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BIOFRESH

Biodiversity of Freshwater Ecosystems: Status, Trends, Pressures, and Conservation Priorities

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Vulnerability of European Freshwater Ecosystems to Climate Change

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ABSTRACT

Freshwater ecosystems are the most threatened on the planet, yet multi-faceted studies on the potential impacts of climate change on freshwater biodiversity at scales that inform integrated management planning are lacking. In this study, we derived a Climate Vulnerability index for 18783 freshwater catchments across Europe based on climate-induced *exposure* to hydrological and temperature regime changes, *sensitivity* to altered environmental conditions of 1685 freshwater species of plants, fishes, molluscs, amphibians, crayfish and turtles, and the *resilience* potential conferred by features within and between catchments, such as topology and connectivity. Using multiple general circulation models, emission scenarios and hydrological models, our methods examine the potential variability in Climate Vulnerability within and among catchments and highlight consensus across methods. We showed consensus that climate vulnerability increases from the 2030s to the 2080s and that the biodiverse Lakes Ohrid, Prespa and Skadar, along with the islands of Rhodes, Lesbos (Greece), Mallorca (Spain), Sicily and Sardinia (Italy) represent just some of the 576 catchments that show high to very high Climate Vulnerability by the 2030s. We suggest these could be a practical starting point as targets for climate change mitigation. Furthermore, the presence of dams significantly reduces *resilience* and elevates Climate Vulnerability, indicating that management actions and development decisions can be taken to mitigate against climate change in freshwater ecosystems. Finally, with protected areas currently covering less than 25% of the most Climate Vulnerable catchments, our results also highlight the need to improve and 'future-proof' Europe's protected area network for freshwater ecosystems.

INTRODUCTION

Freshwaters cover less than one percent of the earth's surface, yet are home to approximately six percent of all known animal species (Woodward et al., 2010). Of those that have been assessed on the Red List of Threatened Species^{TM} (*n*=25007), more than 29% are currently at risk of extinction (IUCN, 2013); primarily due to a combination of pollution, unsustainable land use, overutilization of freshwater resources, anthropogenic disruption of hydrologic habitat connectivity and introduction of alien species(Dudgeon et al., 2006). These threats and the non-substitutional nature of freshwater for human development, suggests that freshwater ecosystems and the biodiversity they support are, and will remain, among the most endangered globally(Palmer et al., 2008).

Climate change is expected to exacerbate these current threats to freshwater ecosystems, leading to alterations in the magnitude, frequency, duration, timing and variability of freshwater thermal and hydrological attributes (Bates et al., 2008, Heino et al., 2009, Woodward et al., 2010, Poff et al., 2012). However, predictions of the full scope of interactions, feedback loops and synergies among stressors are still clearly beyond the capacities of existing models. Furthermore, many freshwater species are already shifting their ranges and phenology in response to recent climate change (Hickling et al., 2005, Parmesan, 2006, Comte et al., 2013, Domisch et al., 2013), with dispersal possibilities of obligate aquatic species strongly restricted by the dendritic hierarchical structure of river networks and numerous dispersal barriers present therein, such as dams and natural obstacles (Liermann et al., 2012).

To date, assessments of the potential effects of climate change on freshwater biodiversity have been restricted to single taxonomic groups or countries through the application of the niche-based species distributions models (see D'Amen et al. (2011), Markovic et al. (2012), Comte et al. (2013), Domisch et al. (2013)). However, as outlined by Dawson et al. (2011), to assess the biodiversity consequences of climate change one must go beyond niche based modelling and consider all aspects of vulnerability i.e. exposure, sensitivity and resilience. Most existing studies addressing integrated risk or assessing vulnerability are primarily focussed on sociological, economic and agricultural systems, with each study defining and assessing vulnerability in different ways (Brooks et al., 2005, Gallopín, 2006, Nelson et al., 2010, Pearson et al., 2011). However, there are an increasing number of studies that consider vulnerability in the field of ecosystems and climate change, although mainly for marine ecosystems (Chin et al., 2010, Foden et al., 2013). Comprehensive climate change vulnerability assessments are still lacking for freshwater ecosystems.

The present study seeks to address this knowledge gap and assess the vulnerability of European freshwater ecosystems to climate change at the catchment scale. We focus on European river and lake systems, represented by 18,783 catchments, and include data on 1,685 freshwater species of plants, fishes, molluscs, amphibians, crayfish and turtles. Following the vulnerability terminology of Turner et al. (2003), as adopted for freshwater ecosystems by Poff et al. (2012), the three dimensions of freshwater ecosystems vulnerability to climate change are: 1) extrinsic *exposure* to climate change (i.e. the extent to which environmental conditions in each catchment will change); 2) intrinsic *sensitivity* to altered environmental conditions (i.e. the lack of potential for freshwater ecosystems to persist in a catchment), and 3) *resilience* (i.e. the aspects of a catchment that enable an ecosystem to cope under climate change). Within the exposure assessment, to account for uncertainty in climate change projections, we used multiple climate models, hydrological models and emission scenarios to address future alterations in both thermal and hydrological regimes. Within the sensitivity assessment, catchment biodiversity was supplemented with multiple aspects of species sensitivity (e.g. extinction risk, rarity, thermal tolerance etc.). Finally, catchment connectivity and its effects on the opportunities for species to disperse through freshwater networks was the focus of the resilience assessment. The exposure, sensitivity and the resilience estimates were combined to provide comprehensive assessments of the vulnerability of European river and lake systems to climate change (classified as *'low', 'medium', 'high'* and *'very high'*). To facilitate the development of climate change conservation management strategies, we provide estimates of the catchment area coverage of each vulnerability category for the current European protected areas network.

METHODS

Species data

Distribution maps were obtained for 1,685 European freshwater species including 323 plants, 508 fishes, 657 molluscs, 133 odonates, 54 amphibians, 5 crayfish and 4 turtles (www.iucn.org/species_BioFresh). The data were compiled by the IUCN Global Species

Programme as part of the Red List assessment process (IUCN, 2014) and were mapped to the HydroBasins level 8 resolution catchments (http://project.freshwaterbiodiversity.eu/index.php/global-hydrobasins). At this particular resolution, the European river and lake systems are represented by 18,783 catchments (hereafter called ‘HB8 catchments’; see Supporting Information, Appendix S1, Fig. S1). Given the dendritic, hierarchical structure of river and stream networks, the catchment resolution is more appropriate for mapping freshwater species occurrences than grid cell mapping, and ensures compatibility between the analysis and management scales (Luck et al., 2009).

Baseline and future climatic and the hydrological data

The climatic and hydrological data describing the thermal and hydrological regimes across Europe for the 20th and 21st century were derived from the global gridded 0.5° × 0.5° WATCH (Water and Global Change) dataset (Hagemann et al., 2011, Weedon et al., 2011) (retrieved from https://gateway.ceh.ac.uk/). Specifically, we used the bias corrected (see Piani et al. (2010)) daily data on air temperature and naturalised flows generated by WaterGAP (Döll et al., 2003), GWAVA (Meigh et al., 1999) and LPJmL (Bondeau et al., 2007) hydrological models (HMs) for three time periods: 1971-2000 (hereafter called ‘baseline’), 2021-2050 (hereafter called ‘2030s’) and 2071-2100 (hereafter called ‘2080s’). We focussed on naturalised flows obtained from running the hydrological component of the HMs only (i.e. without the water usage component) due to the substantial differences between how each HM represented the anthropogenic and social impacts on river flow (Haddeland et al., 2011). Consequently, our results are more comparable across models. In addition to the WATCH dataset, we also used the Worldclim 30 arc-second (approximately 1 km ×1 km) gridded average and maximum temperatures dataset for the period 1960-2000 (Hijmans et al. (2005); www.worldclim.org).

All future projections were based on three General Circulation Models (GCMs); ECHAM5, CNRM and IPSL, with each following the A2 and B1 emission scenarios. A2 and B1 storylines describe a world with continuously increasing global population and regionally oriented economic growth (A2), and a world where global population peaks mid-century and declines thereafter and introduces clean and resource-efficient technologies (B1) (Nakicenovic et al., 2000). Consequently, the climatic data includes 18 distinct sets (3GCMs × 2 scenarios × 3 timelines) and the hydrological data includes 54 distinct sets (3 HMs × 3 GCMs × 2 scenarios × 3 timelines, see Fig. S4).

Protected areas

The protected areas used in this analysis include data obtained from the World Database on Protected Areas (WDPA, www.wdpa.org) and the NATURA 2000 database (www.eea.europa.eu) (Fig. S2). From the WDPA dataset, we only considered protected areas with IUCN categories I-IV, corresponding to strict nature reserves, wilderness areas, ecosystem conservation and protection areas, conservation areas for natural features and areas with conservation through active management. All Natura 2000 sites were used in our study, as they comprise Special Protected Areas (SPA) and adopted Sites of Community Importance (SCI), designated by EU Member States under the Birds Directive (79/409/EEC) and the

Habitats Directive (92/43/EEC) with the aim of long-term protection of Europe's most valuable and threatened species and habitats. The total area protected (PA) within each individual catchment was calculated by overlaying the union of the WDPA and Natura 2000 layers with the HB8 layer using ESRI ArcGIS analysis tools (Fig. S3).

Exposure assessment

The conceptual framework for calculation of the exposure indicators is based on the Indicators of Hydrological Alteration (IHA) and Range of Variability Approach (RVA) introduced by Richter et al. (1996 & 1997) and further elaborated by Laizé et al. (2010) within the Ecological Risk due to Flow Alteration (ERFA) framework. The underlying assumption of these approaches is that the major ecologically relevant hydrological and thermal regime alterations due to environmental or anthropogenic influences are in magnitude, frequency, duration, timing and variability of regime attributes (see also Poff et al. (2012)).

Magnitude. The magnitude of hydrological and thermal events reflects the availability of freshwater habitat for both in-stream and riparian species. In addition, the magnitude of thermal events plays a fundamental role in the quality of water and distribution of aquatic species (Caissie, 2006, Comte et al., 2013).

Frequency. The frequency of events occurrence, in particular high and low extremes (such as floods and droughts or heat and cold waves), affects population dynamics through impacts on the reproduction of species or increases in species mortality (Richter et al., 1996).

Duration. The duration of an event, in particular increases in the duration of droughts and summer heat stress, may lead to significant distortions in community structure and composition and poses elevated, potentially lethal risks for cold-water species (Markovic et al., 2013).

Timing. The timing of an event, in particular the timing of annual extremes, may impair ecological success of a particular life-stage of a species. Thus, changes in event timing may result in the weakening or breakage of trophic interactions (Woodward et al., 2010).

Variability. The variability of hydrologic and thermal regimes strongly affects food-web synchrony. Changes in regime variability may affect habitat availability and lead to the disruption of established patterns in food-web synchrony (Kishi et al., 2005).

To address the above alterations in hydrological and thermal catchment attributes we used a set of indicators specified in Table 1. Firstly, the indicator change (‘IC’) between baseline conditions and future time periods (2030s and 2080s) was determined (see Fig. S4) and, for hydrological indicators, the results were merged together for each GCM and emission scenario by averaging the corresponding indicator values per grid cell across all HMs. Secondly, the grid cell related exposure (hydrological vs thermal components) were calculated by counting the number of indicators exceeding the corresponding thresholds (see Table 1). The threshold values were selected following Laizé et al. (2014) and van Vliet et al. (2013). Thirdly, the HB8 catchment related hydrological and thermal exposure components were calculated from the corresponding gridded layers using the ESRI ArcGIS zonal statistics tool. The final exposure maps, comprising both the hydrological and thermal alterations, were calculated by merging the two exposure components and normalising to a 0-1 numerical scale.

Sensitivity assessment

Threatened, endemic, restricted-range or rare species and species with narrow environmental tolerances have generally lower capacity to recover from extreme, catastrophic or local extinction events than more common and/or widespread species (Foden et al., 2013). This suggests that freshwater ecosystems containing such species are likely to suffer greater impacts from climate change than ecosystems containing only more common and/or widespread species.

The sensitivity assessment applied here combines various concepts including the threat, range-restricted and ecoregion-restricted criteria of freshwater Key Biodiversity Areas (KBA) (Holland et al., 2012), the irreplacebility of Alliance for Zero Extinction sites (Ricketts et al., 2005) and the species traits approach (e.g. Foden et al. (2013)). HB8 catchment specific sensitivity values were then derived as an average across the individual scores of the five sensitivity attributes considered. The sensitivity based on a) the conservative catchment scoring and b) the relative species numbers are referred hereafter as ‘conservative sensitivity’ and ‘standard sensitivity’ respectively. The following attributes of sensitivity were considered:

Presence of threatened species. This criterion reflects species’ risk of extinction following the IUCN Red List of Threatened Species™, which classifies threatened species into categories ‘Critically Endangered’ (CR), ‘Endangered’ (EN), or ‘Vulnerable’ (VU) based on a globally accepted set of quantitative criteria (IUCN, 2014). Given that CR, EN and VU species are at extremely high risk or very high risk of extinction in the wild (IUCN, 2014), we consider climate change as an additional threat increasing their extinction risk. We assigned a normalized score based on the total number of species classified in any of the three categories (i.e. 0 for a catchment with no threatened species and 1 for a catchment with the maximum number of threatened species). In addition, within the ‘conservative catchment scoring’ approach, a presence of at least one threatened species was considered sufficient to trigger catchment classification as ‘sensitive to climate change’ (i.e. catchment with CR, EN or VU species was assigned the score 1, otherwise, 0). Two estimates of this sensitivity component were calculated, with one using the European, and the other using the global species’ Red List Status.

Presence of species of restricted range. Species with small (restricted) ranges generally have higher extinction risk than widespread species (Purvis et al., 2000). As such, the inherent vulnerability of restricted-range species to external pressures is compounded by climate change related effects. Following Holland et al. (2012) we used a threshold value for the extent of occurrence of 50,000 km^2 for odonates and 20,000 km^2 for other taxa groups. Here, as a proxy for the species’ extent of occurrence (EOO), we used the total range size for each species derived by summing the total catchment area with known species occurrences. The normalized scores were obtained by calculating the total number of species of restricted range per catchment relative to a catchment with the highest number of such species (i.e. 0 for a catchment with no species of restricted range and 1 for a catchment with the maximum number of such species). In addition, within the ‘conservative catchment scoring’ approach, a presence of a single restricted-range species was considered sufficient to trigger catchment classification as ‘sensitive to climate change’ (i.e. catchment with a single restricted range species was assigned the score 1, otherwise, 0).

Presence of species that are confined to an appropriate biogeographic unit. Regions with unique species assemblages are generally sensitive to environmental change (Malcolm et al., 2006). Here, freshwater ecoregions of the world developed by Abell et al. (2008) are used as the biogeographic units. For each catchment, we identified the proportion of species that occur in a single freshwater ecoregion. Thresholds for the proportion of ecoregion-restricted species relevant to classify a particular catchment as 'sensitive to climate change' impact are 25% for fish and 5% for all other taxa groups. These were adapted from thresholds used in Holland *et al.* 2012 to identify Key Biodiversity Areas (KBAs) based on ecoregion-restricted assemblages. If in a given catchment for any of the taxa groups studied the given thresholds were exceeded, then this sensitivity attribute was assigned the score 1, otherwise, 0.

Irreplaceability of catchments. If a catchment represents the entire known range of any of the species then it was considered irreplaceable, and thus the catchment's biodiversity is highly sensitive to climate change effects (Linke et al., 2008). We calculated the irreplaceability value of all HB8 catchments for each species as the ratio between the catchment area occupied by a species (0 if the species is currently not present, otherwise the catchment area size) and the total species' range area. Consequently, the irreplaceability value of a catchment for a particular species is between 0 (for a catchment that does not belong to species range) and 1 (for a catchment representing the entire species range). The final HB8 catchment specific score for this sensitivity component ('Iscore') is the maximum of a catchment's irreplaceability values ('IRval') based on a catchment's species composition; $\mathrm{Iscore}\ (\mathrm{c}) = \max(\mathrm{IRval}_s), s = 1, \ldots, s_c$, where s_c denotes the species inhabiting catchment *c*.

Narrow species' environmental tolerance breadths. Tolerance to a wide range of climatic conditions is tightly linked to the ability of a species to resist and recover from environmental change (Poff et al., 2012). We used the temperature range (maximum-minimum) over the extended baseline period (1960-2000) across species' current ranges as a proxy for species environmental tolerance breadths. The cumulative distribution function of unique species' tolerance breadths ('TB_s') was then created and each species was assigned a normalised score such that $TBn_s=1-(TB_s-TB_{min})/(TB_{max}-TB_{min})$ (i.e., 0 for species with the highest tolerance ('TB_{max}'), and 1 for species with the lowest ('TB_{min}')). The HB8 catchment specific score for this sensitivity attribute ('TB_{score}') was then calculated as the maximum species normalised tolerance breadth score, given the catchment's species composition; $\mathrm{TB}_{score}(c) = \max(TBn_s), s = 1, .., s_c$, where s_c denotes the species inhabiting the catchment *c*.

Resilience assessment

Habitat connectivity and availability of diverse freshwater environments (e.g. from mountainous streams to lowland rivers) are one of the key factors influencing recolonisation ability of species, and thus species resilience to climate change. Therefore, we adopted the resilience concept of Poff et al. (2012), which considers resilience more broadly as a feature of the landscape and not as a species' trait.

Lack of hydrological catchment connectivity due to natural dispersal barriers (such as drainage divides of the 'major' basins i.e. basins with sea or ocean outlet) and anthropogenic barriers (such as dams and weirs), reduces species success at tracking spatial shifts in suitable habitats. Here, drainage divides (estimated using the Pfafstetter coding system) and dams were considered as dispersal barriers that contributed towards the disruption of connectivity. The geographic location of about 5,500 dams across the European catchments was extracted from the ECRINS (European catchments and Rivers network system) database (http://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network).

Within the resilience assessment we considered two dispersal scenarios: 1) a scenario with dams and, 2) an optimistic scenario without dams. Consequently, the set of hydrologically connected upstream and downstream catchments for an individual HB8 catchment is different for the majority of catchments between the two dispersal scenarios. The resilience assessment was based on the following catchment attributes:

Altitudinal range. Altitudinal range provides an indirect measure of the basin specific differences in the opportunities available to freshwater species to escape thermal stress, where basins with a small altitudinal range provide less opportunity than those with alpine streams (e.g. Comte et al. (2013)). Here, for each catchment, the maximum altitudinal range across the connected catchments was used.

Latitudinal gradient. Many freshwater species are already expanding their ranges to higher latitudes in response to climate change (Hickling et al., 2005, Domisch et al., 2013). Consequently, the basins' latitudinal range can be used as a proxy for resilience to adverse effects of climate change. To assess the opportunity for species to move northwards as a response to increasing temperatures we calculated the maximum latitudinal range for each catchment as the difference between latitudes of the northernmost border of the northernmost connected catchment and southernmost border of the southernmost connected catchment.

Network density. The network density represents a natural source of resilience for freshwater species within a catchment (Campbell Grant et al., 2007) and was quantified as the ratio between the total length of river network in a catchment and the catchment area.

Network complexity. Similar to the network density, the network complexity represents a natural source of resilience for freshwater species (Campbell Grant et al., 2007). This was quantified as the total number of connected catchments to each catchment within the study area.

For each resilience attribute all catchments were sorted by score and then normalized to the 0-1 scale (i.e. 0 for a catchment with the smallest and 1 for a catchment with the largest value for the particular resilience attribute). Finally, catchment specific resilience was derived as an average of the corresponding values for the resilience attributes and an inverse resilience score (1 – resilience) was calculated for each catchment to equate the results to those of exposure and sensitivity.

Climatic vulnerability assessment

Each of the three dimensions that make up the vulnerability of freshwater ecosystems to climate change, namely exposure, sensitivity and 1 – resilience, were assigned a category of 'low' (<0.25), 'medium' (0.25-0.49), 'high' 0.5-0.74) or 'very high' (≥0.75); similar to van Vliet et al. (2013). Note that these categories are distinct from those used below to denote climate vulnerability and are hereafter referred to as 'L', 'M', 'H' and 'VH' respectively. Given that vulnerability is considered here as a combination of all three dimensions, each having four categories, the three dimensional logical matrix has 64 score combinations (Table 3).

The numerous dimension score combinations can be mapped to overall Climate Vulnerability (CV), also split into *'low'*, *'medium'*, *'high*' or *'very high'* categories, in a variety of ways (e.g. Chin et al. (2010), Comer et al. (2012)). To account for the variability in the various options, we used four distinct methods (see Table S1 for details): Vulnerability Method 1 (VM_1) is the most pessimistic approach, with the CV score calculated as the mean value of the individual dimension scores and classified as *'low'* (<0.25), *'medium'* (0.25-0.49), *'high'* (0.5-0.74) or *'very high'* (≥0.75). As such, VM_1 has 7 score sets in the category *'low'*, 22 *'medium'*, 25 *'high'* and 10 *'very high'*. VM_2 and VM_3 are based on an alternative approach that assigns categories based on cumulative distributions of possible score combinations. VM_2 uses a symmetric cumulative distribution function to assign 10 score combinations to the category *'low'*, 22 to *'medium'*, 22 to *'high'* and 10 to *'very high'*. VM_3 is based on a positively skewed cumulative distribution function that assigns 19 score combinations to the category *'low'*, 19 to *'medium'*, 19 to *'high'* and 7 to *'very high'*. VM_4 is the most optimistic approach and employs the logic rule that categories are assigned to possible score combinations based on the lowest dimension score; e.g. 'low; (L)' score in any vulnerability dimension must lead to a *'low'* CV and so forth, with the *'very high'* CV category only assigned if all three vulnerability dimensions scored 'very high; (VH)'. This results in 37 score combinations in the category *'low'*, 7 in *'medium'*, 19 in *'high'* and 1 in *'very high'*.

To help inform and facilitate the development of climate change conservation management strategies, we assessed the number of catchments within the European protected areas network (Natura 2000 and WDPA) for each of the vulnerability assessment approaches (VM_1 to VM_4) and for the consensus patterns (VM_1 to VM_3 and VM_1 to VM_4). Within the consensus patterns, a catchment was assigned a particular vulnerability category only if the same category was assigned for all considered approaches, otherwise it was categorised as *'no consensus'*.

RESULTS

To explore the vulnerability of European freshwater ecosystems to climate change, each vulnerability dimension (exposure, sensitivity and resilience) was analysed separately and in combination with all others. The three dimensions show absolute Pearson correlations of below 0.1 for all combinations of SRES scenarios (A2, B1), time periods and dispersal scenarios, indicating very little statistical dependence between dimensions.

Overall, regardless of whether pessimistic or optimistic approaches were used, the river and lake catchments across the Balkan countries (Croatia, Macedonia, Albania, and Greece), southern Europe (Spain and Italy) and northernmost parts of Russia and Finland emerge as regions with *'high'* to *'very high'* climate change vulnerability (CV).

Exposure

The predicted changes in thermal components of European freshwater ecosystems are higher than those predicted for the hydrological components, and suggest high risk for species in the Ebro basin in Spain, Garonne in France, Pechora in Russia and catchments in Croatia and northern Scandinavia (Fig. S5). Changes to hydrological regimes will mainly affect southern Europe by the 2030s, but are predicted to increase by the 2080s and affect the Pechora, Northern Dvina and Mezen River basins in Russia and northern Scandinavian catchments. Whilst there is little variability between SRES scenarios for the 2030s (Fig. 1a-b, Fig. S5), variability increases with time so that the percentage area of categories ‘H’ and ‘VH’ increases from 33.6 % for 2030s to 84.8 % for 2080s B1 scenario and from 25.2 % to 92.6 % for 2080s A2 scenario (Fig. S5). Finally, catchments characterised by a combination of large predicted changes in both thermal and hydrological regimes are mainly located in Spain, the Balkan countries and Baltic Sea countries (Fig. 1a-b).

Sensitivity

The sensitivity patterns based on the European Red List are almost identical to those based on the Global Red List (Fig. 1c-d, Fig. S6), and thus only the latter is considered in further analyses. The highest numbers of threatened, restricted range or ecoregion-restricted species were found in catchments along the Croatian Adriatic sea coastline, for the Balkan Lakes Ohrid and Prespa and the Duero, Tajo and Guadiana River basins in Spain (Fig. S6). These river and lake catchments are also characterised by high irreplaceability. Lake Ladoga, the only home of the fish species *Coregonus ladogae* and the West Highland River basin region in the UK were also found to be highly irreplaceable. Additionally, warm adapted species in the southernmost parts of Europe appear to be less sensitive to climate warming than species in central and northern Europe (Fig. S6f).

The number of globally threatened species per catchment is generally below 5 (84 % of the study area). However, for twenty one catchments it is between 15 and 60. As a result, when using the relative species numbers to calculate the individual sensitivity attributes the majority of catchments were assigned ‘L’ sensitivity (Fig. 1, Fig. S7a-b). In contrast, when applying the conservative approach, assuming that a presence of a single species in either of the sensitivity attributes was sufficient to trigger catchment classification as ‘sensitive to climate change’, the majority of catchments (> 90 %) are in the sensitivity categories ‘M’ to ‘H’ (Fig. S7c-d).

Resilience

The degree of connectivity for river and lake catchments has proven to have a prevailing influence on all resilience components. Owing to numerous anthropogenic dispersal barriers, resilience is low in the majority of catchments (Fig. 1e-f). Consequently, the natural potential of the basins’ altitudinal range, latitudinal gradient or river network complexity to provide species the opportunity to disperse to suitable habitats is considerably low, except for the Northern Caucasus region in Russia and the Piedmont region in Italy (Fig. S8a,c,e,g). Without dams and obstacles, the Danube, Neva, Dnieper and the Volga basins could provide ‘H’ to ‘VH’ resilience potential due to their high altitudinal range and latitudinal gradient (Fig. S8b,d,f,h). Consequently, for the dispersal scenario considering dams and obstacles resilience scores only fall into categories ‘L’ and ‘M’ (9.8 %), whilst for the dispersal scenario without dams and obstacles catchments are distributed across the ‘L’ (44.5%), ‘M’ (27.7%), ‘H’ (20.6%) and ‘VH’ (7.3%) categories.

Climatic vulnerability

The variety of options used to evaluate the individual vulnerability dimensions, alongside combing these to form (CV) estimates, has enabled a comprehensive view of the European river and lake catchments' vulnerability to climate change. Tables 2 and S2-S5 contain summary statistics for the number of catchments, % surface area and % protected area for each CV category for each individual vulnerability method, whilst Tables 3 and S6 provide summary statistics for CV based on the consensus approach. There are considerable variations in the spatial distribution of CV scores between each vulnerability method (VM), highlighting the importance of the consensus methodology in combining results. In particular, regardless of scenario, over 96% of the total study area in VM_4 (the most optimistic method) has *'low'* CV scores, with only a maximum of 11 catchments scoring in the *'high'* or *'very high'* categories (Table S5, Fig. S12.). Consequently, when combined with the other vulnerability methodologies, VM_4 almost eradicates *'high'* to *'very high'* CV consensus scores (Table S6, Figure S13). However, such low CV scores across much of Europe in the future is highly unlikely given predicted shifts in climate and widespread impoundment of rivers. Therefore, following the precautionary principle (Myers, 1993), the consensus between VM_1, VM_2 and VM_3 were used in further analyses and to identify priority catchments for management.

The differences between CV scores using the 'standard sensitivity' (Fig. 2) and 'conservative sensitivity' approach (Fig. S9) were compared for VM_1 (Table 2 vs. Table S2). The 'conservative sensitivity' scenarios demonstrated high CV scores across Europe, since the presence of a single threatened or restricted range species was sufficient to trigger catchments as 'sensitive to climate change'. The most pessimistic approach ('conservative sensitivity' assessment and resilience calculation considering dispersal barriers), predicts the majority of catchments to be in the *'high'* to *'very high'* CV categories (up to 18,170 (95.76% of study area) for 2080s A2 scenario with dams, Fig. S9d, Table S2). In comparison, when the 'standard sensitivity' approach was used, the majority of catchments (regardless of time period, dispersal and emission scenario) are predicted to be in the *'medium'* category (between 9,531 and 15,099 (54.2 % and 80.2 % of study area respectively); Fig. 2, Table 2), except for the 2080s (dams scenario and both A2 and B1 emission scenarios) where the majority of catchments have *'high'* CV scores (Fig. 2c,d). The 'standard sensitivity' approach was used for all remaining vulnerability analyses, as it provides a relative sensitivity score for each catchment based on data for the total complement of species. This the more appropriate approach, as the species data available and scope of the project make it unrealistic to focus on individuals species.

Overall, for dispersal scenarios with dams, CV scores are generally one category higher than for those scenarios without dams. The differences between dispersal scenarios are particularly pronounced in the Danube, Neva, Dnieper and the Volga basins (Fig. 3 and Fig. S9-S11). For the 2030s, there is a consensus among the applied methods that the majority of European freshwater ecosystems have *'low'* to *'medium'* CV scores (>65 % of the study area, Table 3, Table S6, Fig. 3, Fig. S13), with up to 576 lake and river catchments predicted to have *'high'* to '*very high'* CV for methods VM_1 to VM_3 (Fig. 3a, Table 3). For the 2080s, there is significant variability between CV estimates, suggesting considerable uncertainty, with most methods indicating increases in CV scores over 2030 values across southern Europe (Spain, Italy, Balkan countries) and northern Europe (Scandinavia and northernmost parts of Russia). At most, a consensus of methods VM_1 to VM_3 predicts that 16.15% of the total study area (2976 lake and river catchments) will have *'high'* to '*very high'* CV scores (Fig. 3d, Table 3).

Regardless of the scenario and time period for VM1 to VM3, *'very high'* CV is attributed to Lake Ohrid (shared by the Republic of Macedonia and Albania) and Lake Prespa (shared by Albania, Greece and the Republic of Macedonia) (note, Lake Prespa consists of two lakes; the Great Prespa Lake and the Small Prespa Lake). Similarly, *'high'* to *'very high'* CV scores are predicted in Lake Skadar (shared between Albania and Montenegro), Lake Ladoga (Russia), the Greek islands of Rhodes and Lesbos, the Spanish island of Mallorca, the Italian islands of Sardinia and Sicily and for catchments along the Adriatic Sea coast, eastern Spain, southern Greece, western Italy, northern Russia, Crimea and in the north-west of England and highlands of Scotland (Fig. 3). Furthermore, these vulnerable lakes and catchments have less than 25% of their combined area covered by the European protected areas network for all VM1 to VM3 consensus scenarios (Table 3). A gap analysis of the CV scores for the two most pessimistic consensus scenarios for the 2030s and 2080s and current European protected areas identified priority catchments for future management actions (Fig. 4).

DISCUSSION

Our results highlight the vulnerability of European freshwater ecosystems to 21st century climate change. Through the combination of exposure, sensitivity and resilience that consider key features of freshwater systems such as species ranges and environmental tolerances and attributes of river networks such as hydrological connectivity and dispersal barriers, we have developed a vulnerability assessment framework tailored to freshwater ecosystems. Application of this framework using a variety of taxonomic groups (plants, fishes, molluscs, amphibians, crayfish and turtles) coupled with the high spatial resolution of our study (> 18,000 European lake and river catchments), has enabled us to decrease uncertainty in our climate change vulnerability estimates. Specifically, our consideration of the magnitude and direction of change in the hydrological and thermal regimes for multiple GCMs and hydrological models has provided more refined estimates of climate change exposure for freshwater ecosystems than has been possible at this spatial scale before. Key Biodiversity Areas (of which AZEs are a subset) are defined as the most important areas for the global persistence of biodiversity. By incorporating KBA criteria into the CVI framework we have identified the KBAs that are most at threat from climate change, complementing the study by Carrizo et al. (2014) and providing an additional means of prioritising catchments for management. Were these KBAs to be overlooked, we could be losing most of Europe's freshwater species diversity. Furthermore, by explicitly including upstream and downstream connectivity our approach has overcome the major limitation of most commonly used bioclimatic methods (see Poff et al. (2012)). Finally, by combining different vulnerability assessment methods, we were able to reduce uncertainties related to each of the individual methods.

However, despite our comprehensive framework, estimates of the vulnerability of European freshwater ecosystems to climate change at the catchment scale are affected by several limitations. Firstly, the model does not account for the significant variability in the dispersal capacity amongst the species studied (e.g. some are capable of passing artificial barriers (e.g. Atlantic salmon) while others are more restricted being relatively weak swimmers (e.g. graylings) or slow (molluscs)). Species dispersal is also mediated by the presence (or lack of) and type of fish passes built into dams. Secondly, the capacity for lake-dwelling species to seek refugia within lake ecosystems has not been included (Angilletta, 2009). However, we underline here that our intention is not to predict individual freshwater species extinction risk due to climate change, as our approach does not allow us to do so with any acceptable degree of accuracy. Our study aims to provide an overview of the vulnerability of European freshwater ecosystems at the catchment scale in the face of 21st century climate change, and to make suggestions as to those catchments most in need of conservation actions.

We found high exposure in terms of thermal and hydrological regime alterations across the Ebro basin in Spain, Garonne in France, Pechora in Russia and catchments along the Adriatic coast and northern Scandinavia, confirming and refining the findings of Laizé et al. (2014) and van Vliet et al. (2013). Since climate change vulnerability is strongly related to species endemism and projected changes in thermal and hydrological regimes, it is not surprising that the biodiversity-rich ancient lakes of Ohrid and Prespa, situated in the central Balkans, are among the most vulnerable European lake and river catchments to climate change. Importantly, Lake Ohrid is probably the most diverse lake in the world given its size (358 km^2), supporting 212 known endemic species (Albrecht and Wilke, 2009). We highlight the Balkan Lakes and Mediterranean islands as most vulnerable to climate change, along with up to 576 lake and river catchments predicted to have *'high'* to *'very high'* CV scores by the 2030s and 2796 by the 2080s according to the majority of considered vulnerability assessment methods.

Our results clearly show that fragmentation of rivers by artificial structures has a strong effect on the resilience of freshwater ecosystems to climate change and their subsequent CV scores. The effect of dams and obstacles was highest in the basins of the Danube, Neva, Dnieper and Volga Rivers, significantly reducing the natural resilience to climate change through reduction of species' dispersal potential. Given that the Danube River Basin is one of the most heavily obstructed river basins worldwide (Liermann et al., 2012), urgent management interventions are required to address this issue. Specifically, strictly aquatic species such as diadromous fishes (those that migrate between sea and freshwaters to complete their life cycle) and endemic fishes like most of the sculpins (Cottus spp.) (Liermann et al., 2012), are among the most impacted by this connectivity loss. Given that most of the European diadromous fish species are endangered and connectivity of suitable freshwater habitats is crucially important for the dispersal of obligate aquatic species, the potential consequences of climate change need to be considered within current conservation plans for these species (see Lassalle et al. (2008)). Furthermore, high mountain ranges present dispersal barriers for amphibians and odonates and molluscs are also at high risk due to their limited dispersal velocity (0.1 to 1.0 km/year; Kappes and Haase (2012)). Ultimately, options for assisted colonisation (Hoegh-Guldberg et al., 2008) will need to be investigated for these and other lentic species. In summary, future biodiversity patterns across European river and lake catchments are strongly related to the impact of barriers on individual species. Since dispersal is a key behavioural mechanism for adaption to climate change (Loarie et al., 2009), there is a critical need to improve our understanding on the effects that connectivity within suitable habitats, species dispersal traits and climate change velocity has on species ability to deal with climate change.

Our results also demonstrate that less than 25% surface area of the most vulnerable European lake and river catchments to climate change are situated within current protected area networks. The locations of these overlaps and the reasons underpinning catchment vulnerability scores must inform a review of the current protected area network, such that sound adjustments and management decisions can be made to safeguard freshwater systems now and under climate change. Additionally, it cannot be assumed that the inclusion of vulnerable catchments within current protected areas implies protection against climate change (Pittock et al., 2008). To address these issues, an integrated, systematic conservation and land use planning approach is required that explicitly considers freshwater biodiversity and ecosystems in the context of climate change and other stressors (Nel et al., 2009). This should inform novel protected area management practices that account for the multi-dimensional connectivity within freshwater systems, balance the contrasting social, economic and biological demands and constraints placed on ecosystems and facilitate dispersal of species to more suitable habitats (Linke et al., 2011, Nel et al., 2011, Bagchi et al., 2013). The catchments identified in the gap analysis (Fig. 4) could provide a practical starting point for future planning and mitigation strategies.

Climate change is expected to amplify existing threats within catchments in addition to causing novel shifts in the hydrological, thermal and biotic components of freshwater ecosystems (Woodward et al., 2010). The ability of species and communities to adapt to this change, alongside the availability of refugia options will become increasingly important as time progresses. Additionally, an important and typically overlooked factor is the human response to climate change though management actions and mitigation strategies (Stein et al., 2013). Therefore, to sustain freshwater biodiversity in the future, a strategic, proactive and holistic management approach is needed that addresses the contrasting needs of all ecosystem actors. This study redresses the current paucity of integrated climate change assessments for freshwater ecosystems by presenting an overview of climate change vulnerability at the European scale that offers a basis for informing these new management approaches.

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Table 1: Exposure indicator methodologies and thresholds

Indicator	Type	Methodology	Threshold
Discharge			
Average monthly flows	Magnitude	$\lvert Q_{50,future}-Q_{50,baseline}\rvert / Q_{50,baseline}$; *$Q_{50}$-average values*	>30%
High flows	Magnitude	$(Q_{90,future}-Q_{90,baseline}) / Q_{90,baseline}$; *$Q_{90}$ -90th percentile*	>30%
Low flows	Magnitude	$(Q_{10,future}-Q_{10,baseline}) / Q_{10,baseline}$; *$Q_{10}$ -10th percentile*	<-30%
Frequency of high flows	Frequency	$(NMQ_{90,future}-36) / 36$; *$NMQ_{90}$ - the number of months with values above Q_{90} for the baseline period*	>30%
Frequency of low flows	Frequency	$(NMQ_{10,future}-36) / 36$; *$NMQ_{10}$ - the number of months with values below Q_{10} for the baseline period*	>30%
Timing of maximum flow	Timing	$\lvert MMQ_{max,future}-MMQ_{max,baseline}\rvert$; *MM-modal month over 30 years*	≥1 month
Timing of minimum flow	Timing	$\lvert MMQ_{min,future}-MMQ_{min,baseline}\rvert$; *MM-modal month over 30 years*	≥1 month
Duration of high flows	Duration	$(NCMQ_{90,future}-NCM\ Q_{90,baseline}) / NCM\ Q_{90,baseline}$; *$NCMQ_{90}$- the annual mean number of consecutive months above baseline 90th percentile*	>30%
Duration of low flows	Duration	$(NCMQ_{25,future}-NCM\ Q_{25,baseline}) / NCMQ_{25,baseline}$; *$NCMQ_{25}$- the annual mean number of consecutive months below baseline 25th percentile*	>30%
Flow range	Variability	$\lvert QR_{future}-QR_{baseline}\rvert / QR_{,baseline}$; *QR- the flow range ($Q_{max}$-$Q_{min}$)*	>30%
Flow annual cycle	Variability	$\frac{1}{12}(\sum_{i=1}^{12}\lvert Q_{i,future}-Q_{i,baseline}\rvert / Q_{i,baseline})$; *i-month*	>30%
Flow seasonality	Variability	$\lvert std(Q_{future})- std(Q_{baseline})\rvert / std(Q_{50,baseline})$; *std-standard deviation*	>30%
Temperature			
Average monthly temperatures	Magnitude	$(T_{50,future} - T_{50,baseline})$; *T_{50}-average values*	>2 °C
Temperature extremes	Magnitude	$(T_{90,future} - T_{90,baseline})$; *$T_{90}$ -90% percentile*	>2 °C
Frequency of high temperatures	Frequency	$(NMT_{90,future}-36)/ 36$; *NMT_{90} - the number of months with values above T_{90} for the baseline period*	>30%
Duration of heat stress	Duration	$(NCMT_{90,future}-NCM\ T_{90,baseline}) / NCM\ T_{90,baseline}$; *$NCMT_{90}$- the annual mean number of consecutive months above baseline 90th percentile*	>30%
Timing of maximum temperature	Timing	$\lvert MMT_{max,future}-MMT_{max,baseline}\rvert$; *MM-modal month over 30 years*	≥1 month
Temperature range	Variability	$\lvert TR_{future}-TR_{baseline}\rvert$; *TR- the temperature range (T_{max}-T_{min})*	>2 °C
Temperature annual cycle	Variability	$\frac{1}{12}(\sum_{i=1}^{12}\lvert T_{i,future}-T_{i,baseline}\rvert$; *i-month*	>2 °C
Temperature seasonality	Variability	$\lvert std(T_{future})- std(T_{baseline})\rvert / std(T_{50,baseline})$; *std-standard deviation*	>30%

Table 2: Summary statistics for the VM_1 based climate vulnerability (CV) categories

	Scenario	2030s B1 dams	2030s A2 dams	2080s B1 dams	2080s A2 dams	2030s B1 no dams	2030s A2 no dams	2080s B1 no dams	2080s A2 no dams
No. catchments	*low*	13	13	13	13	1099	1092	21	24
	medium	13161	14243	6333	4166	14502	15099	11343	9531
	high	5607	4525	12435	14597	3180	2590	7417	9222
	very high	2	2	2	7	2	2	2	6
surface area [%]	*low*	0.00%	0.00%	0.00%	0.00%	6.01%	5.94%	0.00%	0.02%
	medium	71.90%	76.94%	38.89%	25.78%	77.22%	80.19%	63.63%	54.20%
	high	28.09%	23.05%	61.10%	74.14%	16.76%	13.87%	36.36%	45.70%
	very high	0.01%	0.01%	0.01%	0.08%	0.01%	0.01%	0.01%	0.08%
protected area [%]	*low*	1.37%	1.37%	1.37%	1.37%	7.77%	12.45%	0.25%	63.26%
	medium	10.07%	10.02%	9.37%	8.40%	10.95%	10.42%	10.33%	10.17%
	high	17.19%	18.92%	13.78%	13.33%	18.78%	21.44%	15.11%	14.26%
	very high	81.66%	81.66%	81.66%	36.43%	81.66%	81.66%	81.66%	36.11%

No. catchments is the number of HydroBasins level 8 catchments in each vulnerability category ('low', 'medium', 'high'* and *'very high'*). Surface area denotes the percentage of the total study area (10,115,519 km^2), and protected area denotes the percentage of the surface area found within the European protected area networks (Natura 2000 and WDPA for IUCN categories I-IV). The mapping of the sensitivity, 1-resilience and exposure scores to vulnerability categories is provided in Table S1.

Table 3: Summary statistics for the consensus climate vulnerability (CV) patterns

	Scenario	2030s B1 dams	2030s A2 dams	2080s B1 dams	2080s A2 dams	2030s B1 no dams	2030s A2 no dams	2080s B1 no dams	2080s A2 no dams
No. catchments	*low to medium*	12059	13315	3138	2949	14835	15490	9974	8777
	high to very high	576	547	2149	2976	456	378	1490	1736
	no consensus	6148	4921	13496	12858	3492	2915	7319	8270
surface area [%]	*low to medium*	65.71%	71.19%	18.43%	17.94%	79.12%	82.02%	55.80%	50.08%
	high to very high	5.15%	4.80%	12.90%	16.15%	3.91%	3.20%	8.67%	10.03%
	no consensus	29.14%	24.01%	68.68%	65.91%	16.97%	14.78%	35.54%	39.89%
protected area [%]	*low to medium*	9.71%	9.84%	11.23%	7.27%	10.48%	10.41%	10.08%	9.74%
	high to very high	23.57%	23.34%	20.99%	19.66%	24.09%	26.59%	20.96%	21.16%
	no consensus	15.37%	16.45%	10.62%	11.52%	16.74%	18.17%	13.03%	12.72%

No. catchments is the number of HydroBasins level 8 catchments according to all of the major vulnerability estimation methods (VM_1, VM_2 and VM_3) in the vulnerability categories ('low to medium'* and *'high to very high'*, with *'no consensus'* denoting catchments where the three vulnerability estimation methods did not agree on the vulnerability category (see Figure 3)). Surface area denotes the percentage of the total study area (10,115,519 km^2), and protected area denotes the percentage of the surface area that is within the European protected area networks (Natura 2000 and WDPA for IUCN categories I-IV). The mapping of the sensitivity, 1-resilience and the exposure scores to vulnerability categories is provided in Table S1.

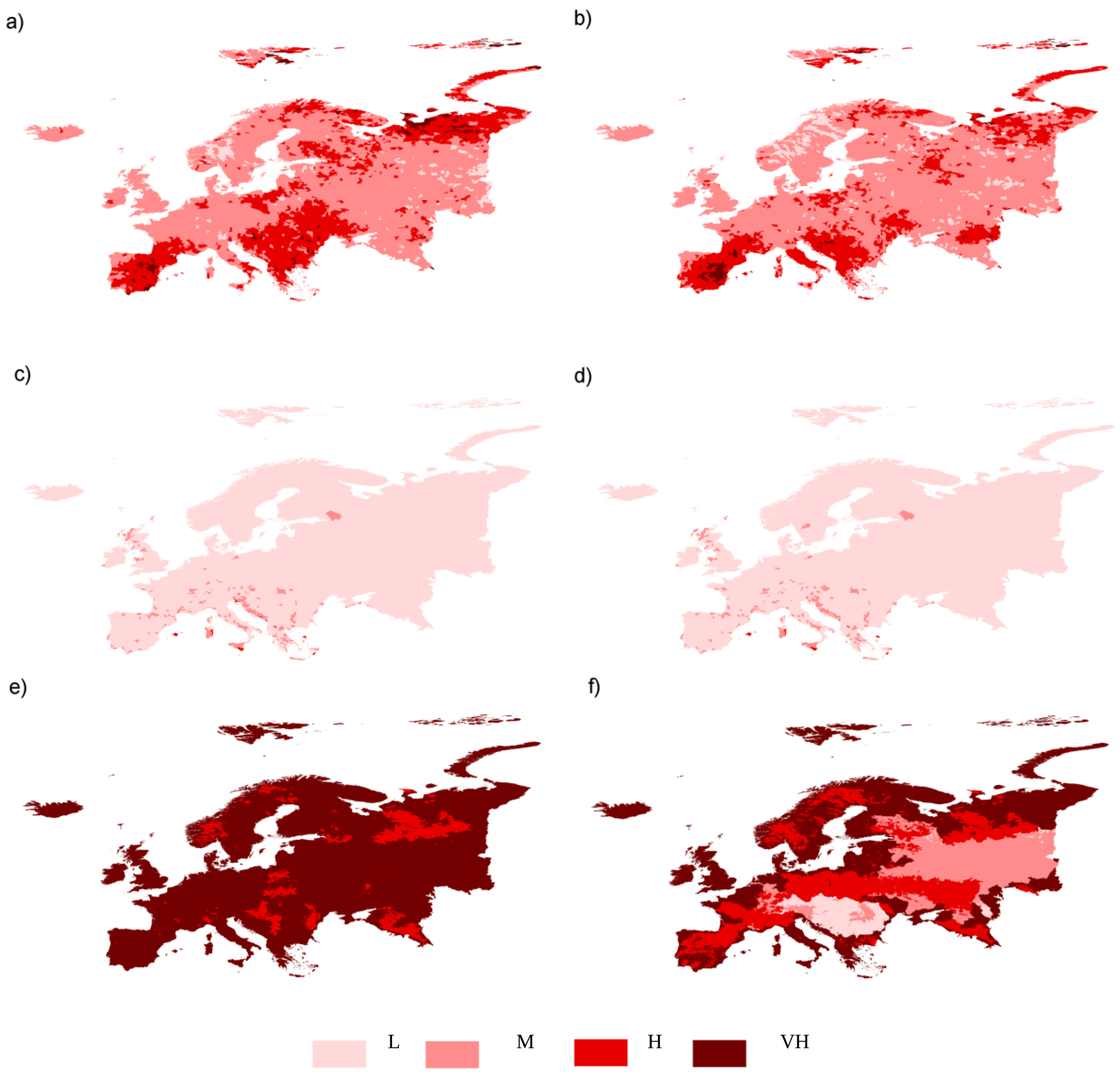

Figure 1: The final scores for the exposure (a, b), sensitivity (c, d), and 1- resilience (e, f) following different scenarios: a) the exposure score for 2030s following B1 scenario; (b) the exposure for 2030s following A2 scenario; c) the sensitivity score based on all five sensitivity dimensions with the 'presence of threatened species' using the European Red List and d) using species' global Red List status; (e, f) shows 1- resilience score with (e) and without (f) consideration of the influence of dispersal barriers.

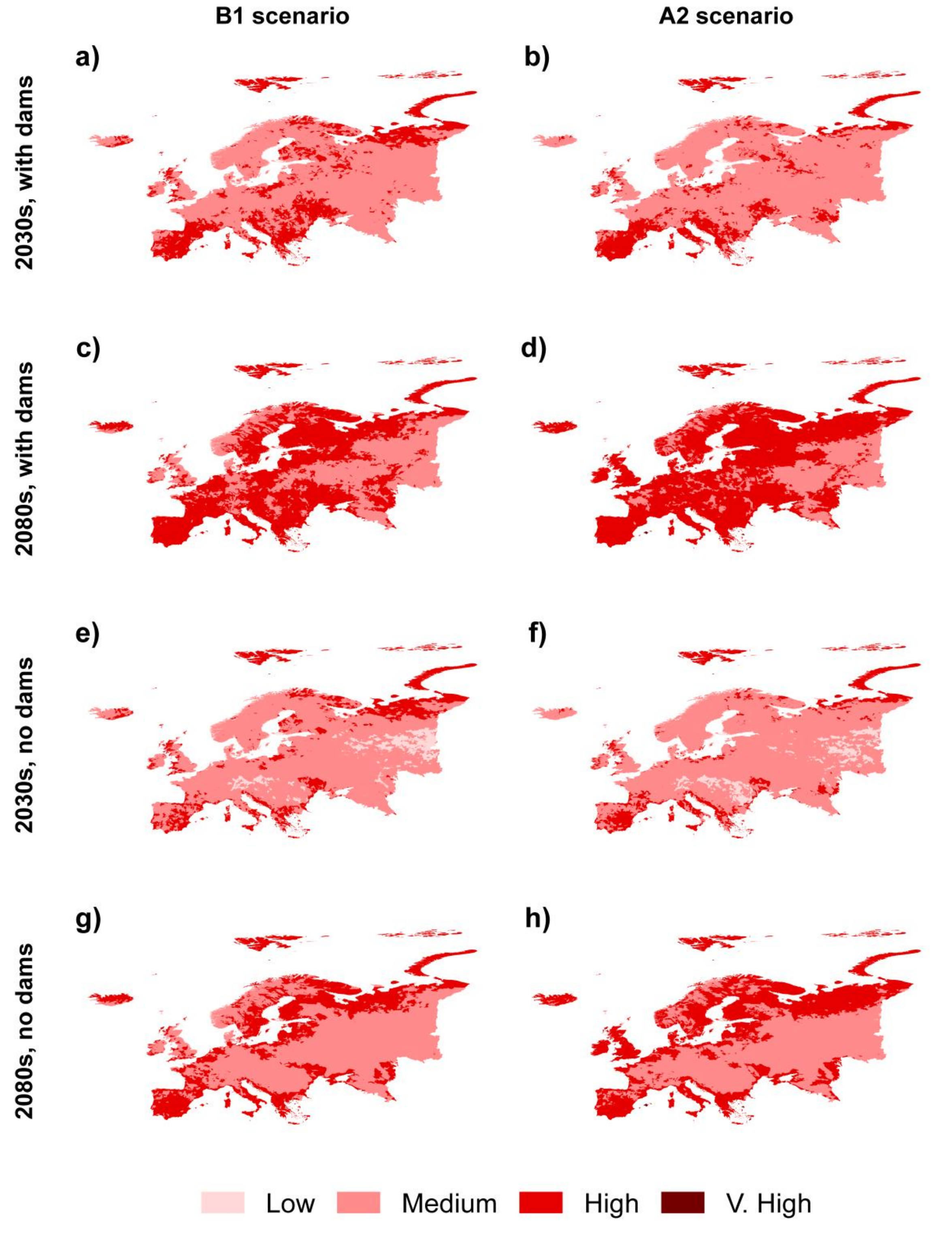

Figure 2: The climate change vulnerability (CV) of freshwater ecosystems for European catchments: a) 2030s exposure, B1 scenario, with barriers; b) 2030s exposure, A2 scenario, with barriers; c) 2080s exposure, B1 scenario, with barriers; d) 2080s exposure, A2 scenario, with barriers; e) 2030s exposure, B1 scenario, without barriers; f) 2030s exposure, A2 scenario, without barriers; g) 2080s exposure, B1 scenario, without barriers; h) 2080s exposure, A2 scenario, without barriers; The sensitivity dimension is based on the species Global Red List status and adopts the standard approach. The CV calculation is based on the methodology VM_1 (see Table S1). Summary statistics found in Table 2.

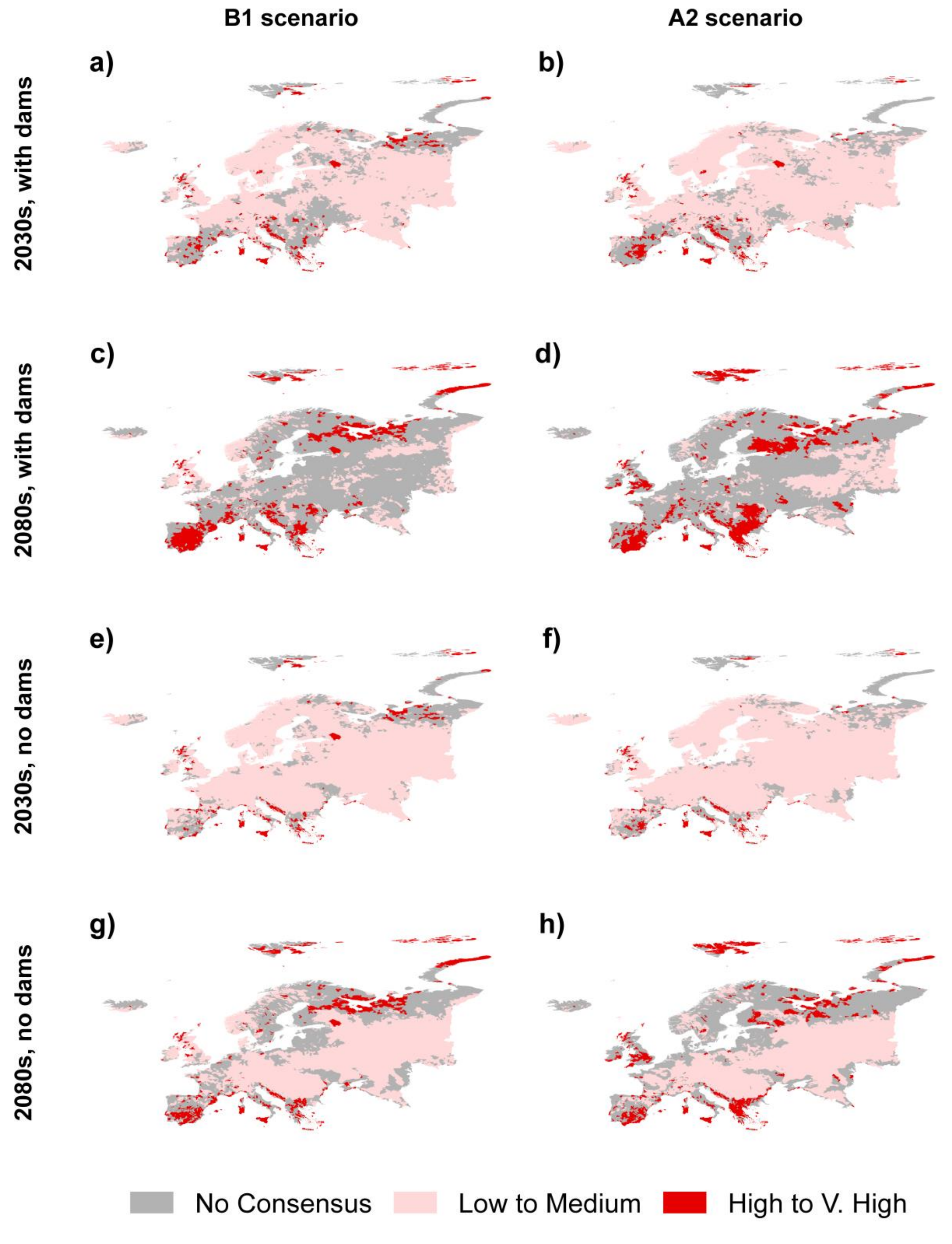

Figure 3: Consensus pattern of the climate change vulnerability (CV) for: a) 2030s exposure, B1 scenario, with barriers; b) 2030s exposure, A2 scenario, with barriers; c) 2080s exposure, B1 scenario, with barriers; d) 2080s exposure, A2 scenario, with barriers; e) 2030s exposure, B1 scenario, without barriers; f) 2030s exposure, A2 scenario, without barriers; g) 2080s exposure, B1 scenario, without barriers; h) 2080s exposure, A2 scenario, without barriers. Within the consensus approach, a catchment was assigned the category 'low to medium' or 'high to very high' only if the same category was assigned for VM_1, VM_2 and VM_3 methodologies (see Table S1); otherwise it was assigned 'no consensus'. Summary statistics found in Table 3.

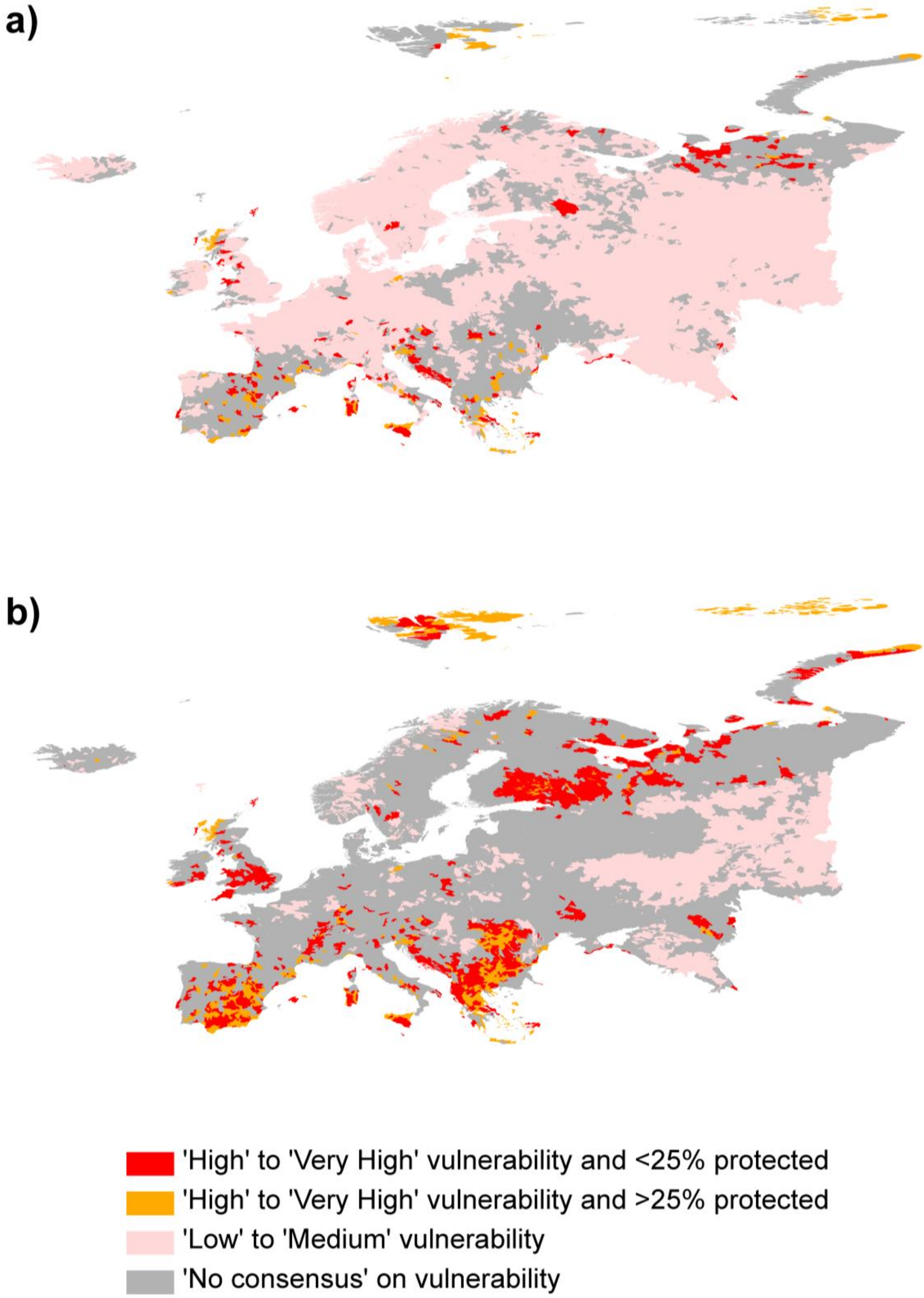

Figure 4: Gap analysis of Protected Areas and Climate Vulnerability. The most pessimistic scenarios were chosen for the 2030s and 2080s from the consensus of VM_1, VM_2 and VM_3 methodologies to highlight catchments most in need of management actions (< 25 % of their area protected by the current European protected area network and *'high'* to *'very high'* climate change vulnerability) a) 2030s exposure, B1 scenario, with barriers; b) 2080s exposure, A2 scenario, with barriers. Summary statistics found in Table 3.

Appendix S1

SUPPORTING INFORMATION

Vulnerability of European Freshwater Ecosystems to Climate Change

Danijela Markovic, Jonathan David, Savrina Carrizo, Paul Jepson

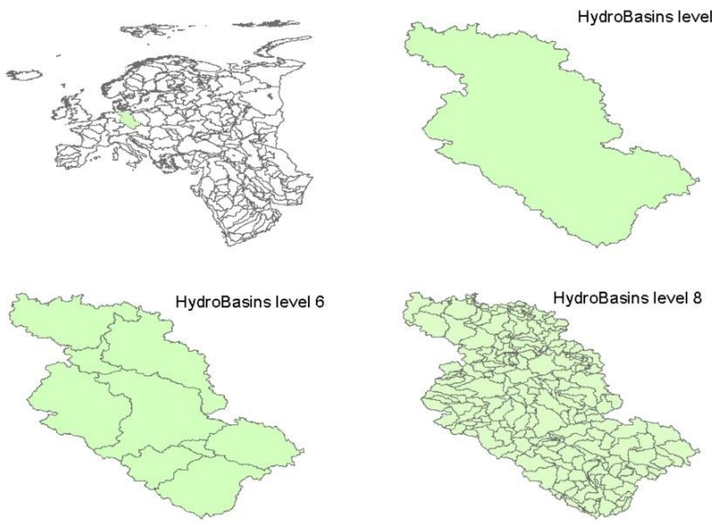

Figure S1: A comparison of different HydroBasins dataset resolutions for the Elbe River Basin (green). The average catchment area at the HydroBasins level 8 resolution is 536.3 km^2.

Figure S2: European protected area network (Natura 2000 and WDPA data with IUCN categories I-IV). Total area of protected areas is 1,221,230km^2.

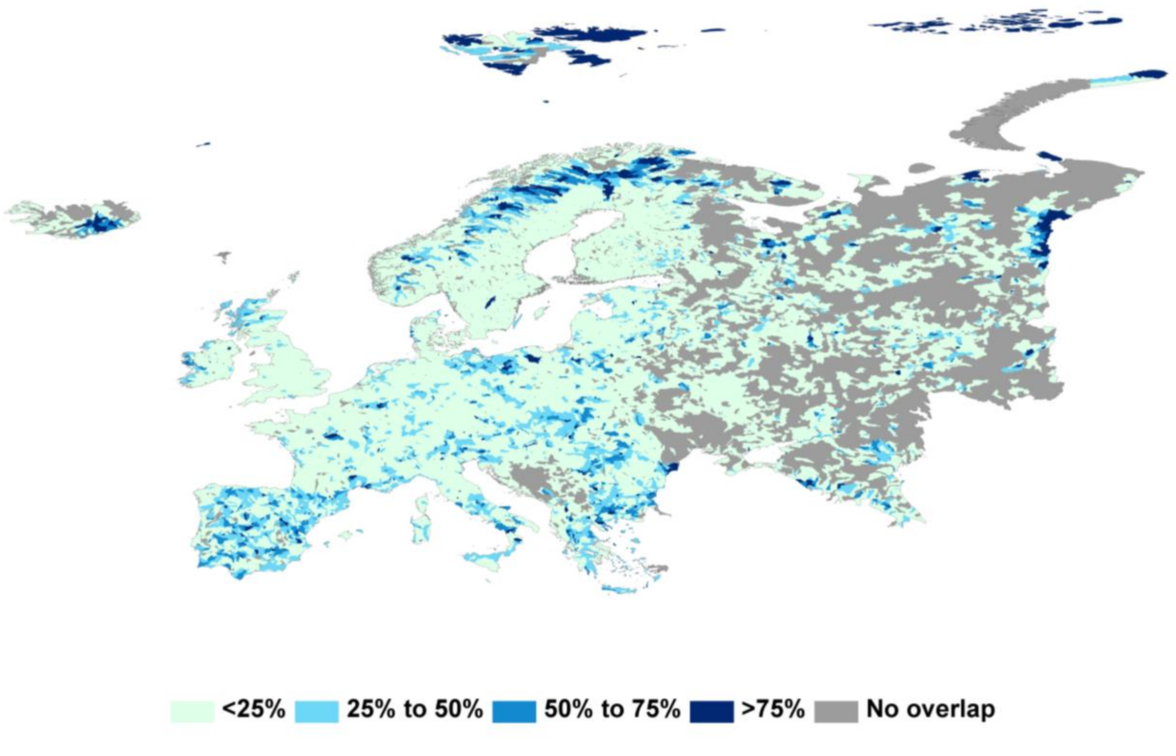

Figure S3: Percentage area per catchment overlapped by the European protected area network in Figure S2.

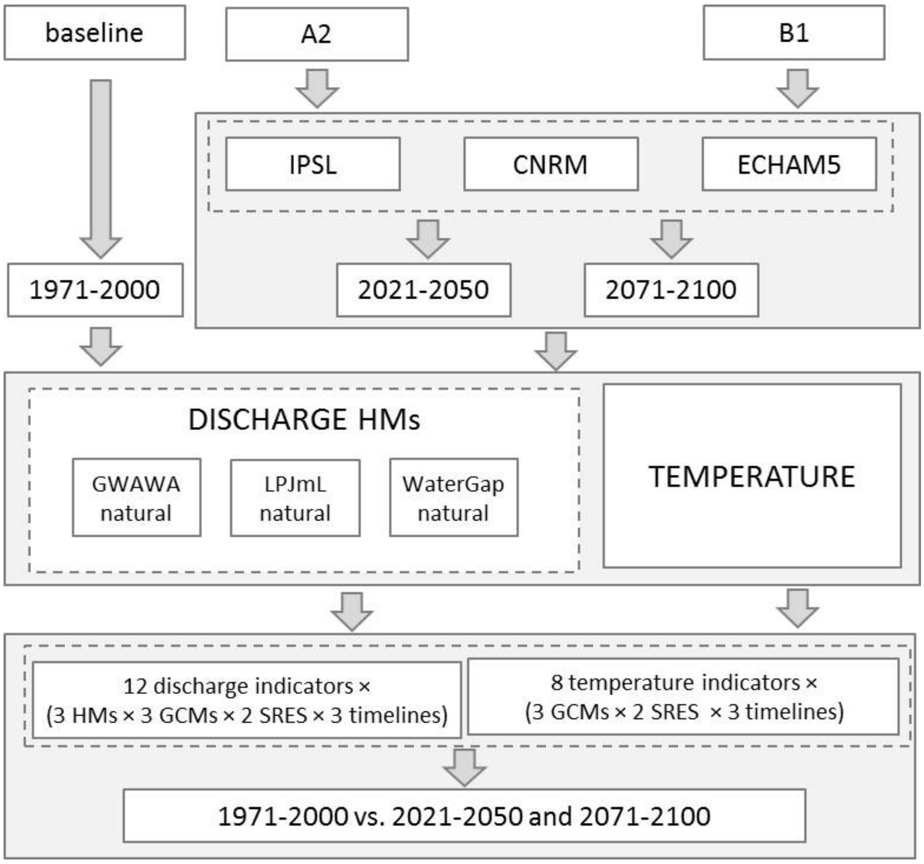

Figure S4: Flow chart for the derivation of climatic and hydrological change indicators.

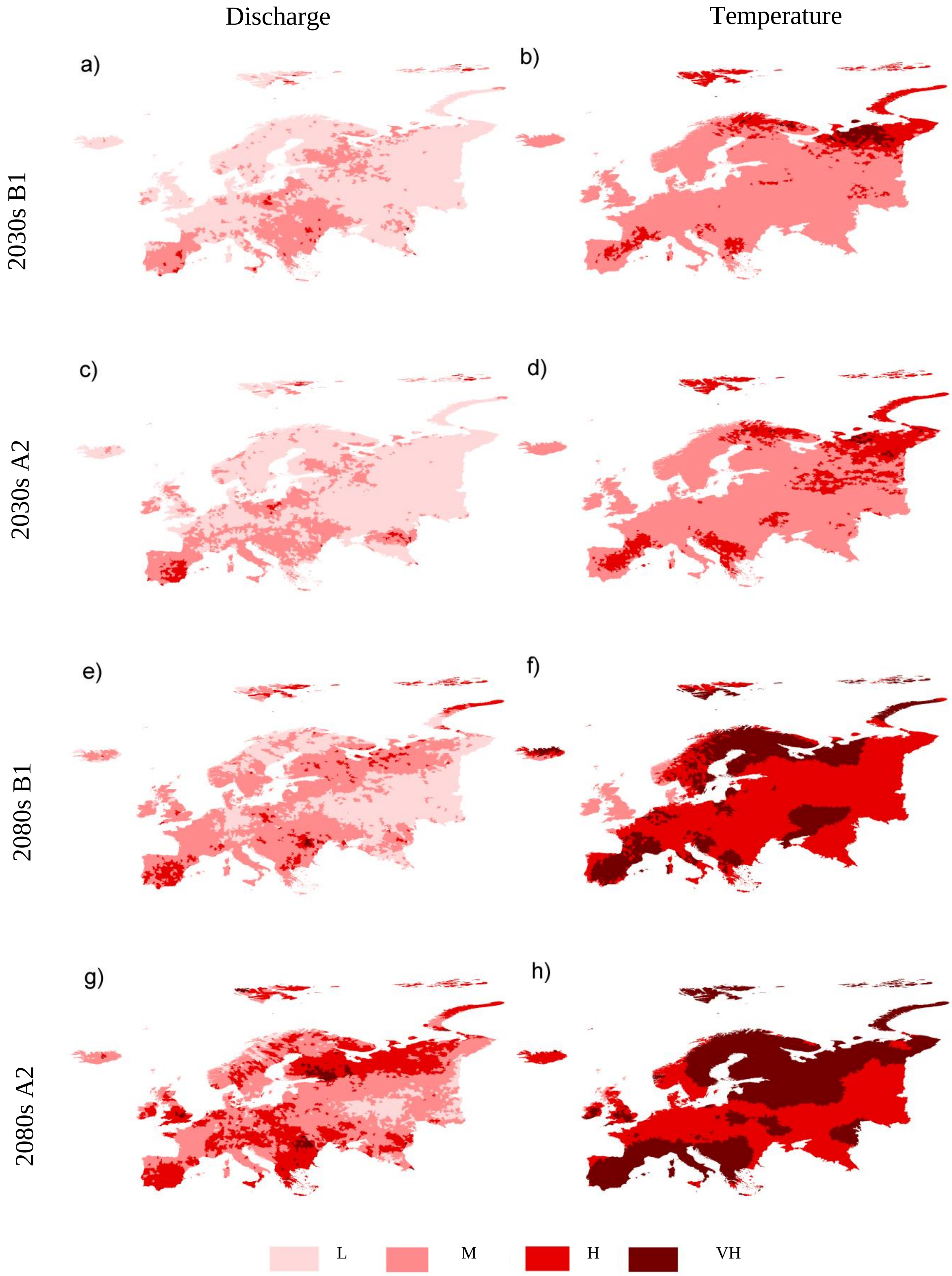

Figure S5: Individual components of the climate change exposure at the European catchment scale for the 2030s (a-d) and 2080s (e-h): a) 2030s, discharge indicators, B1 scenario; b) 2030s, temperature indicators, B1 scenario; c) 2030s, discharge indicators, A2 scenario; d) 2030s, temperature indicators, A2 scenario; e) 2080s, discharge indicators, B1 scenario; f) 2080s, temperature indicators, B1 scenario; g) 2080s, discharge indicators, A2 scenario; h) 2080s, temperature indicators, A2 scenario.

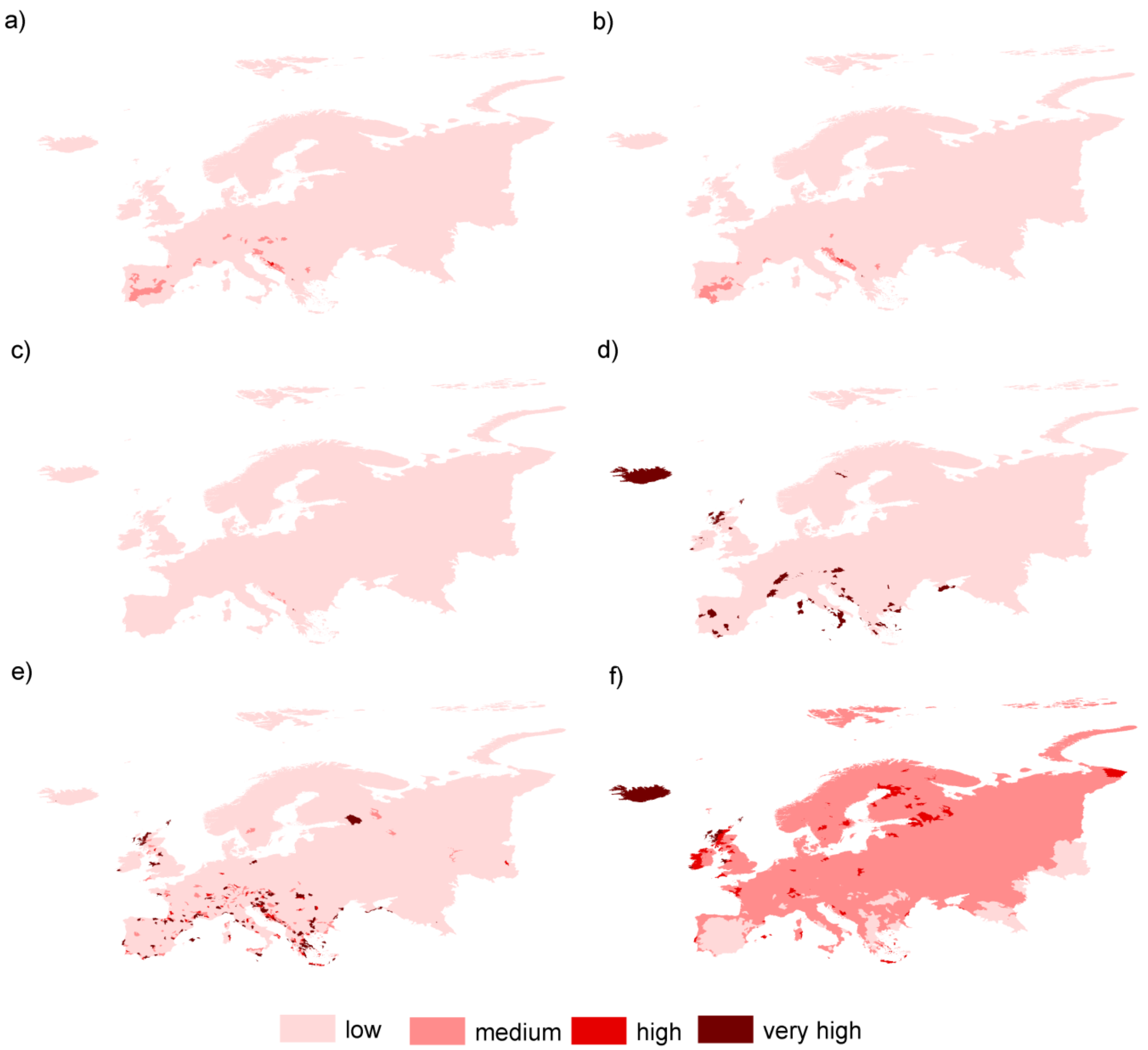

Figure S6: Individual attributes of climate change sensitivity for freshwater ecosystems at the European catchment scale: a) presence of threatened species (Global Red List); b) presence of threatened species (European Red List); c) presence of species of restricted range; d) presence of species that are confined to a single freshwater ecoregion; e) irreplaceability of catchments and f) species' environmental tolerance breadths.

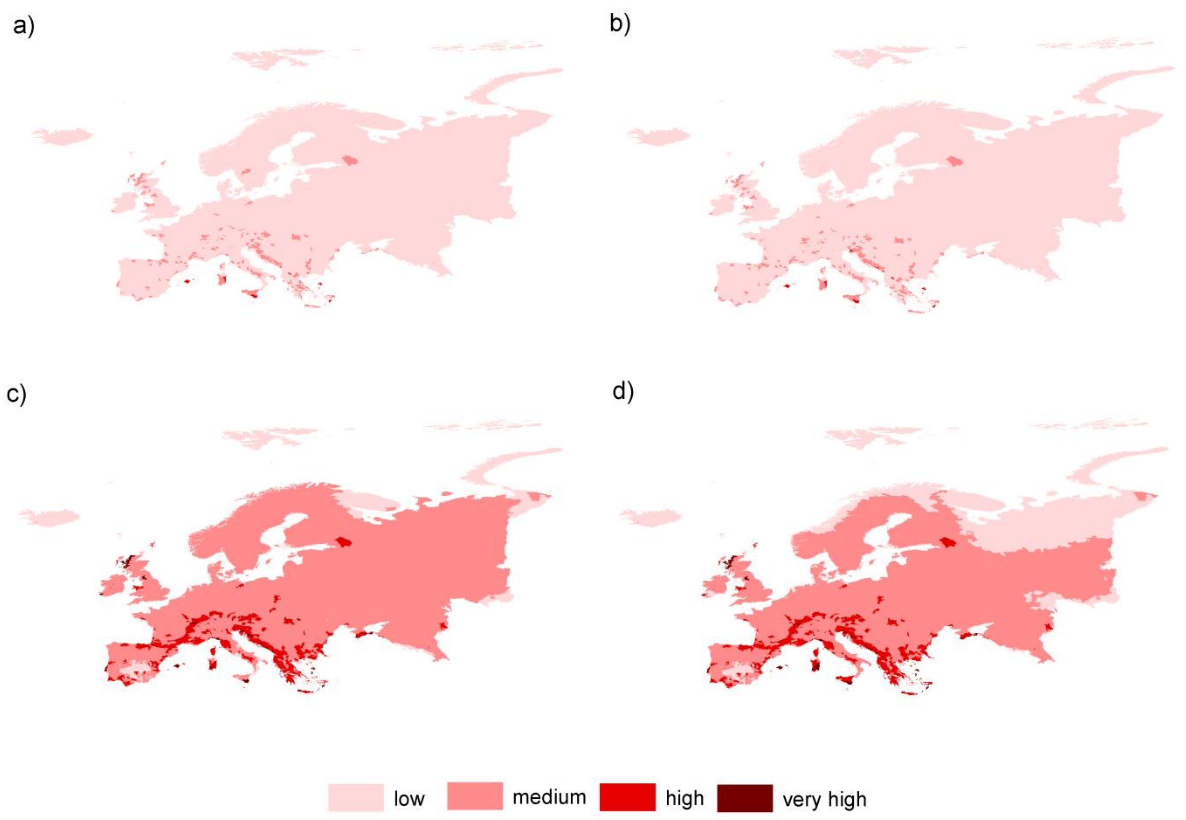

Figure S7: Climate change sensitivity of freshwater ecosystems at the European catchment scale. For a) and c) the sensitivity is based on the Global Red List of threatened species, whilst b) and d) show sensitivity estimates based on the European Red List. Within a) and b) the relative numbers of species that are either threatened or of restricted range were used, whilst for c) and d) the presence of a single species in either category was sufficient to trigger classification as 'sensitive to climate change' (i.e. the 'conservative approach').

L M H VH

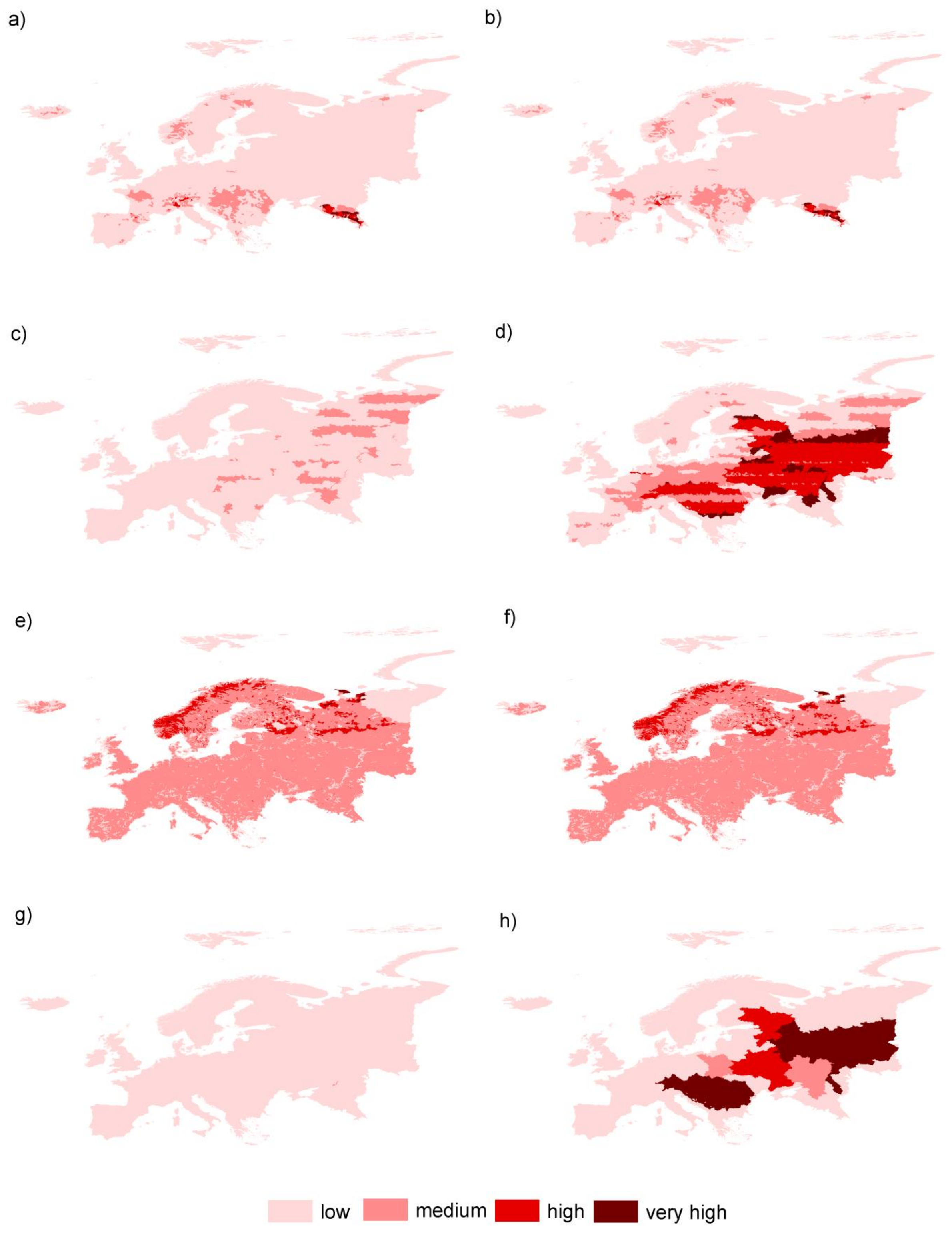

Figure S8: Individual attributes of the climate change resilience for freshwater ecosystems at the European catchment scale, considering dams and obstacles (left panel) and assuming no dams and obstacles (right panel): (a –b) altitudinal range; (c-d) latitudinal gradient; (e-f) network density; (g-h) network complexity.

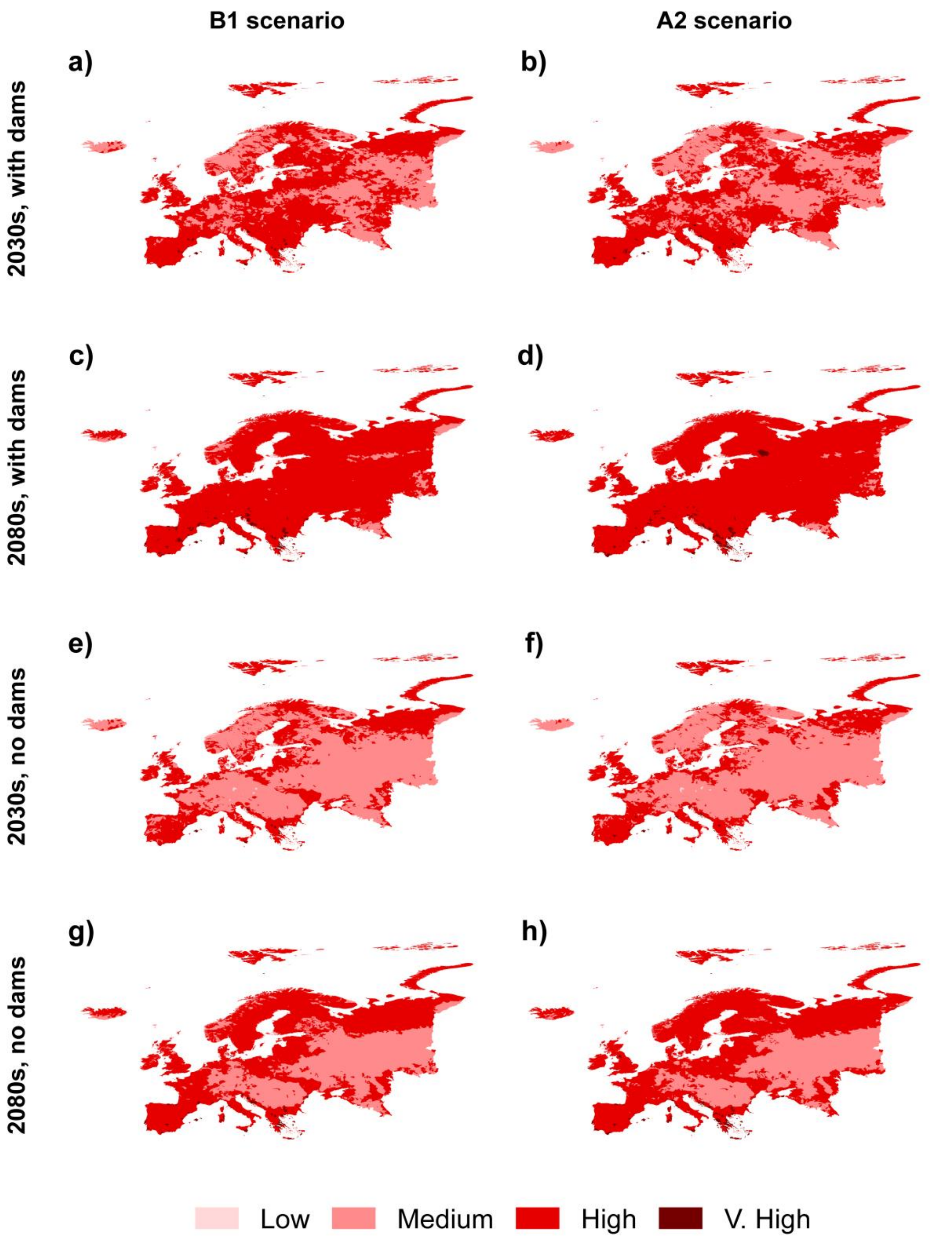

Figure S9: Vulnerability index (CV) based on the methodology VM_1 (see Table S1) for 2030s and 2080s exposure, conservative sensitivity estimates and resilience calculation with dispersal barriers (a-d) and without dispersal barriers (e-h): a) 2030s exposure, B1 scenario, with barriers; b) 2030s exposure, A2 scenario, with barriers; c) 2080s exposure, B1 scenario, with barriers; d) 2080s exposure, A2 scenario, with barriers; e) 2030s exposure, B1 scenario, without barriers; f) 2030s exposure, A2 scenario, without barriers; g) 2080s exposure, B1 scenario, without barriers; h) 2080s exposure, A2 scenario, without

barriers; The sensitivity dimension is based on the species Global Red List status. Summary statistics found in Table S2.

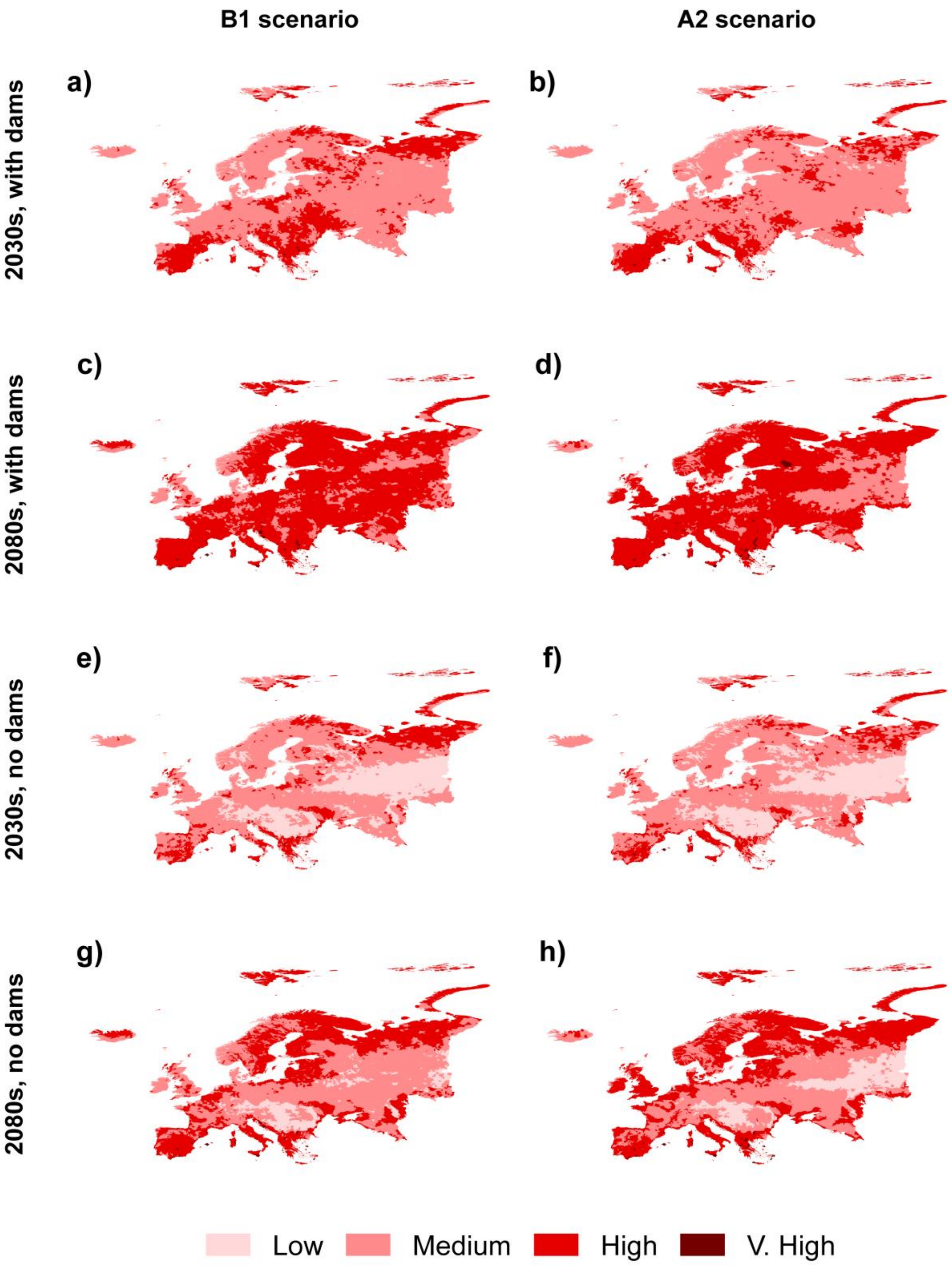

Figure S10: Vulnerability index (CV) based on the methodology VM_2 (see Table S1) for 2030s and 2080s exposure and resilience calculation with dispersal barriers (a-d) and without dispersal barriers (e-h): a) 2030s exposure, B1 scenario, with barriers; b) 2030s exposure, A2 scenario, with barriers; c) 2080s exposure, B1 scenario, with barriers; d) 2080s exposure, A2 scenario, with barriers; e) 2030s exposure, B1 scenario, without barriers; f) 2030s exposure, A2 scenario, without barriers; g) 2080s exposure, B1 scenario, without barriers; h) 2080s exposure, A2 scenario, without barriers; The sensitivity dimension is based on the species Global Red List status. Summary statistics found in Table S3.

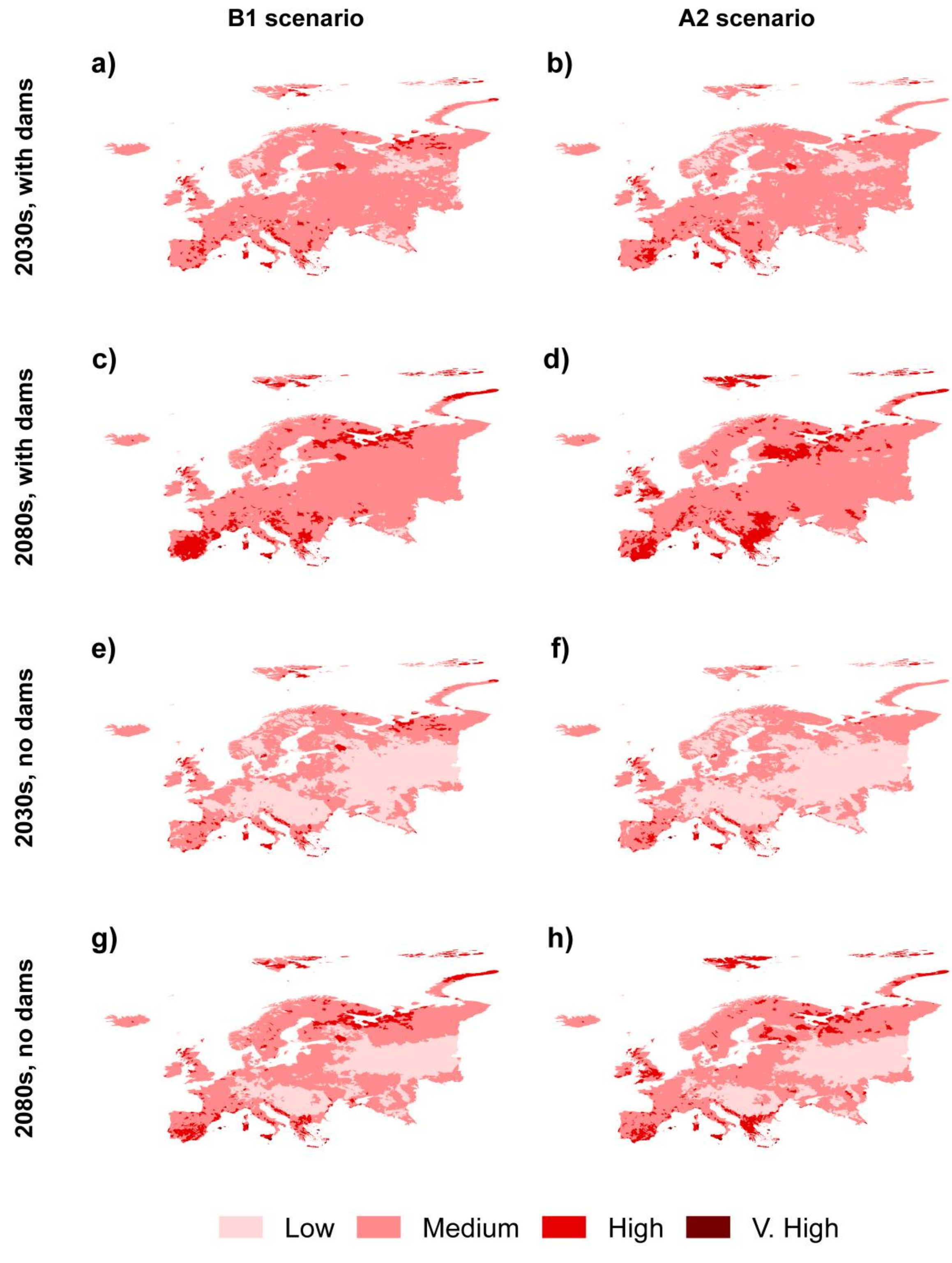

Figure S11: Vulnerability index (CV) based on the methodology VM_3 (see Table S1) for 2030s and 2080s exposure and resilience calculation with dispersal barriers (a-d) and without dispersal barriers (e-h): a) 2030s exposure, B1 scenario, with barriers; b) 2030s exposure, A2 scenario, with barriers; c) 2080s exposure, B1 scenario, with barriers; d) 2080s exposure, A2 scenario, with barriers; e) 2030s exposure, B1 scenario, without barriers; f) 2030s exposure, A2 scenario, without barriers; g) 2080s exposure, B1 scenario, without barriers; h) 2080s exposure, A2 scenario, without barriers; The sensitivity dimension is based on the species Global Red List status. Summary statistics found in Table S4.

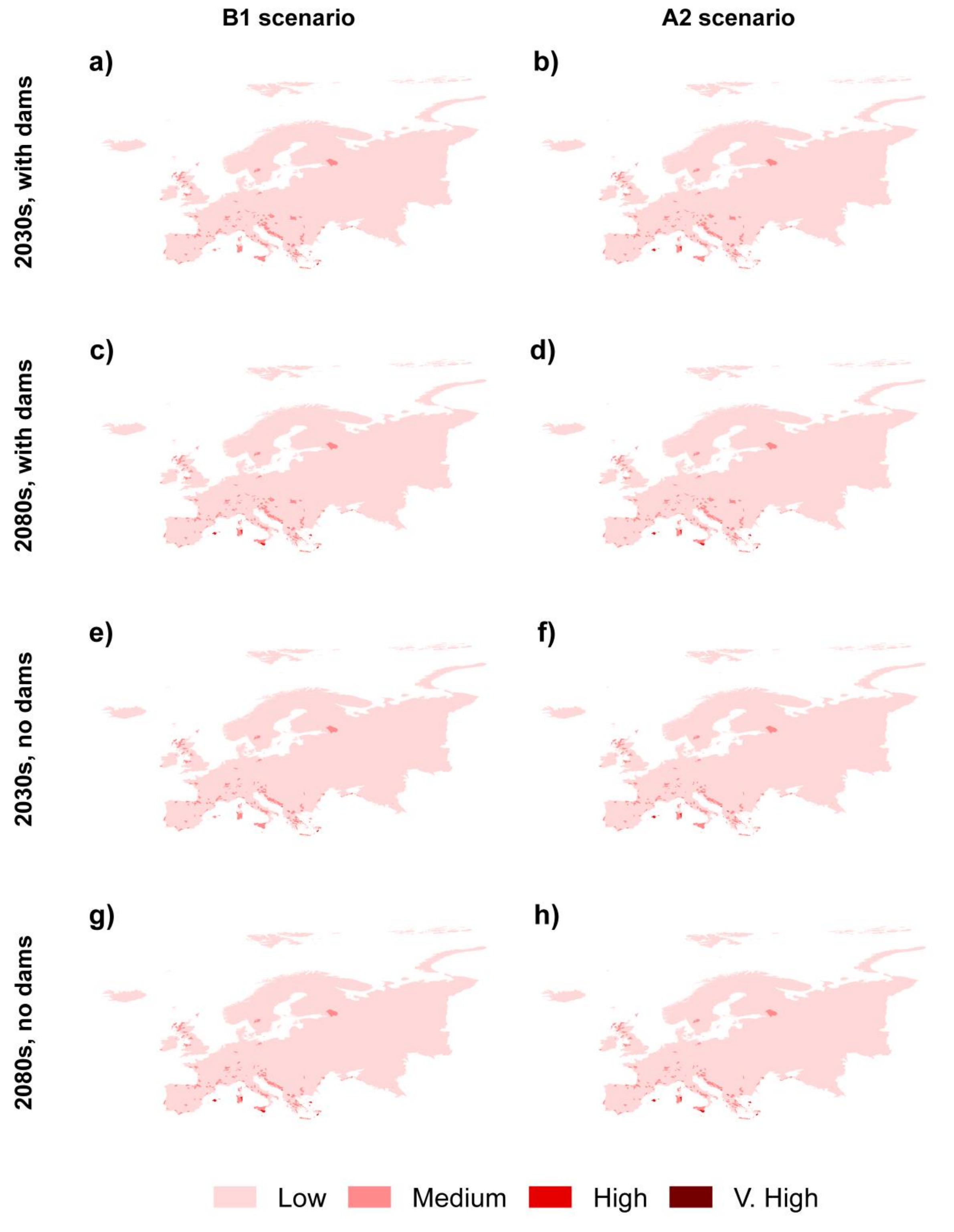

Figure S12: Vulnerability index (CV) based on the methodology VM_4 (see Table S1) for 2030s and 2080s exposure and resilience calculation with dispersal barriers (a-d) and without dispersal barriers (e-h): a) 2030s exposure, B1 scenario, with barriers; b) 2030s exposure, A2 scenario, with barriers; c) 2080s exposure, B1 scenario, with barriers; d) 2080s exposure, A2 scenario, with barriers; e) 2030s exposure, B1 scenario, without barriers; f) 2030s exposure, A2 scenario, without barriers; g) 2080s exposure, B1 scenario, without barriers; h) 2080s exposure, A2 scenario, without barriers; The sensitivity dimension is based on the species Global Red List status. Summary statistics found in Table S5.

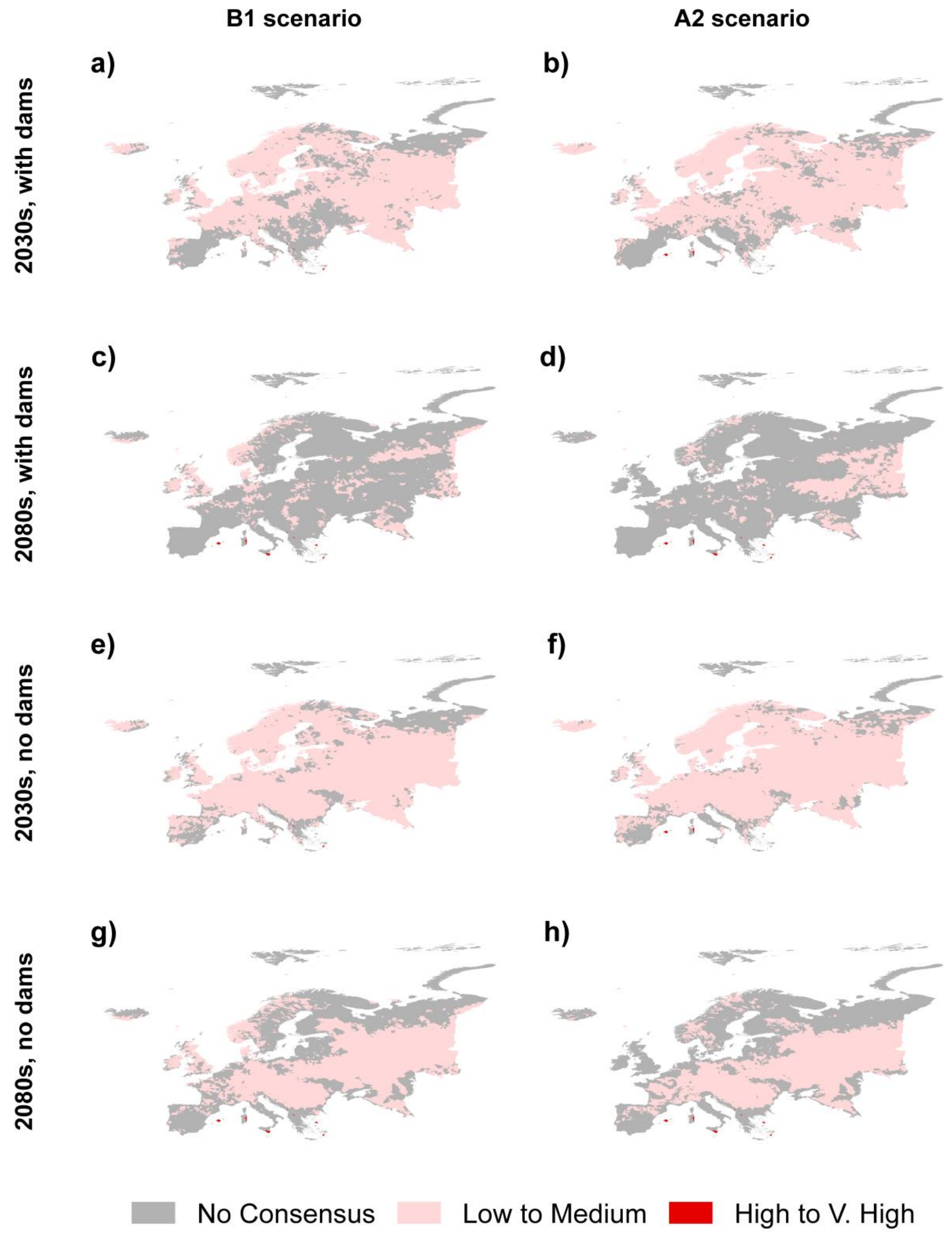

Figure S13: Consensus patterns for climate change vulnerability (CV) based on VM_1, VM_2 , VM_3 and VM_4 methodologies for: a) 2030s exposure, B1 scenario, with barriers; b) 2030s exposure, A2 scenario, with barriers; c) 2080s exposure, B1 scenario, with barriers; d) 2080s exposure, A2 scenario, with barriers; e) 2030s exposure, B1 scenario, without barriers; f) 2030s exposure, A2 scenario, without barriers; g) 2080s exposure, B1 scenario, without barriers; h) 2080s exposure, A2 scenario, without barriers. Within the consensus approach, a catchment was assigned the category 'low to medium' or 'high to very high' only if the same category was assigned for all four vulnerability estimations; otherwise it was assigned 'no consensus' (see Table S1 for VM_1, VM_2, VM_3 and VM_4 for methodologies). Summary statistics found in Table S6.

Table S1: Different methodologies for climatic vulnerability (CV) estimation

Score combinations for vulnerability components			No. pm.	VM_1	VM_2	VM_3	VM_4
VH	VH	VH	1	*very high*	*very high*	*very high*	*very high*
H	VH	VH	3	*very high*	*very high*	*very high*	*high*
H	H	VH	3	*very high*	*very high*	*very high*	*high*
VH	VH	M	3	*very high*	*very high*	*high*	*medium*
H	H	H	1	*high*	*high*	*high*	*high*
VH	H	M	6	*high*	*high*	*high*	*medium*
H	H	M	3	*high*	*high*	*high*	*medium*
VH	M	M	3	*high*	*high*	*high*	*medium*
VH	VH	L	3	*high*	*high*	*high*	*low*
L	H	VH	6	*high*	*high*	*medium*	*low*
H	M	M	3	*high*	*medium*	*medium*	*medium*
M	M	M	1	*medium*	*medium*	*medium*	*medium*
H	H	L	3	*medium*	*medium*	*medium*	*low*
L	M	VH	6	*medium*	*medium*	*medium*	*low*
H	M	L	6	*medium*	*medium*	*low*	*low*
VH	L	L	3	*medium*	*medium*	*low*	*low*
M	M	L	3	*medium*	*low*	*low*	*low*
L	L	H	3	*low*	*low*	*low*	*low*
M	L	L	3	*low*	*low*	*low*	*low*
L	L	L	1	*low*	*low*	*low*	*low*

The score combinations are the unique sets of 3 scores, irrespective of the order of the individual scores. No. pm. is the number of possible permutations per each score set. Within the methodology VM_1 the vulnerability classes are calculated as the mean value of the individual scores for the three vulnerability components (i.e. depending on the mean value of the sensitivity, 1-resilience and exposure score the vulnerability was classified as: 0-0.24 *'low'*, 0.25-0.49 *'medium'*, 0.5-0.74 *'high'*, ≥0.75 *'very high'*). The methodologies VM_2 and VM_3 are based on the cumulative distribution function of the possible score combinations including all permutations (i.e. 64 score sets) such that VM_2 is symmetric (10 in the category *'low'*, 22 *'medium'*, 22 *'high'* and 10 *'very high'*) and the VM_3 is positively skewed (19 in the category *'low'*, 19 *'medium'*, 19 *'high'* and 7 *'very high'*). For comparison, the methodology VM_1 is negatively skewed and thus most pessimistic, with 7 score sets in the category *'low'*, 22 *'medium'*, 25 *'high'* and 10 *'very high'*. The VM_4 follows the approach that a *'low'* score in any vulnerability dimension must lead to a *'low'* vulnerability and so forth, with the *'very high'* score only assigned if all three vulnerability dimensions scored *'very high'* (i.e. it is the most optimistic approach with 37 score sets in the category *'low'*, 7 *'medium'*, 19 *'high'* and 1 *'very high'*).

Table S2: Summary statistics for the VM_1 based vulnerability (CV) categories and the conservative sensitivity assessment.

	Scenario	2030s B1 dams	2030s A2 dams	2080s B1 dams	2080s A2 dams	2030s B1 no dams	2030s A2 no dams	2080s B1 no dams	2080s A2 no dams
No. catchments	*low*	13	13	13	13	32	29	12	12
	medium	5560	6739	719	366	10929	11596	6882	6026
	high	13166	11981	17884	18170	7789	7125	11795	12605
	very high	44	50	167	234	33	33	94	140
surface area [%]	*low*	0.00%	0.00%	0.00%	0.00%	0.08%	0.09%	0.00%	0.00%
	medium	33.12%	38.51%	4.32%	2.09%	60.31%	62.69%	39.52%	34.91%
	high	66.46%	61.06%	94.18%	95.76%	39.29%	36.91%	59.45%	63.69%
	very high	0.42%	0.43%	1.49%	2.15%	0.32%	0.31%	1.03%	1.39%
protected area [%]	*low*	1.37%	1.37%	1.37%	1.37%	17.90%	16.08%	4.76%	4.76%
	medium	9.10%	9.27%	11.53%	14.53%	9.71%	9.64%	8.50%	8.08%
	high	13.39%	13.72%	11.84%	11.74%	15.51%	16.09%	14.14%	13.93%
	very high	37.72%	28.32%	28.35%	24.40%	34.56%	24.64%	29.46%	27.33%

No. catchments is the number of HydroBasins level 8 catchments in each vulnerability category ('low'*, *'medium'*, *'high'* and *'very high'*). Surface area denotes the percentage of the total study area (10,115,519 km^2), and protected area denotes the percentage of the surface area found within the European protected area networks (Natura 2000 and WDPA for IUCN categories I-IV). The mapping of the sensitivity, 1-resilience and exposure scores to vulnerability categories is provided in Table S1.

Table S3: Summary statistics for the VM_2 based vulnerability (CV) categories.

	Scenario	2030s B1 dams	2030s A2 dams	2080s B1 dams	2080s A2 dams	2030s B1 no dams	2030s A2 no dams	2080s B1 no dams	2080s A2 no dams
No. catchments	*low*	96	126	2	0	4374	4606	1563	2225
	medium	13146	14329	3891	3988	11293	11650	9238	7587
	high	5532	4316	14842	14726	3108	2516	7943	8919
	very high	9	12	48	69	8	11	39	52
surface area [%]	*low*	0.53%	0.70%	0.01%	-	24.68%	26.02%	8.48%	12.95%
	medium	69.10%	74.07%	21.58%	23.05%	58.03%	59.03%	51.57%	42.56%
	high	30.29%	25.09%	77.86%	76.02%	17.23%	14.82%	39.52%	43.94%
	very high	0.08%	0.14%	0.54%	0.93%	0.06%	0.13%	0.44%	0.55%
protected area [%]	*low*	14.92%	13.86%	62.81%	-	8.22%	8.90%	11.90%	8.02%
	medium	10.26%	10.29%	11.26%	8.09%	12.12%	11.69%	9.98%	10.74%
	high	16.04%	17.17%	12.18%	13.11%	17.30%	18.97%	14.65%	14.30%
	very high	58.13%	32.73%	28.11%	25.82%	53.62%	34.94%	28.74%	32.11%

No. catchments is the number of HydroBasins level 8 catchments in each vulnerability category ('low'*, *'medium'*, *'high'* and *'very high'*). Surface area denotes the percentage of the total study area (10,115,519 km^2), and protected area denotes the percentage of the surface area found within the European protected area networks (Natura 2000 and WDPA for IUCN categories I-IV). The mapping of the sensitivity, 1-resilience and exposure scores to vulnerability categories is provided in Table S1.

Table S4: Summary statistics for the VM_3 based vulnerability (CV) categories.

	Scenario	2030s B1 dams	2030s A2 dams	2080s B1 dams	2080s A2 dams	2030s B1 no dams	2030s A2 no dams	2080s B1 no dams	2080s A2 no dams
No. catchments	*low*	1680	2053	217	182	8421	8974	5210	4993
	medium	16516	16170	16413	15623	9892	9419	12073	12042
	high	582	553	2142	2967	465	383	1490	1738
	very high	5	7	11	11	5	7	10	10
surface area [%]	*low*	8.91%	10.23%	1.14%	0.99%	47.09%	49.14%	29.30%	28.82%
	medium	85.80%	84.79%	85.94%	82.87%	48.81%	47.49%	61.94%	61.04%
	high	5.27%	4.90%	12.77%	16.00%	4.08%	3.30%	8.61%	9.99%
	very high	0.03%	0.07%	0.15%	0.15%	0.03%	0.07%	0.15%	0.15%
protected area [%]	*low*	9.50%	11.46%	18.87%	17.73%	9.48%	9.53%	8.97%	8.09%
	medium	11.65%	11.51%	10.65%	10.53%	13.60%	13.72%	12.30%	12.46%
	high	23.10%	22.91%	20.87%	19.58%	23.51%	25.83%	20.74%	20.96%
	very high	51.46%	29.90%	28.63%	28.63%	51.46%	29.90%	28.44%	28.44%

No. catchments is the number of HydroBasins level 8 catchments in each vulnerability category ('low'*, *'medium'*, *'high'* and *'very high'*). Surface area denotes the percentage of the total study area (10,115,519 km^2), and protected area denotes the percentage of the surface area found within the European protected area networks (Natura 2000 and WDPA for IUCN categories I-IV). The mapping of the sensitivity, 1-resilience and exposure scores to vulnerability categories is provided in Table S1.

Table S5: Summary statistics for the VM_4 based vulnerability (CV) categories.

	Scenario	2030s B1 dams	2030s A2 dams	2080s B1 dams	2080s A2 dams	2030s B1 no dams	2030s A2 no dams	2080s B1 no dams	2080s A2 no dams
No. catchments	*low*	18480	18479	18479	18479	18499	18498	18498	18498
	medium	298	297	293	293	279	278	275	275
	high	5	7	10	10	5	7	9	9
	very high	0	0	1	1	0	0	1	1
surface area [%]	*low*	96.36%	96.36%	96.36%	96.36%	96.73%	96.73%	96.73%	96.73%
	medium	3.61%	3.57%	3.49%	3.49%	3.24%	3.20%	3.12%	3.12%
	high	0.03%	0.07%	0.15%	0.15%	0.03%	0.07%	0.15%	0.15%
	very high	-	-	0.00%	0.00%	-	-	0.00%	0.00%
protected area [%]	*low*	11.71%	11.71%	11.71%	11.71%	11.74%	11.74%	11.74%	11.74%
	medium	21.38%	21.43%	21.30%	21.30%	21.62%	21.68%	21.55%	21.55%
	high	51.46%	29.90%	27.58%	27.58%	51.46%	29.90%	27.39%	27.39%
	very high	-	-	73.09%	73.09%	-	-	73.09%	73.09%

No. catchments is the number of HydroBasins level 8 catchments in each vulnerability category ('low'*, *'medium'*, *'high'* and *'very high'*). Surface area denotes the percentage of the total study area (10,115,519 km^2), and protected area denotes the percentage of the surface area found within the European protected area networks (Natura 2000 and WDPA for IUCN categories I-IV). The mapping of the sensitivity, 1-resilience and exposure scores to vulnerability categories is provided in Table S1.

Table S6: Summary statistics for the VM_1, VM_2, VM_3 and VM_4 consensus vulnerability (CV) patterns

	Scenario	2030s B1 dams	2030s A2 dams	2080s B1 dams	2080s A2 dams	2030s B1 no dams	2030s A2 no dams	2080s B1 no dams	2080s A2 no dams
No. catchments	*low to medium*	12059	13315	3138	2949	14835	15490	9974	8777
	high to very high	5	7	11	11	5	7	10	10
	no consensus	6719	5461	15634	15823	3943	3286	8799	9996
surface area [%]	*low to medium*	65.71%	71.19%	18.43%	17.94%	79.12%	82.02%	55.80%	50.08%
	high to very high	0.03%	0.07%	0.15%	0.15%	0.03%	0.07%	0.15%	0.15%
	no consensus	34.27%	28.74%	81.42%	81.91%	20.86%	17.91%	44.05%	49.77%
protected area [%]	*low to medium*	9.71%	9.84%	11.23%	7.27%	10.48%	10.41%	10.08%	9.74%
	high to very high	51.46%	29.90%	28.63%	28.63%	51.46%	29.90%	28.44%	28.44%
	no consensus	16.57%	17.57%	12.23%	13.09%	18.08%	19.63%	14.54%	14.38%

No. catchments is the number of HydroBasins level 8 catchments according to all vulnerability estimation methods (VM_1, VM_2, VM_3 and VM_4) in the vulnerability categories ('low to medium'* and *'high to very high'*, with *'no consensus'* denoting catchments where vulnerability estimation methods did not agree on the vulnerability category; see Figure S10). Surface area denotes the percentage of the total study area (10,115,519 km^2) , and protected area denotes the percentage of the surface area found within the European protected area networks (Natura 2000 and WDPA for IUCN categories I-IV). The mapping of the sensitivity, 1-resilience and the exposure scores to vulnerability categories is provided in Table S1.