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Climate Change Risks on Mediterranean River Ecosystems and Adaptation Measures (Spain)

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Abstract
The Mediterranean is one of the most vulnerable regions to climate change impacts. Climate change scenarios predict that water temperature will increase up to 2.2–2.9ºC by the end of the century in Mediterranean rivers. This will cause an impact on water quality (oxygen dissolved reduction), reduce the available habitat of cold-water fish species and affect macroinvertebrates. Risk assessment methodology develops indicators that integrate hazard, exposure and vulnerability. Risk maps are key tools to prioritize the areas in which adaptation measures should be implemented in order to improve the adaptive capacity of ecosystems. The risk of habitat loss and ecosystem damage is very high in Mediterranean rivers. For RCP8.5, the 80% of the waterbodies that currently have brown trout presence are in High Risk (HR) or Very High Risk (VHR) of disappearing in the long term future (2070–2100) and the 35% in the short term (2010–2040). It will affect the middle sections first and the headwaters of the rivers later. The 92% of the waterbodies are in HR-VHR of macroinvertebrate family's affection (2070–2100) and dissolved oxygen may be reduced by 0.5–0.75 mgO_2/l (2070–2100). The restoration of the riverside vegetation is the main adaptation measure. This reduces significantly the stream temperature. Other measures are the groundwater protection and cold-water discharge from the reservoirs.

Keywords (max 6) Climate Change Adaptation · River Ecosystems · Climate Change Impact · Risk Assessment

1 Introduction

Human-induced climate change has caused widespread adverse impacts and related losses in terrestrial, freshwater and coastal and marine ecosystems (IPCC, 2022). Changes in climate, especially increases in air temperature and changes in rainfall patterns, alter freshwater systems and change the composition of fish in river ecosystems (Tsang et al. 2021).

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Global surface temperature was 1.09 °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 °C) than over the ocean (0.88 °C). (IPCC, 2021) and the Mediterranean is one of the most vulnerable regions to climate change (Kim et al. 2019; Noto et al. 2022). Particularly high warming has been observed over the Iberian Peninsula (C3S, 2020). Climate modelling has been used to estimate future climate change for different emissions' scenarios. The increase in global mean surface temperature in the late 21st century (2081–2100) relative to 1986–2005 is likely to be 1.7 −3.2 °C under RCP 4.5, and 3.2 −5.4 °C under RCP 8.5 (Allen et al. 2018).

Temperature changes lead to changes in the distribution patterns of freshwater species (IPCC, 2022). Cold-water aquatic organisms such as Brown trout (*salmo trutta*) are very sensitive to predicted temperature changes in rivers (Cianfrani et al. 2015). Temperature affects migration (García-Vega et al. 2018) and modifies brown trout relationships and social behavior, which affect group cohesion and can influence their survival and dispersal (Colchen et al. 2016). It also affects to older and larger trout due to increased metabolic costs and decreased energy inputs (Ayllón et al. 2019) and causes a loss of potential habitat (Valerie and Daniels 2021). The presence of the different families of macroinvertebrates in riparian ecosystems is also related to water temperature (Haidekker et al., 2008; Itsukushima, 2021). Global warming may cause important changes in the macroinvertebrate composition in Mediterranean streams (Pedreros et al. 2020) especially in those with excellent conditions (Daneshvar et al. 2017). Water quality may also be compromised because of the temperature rise that reduce, among other factors, the dissolved oxygen in water (Null et al. 2017; Jiang et al. 2021; Rajesh and Rehana 2022).

Climate change risk assessment is based on a formal analysis of the consequences, probabilities and responses to climate change impacts (Adger et al. 2018). Risk assessment results from interactions between hazard, exposure and vulnerability. Since the impacts of climate change affect nature in different ways, the objectives of adaptation depend on the impact that is managed and the measures that are taken (IPCC, 2022). Climate risk assessments are useful to know where we should implement adaptation measures to reduce the risks associated with climate change.

Various studies have been carried out at the basin scale on the impact of climate change on water resources, especially evaluating the reduction of rainfall and flows (Amraoui et al. 2019; Mehrazar et al. 2020; Dau et al. 2021; Maurya et al. 2023), extreme events (Suárez-Almiñana et al. 2020; Tegegne and Melesse 2020) or sea level rise and its effects in coastal wetlands (Estrela-Segrelles et al. 2021). This research stands out for studying the effect of climate change on the ecological status of water bodies at country level, something that had not been evaluated up to now. It provides a deep knowledge of the risks of climate change in the most sensitive areas and allow Water Management River Authorities to reduce vulnerability, propose climate change adaptation measures and incorporate them in the several River Basin Management Plans. The main novelties are: (1) it establishes a replicable methodology to assess the risks derived from climate change in water bodies; (2) it classifies the risks on water bodies highlighting those where apply adaptation measures first; (3) it analyzes the risks for cold water species, macroinvertebrates and the reduction of dissolved oxygen.

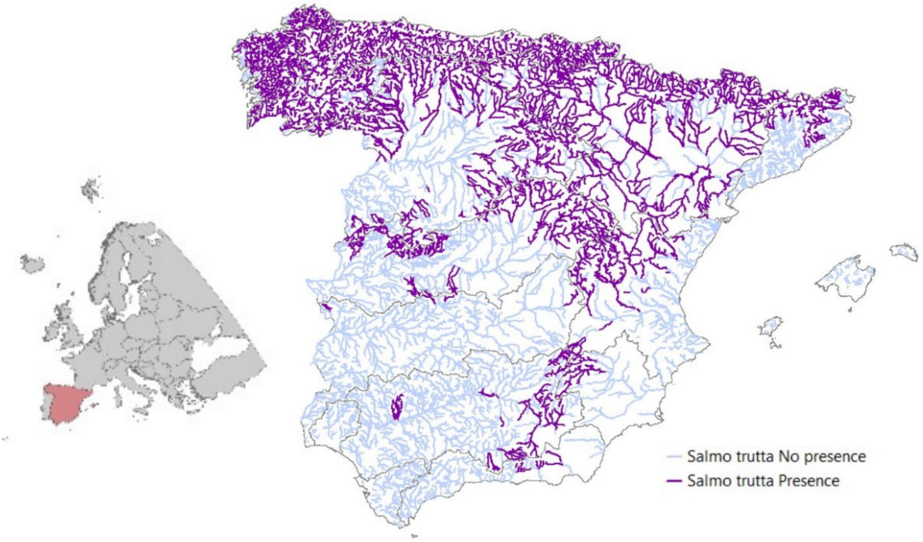

Fig. 1 Location of Spain in the Mediterranean region and Brown trout real presence map based on Doadrio (2002)

2 Methodology and Study Case

The aim of climate change risk assessments is to obtain risk maps which show the areas where adaptation measures must be applied. Spain, located in the Mediterranean region, is a country with great climatic and geographic variability (Fig. 1) where climate change will have a great impact (Estrela et al. 2012; Chirivella et al. 2015). This methodology has been applied in the 5017 surface water bodies that compose the basic hydrographic network of Spain.

The Water Framework Directive 2000/60/EC stipulates that to achieve good status, ecological and physicochemical status are required to be good. Ecological status is influenced by habitat degradation and is evaluated with several indicators such as IBMWP or specific fish index. Physicochemical status is evaluated by comparing the values measured with the established values of variables such as dissolved oxygen, the concentration of nitrates or phosphorus. Brown trout, macroinvertebrates and dissolved oxygen have been selected as indicators of the state of water bodies to take into account both the ecological and physicochemical impact on water bodies. They clearly affect the good ecological and physical-chemical status of the water bodies. This work has analyzed these variables for RCP4.5 and RCP8.5 climate change scenarios in the short term (2010–2040), the medium term (2041–2070) and the long term (2071–2100).

In this study, **hazard maps** show the spatial and temporal distribution of stream temperature increase. To evaluate water temperature in the scenarios proposed, air temperature increase have been obtained from multimodel average. Six global circulation models (CNRM-CM5, MPI.ESM.MR, inmcm4, bcc-csm1-1, MIROC.ESM, MRI.CGCM3) were used. They have been regionalized using the Spanish Meteorological Agency's analogues method for the established scenarios. Data on air temperature variable have been obtained from the Spanish Office for Climate Change and the AdapteCCa Platform (https://escenarios.adaptecca.es).

There are various approaches in air-water temperature modeling. Linear expression considers the relationship between air and water temperature as follows (Eq. 1). Mohseni et al. (1998) propose non-linear expression (Eq. 2). Webb et al., (2003) and Neumann et al., (2003) suggest there is little advantage in using the more complex logistic models for their rivers.

$$Linear\, T_w = a_0 + a_1 T_a \tag{1}$$

$$Non - Linear\, T_w = \mu + \frac{\alpha - \mu}{1 + e\gamma\,(\beta - T_a)} \tag{2}$$

Where T_w is water temperature, T_a is air temperature, a_0 and a_1 are the regression coefficients (Johnson 1971), α is the maximum stream temperature, γ is a measure of the steepest slope of the function, β is the air temperature at the inflection point and μ estimate minimum water temperature in warmer rivers.

Water temperature in August is determined from the average air temperature in August and linear expressions (Eq. 1) that relate air temperature (Ta) and water temperature (Tw) for each river's ecotype, in accordance with the Water Framework Directive and CEDEX (2012). For this study, a_0=0.8364 [0.5352; 1.0087] and a_1=2.9014 [0.10087; 9.2289].

According to historical data, August is the month with the warmest water temperature in Spain. In the case of trout habitat and dissolved oxygen, the month with the highest temperature was used, since it is the main limiting factor for mortality. In the case of macroinvertebrates, mean annual temperature was used because the life cycle of macroinvertebrate families may be less than one year and mean conditions for the entire year are considered.

In this work, **the exposure map** shows the presence or absence of *salmo trutta* in the water bodies, the IBMWP macroinvertebrate index and the dissolved oxygen values that define good conditions according to the Spanish regulation. Cold-water species such as Brown trout are highly conditioned by the stream temperature. They are present in the headwaters and upper reaches of rivers, characterized by a steep slope, strong current, low temperature and heterogeneity of the substrate. This is shown in the northern part of peninsular Spain, the headwaters of the Duero, Júcar and Segura rivers and the Pyrenees area (Fig. 1).

In relation to the habitat loss of cold-water species, the existing scientific literature (Wehrly et al. 2007; Santiago et al. 2016) determines the ideal water temperature range for the species. Based on the literature, the Spanish territory has been classified into three zones: the optimal zone where the highest reproduction rate occurs, the physiological pressure zone and intolerance zone where a total habitat loss occurs. The temperature value that determines the entry into the pressure zone has been established at 18.7 ºC. The thermal barrier or lethal limit has been established at 21.8 ºC.

The impact of reduced oxygen dissolved (DO) in water (mgO_2/l) has been determined based on the two main variables that determine solubility, air temperature and atmospheric pressure, both depending on altitude (Julien P., 2018). The linear (Eq. 3) and the exponential (Eq. 4) are the two main models that relate dissolved oxygen and temperature in water. Both models are similar but the adjustment for low concentrations and high temperatures is slightly better in the exponential model. In the linear model, the range of the parameters for a_0 is [13.21, 14.46] and for a_1 [-0.27, -0.41]. In the exponential model, the range of the parameters for b_0 is [2.59, 2.69] (or c_0 [13.3, 14.7]) and for b_1 [-0.03, -0.04] (Harvey et al. 2011).

$$Linear:\ DO = a_0 + a_1T_w \tag{3}$$

$$Exponential:\ DO = e^{(b_0+b_1T_w)} = c_0 \cdot e^{(b_1T_w)} \tag{4}$$

The inclusion of altitude improves the estimation of dissolved oxygen content in water bodies above 1000 m altitude (Julien 2018), by reducing the c_0 coefficient (Eq. 5). The mean value of the percentile above 80% is 9.5 mgO_2/l, both observed and calculated, obtaining a very good fit for values with higher oxygen content. The expression used has a mean value of a_0 of 2.69 ($c_0 = 14.7$) and a value of b_1 of -0.0225, following the following expression:

$$DO\left(\frac{mg}{l}\right) = (14.7 - 0.0017Alt\,(m))e^{(-0.0225T_w(^\circ C))} \tag{5}$$

Three exposure zones have been established: zone with optimal DO (DO > 9 mg/l), zone with medium DO (5 mg/l < DO < 9 mg/l) and zone with low DO (DO < 5 mg/l). The zone limits have been established based on the dissolved oxygen requirements of cold-water species.

In the case of macroinvertebrate families, the hypothesis is that all water bodies are exposed.

Impact maps determine the degree of impact caused by climate change. They were calculated by the combination of hazard and exposure maps. If an exposed waterbody has a significant loss in the state, it will have a Very High Impact. If it has a moderate loss of the state, it would have a High Impact and if it does not change state or is not exposed it would have a No Impact.

If in a waterbody with the presence of brown trout at present, the temperature in a future scenario exceeds the thermal barrier, it enters the intolerance zone, and a Very High Impact will be assigned. On the other hand, if the increase in temperature produces a change from the optimal state to the pressure zone, the result will be a High Impact (Table 1. Supplementary material).

CEDEX (2012) show that an increase of 0.5 ºC would affect the 20% of the total macroinvertebrates' families studied and 2 ºC increase would affect the 55% of the families. These values have been adjusted using the following expression:

$$MacroinvertebratesAffection\,(\%) = 8.52 + 24.98 \times \Delta T \tag{6}$$

The determination of the macroinvertebrates impact takes the current value of the IBMWP index that defines the Very Good Condition as a starting point, obtained according to the Spanish legislation on water quality. For each future scenario, a new value of the IBMWP is determined applying expression (5). If the affection exceeds 50% of individuals or produces a decrease in the value of the IBMWP below the reference level of moderate, it is considered to have a Very High Impact. Whether the affection is greater than 30% or there is a reduction of the indicator below the reference value of Good, it is considered a High Impact.

The **vulnerability map** is defined as the propensity or predisposition to be negatively affected and includes information on the adaptive capacity of the system. In this study, it has been determined from the state of the riverbank vegetation. A good state of the riverbank vegetation reduces vulnerability by providing shading areas and reducing the amount of incident solar radiation over water, in addition to providing shelters for the ecosystem. The Riparian Forest Quality Index - QBR (Munné et al. 2003) has been used as an indicator of the state of the riverside vegetation. Data have been collected from water quality control programs of the River Basin Authority (observed values). According to the Spanish legislation, each waterbody can be in Very Good state (Low Vulnerability) or Worse than Very Good state (High Vulnerability).

Risk maps are defined as eventual consequences in situations in which something valuable is in danger and the outcome or consequence is uncertain (IPCC, 2014). Risk maps have been defined as a combination of the impact degree and vulnerability (Table 2. Supplementary material). The water bodies of the different River Basin Districts have been classified into Low, Medium, High and Very high risk.

3 Results and Discussion

3.1 Climate Change Scenarios and Hazard maps

The set of climate change models, multimodel average, show for Spain an increase in the average daily temperature between 0.9 and 1.0 ºC in the short term, an increase between 1.6 and 2.3 ºC in the medium term, and an increase of between 2.0 and 3.8ºC in the long term. The increase in temperature is greater during warmer months with an increase in the average daily temperature for the month of August which goes from 1.2 to 1.6 ºC in the short term, an increase from 2.2 to 2.9 ºC in the medium term and between 2.7 and 4.7 ºC in the long term.

Air temperature increase produces a water temperature's rise between 0.7 and 0.8 ºC in the short term, between 1.3 and 1.9 ºC in the medium term, and between 1.7 and 3.1 ºC in the long term and it is a generalized and homogeneous increase throughout the whole country's territory (Fig. 1). Stream temperature in August rises between 1.0 and 1.3ºC in the short term, between 1.8 and 2.4ºC in the medium term, and between 2.2 and 3.9ºC in the long term (Fig. 2).

Our results are consistent with Morrill et al., (2005) results. They conclude that most streams showed a 0.6–0.8 °C water temperature increase for every 1 °C air temperature increase.

3.2 Model Validation

Air-water temperature model has been validated in two ways. First, the observed and calculated water temperature in August have been compared. River Basin Authority provided stream temperature real observations. Then, the current presence of trout (Fig. 1) was compared with the potential cold fish habitat (Fig. 3b) in the water bodies. Data of current presence of common trout have been collected from the Atlas and Red Book of Fish (Doadrio 2002). Global results obtained from the observed and calculated stream temperature r = 0.64

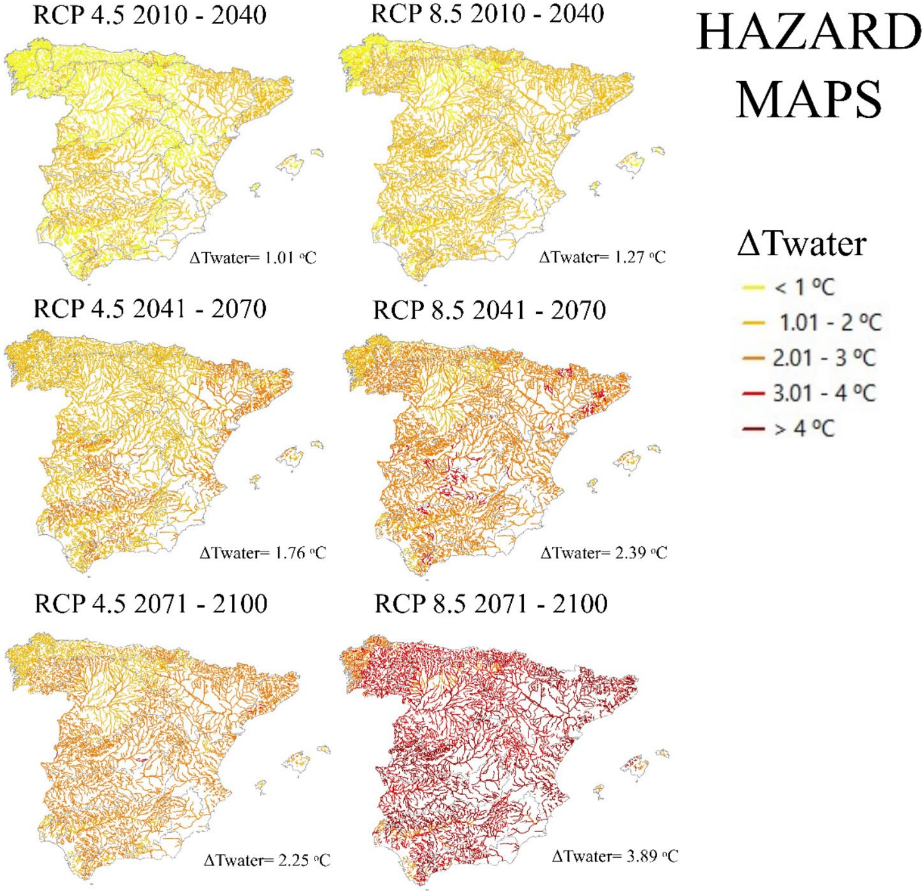

Fig. 2 Hazard Map. Anomaly water temperature in August

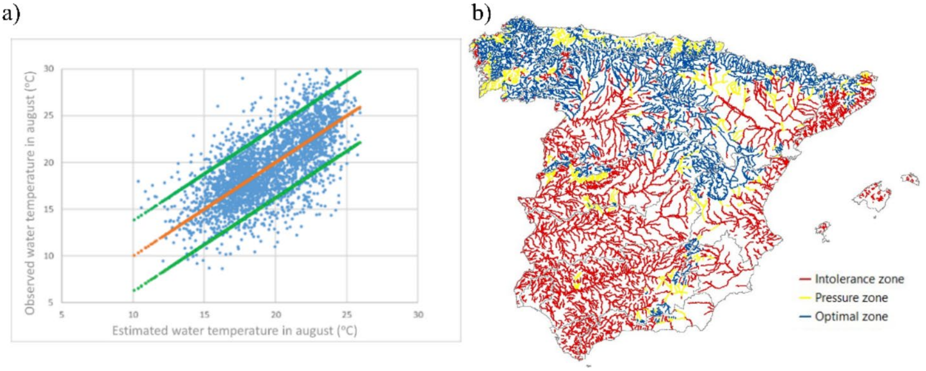

Fig. 3 (a) Correlation of observed and estimated stream temperature in August (ºC) (b) Salmo trutta exposure map

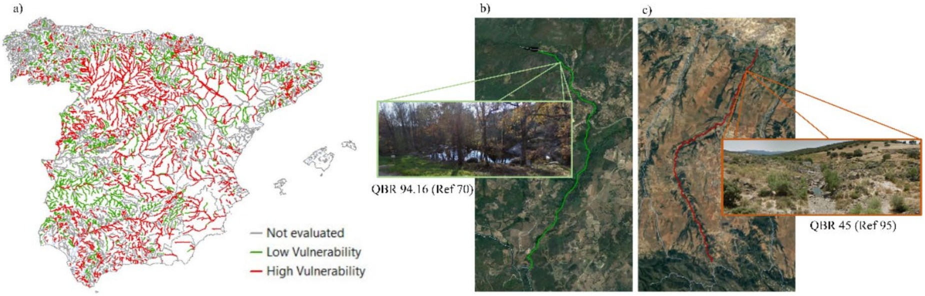

Fig. 4 (a) Vulnerability map based on QBR index (b) Example (1) From Gualtaminos dam to Tiétar River (c) Example (2) Pusa River (Google, Inc.)

(Fig. 3a) and the two maps, current presence and potential habitat of brown trout, have been considered reasonable on a large basin scale, which is the purpose of the work. Other factors such as dam regulations or thermal discharges may also affect water temperature and may require regional studies.

At present, there are 1841 water bodies classified as optimal zone, 471 as a pressure zone and 2705 as an intolerance zone. The impact on brown trout habitat in relation to the temperature increase is progressive as the 21st century progresses and greater in RCP 8.5. In addition, it first affects the middle sections of the rivers and then the thermal barrier moves upstream with altitude towards headwaters. For RCP 8.5, the 16% of water bodies will lose the habitat conditions for cold-water species in the short term. The amount rises to 23% in the medium term, and 40% in the long term.

Our results are in line with Muñoz-Mas et al., (2016, 2018) who conclude that the adequate spawning habitat will be reduced between 15.4 and 48.7% in their study area. The results are comparable with the decrease observed in the brown trout catch (García-Vega et al. 2018; Cianfrani et al. 2015; Santiago et al. 2016) and with the studied carried out by Sedighkia et al., (2019).

The estimated dissolved oxygen has been contrasted with the information observed from the water bodies' control programs carried out by the River Basin Authority.

The vulnerability map shows that the 60% of the total water bodies evaluated are classified as High vulnerability. The rest are classified as Very Good state and have Low vulnerability (Fig. 4a). This results have been contrasted with reality in different points (Fig. 4b and c). Figure 4b shows the water body "From Gualtaminos dam to Tiétar River" has a QBR value = 94.16 out 70, classified as Very Good state. In the figure, the presence of riverside vegetation in practically the entire water body is relevant. Figure 4c shows the water body "Pusa River", has a QBR value = 45 out 95, classified as Worse than very good state. Here the presence of agricultural areas in the riverbanks and the lack of natural vegetation are relevant.

3.3 Risk maps

Risk maps have been obtained for the several climate change scenarios and variables analyzed. The results for the *salmo trutta* habitat loss show the gradual increase in the water bodies with high or very high risk, affecting firstly the middle sections of the rivers and then

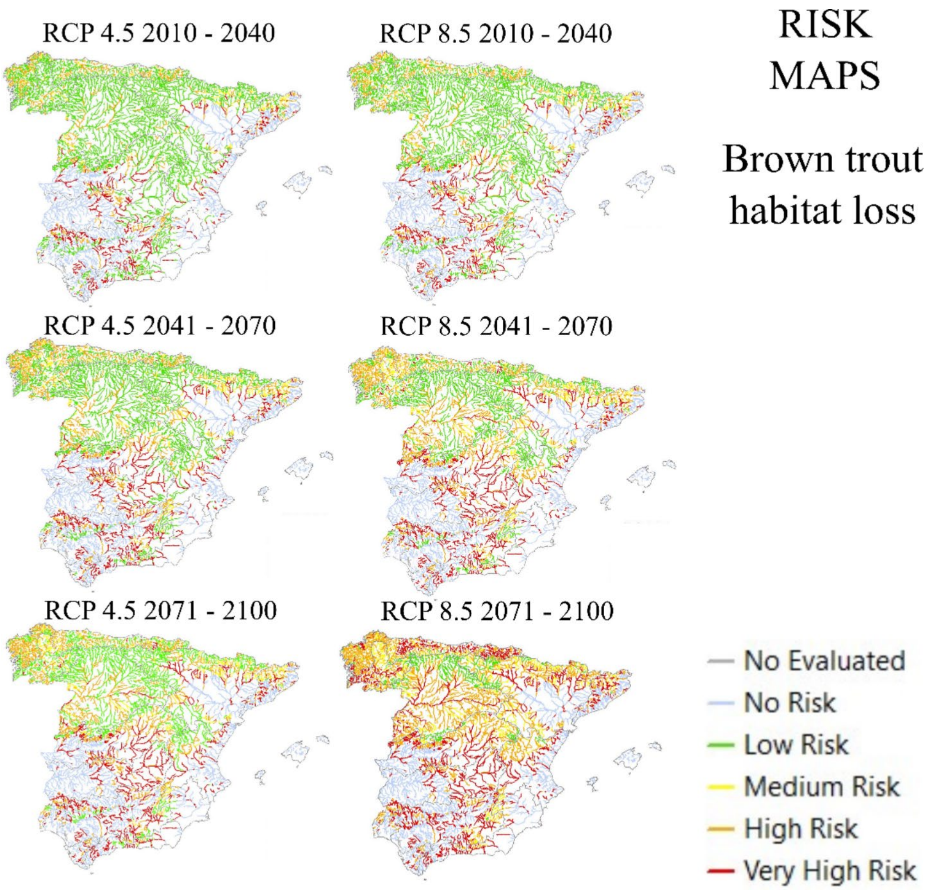

Fig. 5 Risk maps of habitat loss for Brown trout

affecting he headwaters and the coldest areas of the rivers. This implies a reduction of the total potential habitat and fragments the ecosystems. The rivers of the eastern Peninsula flow into the Mediterranean Sea, while the rest flow into the Atlantic Ocean. The maps show that the Mediterranean watersheds will be affected first and then the Atlantic watersheds and the south is affected before the north of the country (Fig. 5).

In the short term, the water bodies identified with Very High Risk are in the middle section of the rivers. In the medium term, they are in the middle sections of the main rivers and in the area of Galicia and the Cantabrian Coast. In the long term, towards the end of the 21st century, the 80% of the water bodies with potential habitat suitable for the survival of Brown Trout at present have a very high or high risk of losing these conditions for the RCP 8.5 scenario.

Regarding the families of macroinvertebrates, as the stream temperature rises, the percentage of individuals affected increases. Figure 6a show how the risk of affecting macroinvertebrate families increases significantly throughout the century, affecting practically all surface water bodies at the end of the 21st century. Our results are consistent with Pedreros

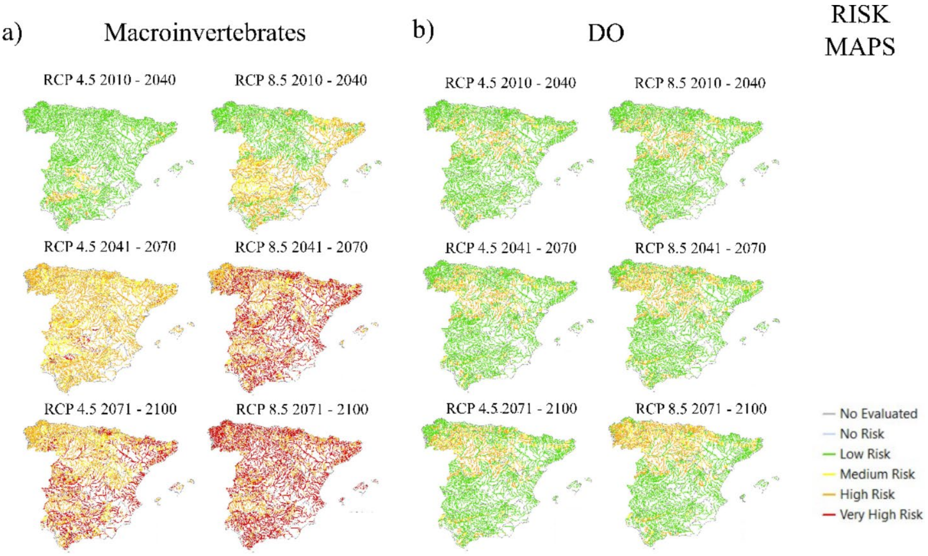

Fig. 6 Risk maps of (a) Macroinvertebrates affection and (b) Dissolved oxygen reduction

et al., (2020) conclusions and with Li et al., (2013) results that show a possible loss of 55% macroinvertebrate species by 2080.

Regarding dissolved oxygen, the areas with high content of dissolved oxygen (>9 mgO_2/l) are in the headwaters and in the Duero and North basins. The areas with average oxygen content, between 9 and 5.5 mgO_2 / l, are in the rest of the territory. Figure 6b show that no water body has an oxygen concentration lower than 5.5 mgO_2/l in any of the analyzed scenarios so there is not Very High Risk but temporal evolution shows how the number of High Risk water bodies gradually increases.

3.4 Adaptation Measures

Stream temperature is expected to rise. This will significantly impact on the habitat of cold-water fish species such as Brown trout, macroinvertebrates and oxygen conditions in rivers. The main measure to reduce vulnerability is the restoration of riverside vegetation. It provides shaded areas, reduces direct sunlight radiation over streams and water temperature. Besides, it favors biodiversity and provides refuge for species. It increases the adaptation capacity and resilience of the water body. Providing thermal refugia for the biota can contribute to reduce risks. Other measures may also contribute to reduce the risk such as groundwater protection in aquifers connected with surface water bodies that allows the drainage of groundwater with lower temperatures or the release of cold-water releases from the existing dams in the water bodies located downstream. In the water bodies with very high risk located upstream of the existing dams, river restoration, groundwater protection or artificial recharge in poor conditions aquifers seems to better fit. In those water bodies located downstream of dams, cold-water can be released from the reservoirs during summer months.

Our results are in line with other researches as follows. Kristensen et al., (2013) stands that relatively short stretches of forest next to streams can combat the negative effects of stream water heating, the presence of riparian forest has a cooling effect that varies from 1 ° C to 3 ° C. Fullerton et al., (2015); Justice et al., (2017) and Dugdale et al., (2018) agree that river and bank restoration and thermal refugia can promote the resilience of aquatic biota to climate change. Pérez-Martín et al., (2014) and Briggs et al., (2018) conclude that river-aquifer interactions may provide a refugia to allow cold-water fish species to survive and Zhang et al. (2021) suggest adjusting hydropower operating rules to lower water temperatures and keep fish populations cool.

4 Conclusion

The Mediterranean is one of the most vulnerable areas to the effects of climate change. The risk assessment is a useful tool to determine which water bodies will be more affected by climate change. The study has been carried out on a country scale (Spain). The methodology derives from air temperature anomaly obtained from climate change scenarios and develops hazard, exposure, impact, vulnerability and risk maps.

The increase in air temperature will produce an increase in streams temperature, from 1.0 to −3.9 ºC depending on the scenario. This will lead into a reduction of the potential habitat for cold-water species and affect macroinvertebrate families. The impact on brown trout habitat throughout the XXI century is progressive. Risk maps identify the areas for improvement. In the short term, 27% (RCP 4.5) – 35% (RCP 8.5) water bodies have a High or Very High Risk of loss or significant reduction of habitat for cold-water species and the intermediate sections of the rivers are the most affected. In the long term, 55 −80% of water bodies and the thermal barrier moves with altitude, increasing the affected area and dividing the ecosystems.

Regarding the effects on macroinvertebrates, in the short term, between 4 −32% of the water bodies are at High risk whereas in the long term, 83 −92% of the water bodies have a High or Very High Risk. That means there is an affection in all the rivers sections: headwaters, middle and low section. In connection with the effect in the dissolved oxygen, in the short term the 11 −12% of the water bodies are at High risk of oxygen depletion whereas in the long term, the percentage rises to 21 −32%. This is the least significant impact of those analyzed in the study.

The results of this study address the lack of knowledge in relation to climate change risks in the study area, provide a better understanding for decision makers on how vulnerable the country is to the hazards caused by climate change and help decision makers to prioritize the areas where apply adaptation measures. They show an increase in water bodies' risk associated with the gradual advance of temperature increase. This implies the need to start a progressive implementation of adaptation measures. The main measure to reduce risk is the improvement of riverside vegetation. Other measures are the provision of thermal refugia, cold-water releases from the existing dams and groundwater protection.

Author contribution C Estrela-Segrelles and MA Pérez-Martín contributed to the study conception and design, material preparation, data collection, analysis, writing and review. G Gómez-Martínez did a language review. All authors read and approved the final manuscript.

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Data Availability Not applicable.

Statements and Declarations

Competing Interests The authors have non-financial interests to disclose.

Ethical Approval The manuscript complies with Water Resources and Management ethical standards.

Consent to Participate The authors declare that they are aware and consent their participation in this paper.

Consent to Publish The authors declare that they consent he publication of this paper.

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