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Impacts of existing and planned hydropower dams on river fragmentation in the Balkan Region

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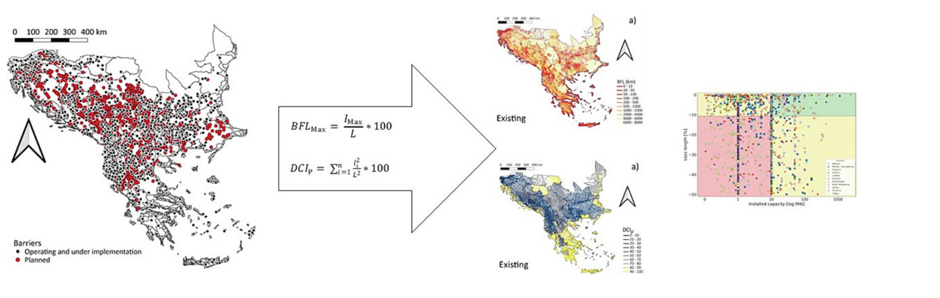
HIGHLIGHTS

- Balkan rivers are the best connected in Europe but the most threatened by new dams.
- Every one of nine future dam building scenarios considered will result in a significant loss of connectivity.
- Large dams will fragment less and generate more hydropower than building small dams.
- Trade-offs between hydropower and river connectivity need to be explicitly considered in planning.

GRAPHICAL ABSTRACT



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ABSTRACT

The Balkan region has some of the best conserved rivers in Europe, but is also the location of ~3000 planned hydropower dams that are expected to help decarbonise energy production. A conflict between policies that promote renewable hydropower and those that prioritise river conservation has ensued, which can only be resolved with the help of reliable information. Using ground-truthed barrier data, we analysed the extent of current longitudinal river fragmentation in the Balkan region and simulated nine dam construction scenarios that varied depending on the number, location and size of the planned dams. Balkan rivers are currently fragmented by 83,017 barriers and have an average barrier density of 0.33 barriers/km after correcting for barrier underreporting; this is 2.2 times lower than the mean barrier density found across Europe and serves to highlight the relatively unfragmented nature of these rivers. However, our analysis shows that all simulated dam construction scenarios would result in a significant loss of connectivity compared to existing conditions. The largest loss of connectivity (−47 %), measured as reduction in barrier-free length, would occur if all planned dams were built, 20 % of which would impact on protected areas. The smallest loss of connectivity (−8 %) would result if only large dams (>10 MW) were built. In contrast, building only small dams (<10 MW) would cause a 45 % loss of connectivity while only contributing 32 % to future hydropower capacity. Hence, the construction of many small hydropower plants will cause a disproportionately large increase in fragmentation that will not be accompanied by a corresponding increase in hydropower. At present, hydropower development in

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the Balkan rivers does not require Strategic Environmental Assessment, and does not consider cumulative impacts. We encourage planners and policy makers to explicitly consider trade-offs between gains in hydropower and losses in river connectivity at the river basin scale.

1. Introduction

Europe has possibly the most fragmented rivers in the world (Belletti et al., 2020), but also one of the highest demands for renewable energy worldwide (European Commission, 2019; Gielen et al., 2019). To meet the targets of the EU Green Deal Agenda two seemingly antagonistic objectives need to be met by 2030: on the one hand, at least 25,000 km of rivers need to be reconnected and be made free-flowing, while on the other hand, greenhouse gas emissions need to be reduced by 55 % (European Council, 2021). The former objective calls for the removal of old and inefficient dams (i.e. those instream structures that raise the water level and result in ponding) and the halting of current rates of river fragmentation. The latter objective calls for a 10 % increase in hydropower production and a 40 % increase in pumped hydroelectric energy storage (European Commission, 2020a), which will likely involve the construction of new dams. Hence, issues surrounding hydropower dams are at the heart of the green energy transition and the new biodiversity strategy: building new dams is being touted as important for securing clean energy and implementing the Renewable Energy Directive (European Commission, 2018; European Council, 2009), while halting dam construction (and removing old and inefficient dams) is seen as a necessary step for reconnecting Europe's broken rivers (Baffert and Macalister, 2021; Belletti et al., 2020; European Commission, 2022).

Hydropower is the leading source of renewable energy worldwide (International Hydropower Association, 2020a; Moran et al., 2018) and accounts for 36 % of the renewable energy (European Commission, 2019) and 13 % of all the electricity generated in Europe as of 2020 (International Hydropower Association, 2020b). However, dams used to generate hydropower also fragment rivers and cause significant ecological and sociological impacts (Wu et al., 2019). Dams disrupt the movement of fish (Nyqvist et al., 2017; Rincón et al., 2017; Winemiller et al., 2016), macroinvertebrates (Katano et al., 2009; Wang et al., 2019) and vascular macrophytes (Jones et al., 2020a), create reservoirs that result in thermal stratification (Poff et al., 2007), damage the riparian vegetation (Braatne et al., 2008; New and Xie, 2008), and modify the hydrological regime of rivers with major consequences for floodplains and coastal systems (Kondolf et al., 2018). Dams also have a major impact on the flux of sediments (Arnaud et al., 2019; Fryirs et al., 2007; Tangi et al., 2019; Wohl et al., 2015), while the release of very large flows associated with some forms of hydropower (hydropeaking) has major downstream impacts on hydrology (Almeida et al., 2020) and riverine communities (Bruno et al., 2013).

However, dams are not the only structures that fragment rivers, and most dams are not used for hydropower (World Commission on Dams, 2000). Many other human activities, such as water abstraction, flood control, navigation, or crossing waterways, break longitudinal river continuity and impact on riverine habitats and fluvial ecosystems (Carpenter et al., 2011; Grizzetti et al., 2017). Dams represent fewer than 10 % of all the surveyed barriers in Europe and 68 % of barriers are weirs, culverts, ramps, sluices and fords <2 m in height whose operation is unrelated to hydropower (Belletti et al., 2020). Compared to large dams, low head barriers have lower per capita intrinsic impacts on rivers, but they are typically much more numerous (Garcia de Leaniz, 2008; Jones et al., 2019) and they have, collectively, a greater cumulative impact on river fragmentation (Consuegra et al., 2021; Fencl et al., 2015). Large dams, in contrast, are not as numerous but tend to cause the most severe impacts on fluvial habitats, which has prompted an interest in smaller, run-of-the-river (ROR) mini-hydropower plants (Bódis et al., 2014).

Many of the large hydropower dams in Europe are becoming too old and inefficient (Perera et al., 2021), and as most of the mountainous rivers in Southern and Central Europe are already exploited for hydropower, there is growing interest in sites that have untapped hydropower potential, such as those located in the Balkan region (Schwarz, 2019; Zarfl et al., 2019). The Balkan region is home to some of the best conserved rivers in greater Europe (Schiemer et al., 2020; Schwarz, 2012) and a global biodiversity hotspot (Freyhof, 2012; Kryštufek and Reed, 2004; Weiss et al., 2018). For example, the Vjosa River in Albania has been flagged as an example of a near pristine river, yet there are fears that this and similar Balkan rivers might be severely impacted by future hydropower developments (Schiemer et al., 2020).

Such trade-offs between the need for renewable hydropower and the conservation of river biodiversity (Jackson, 2011; Seliger et al., 2016) pose a challenge for resource managers and policy makers and can only be resolved with the help of reliable information. Crucially, assessments of river continuity (beyond data on barrier density) are lacking in the Balkan region, and it is unclear how different hydropower configurations might impact on river fragmentation. The objectives of our study were, therefore, twofold. We first assessed the extent of river fragmentation in the Balkan region, building on a recent pan-European inventory of longitudinal barriers, ground-truthed with field data (Belletti et al., 2020). This enabled us to calculate several indices of river connectivity and identify the best connected (i.e. least fragmented) basins. Secondly, we used *what if* simulations to estimate the loss of connectivity that would occur under different scenarios of planned hydropower plant (HPP) construction and additional hydropower capacity, while also accounting for dam location in relation to conservation hotspots. Ultimately, the aim of our study was to help decision makers better understand the consequences of planned hydropower developments by quantifying trade-offs between gains in hydropower capacity and losses in river continuity.

2. Methods and materials

2.1. Study area

We considered as the Balkan region the area that includes fully or partially the countries of Bosnia and Herzegovina, Serbia, Montenegro, Kosovo, Albania, North Macedonia, Bulgaria, European Turkey, Greece, Slovenia, Croatia, Romania south of the Danube River, and the headwaters of Hungary draining into the Balkan basin (Reed et al., 2004). The study area includes 1072 rivers with a combined length of 253,734 km using the ECRINS river network (EEA, 2012), 44 % of which corresponds to the Danube River Basin, which was divided into 19 ECRINS sub-basins for better assessment of fragmentation.

2.2. Barrier data

Information on existing longitudinal barriers was obtained from the AMBER Barrier Atlas database (Belletti et al., 2020), available from the Global Dam Watch repository (Mulligan et al., 2021). This data set was ground-truthed during August–November 2018 by carrying out 31 standardized ~20 km river walkover surveys in 9 Balkan countries totalling 629 km (Table S1). From these, field-derived correction factors were applied to obtain more realistic barrier abundance estimates and account for under-reporting (Table S2), as described in Belletti et al. (2020). The median density of unreported barriers (i.e. those not present in national barrier inventories) was 0.26 barriers/km (bootstrapped 95 CI = 0.18–0.34, Table S2).

2.3. Planned hydropower development and installed capacities

Information on planned hydropower developments was obtained from Huđek et al. (2020); Schwarz (2019) and national and regional databases (Table S3).

These listed the planned, operating and under implementation hydropower plants classified into five installed capacities (0.1–1 MW; 1–10 MW; 10–50 MW; 50–100 MW; >100 MW). We were able to derive more precise figures for installed capacities in 40 % of cases. For the rest, precise information was not available and the maximum installed capacity in each category was used for analysis. These were mostly (98 %) small hydrodevelopments (<10 MW) and those in the very early planning stages without detailed documentation. According to our data, the current capacity for hydropower production in the Balkans is 19,577 MW, additional 1106 MW are under implementation, and the installation of 28,265 MW is planned.

2.4. Simulation of fragmentation scenarios

In the analysis of current river fragmentation we included all transversal barriers (i.e. barriers disrupting longitudinal continuity) reported in the AMBER database regardless of use (e.g., including hydropower, bed stabilization, irrigation, etc.), while only information on planned hydropower dams was included in future scenarios. We simulated 9 future fragmentation scenarios and compared them to the current baseline condition (B1-“existing”), calculated considering all existing barriers as well as those already under construction, as detailed in Table 1. The 9 future scenarios (scenarios S1–S9), included the extreme case where all planned dams are built (‘build all’, the worst case scenario, S1), as well as eight intermediate scenarios where dams are not built in nature protected areas (S2), where only large (S3) or small dams (S4) are built, where varying proportions (20–80 %) of randomly selected dams are built (S5–S8), or where the most impactful dams (i.e. those that cause the greatest loss of connectivity) are excluded (S9). The most impactful dams were identified as those that were predicted to cause a loss of 50 % or more in barrier-free length (*BFL*, see below) in river segments longer than 5 km. The rationale for using these scenarios is that they provide plausible upper and lower bounds to the impacts of new dams on fragmentation (Schwarz, 2015; Schwarz, 2019), while also taking into account the location of nature reserves and biodiversity hotspots (Freyhof, 2012; Schiemer et al., 2020; Weiss et al., 2018).

2.5. Estimation of river fragmentation

To quantify the extent of river fragmentation we used two estimates of barrier density that do not require precise information on barrier location: the number of barriers per basin and the number of barriers per km of stream (Belletti et al., 2020; Jones et al., 2019). These are useful because they can exploit the value of walkover field-surveys and account for barrier under-reporting, where the number of missing barriers can be estimated but their precise location is not known. We also calculated several connectivity metrics that make use of information on barrier location and provide more detailed information on the extent of fragmentation: Barrier Free Length (*BFL*) and the derived indices, I_{Max}, and BFL_{Max}, as well as the Dendritic Connectivity Index (*DCI*).

Barrier Free Length (*BFL*) is defined as the length between pairs of consecutive barriers in each basin (Jones et al., 2019) and represents the length of the river network that is free of barriers (Pistocchi et al., 2017), and therefore the length that an organism (or sediment) could travel unimpeded before encountering a barrier. We calculated BFL_{Max} as the standardized longest barrier-free segment in each basin:

$$BFL_{Max} = \frac{I_{Max}}{L} * 100$$

where I_{Max} is the length of the longest barrier-free segment and L is the total length of the river network in each basin. The rationale for using BFL_{Max} is that given that barriers tend to be clustered and not randomly distributed (Garcia de Leaniz and O'Hanley, 2022), it quantifies how much of the original river network remains free of barriers. We also calculated the dendritic connectivity index DCI_P for potadromous (i.e., freshwater resident) fish as:

$$DCI_P = \Sigma_{i=1}^{n} \frac{l_i^2}{L^2} * 100$$

where, as above, n is the number of river segments delimited by the location of barriers, l_i is the length of segments $i = 1$ to n, and L is the total length of the river network for each basin. DCI_P measures the probability that a fish can move between two randomly chosen points in a river network (Cote et al., 2009; Grill et al., 2014), ranging from 0 (maximum fragmentation with no connection between segments) to 100 (maximum connectivity, i.e., no barriers). DCI_P considers that all barriers are ‘impassable’ (Cote et al., 2009). Although this may seem overly restrictive for some fish species, all planned dams will reduce stream connectivity and by ‘impassable’ we really mean ‘impactful’, as we acknowledge that all barriers have selective effects on river-resident fish (Jones et al., 2020b; Jones et al., 2021a) as well as wider impacts on taxa other than fish (Jones et al., 2020a; Jones et al., 2021b).

BFL and I_{Max} are measured in km, are scale-dependent and increase with basin size for a given number of barriers. In contrast, BFL_{Max} and DCI_P are relative measures (measured as %) and are standardized by basin size to allow comparisons between basins of different sizes.

2.6. Statistical analysis

Differences in connectivity metrics between fragmentation scenarios were tested by non-parametric methods as data did not meet the assumptions of linear parametric models, and transformations were not always successful in normalizing and stabilizing the variance of residuals. To

Table 1
Dam building scenarios (S1–S9) considered in the simulations of river connectivity in the Balkan study region depending on the number and type of planned hydropower dams that are built compared to current baseline conditions (B1).

Scenario	Description	Metric			
		No. barriers	No. basins impacted	Mean no. barriers per basin	Barrier density (No./km)
Existing conditions					
B1. All reported barriers[a]	All barriers reported in the AMBER Barrier Atlas	3167[a]	110	2.91	0.012
Dam building scenarios					
S1. Worst case	All planned dams are built in addition to the known (reported) barriers	6150	125	5.64	0.024
S2. Excludes protected areas	Only dams outside protected areas are built	5549	123	5.09	0.022
S3. Only large dams	Only dams with >10 MW installed capacity are built	3440	114	3.17	0.014
S4. Only small dams	Only dams with ≤10 MW installed capacity are built	5877	125	5.38	0.023
S5. 80 %	80 % of planned dams are built, randomly selected	5553	125	5.09	0.022
S6. 70 %	70 % of planned dams are built, randomly selected	5255	124	4.82	0.021
S7. 50 %	50 % of planned dams are built, randomly selected	4658	121	4.27	0.018
S8. 20 %	20 % of planned dams are built, randomly selected	3763	116	3.45	0.015
S9. Excludes most impactful dams	Excludes dams that decrease connectivity by >50 % for BFLs larger than 5 km	5906	112	5.42	0.023

[a] Excludes 14 barriers in small costal catchments.

compare *BFL* between scenarios we used the non-parametric Kruskal-Wallis test followed by Dunn's post hoc pairwise tests with Bonferroni correction. Variation in proportions of different barrier types was obtained by calculating 95 % binomial confidence intervals (Krebs, 1999). Changes in l_{Max}, BFL_{Max} and DCI_P with respect to baseline conditions were assessed by the Friedman test (Liermann et al., 2004) followed by Conover post hoc comparisons adjusted with a Bonferroni correction (Conover, 1999), as each basin was considered to provide a paired before-after treatment comparison. For before-after scenario comparisons, only basins that were impacted by new dams were considered, these accounted for 86 % of the total river network. We defined the most impactful dams, as those whose construction would cause a 50 % or more reduction in *BFL* compared to existing conditions.

All analyses were conducted in Python using the packages *pandas* (McKinney, 2010), *numpy* (Harris et al., 2020), *scipy* (Virtanen et al., 2020), and *scikit_posthocs* (Terpilowski, 2019). We used the *matplotlib* package (Hunter, 2007) to produce the figures and QGIS (QGIS Development Team, 2009) to generate the maps.

3. Results

3.1. Current extent of fragmentation

We identified 3181 unique barrier records in the Balkan region reported in the AMBER barrier Atlas (i.e., excluding barrier duplicates) that affected 110 basins (Table 2, Fig. 1); 14 barriers were located in small coastal streams and were excluded from analysis. However, our river walkovers indicated that existing inventories grossly underestimated barrier numbers (Tables S1, S2). Barrier under-reporting error ranged from 38 % for Croatia to 95 % for Greece and 98 % for Albania. The number of barriers corrected for under-reporting was estimated to be 83,017, yielding a field corrected barrier density of 0.33 barriers/km, compared to an uncorrected density of 0.01 barriers/km based on official barrier records.

The most abundant barrier types encountered during the walkover surveys ($n = 220$) were structures designed to store water, such as dams, weirs and sluices. These made up 46 % of the barriers, followed by ramps and bed-sills used to stabilise riverbed and banks (24 %), unclassified barriers (24 %), and fords and culverts at river-road crossings (7 %). The latter are probably the most under-represented barrier types, as they tended to be located in the headwaters and low order streams (Table S1) which are more difficult to access.

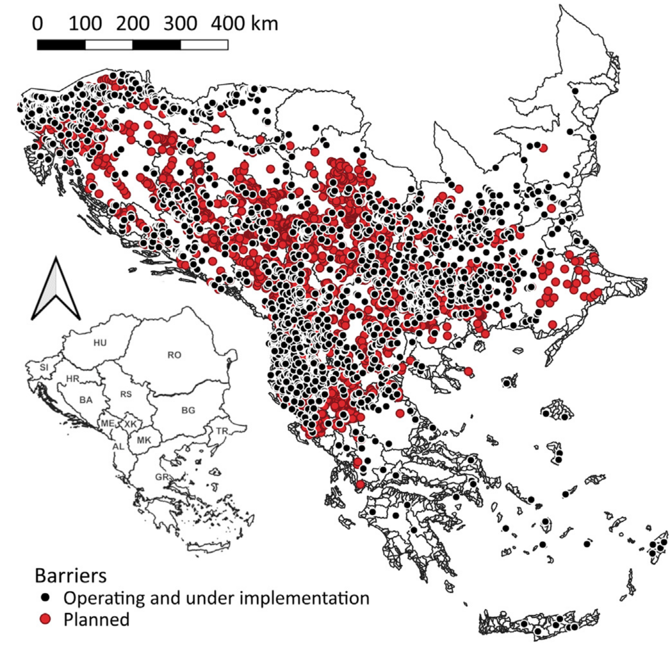

Fig. 1. Location of unique barrier records listed in the AMBER Barrier Atlas (all barrier types; Belletti et al., 2020) and planned hydropower dams in the Balkan region. Note that barrier data is underreported by 38–98 % across these countries (mean = 85 %).

Of the water storing structures encountered in the field, 25 were dams, 21 of which were listed in the existing barrier inventories. Dams made up 11.4 % of all barriers found in the test river reaches (95 % binomial CI = 7.8–15.6 %). If we apply this empirically determined incidence of dams to the estimate of 83,017 barriers for the Balkan region, it means there are probably 9431 dams, giving an estimated density of 0.04 dams/km (95 % CI = 0.02–0.05; Fig. 2a).

The mean stream length between barriers (i.e. *BFL*) listed in the AMBER Atlas was estimated to be 78 km for the whole Balkan region (SD = 360)

Table 2
Unique barrier records extracted from the AMBER Barrier Atlas (Belletti et al., 2020) listed by barrier type and country. Corrected barrier densities were obtained by applying bootstrapped correction factors on the level of barrier underreporting inferred from fields surveys (see Methods and materials). No barrier data was available for European Turkey.

Country	ECRINS river network (km)	Number of each barrier type in AMBER Atlas									Atlas barrier density (no/km)	Corrected barrier density (no/km)	Corrected no. barriers
		Dam	Weir	Sluice	Culvert	Ford	Ramp	Other	Unknown	Total			
Albania (AL)	16,717	210							308	518	0.03	0.51	8607
Bosnia-Herzegovina (BA)	25,019	20	1					11	182	214	0.01	0.2	5150
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
European Turkey (TR)	6384	–							–	–	–	–	–
Greece (GR)	61,994	143							75	218	0.00	0.36	22,508
Hungary (HU)[a]	2345	77	70	43					2	192	0.08	0.15	352
Kosovo (XK)[b]	4747	8							32	40	0.01	0.59	2801
Montenegro (ME)	7621	5							33	38	0.00	0.00	38
North Macedonia (MK)	12,876	7							166	173	0.01	0.37	4731
Romania (RO)[a]	16,729	10						3	0	13	0.00	0.23	3848
Serbia (RS)	25,376	65	3						165	233	0.01	0.59	14,972
Slovenia (SI)	9891	23	1						669	693	0.07	0.13	1321
Total[c]	247,350	780	75	43	0	0	0	14	2269	3181	0.01	0.33	83,017

[a] Data for Hungary and Romania refer to tributaries draining into the Balkan study region.
[b] Barriers in Kosovo had previously been assigned to Serbia and the corrected barrier density (0.59) was assumed to be the same for both countries.
[c] Excluding European Turkey.

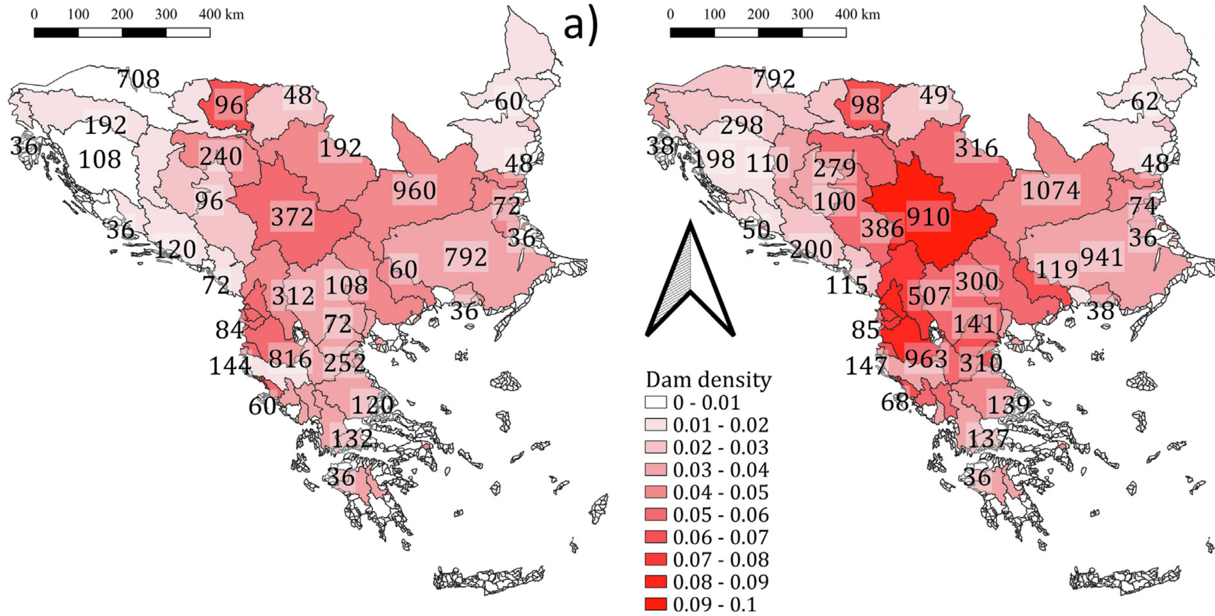

Fig. 2. Estimated density of (a) existing dams obtained by applying bootstrapped correction factors on the level of barrier underreporting inferred from field surveys, and (b) current and planned dams.

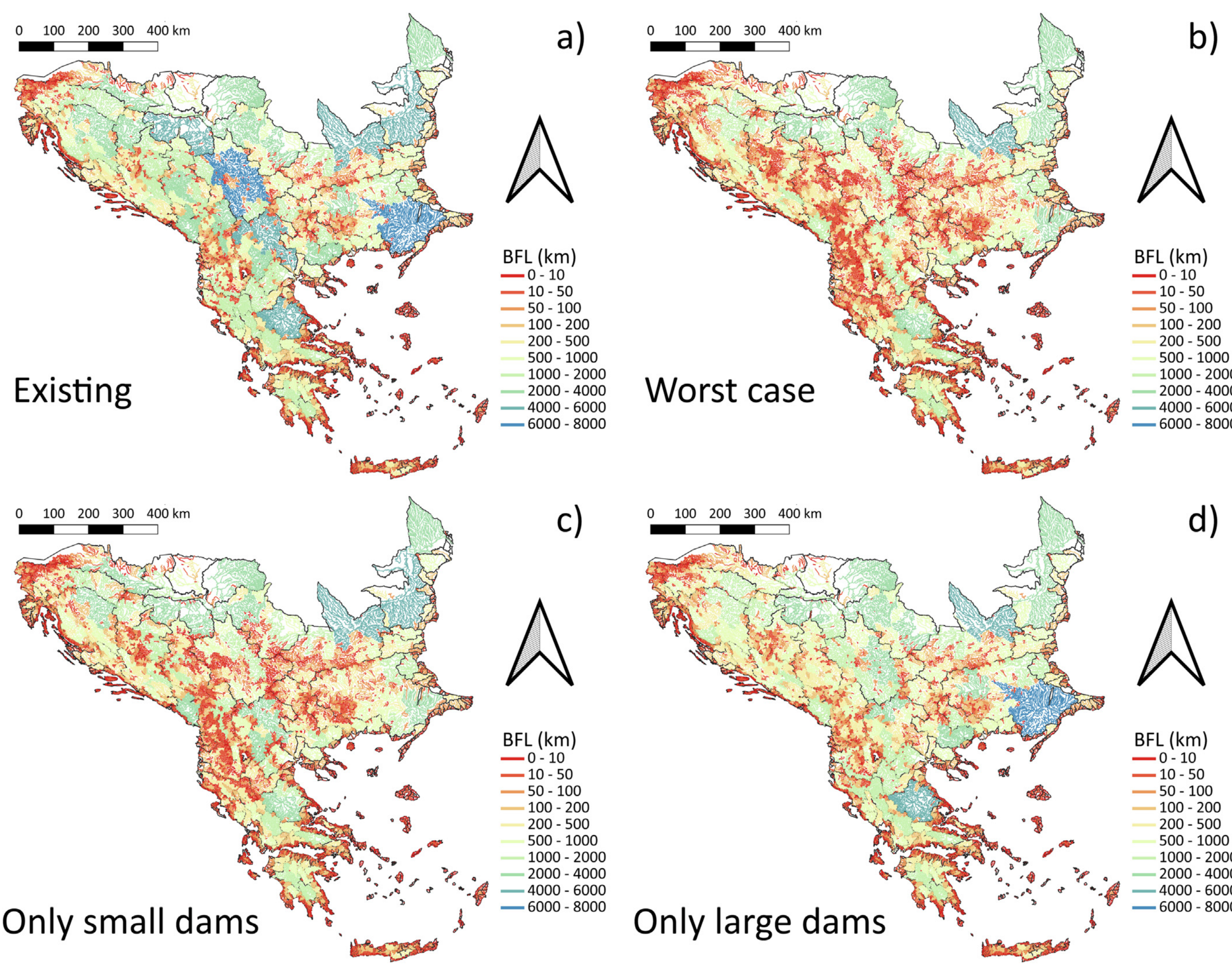

Fig. 3. Predicted changes in river fragmentation measured as Barrier Free Length (*BFL*, km) between (a) existing conditions; (b) worst case scenario (scenario S1, all planned hydropower dams are built); (c) only small dams ($\leq$10 MW) are built (scenario S4) and (d) only large dams (>10 MW) are built (scenario S3).

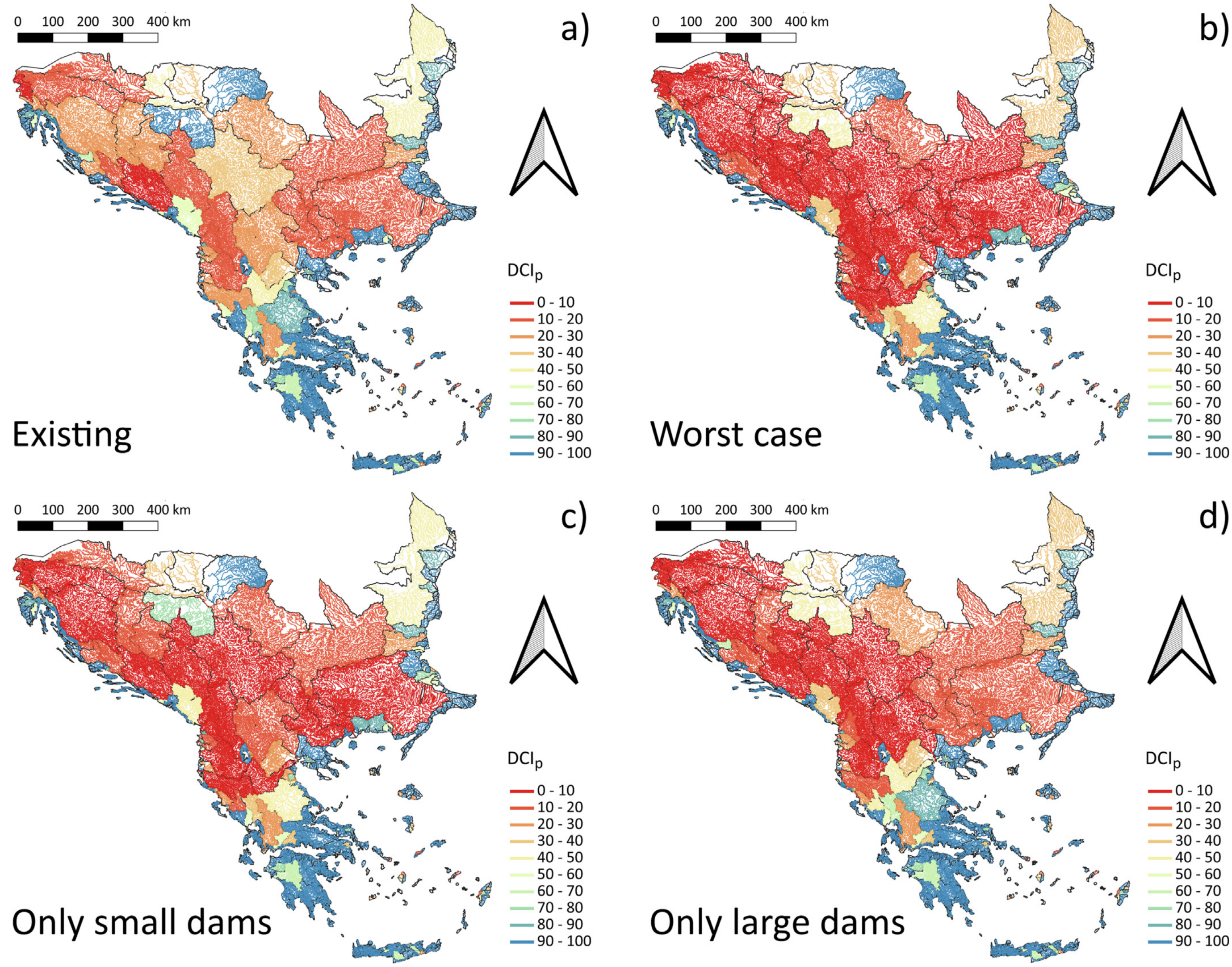

Fig. 4. Predicted changes in river fragmentation, measured as the Dendritic Connectivity Index for potadromous fish (DCI_P, %) between (a) existing conditions; (b) worst case scenario (scenario S1, all planned hydropower dams are built); (c) only small dams (≤10 MW) are built (scenario S4) and (d) only large dams (>10 MW) are built (scenario S3).

and the longest barrier-free length (i.e. unimpeded by barriers, I_{Max}) was 801 km, although variation was very high (SD = 1465) and true fragmentation is in reality much greater due to barrier under-reporting. Barriers are not evenly distributed, and the mountainous basins of the northern and central parts of Serbia have relatively high barrier densities, while some basins in the eastern of the region have much fewer barriers (Figs. 3a, 4a).

3.2. Loss of connectivity under different dam building scenarios

Our research identified 2983 new hydropower dams at the planning stage (Fig. 1), 91 % of which are small dams with an installed capacity of 10 MW or less (n = 2710) and 9 % are moderate to large dams with >10 MW installed capacity (n = 273; Table 3). Most of the planned new dams would be built in Serbia, Greece and Albania and together would have a combined installed capacity of 29 GW.

Our analysis also indicates that every one of the 9 dam building scenarios would result in a statistically significant increase in fragmentation compared to existing conditions (Table 4), especially in the central part of the region and in the Adriatic basins. However, some scenarios are more impactful than others, and their impacts depend to some extent on the connectivity metric that one considers (Figs. 3–4).

Predictably, the largest loss of connectivity will occur if all the planned dams were built (scenario S1, worst case scenario), as this would affect 125 basins and impact on 86 % of the total river network. This would bring the total reported number of barriers in the region to 6150, which represents a

Table 3
Planned hydropower dams in the Balkan region.

Country	No. new dams	% share	Installed capacity (MW)	% small (≤10 MW)	% large (>10 MW)
Albania (AL)	386	12.9	4372	91.97	8.03
Bosnia and Herzegovina (BA)	320	10.7	4532	81.25	18.75
Bulgaria (BG)	334	11.2	1705	97.90	2.10
Croatia (HR)	164	5.5	2298	76.83	23.17
Greece (GR)	387	13.0	3071	96.90	3.10
Kosovo (XK)	81	2.7	1124	92.59	7.41
Montenegro (ME)	93	3.1	2688	64.52	35.48
North Macedonia (MK)	163	5.5	1595	87.73	12.27
Serbia (RS)	847	28.4	5904	96.10	3.90
Slovenia (SI)	179	6.0	1632	82.68	17.32
European Turkey (TR)	29	1.0	127	93.10	6.90
Total	2983	100.0	29,048	90.85	9.15

Table 4
Connectivity metrics (mean, SD) for each fragmentation scenario (S1-S9) considered for hydroelectric development in the Balkan region. The Kruskal Wallis test was used to test for differences in *BFL* and the Friedman repeated measures test for the other connectivity metrics.

Fragmentation scenario	Connectivity metric			
	BFL (km)	I_{MAX} (km)	BFL_{MAX} (%)	DCI_P (%)
B1. Existing conditions	78.4 (360.0)	801 (1465)	61.7 (27.7)	53.6 (31.2)
S1. Build all dams. Worst case	41.4 (164.7)	466 (816)	53.8 (28.6)	43.9 (29.9)
S2. Excl. protected areas	45.8 (177.6)	491 (842)	55.4 (28.7)	45.7 (30.7)
S3. Only large dams	71.9 (274.3)	610 (1089)	59.7 (28.7)	50.4 (31.8)
S4. Only small dams	42.8 (188.6)	549 (964)	55.4 (27.6)	45.0 (29.6)
S5. 80 % of planned dams	45.2 (178.4)	486 (856)	55.3 (28.9)	45.4 (30.5)
S6. 70 % of planned dams	47.5 (184.4)	494 (859)	55.3 (28.7)	45.5 (30.3)
S7. 50 % of planned dams	53.6 (211.8)	538 (940)	56.9 (28.8)	47.2 (31.0)
S8. 20 % of planned dams	65.7 (258.7)	623 (1070)	59.3 (28.2)	49.8 (31.5)
S9. Excl. most impactful dams	43.3 (177.8)	515 (888)	58.7 (30.9)	50.0 (33.4)
Test-statistic	170.1	146.7	768.2	392.7
Significance value	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$

94% increase over existing condition ($n = 3167$ reported; $n = 83{,}017$ estimated) and would decrease connectivity by 47 % using barrier free length (Table 4). Approximately 20 % of the new dams would impact on protected areas. If we consider only dams, fragmentation would increase by ~32 % (from 9431 to 12,414 dams, Fig. 2a, b).

The Alpine region in the northwest of the study area already has a relatively high concentration of barriers and any new dams constructed there would only make this worse. Approximately 30 % of the new dams are planned in the western coastal basins, including the Devoll and Drini rivers in Albania, North Macedonia and Kosovo, as well as in the central part of the region, including the Velika Morava River basin in Serbia, and parts of Bulgaria and North Macedonia (Figs. 3b, 4b).

If all the new dams were built, fragmentation would increase by >50 % in some basins (Fig. 3b, 4b). For example, DCI_P would decrease by 55 % in the Sava River running through Slovenia, Croatia, Bosnia and Herzegovina and Serbia, by 77 % in the Zrmanja River (Croatia), and by 93 % in the Zapadna Morava River (Serbia). Substantial losses of connectivity can also be expected in the iconic Vjosa River (Albania), where DCI_P would decrease by 85 % if all planned dams were built.

The next most impactful scenarios involving subsets of all planned dams would be the building of 80 % of the planned dams (scenario S5), followed by the building of only small dams (scenario S4), which are the most numerous types of dams and would cause a 45 % loss of connectivity, measured as *BFL* (Fig. 3c). In contrast, the least impactful scenarios, i.e. the ones that would cause the smallest loss of connectivity compared to current conditions, are scenario S3 (build only large dams), followed by scenario S8 (build only 20 % of the dams being planned) and scenario S9 (exclude the most impactful dams; Table 4). Building only large dams would cause the smallest loss of connectivity (8 % reduction in *BFL* - Figs. 3d, 4d) because their number is relatively low, as large dams only represent 9 % of the dams being planned.

Building only 20 % of the dams (scenario S8) would minimize the loss of connectivity according to I_{MAX} and produce values of BFL_{MAX} very similar to those achieved in the best scenario. Excluding the most impactful dams (scenario S9) would result in smaller impacts according to BFL_{Ratio} (i.e. maintain absolute connectivity) and DCI_P (make it as easy as possible for fish to move along the river network) compared to S8. The most impactful dams ($n = 244$; i.e. those that would cause a 50 % or more loss in *BFL*) represent 8 % of all planned dams.

3.3. Trade-offs between hydropower production and loss of connectivity

We explored potential trade-offs between hydropower production and river fragmentation in two ways: (1) by assessing gains in installed capacity against corresponding losses in connectivity and (2) by classifying all planned dams according to their relative contribution to installed capacity and their negative impact on river fragmentation. The results indicate that under all scenarios, any significant further increases in installed capacity would result in a drastic reduction in connectivity, but that such reduction would plateau at ~20,000 MW (Fig. 5). It also shows that building many small dams results in a greater loss of connectivity - for a given increase in hydropower - than building fewer, larger dams. For example, the fragmentation cost of installing 25 GW of additional hydropower capacity would be a ~50 % reduction in connectivity using small dams compared to a ~20 % loss if larger dams were used (Fig. 5). Assessment of individual dams (Fig. 6) can help identify dams that will contribute little to

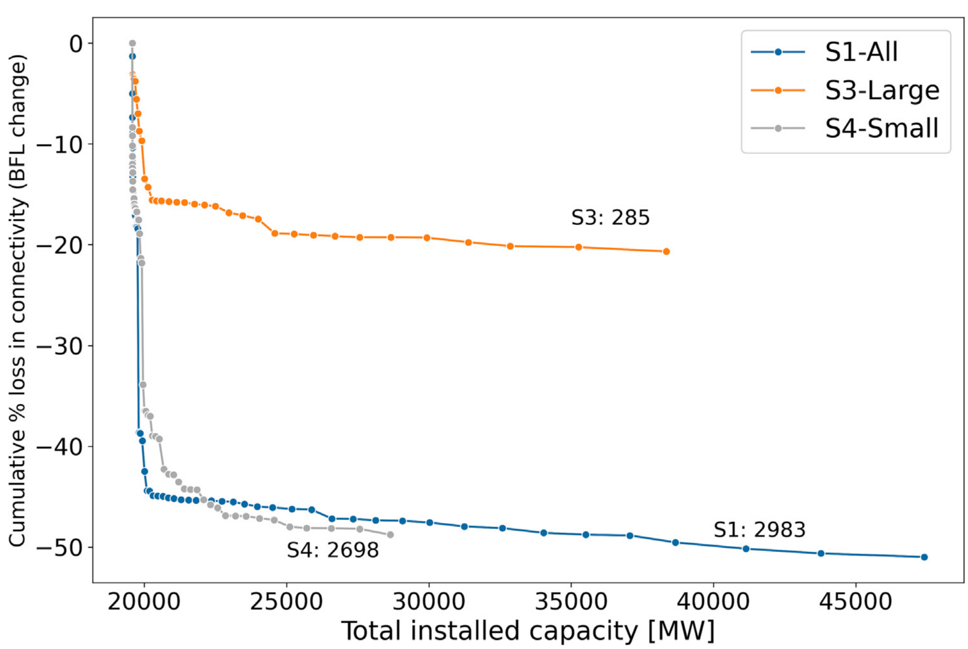

Fig. 5. Predicted loss in river connectivity (% loss in *BFL*) with increased installed hydropower capacity for three selected scenarios: Scenario S1 – all planned hydropower dams are built; Scenario S3 - only large dams (>10 MW) are built; Scenario S4 - only small dams (≤10 MW) are built. The other dam building scenarios considered show similar steep declines and fall within the extremes shown here.

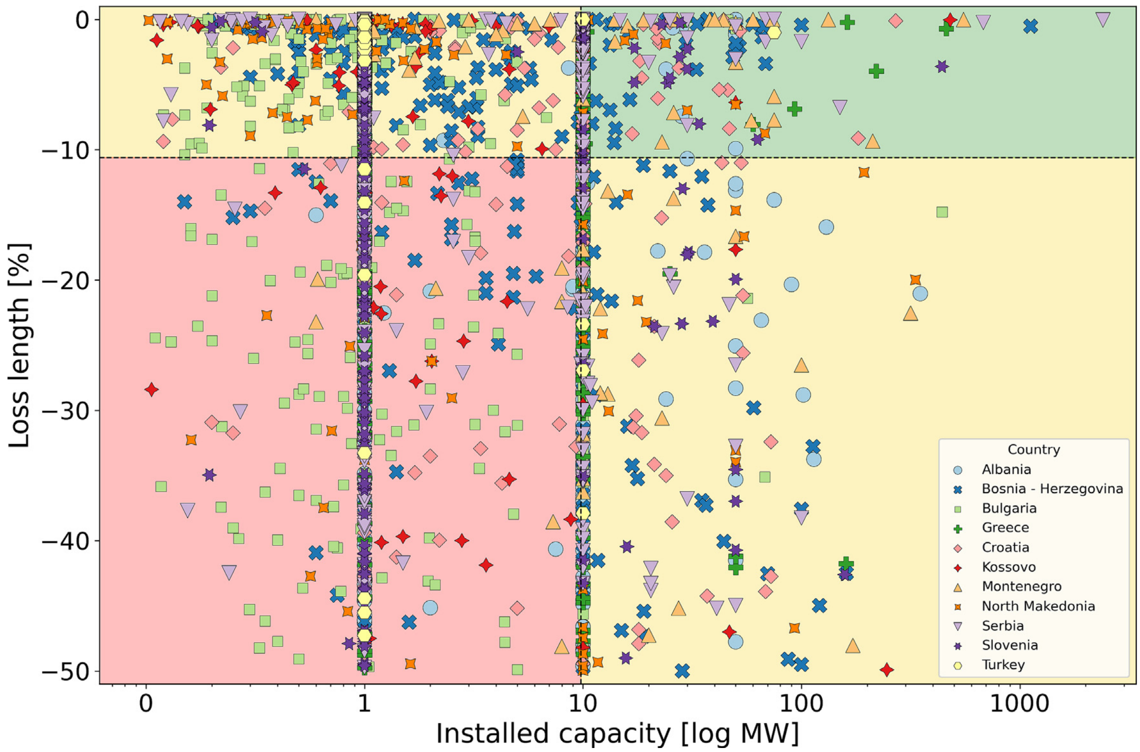

Fig. 6. Trade-offs between installed hydropower capacity and loss of connectivity (% loss in *BFL*) for all planned hydropower dams in the Balkan Region. The plot is divided into four quadrants defined by the mean values of installed hydropower capacity (mean = 9.75 MW) and expected connectivity loss (mean = 10.6 % loss). The red quadrant represents the suboptimal choices and includes those dams that will contribute less than average to hydropower capacity but will have a higher than average impact on river fragmentation (low energy, high impact); the green quadrant represents better choices and includes dams that will contribute more than average to hydropower capacity and less than average to river fragmentation (high energy, low impact); the two yellow quadrants includes dams that will have either a low impact on river fragmentation or a high contribution to hydropower capacity, but not both. Note that for many small hydropower plants the exact installed capacity is not reported, only the nearest class (1 MW or 10 MW). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hydropower and have a high impact on river fragmentation (red quadrant suboptimal choices), as well as those that will contribute more to hydropower and have a lower impact on river fragmentation (green quadrant - optimal choices). Spatial analysis indicates that Bulgaria stands out as having a much higher frequency of planned dams with higher than average fragmentation and lower than average energy production (red quadrant; std. residual = 7.64), while Montenegro (std. residual = 5.25) and Greece (std. residual = 3.87) have a higher incidence of dams in the green quadrant (lower than average fragmentation and higher than average energy production; $\chi^2 = 118.64$, df = 10, $P < 0.001$).

4. Discussion

Loss of continuity caused by artificial stream barriers is one of the main reasons for the poor ecological status of many European rivers (Grizzetti et al., 2017; Grizzetti et al., 2019). However, information on the continuity of Balkan rivers is scant and barrier data hard to obtain, which makes the assessment of current levels of fragmentation and the evaluation of impacts of planned hydropower particularly difficult to assess (Huđek et al., 2020). Most existing HPPs in the Balkan region (98 %) do not monitor flow alterations caused by hydropower, and existing national legislations are still not fully aligned with the requirements of the WFD (Huđek et al., 2020; Schwarz, 2019).

We restricted our study to longitudinal connectivity, as this is the dimension of river continuity most impacted by hydropower dams and no information on lateral or vertical barriers was available for the Balkan Region to permit other measures of connectivity to be calculated (Grill et al., 2019). We found via field walkovers that most barrier inventories in the Balkan region grossly underestimated the extent of fragmentation. Existing barrier inventories tend to list only large structures, such as dams and big weirs, but do not include most low head structures such as ramps, bed-sills, culverts, and fords at river-roads crossings. Although this type of bias is not unique to the Balkan region (Atkinson et al., 2020; Belletti et al., 2020; Buchanan et al., 2022; Jones et al., 2019), barrier under-reporting was particularly high in the Balkan countries. Underestimation of barrier numbers was 98 % in Albania, 97 % in Greece, 95 % in Romania, 87 % in Serbia, 76 % in Bulgaria and 73 % in Bosnia-Herzegovina, which are higher than an average of 61 % barrier under-reporting found across Europe (Belletti et al., 2020). Underestimation of river fragmentation is problematic because it can hinder restoration efforts, which rely on having good information on the number, size, type, and location of barriers to restore continuity effectively (Kemp and O'Hanley, 2010; Seliger and Zeiringer, 2018).

We estimated that the number of barriers in the Balkan region is probably close to 83,000 which would yield a barrier density of 0.33 barriers/km after accounting for barrier under-reporting. This is ~50 % lower than the barrier density found across Europe (mean = 0.74 barriers/km) reported by Belletti et al. (2020). Other measures of connectivity also corroborate the better connectivity of Balkan rivers. For example, average barrier free length was estimated to be ~12 km in Scotland, ~7 km in Wales and ~5 km in England (Jones et al., 2019), compared to ~78 km across the Balkan region, based on the AMBER barrier Atlas data. Likewise, while the median distance between barriers is only 108 m across Europe (Belletti et al., 2020), we found long river reaches in the Balkan region, some up to 800 km long, seemingly without barriers. Hence, although all Balkan basins are fragmented to some extent - and no river can be considered totally free of barriers - our study shows that the Balkan region has some of the best examples of largely free-flowing rivers found anywhere in Europe, and it is against this background that the impacts of planned hydropower development must be assessed.

All dam construction scenarios considered in our study resulted in a significant loss of connectivity. As remarked by others, we found that 'there are no win-wins with hydro power, only compromises' (Armstrong and

Bulkeley, 2014). Most of the hydropower dams being planned in the Balkan region will be small (<10 MW), as seen in other parts of the world (Berga, 2016; Zarfl et al., 2015). While this may seem to be a less impactful scenario, this is not necessarily the case. The ecological and social impacts of large dams are well known (Kibler and Tullos, 2013; Liermann et al., 2012; Moran and Athayde, 2019; Moran et al., 2018; Piria et al., 2019; Zarfl et al., 2019), but there is much less awareness of the impacts of small HPPs (Huđek et al., 2020), particularly the overflowing or run-of-the-river (ROR) type, which are typically not subjected to the same level of scrutiny as large dams (Huđek et al., 2020; Moran and Athayde, 2019). In common with other studies (Morden et al., 2022; Seliger et al., 2016), we found that the cumulative impact of building numerous small dams in the Balkan region would be substantial, while they would only make a small contribution to increasing energy production. We estimated that small dams would be responsible for 91 % of the predicted loss of connectivity while contributing only 32 % to the installed capacity.

Our trade-off analysis of gains in hydropower vs. loss of river continuity reveal some important results (Fig. 5). For example, we estimated that in order to achieve a 25 GW increase in hydropower capacity a ~50 % loss in river connectivity would occur if small dams were built, compared to a ~20 % loss building large dams. Simulations in the Austrian Alps also indicated that building small ROR dams would cause more cumulative ecological impacts than building a smaller number of larger dams of the same combined capacity (Seliger et al., 2016). Likewise, in Brazil the construction of many small hydropower plants is expected to result in a loss of connectivity five times greater than that caused by the construction of large hydropower dams (Couto et al., 2021).

Micro-hydro development has widely been promoted as a less impactful alternative to the construction of large dams (Bódis et al., 2014; Kuriqi et al., 2021). Yet, as our study and others indicate (Athayde et al., 2019; Consuegra et al., 2021; Couto et al., 2021; Wagner et al., 2019), the cumulative impacts of small ROR dams can be considerable, prompting some authors to rename them as "ruin-of-the-river" dams (Roberts, 1995). We found that many dams being planned in Bulgaria will contribute little to hydropower production but have a disproportionately high impact on fragmentation, while some dams in Greece and Montenegro will have more favourable trade-offs. In Romania, small HPPs make up 69–86 % of existing hydropower dams but provide only ~3 % of the country's electricity production (Costea et al., 2021). Clearly a critical reappraisal of the benefits of building small hydropower dams is urgently required.

As shown in Fig. 6, the range of the optimal choices (values within the 'green box') is rather narrow, indicating that careful planning is required, whereas there are ample possibilities for choosing non-optimal projects ('red box'). As in the Amazon basin (Couto et al., 2021; Flecker et al., 2022), basins in the Balkan region span several countries and this will require substantial transboundary cooperation among nations for strategic hydropower planning. Dam impacts on river fragmentation depend strongly on their spatial configuration but also on their number, which determine cumulative impacts (Flecker et al., 2022).

Our results can help decision makers understand the trade-offs between new hydropower developments and fragmentation, particularly the small benefits and high impact of small hydropower stations. They can also help identify those dams that will have a high impact on fragmentation and a low contribution to energy production. However, our study does not provide an optimal portfolio of dams to be prioritised for construction; for that, much more detailed barrier inventories and Pareto optimization would be required (Flecker et al., 2022; Garcia de Leaniz and O'Hanley, 2022; Roy et al., 2018; Ziv et al., 2012), which are beyond the scope of this study. Furthermore, our study focuses on trade-offs between hydropower and connectivity, but it does not take into account other factors such as biodiversity, river types, or flow regimes. To get an optimal portfolio of dams to be prioritised for construction, such factors should also be taken into account.

The Balkan region represents a global hotspot for freshwater biodiversity (Weiss et al., 2018), but also one of world's regions that has the greatest proportion of native freshwater fauna threatened by hydropower development (Zarfl et al., 2019). It has been predicted that >60 % of native endangered freshwater fish could become extinct or near extinct if all planned HPPs were built (Weiss et al., 2018).

Hydropower represents an important source of renewable energy in Europe (up to 98 % in some countries), and will play a major role in the transition to a decarbonised energy sector (Wagner et al., 2019), as part of a mix of renewable energies that can buffer against variation in the availability of wind and solar power (Berga, 2016; Moran et al., 2018). Hydropower can contribute to mitigate the impacts of climate change and improve energy security (Berga, 2016), but this should not be done at the expense of losing biodiversity. As pointed out by others (CEE Bankwatch Network, 2018), it is difficult to see how the new dams being planned in the Balkan region could be built without breaching the mandates of the EU Water Framework Directive, the Birds and Habitats Directives, and the "do not significant harm" policy of the Sustainable Finance Taxonomy Regulation (European Commission, 2020b/852). The hydropower development being planned in the Balkan rivers is also in conflict with the mandate of the new EU Biodiversity Strategy, and would jeopardize efforts to achieve at least 25,000 km of free-flowing rivers by 2030 (European Commission, 2020a). Given what is at stake, an alternative to building new dams - large or small - might be to upgrade and retrofit existing ones to make them more efficient and less impactful (Belletti et al., 2020) as shown recently in the case of the Poutès dam in the River Allier (Baffert and Macalister, 2021). A recent study has shown that HPP retrofitting could increase global hydropower capacity by 9 % without the need for building new dams (Garrett et al., 2021), and such an option should be explored to increase energy production in the region.

5. Conclusions

The rivers of the Balkan region are much less fragmented than most other European rivers and represent a unique hotspot of aquatic biodiversity which is threatened by hydropower development. Our analysis shows that over 90 % of the projected HPPs waiting to be constructed are small dams that will contribute little to the total installed capacity but will have an enormous impact on river fragmentation.

Strategic Environmental Assessments (SEA) in the Balkan rivers do not currently consider the impacts of hydropower. Consequently, HPP development has tended to proceed with little or no strategic planning, or adequate consideration of cumulative impacts at the scale of entire river basins or regions (Costea et al., 2021; Huđek et al., 2020). We suggest that any further hydropower development in the Balkans should be subjected to SEA at the basin level in a way that explicitly acknowledges the loss of connectivity and the wider impacts of barriers on river biodiversity; HPPs that generate substantial energy with minor environmental impacts on fragmentation and biodiversity should be prioritised.

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CRediT authorship contribution statement

Carolli: Conceptualization, Writing - Original draft preparation, Visualization, Software, Analysis

Garcia de Leaniz: Conceptualization, Writing - Original draft preparation, Analysis

Jones: Conceptualization, Writing - Reviewing and Editing, Software

Belletti: Conceptualization, Writing - Reviewing and Editing

Huđek: Conceptualization, Writing - Reviewing and Editing, Analysis

Pusch: Conceptualization, Writing - Reviewing and Editing

Pandakov: Conceptualization, Writing - Reviewing and Editing

Börger: Conceptualization, Writing - Reviewing and Editing

van de Bund: Conceptualization, Writing - Reviewing and Editing

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare no competing interest.

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