from new dam developments" It is not clear to the reader why these require urgent protection. Is it simply because they are relatively unfragmented or are these rivers particularly important for e.g. biodiversity. There is no further mention of protection in the manuscript to clarify this.

We appreciate this was vague – thank you for highlighting this; we clarified it the revised text (L176-181):
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.

L320: "Briefly, we chose 2-6 test rivers per country". What criteria, if any were used to decide on these test rivers?

This is clarified now: (L496-499)

We used expert judgement to choose 2-6 test rivers per country that were broadly representative of the river types found in Europe in terms of altitude, slope, stream order[56] and, depending on accessibility, biogeography and land use.

L385-388: "The relatively high amount of unexplained variance may be due to the coarse resolution of our predictors, but also likely to the omission of key predictors of barrier density, for example unaccounted variation in barrier use, or possibly in barrier age. Instream barriers in Europe vary widely in age, and many are over 50 years or even much older"

The authors correctly note the high amount of unexplained variance in the model and explain this may be due to the coarse resolution of predictors. It would be helpful to add the resolution of the predictors used as this is not clear from Extended data table 3. The authors also note the omission of key predictors of barrier density as well as the temporal mismatch between drivers that governed barrier construction in the past and the current landscape. This raises the question whether the approach of using recent human influence datasets as predictors is a suitable approach to estimate densities. At least 9 of the 11 predictor variables used in the model will have changed considerably in the past 50 years.

We have now included the resolution of the predictors in ED Table 4. The working resolution is ultimately determined by the size of the smallest catchments we used in the model (i.e. ECRINS model ED Table 5). Our aim was not to 'explain' the distribution of barriers, but to estimate how many missing barriers there might be from knowledge of existing ones. For this, we used only comparable data, available at the pan-EU scale. We have expanded on the mismatch between predictors (L589-600) and discussed how inclusion of additional predictors might improve future modelling of barrier abundance:

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).

L375-376: “This step was used to reduce the influence of confounding local factors, unrelated to the predictors” It would be good to elaborate on what these confounding local factors are that influence the model estimates.

This was poorly explained and ‘confounding’ was the wrong term. We meant factors operating at local scales, for example removal of barriers, or the existence of canals for navigation, or pipes and aqueducts for water abstraction that means that barriers are in some cases located some distance away from the point of use. We have reworded as follows: (L551-552):

This step was used to reduce the influence of unaccounted local factors operating at finer spatial scales than the predictors.

Table 1: I am a bit confused about the categories. L113-119 mention there are six main categories as well as types that cannot be classified. I expected these to be in the ‘other’ category in Table 1 but there is also a NA category which in some cases has a lot of records but it’s not clear what the NA category represents.

We have clarified this. There are six functional barrier types + other + unknown (NA). NA stands for ‘not available’ but we have replaced by ‘unknown’ in Table 1 for clarity. We have also reworded the text (L456-459):

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).

Minor issues:
Line 82 Great Britain

Done

Line 122. "easily missed" in what sense? With automated procedures or in surveys?

Both. We have reworded: (L128-130)

which probably explains why so many barriers can be easily missed in surveys and automated procedures, and why low-head structures are under-represented in most barrier inventories.

Line 139. Perhaps add Strahler reference (Strahler, 1957).

Done

Line 160. Central or central. Line 43 uses capital

Corrected to ‘Central Europe’

Line 345 Corine reference needed

Done

Line 376 what confounding local factors influence the model estimates?

We answered above; ‘confounding’ was the wrong term. We have reworded (L551-552):

This step was used to reduce the influence of unaccounted local factors operating at finer spatial scales than the predictors.

Extended data figure 6. What do the different colours represent? This is not clear from the legend or the caption

We have removed this figure as it was largely redundant. The information is now in a Table in figshare, as suggested by the Editor.

References:
Steward AL, von Schiller D, Tockner K, Marshall JC, Bunn SE. When the river runs dry: Human and ecological values of dry riverbeds. Frontiers in Ecology and the Environment. 2012;10:202–209.

Strahler, A. N., 1957. Quantitative analysis of watershed geomorphology. Transactions of the American Geophysical Union 38: 913–920.

Strahler reference is cited now

Reviewer Reports on the First Revision:

Referee #1 (Remarks to the Author):

Dear Editor, Dear Authors,
thanks a lot for the revised manuscript and the very careful consideration of the three reviewers' comments and suggestions. I have carefully reviewed both, the new version of the manuscript as well as the authors's responses. I am convinced that the authors appropriately tackled all comments from my point of view and especially improved the general structure of the manuscript and complemented important details, e.g. in the method section, for the reader to follow the approach and line of argumentation. I also appreciate the suggestion of the new title "More than one million barriers fragment Europe's rivers" which is better reflecting the actual content and novelty of the manuscript than the earlier title. The improved details (wording, figures, typos and similar) increase the overall quality and readability of the very interesting manuscript. I am happy to recommend this manuscript for publication in Nature.
Some small details on the text are listed here:
I am not a native English speaker, but a native might need to check punctuation, e.g.
l. 43: In Europe, attempts to quantify…
l. 44: Here, we estimate…
l. 52: Across Europe, the main predictors of…
…(potentially more?)
l. 55: …and southern Europe, which require urgent protection… (delete and replace "but")
l. 58: …of Europe's rivers by 2030. Achieving this will require… (split into two sentences and delete "but")
ll. 147/8: "The number of barriers recorded in the field was on average 2.5 times higher than that in existing inventories." ("that" instead of "those" because it refers to "number", right?)

Referee #3 (Remarks to the Author):

The authors responses to my comments are satisfactory and they have made a substantial effort to improve the manuscript based on all reviewers and the editor's comments and I therefore recommend this paper for publication. I only have a few minor issues:

The editor has asked me to also to look at the author's responses to referee #2's comments and I tend to agree with referee #2 that having a dataset aligned with a hydrography would be a logical next step that would increase the usability of the dataset. The authors note in their response that a dendritic analysis is more likely to be precluded due to the lack of an accurate river network map to align to. I also agree with this and I would like to see this point made more strongly in the manuscript. Lines 226- 228 mention that more detailed hydrographic maps are available in many

countries but I think it would be good to add something along the lines of having more consistent high resolution hydrographic data across Europe (i.e. improving on ECRINS) in this section.

L227: dendric or dendritic?

L551-552 The authors provide some good examples of unaccounted local factors in the rebuttal and I think it would be really useful to add these in the actual rewording so a reader is not left guessing what these may be. I suggest something like the following:
"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.

Author Rebuttals to First Revision: (please note that the authors have quoted the reviewers in black text and responded in blue text)

Referee #1 (Remarks to the Author):

Dear Editor, Dear Authors,
thanks a lot for the revised manuscript and the very careful consideration of the three reviewers' comments and suggestions. I have carefully reviewed both, the new version of the manuscript as well as the authors's responses. I am convinced that the authors appropriately tackled all comments from my point of view and especially improved the general structure of the manuscript and complemented important details, e.g. in the method section, for the reader to follow the approach and line of argumentation. I also appreciate the suggestion of the new title "More than one million barriers fragment Europe's rivers" which is better reflecting the actual content and novelty of the manuscript than the earlier title. The improved details (wording, figures, typos and similar) increase the overall quality and readability of the very interesting manuscript. I am happy to recommend this manuscript for publication in Nature.

We are glad for the positive response from Referee #1 and have addressed the remaining few issues below:

Some small details on the text are listed here:
I am not a native English speaker, but a native might need to check punctuation, e.g.
l. 43: In Europe, attempts to quantify…

Done. Comma added after Europe.

l. 44: Here, we estimate…

We believe there is no comma after "Here" as per Nature's instructions
https://www.nature.com/nature/for-authors/formatting-guide

We have also consulted other recent Nature papers and there is no comma after “Here” in any of them either , e.g.

https://www.nature.com/articles/s41586-019-1111-9

https://doi.org/10.1038/s41586-020-2793-8

https://doi.org/10.1038/s41586-020-2810-y

l. 52: Across Europe, the main predictors of…
…(potentially more?)

comma added

l. 55: …and southern Europe, which require urgent protection… (delete and replace “but”)

We believe “but” is right here as we wish to use a conjunction to link two contrasting clauses: i.e. some rivers are still relatively unfragmented BUT risk no longer being so.. however we stand to be corrected and seek advice from the copy editor.

l. 58: …of Europe’s rivers by 2030. Achieving this will require… (split into two sentences and delete “but”)

As per above. We wish to link two sentences with a conjunction but happy to be corrected by the copy editor

ll. 147/8: “The number of barriers recorded in the field was on average 2.5 times higher than that in existing inventories.” (“that” instead of “those” because it refers to “number”, right?)

Yes, we agree. We have replaced by “The number of barriers recorded in the field was on average 2.5 times higher than in existing inventories”.

Referee #3 (Remarks to the Author):

The authors responses to my comments are satisfactory and they have made a substantial effort to improve the manuscript based on all reviewers and the editor’s comments and I therefore recommend this paper for publication. I only have a few minor issues:

We are very grateful for the feedback received from Referee #3 and have addressed all the points below:

The editor has asked me to also to look at the author's responses to referee #2's comments and I tend to agree with referee #2 that having a dataset aligned with a hydrography would be a logical next step that would increase the usability of the dataset. The authors note in their response that a dendritic analysis is more likely to be precluded due to the lack of an accurate river network map to align to. I also agree with this and I would like to see this point made more strongly in the manuscript. Lines 226- 228 mention that more detailed hydrographic maps are available in many countries but I think it would be good to add something along the lines of having more consistent high resolution hydrographic data across Europe (i.e. improving on ECRINS) in this section.

Done, as per the referee suggestion we have added the following sentence:

"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.

L227: dendric or dendritic?

Dendritic is the right term, we have corrected it

L551-552 The authors provide some good examples of unaccounted local factors in the rebuttal and I think it would be really useful to add these in the actual rewording so a reader is not left guessing what these may be. I suggest something like the following:

"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.

We agree. We have reworded as indicated