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A simple and extensible framework to identify key areas for the conservation of single vulnerable freshwater species

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ABSTRACT

One of the main challenges in conservation biogeography of freshwater fishes is the improvement of conservation planning strategies. Nonetheless, the implementation of such strategies has lagged in freshwater systems, limiting their protection to the priorities of land organisms. Since the repercussions and relative importance for conservation across freshwater species can vary tremendously, and the application of such strategies requires information on multiple species, it is valuable to consider extensible and straightforward approaches that can be applied to single species. Here we use a freshwater fish species native to the Colombian Andes (*Brycon henni*) as a model to implement a methodology for spatial conservation prioritization considering four criteria: i) representativeness (protection of species distribution), ii) viability (maximizing probability of success), iii) complementarity (recognition of the currently protected area network), and iv) connectivity (promoting connectivity amongst protected areas). Using the proposed methodology based on the potential distribution of *B. henni* and hydrographic sub-basins as planning units, we recommend the protection of nine sub-basins climatically suitable for the species and with strategic river corridors that would promote the connection amongst basins and the currently protected areas. This methodological proposal can contribute to the current strategy design implemented by the National System of Protected Areas in Colombia to conserve or recover ecosystems and fragmented natural habitats, providing design options that meet ecological and socioeconomic objectives. Lastly, we consider that the methodology proposed here could be used with a more significant number of species of interest and implemented on a regional and global scale.

1. Introduction

The loss of biodiversity in freshwater ecosystems is occurring at a higher rate than terrestrial or marine systems, revealing a significant risk of extinction of freshwater organisms (Reid et al., 2019). This is particularly acute in tropical latitudes where most of the taxonomic and functional diversity reside (Dudgeon et al., 2006; Toussaint et al., 2016), including the services provided by some of these species (Holmlund and Hammer, 1999). Surprisingly, scant attention has been given to developing guidelines on how to prioritize freshwater conservation areas (Albert et al., 2021; Arzamendia and Giraudo, 2012; Naiman et al., 1993) and the majority of national reserve systems were developed ignoring freshwater ecosystems (Abell et al., 2007; Castello and Macedo, 2016; Jimenéz-Segura and Lasso, 2020). Since the repercussions and relative importance for conservation across freshwater species can vary tremendously, and the application of conservation planning strategies often requires information on multiple species, it is valuable to consider extensible and straightforward approaches that can be applied to single species. Here we propose a methodology based on four criteria (representativeness, viability, connectivity, and complementarity) and use it with an endemic, non-threatened, but economically important freshwater species from Colombia.

Colombia is one of the most diverse regions worldwide concerning its freshwater fish fauna (Cala-Cala, 2019; Dagosta et al., 2020). Its aquatic ecosystems, despite not being widely known, provide habitat to 1572 species of fish (DoNascimiento et al., 2020). The spatial distribution of freshwater fishes is mainly uneven, with the majority of species found along the Amazon and Orinoco River basins, but an essential portion of

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endemic species is concentrated in the Magdalena macrobasin, made up of the Magdalena and Cauca rivers, where 77 % of the Colombian population is concentrated. Although the diversity in the Magdalena macrobasin is low compared with the Amazon and Orinoco basins, it is considered one of the regions on the planet with the highest percentage of endemism (68.1 %, 158 endemic species) (DoNascimiento et al., 2020). Unfortunately, the aquatic ecosystems in this macrobasin are amongst the most affected by human activity throughout the country (Angarita et al., 2018; Carvajal-Quintero et al., 2015; Jiménez-Segura et al., 2014; Patino and Estupinan-Suarez, 2016; Rodríguez, 2015). Consequently, this macrobasin is not only home to the largest endemic ichthyofauna, but also the greatest percentage of fish species within any category of threat (DoNascimiento et al., 2018; Jiménez-Segura et al., 2016).

Despite the valuable and unique biodiversity found in the Neotropical region, there are few protected areas set apart for the conservation of freshwater ecosystems (Dagosta et al., 2020; Tognelli et al., 2019). This holds particularly true for the Magdalena macrobasin, whose territory and waters are responsible for 77 % of the Colombian Gross Domestic Product–GDP (The Nature Conservancy et al., 2014). This situation reflects many conflicts of interest that have direct implications for conservation efforts. For example, the short-term future projection of hydropower development, the increased use of lands for farming and livestock grazing, the transformation of land use for activities such as mining and deforestation, as well as modifications to the main channels for improved navigation and dam construction, are all activities that affect conservation efforts and impact populations of freshwater species (Albert et al., 2021; Reid et al., 2019). The viability of conservation strategies is thus an important criterion to consider.

For biodiversity conservation, additional criteria need to be considered, such as representativeness, persistence and economy (Arponen, 2012; Pool-Stanvliet et al., 2018; Reddy et al., 2019; Watson et al., 2011). Traditionally, representativeness is viewed as the coverage of all biodiversity surrogates in a conservation area network. Nonetheless, from the perspective of a single species, we can view it as the coverage of its distribution that is being covered by the conservation area network. This is also related to persistence, in the sense that covering a larger area of the distribution of a species will increase its chances of survival. The identification of new conservation areas should also be economical, meaning that the limited resources available for conservation must be efficiently used. A simple step toward efficiency is to identify the current distribution of protected areas to avoid overlap where work is already under-way, and to complement the current system in the most efficient way possible (Stralberg et al., 2020). The principle of complementarity is frequently used in the design of conservation reserves, and it not only takes into account the number of species each reserve protects, but also which species contribute to a given macrobasin that are not protected by other reserves in the same macrobasin (Justus and Sarkar, 2002). An indirect way of applying the complementarity principle is selecting planning units that do not already contain existing reserves. For example, if there is already a protected area within a given basin, trying to identify reserves in other basins would widen the scope of protected species, distribute conservation efforts along the basin, or protect different populations. Thus, it is instrumental in finding areas that contribute to the protection of freshwater organisms in a manner that complements the current system of protected areas.

A particular characteristic of fluvial networks that is essential to guarantee the conservation of many fish species is connectivity (Anderson et al., 2018; Carvajal-Quintero et al., 2019; Herrera-Pérez et al., 2019). Connectivity allows fish to move throughout their feeding and spawning sites, which in many cases are far apart along the fluvial network, and is hence decisive to population dynamics (Tonkin et al., 2018). In addition to affecting the development of conservation projects, the rise in dam construction shatters the connectivity of water bodies and limits the viability of a great diversity of fish (Anderson et al., 2018; Finer and Jenkins, 2012). Therefore, it is of great importance to identify areas that meet the adequate conditions for the protection of freshwater species (i.e., those containing ideal environments for some or all species of interest) and that such areas remain connected.

The method proposed in this study considers the criteria of representativeness, viability, connectivity, and complementarity for the identification of areas for the conservation of the Sabaleta *Brycon henni* Eigenmann 1913, an endemic species to Colombia. We present a method to determine priority conservation areas based on these four criteria associated to the current state of the basin where this species lives (Fig. 1). The reasons for using *B. henni* in this study were its status as an endemic species, its distribution in creeks and rivers in the Andean mountains, its economic importance, the availability of information, and because it helps to clearly visualize each step in the method; we are not proposing the Sabaleta as an umbrella species nor are we suggesting that the use of a single species is preferable to the use of multiple species when making decisions concerning conservation. Eventually, the same criteria can be used with a larger group of species to identify conservation areas for the fish communities of an entire region. There is no silver bullet in terms of conservation strategies, and single-species approaches are a great complement to multi-species or even ecosystem approaches to conservation (Lindenmayer et al., 2007). The high-quality data that can be obtained for a model species may allow mechanistic understanding of the potential threats and opportunities to develop conservation strategies and how they might apply to other species. Single species that are familiar to the general public or even to specific sectors (e.g., fishermen, riverine people), might be also useful to promote conservation actions, environmental awareness and attract further funding for management practices (López-Casas et al., 2018; Moreno-Arias et al., 2021).

Brycon henni is distributed along creeks and rivers in the mountains of the Magdalena macrobasin (Lasso et al., 2011). This fluvial system has been impacted by anthropogenic activities, such as mining, hydroelectric power plants (Angarita et al., 2018; Carvajal-Quintero et al., 2015; Jiménez-Segura et al., 2014), cattle farming (Patino and Estupinan-Suarez, 2016), river engineering, and debris flow accumulated from deforestation areas (Jiménez-Segura et al., 2016; Patino and Estupinan-Suarez, 2016; Rodríguez, 2015). Despite being an endemic species and one of importance to the mountain inhabitants (e.g., it is an important protein source for the indigenous communities and rural populations), *B. henni* has been largely ignored regarding conservation efforts, probably since it is not listed as a threatened species (Mojica et al., 2012). In this study, we present a flexible and simple method, inspired on the principles of systematic conservation planning, that incorporates simultaneously four quantitative criteria (representativeness, viability, connectivity and complementarity) to identify conservation areas for *B. henni*. This method can incorporate data about distribution and habitat suitability, conflicts of interest with other urbanization or resource exploitation initiatives and considers the existing protected area network. We hope this proposal may facilitate the decision-making process in order to promote conservation and proper management of aquatic ecosystems in the Andes.

2. Methods

2.1. Species and study area

Brycon henni is a species native to the Colombian Andes that is found between 300 and 2400 m (GBIF, 2021) in river and lake ecosystems (Magallanes and Tabarez, 1999; Montoya-lópez et al., 2006; Trahl, 1973). To delineate the study area, we used the potential distribution model of *B. henni* (Valencia-Rodríguez et al., 2021) in its binary format (1–0; presence-absence) using the minimum suitability value associated with a training presence as threshold ($p \geq 0.23$) to identify the sub-basins where the model indicated suitable environmental conditions. We eliminated the areas within the Magdalena macrobasin where the potential presence of the species was interpreted as an overprediction of

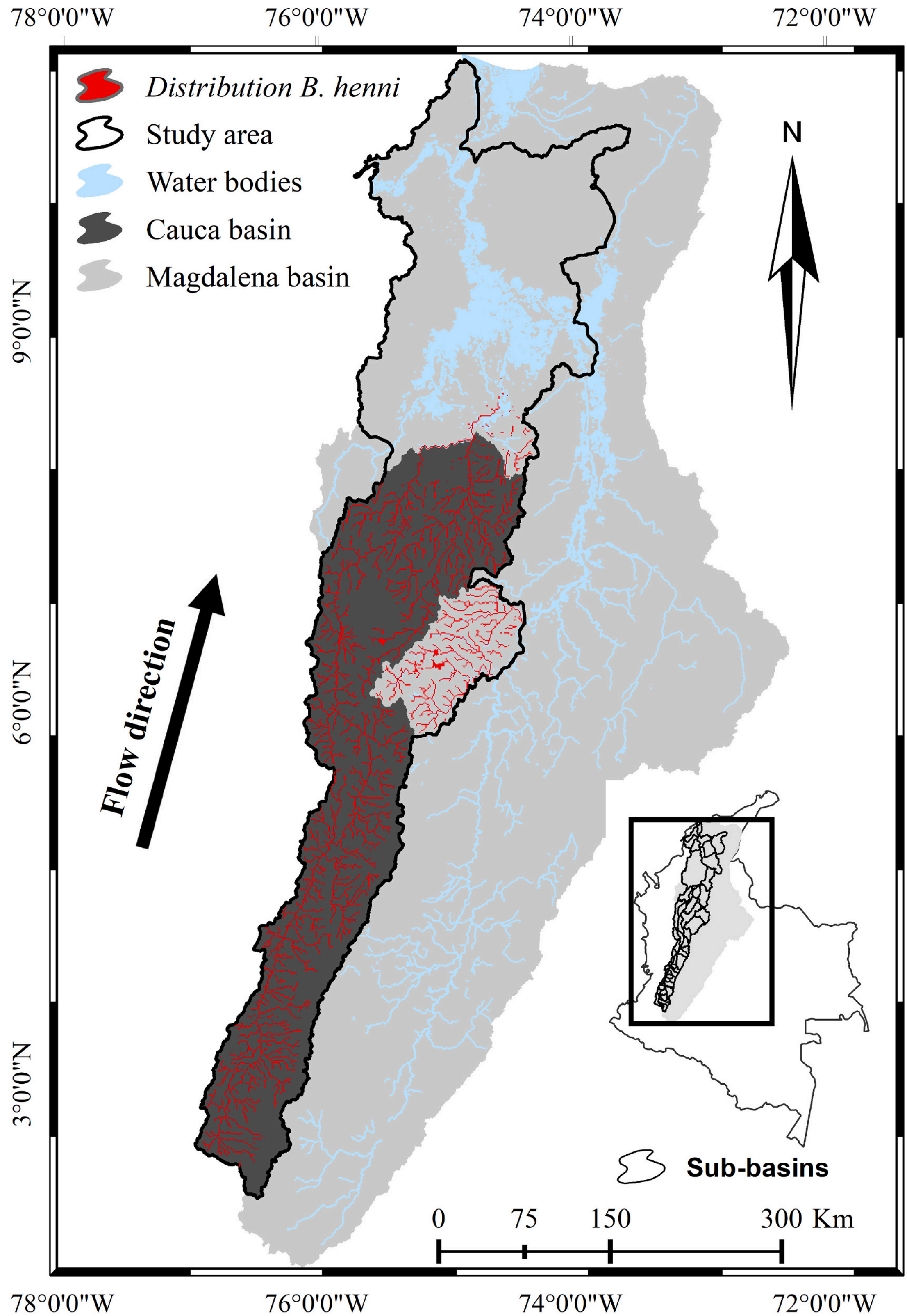

Fig. 1. Study Area. Delineation of the area with suitable conditions for the presence of *B. henni* (red), in the Magdalena and Cauca River basins. The units of study (sub-basins) are presented in the lower, right box. The shapefile of basins was obtained from IGAC (https://geoportal.igac.gov.co/). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the model, and we included all sub-basins north of the Cauca basin despite the inclusion of only a few suitable areas (Fig. A1). A total of 51 sub-basins were included, 79 % of which are part of the Cauca River basin, while the remaining 21 % belong to the Magdalena River basin (Fig. 1). For the purposes of this study, we conducted a decision making protocol for the prioritization of conservation areas at the sub-basin level, since these units are more appropriate for freshwater systems (Hermoso et al., 2011). The basin and sub-basin polygons were downloaded from the Agustín Codazzi Geographical Institute (IGAC, Spanish acronym) at a scale of 1:100,000, and they follow the classification suggested by the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM, Spanish acronym) (2013).

2.2. *Data preparation and criteria quantification*

2.2.1. *Representativeness*

The criterion of representativeness in our case is related to the total amount of area possibly occupied by the species of interest. We acknowledge this is not the traditional meaning (i.e., proportion of total species covered), but believe it is a suitable analogy in single-species approaches. Thus, the sub-basin with the largest proportion of the species potential presence should have a high conservation priority. For the representativeness criterion, we used the map of the potential distribution of *B. henni* in binary format (Fig. 1). We decided to use the binary output to make comparisons across sub-basins easier to interpret and to acknowledge the limitations of the methodology. Nonetheless, results of the method using the continuous output can be visualized in Fig. A2. Using the zonal statistics tool of the raster package (Hijmans et al., 2014), we counted the number of cells with suitable conditions for the species within each sub-basin. We then standardized that value by dividing by the maximum value of area inhabited by the species in a sub-basin; thus, the sub-basin with highest inhabited area received a value of one. Values near one represented sub-basins with the greatest area of suitable environments for the species, hence constituting a priority for its conservation.

2.2.2. *Viability*

The criterion of viability is related to the possibility of conservation efforts in a particular area and the potential conflicts of interest. Areas with many conflicts of interest related to conservation will have a low priority. To represent the viability criterion, we used the Global Human Modification of Earth Systems dataset, version one in raster format at a resolution of 30 s (~1 km^2) available at https://sedac.ciesin.columbia.edu/data/set/lulc-human-modification-terrestrial-systems. The human modification layer was created based on nine layers covering human population pressure (population density), human land-use and infrastructure (built-up areas, nighttime lights, land use/land cover), and human access (coastlines, roads, railroads, and navigable rivers). We then determined the average pressure humans exert within each sub-basin using the zonal statistics function. This allowed us to assign a value to each sub-basin that represented the degree of impact. As with the other criteria, we standardized the values by dividing by the maximum value of human pressure in a sub-basin and calculated its additive inverse [1 − (human modification in the sub-basin/sub-basin with greatest human modification pressure)]. This way, the values near zero represented the sub-basins with greatest impact exerted by human pressure, and the values near one represent the sub-basins least impacted by anthropogenic pressures.

2.2.3. *Connectivity*

The criterion of connectivity represents the connection between occupied areas of a planning unit (i.e., sub-basin) to all other suitable areas of all sub-basins in the study area. To estimate connectivity, we used CIRCUITSCAPE 4.0 (Mcrae and Shah, 2011) along with a layer of conductance (i.e., the inverse of resistance) based on the continuous output of the model of potential distribution for *B. henni* (Valencia-Rodríguez et al., 2021). CIRCUITSCAPE calculates connectivity considering all the possible paths, which in many biological systems relates more with movement amongst separate regions (McRae and Beier, 2007; Mcrae and Shah, 2011). We used a scheme of connection under the "one-to-all" model allowing flow from one cell to the four closest ones. As a result, we obtained connectivity values for each planning unit (i.e., sub-basin) to all other units, where the low values represented sub-basins with low connectivity and the highest values indicated the most connected sub-basins.

2.2.4. *Complementarity*

The complementarity criterion refers to sites that contribute to conservation considering the current protected area network. We used information from the national protected areas at a scale of 1:100,000 that were available from the National System of Protected Areas (http://www.parquesnacionales.gov.co). Of the protected areas that make up the National Single Registry of Protected Areas (RUNAP, Spanish acronym), the following categories were included in the analysis: (i) National Natural Parks (PNN, Spanish acronym), (ii) Protected Forest Reserves (RFP, Spanish acronym), (iii) Regional Natural Parks, (iv) Integrated Handling Districts (DMI, Spanish acronym), (v) Soil Conservation Districts, and (vi) Flora and Fauna Sanctuaries. Then, based on the map of protected areas, we generated a raster layer at a resolution of 30 arc sec (~1 km), which we later overlaid with the map of the water courses in the study area. After that, using the zonal statistics function, we determined the area of the hydrological network within the protected areas for each sub-basin. This made it possible to obtain information that was representative of the protected watercourse concerning each sub-basin; in other words, the area of a sub-basin where the water network overlaps with the protected area. Additionally, we standardized by dividing the protected area of each sub-basin by the area of the sub-basin with the greatest protected area and calculated its additive inverse [1 − (sub-basin protected area/sub-basin with greatest protected area)]. Therefore, values near zero represent sub-basins with a greater amount of protected water bodies, while values near one represent sub-basins with a smaller proportion of protected rivers.

2.3. *Prioritization of sub-basins*

We added all the elements from the four criteria yielding a total value for each planning unit between zero and four, where values near four represent the units with a high conservation priority. The values of the resulting map were divided into quartiles, where the two lower intervals were classified as low-priority areas, the next interval contained areas classified as medium-priority, and the upper interval included areas classified as a high conservation priority (López, 2010) (Fig. 2). Additionally, we carried out the same protocol with alternative metrics: i. Using specific information from human-related aspects rather than using the human modification index for the viability criterion (Table A1), ii. Using the continuous rather than the binary output for the representativeness criterion, iii. Standardizing the viability criterion with the proportion of area occupied (map in binary output format) in each sub-basin, iv. Standardizing the viability criterion using the map in continuous output format, and v. Assigning more weight (double) to the criteria of representativeness and viability, since these have been suggested as highly important criteria in the implementation of conservation plans (Sierra et al., 2002).

3. Results

Of the total area available in the basin (110,613 km^2), the water network area (rivers, streams, marshes, and floodplains) occupies 16,444 km^2, with an average of 14.8 % ± 3.3 of the total area across sub-basins (Fig. 3). The area of the water network never occupies more than 40 % of the total area of a sub-basin. On the other hand, we identified that the system of protected areas occupies a total of 8,633 km^2, which

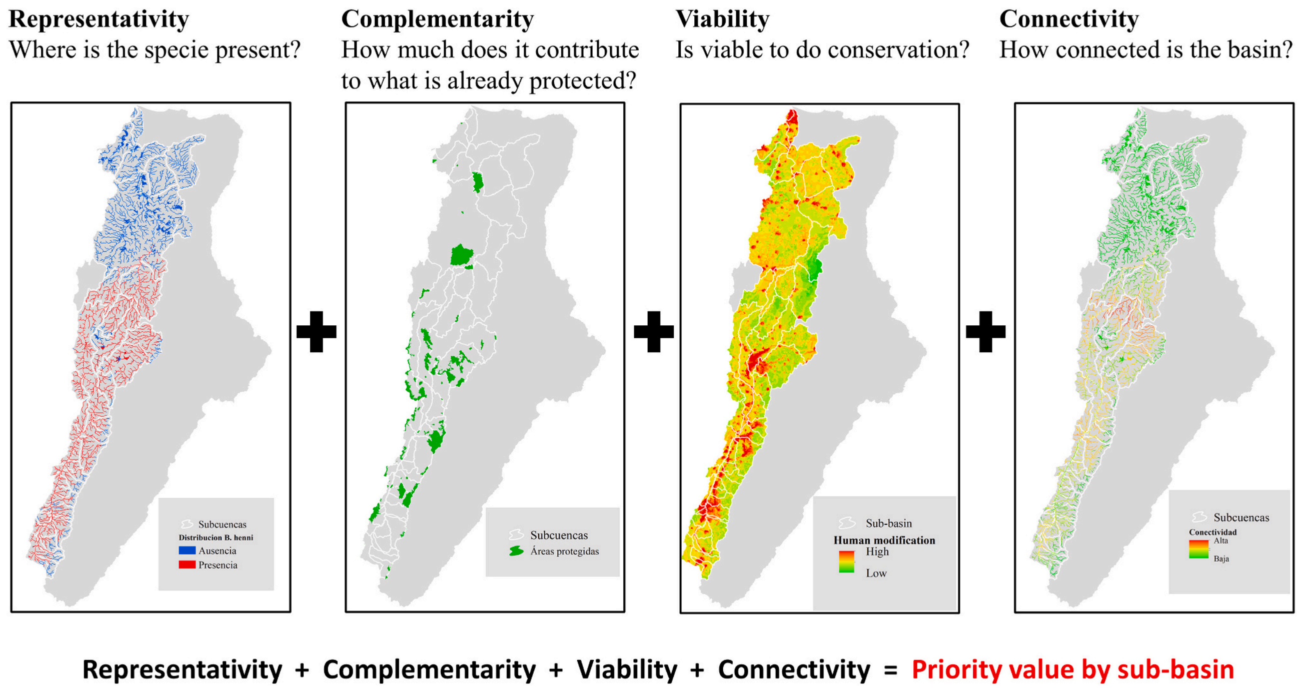

Fig. 2. Representation of the suggested method to prioritize conservation areas for freshwater fish. The planning units (sub-basins) are delineated by white lines. Each of the sub-basins is assigned a quantitative value that represents the contribution of each of the criteria in each sub-basin, and the value obtained from the sum of the four criteria determines the degree of conservation prioritization for each sub-basin.

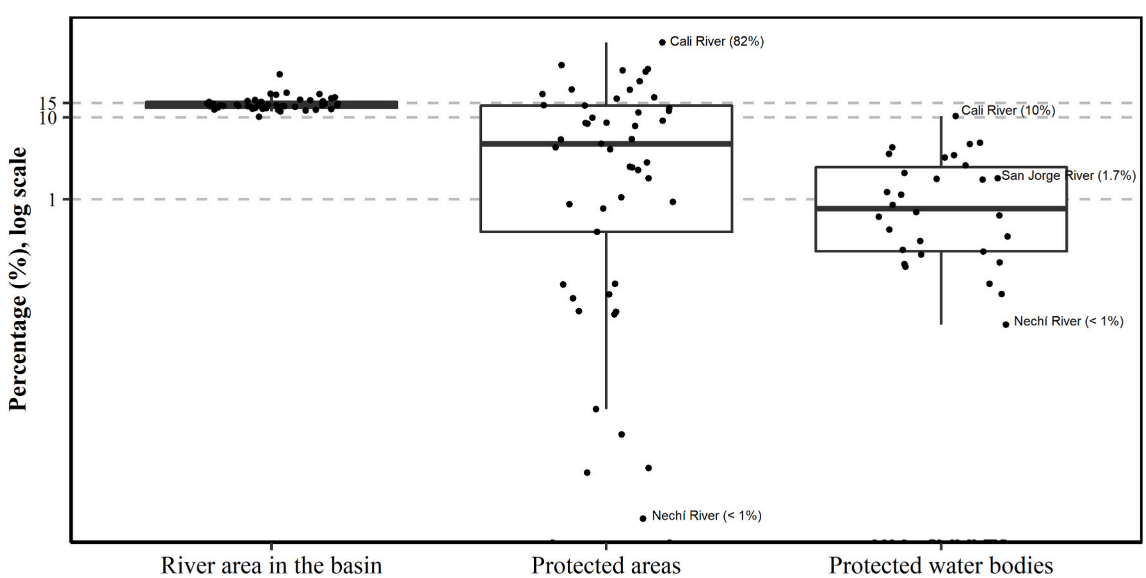

Fig. 3. Current state of conservation and protection of water bodies in the study area – 51 sub-basins. Each point on the diagram represents a sub-basin. The logarithmic scale on the Y axis emphasizes the portion of the figure where most variation exists (i.e., below 10 % of the area), the horizontal lines refer to the percentage of the total area of the sub-basin. Also, highlight some extreme examples of particular sub basins. The protected water bodies parameter corresponds to the percentage of water found within a protected area in each sub-basin.

make up (on average) 10 % of the area of a sub-basin with considerable variation amongst sub-basins (10.2 ± 15.3, mean ± sd; Fig. 3). For example, the Cali River sub-basin has an area of 212 km^2, of which 174 km^2 (82 %) are within protected areas, whereas the sub-basin of the lower Nechí River presents no areas in any category of protection along its 4,492 km^2. Regarding water bodies that are currently within a protection system, we identified an area of 1,134 km^2 which represents (on average) 1 % of the water bodies protected per sub-basin (1.02 ± 1.9, mean ± sd; Fig. 3). The Mojana sub-basin in the lower San Jorge River contains the largest protected area (298 km^2) representing 1.7 % of protected rivers, but the Cali River sub-basin includes the largest area of protected rivers (10 %).

The sum of the four criteria made it possible to organize the sub-basins according to the priority level for conservation of the species (Fig. 4). The greatest contribution amongst the four criteria for most sub-basins was complementarity and viability (Fig. 4). However, there were several particular cases of interest; for example, in the upper Cauca River basin, the sub-basins with high conservation priority had an important contribution regarding connectivity (e.g., Timba and La Vieja Rivers), while several sub-basins in the middle part of the basin were notorious

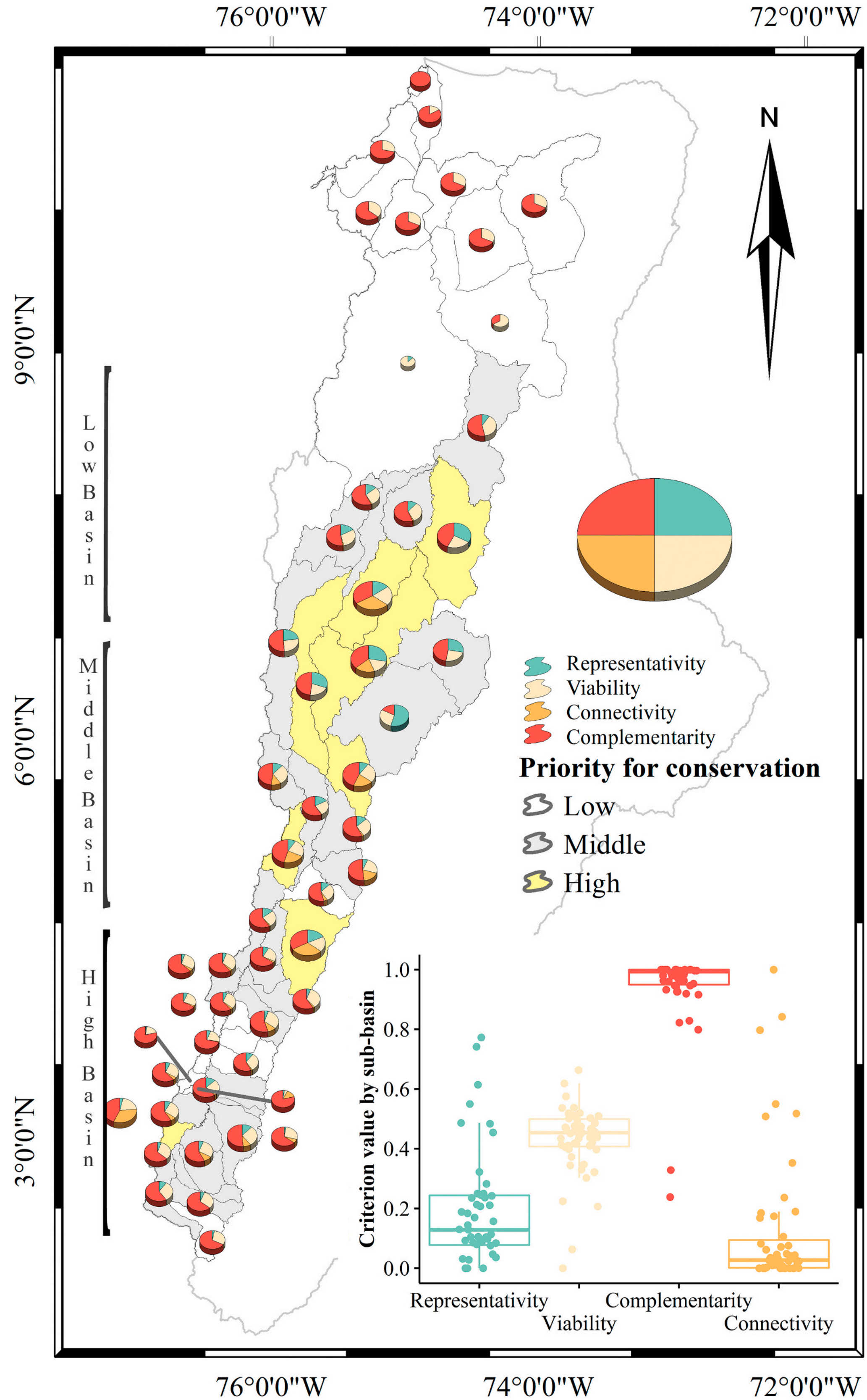

Fig. 4. Contribution and sum of criteria per sub-basin. The size of the pie charts is proportional to the sum of the four criteria. The degree of priority to implement conservation efforts for *B. henni* is represented by white (low priority), gray (intermediate priority), and yellow (high priority). The box plot shows the distribution of values of each criterion for the 51 sub-basins. The shapefile of basins was obtained from IGAC (https://geoportal.igac.gov.co/). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for their representativeness and connectivity (e.g., Risaralda, Arma, and tributaries flowing into the Cauca River between San Juan River and Puerto Valdivia), and in the lower Magdalena-Cauca basin, low conservation priority was influenced by the scarce contribution of representativeness and connectivity criteria. On the other hand, we observed that of the 39 sub-basins that make up the Cauca River basin (~60,165 km^2), eight presented conditions of low conservation priority (10 % of the total area of the Cauca basin). Furthermore, 20 sub-basins (52 %) presented intermediate conditions (~38,764 km^2), and the remaining 11 sub-basins (37 %, ~15,388 km^2) revealed a high priority for species protection. As a result, we observe a corridor of sub-basins with a high conservation priority for *B. henni* along the entire inter-Andean valley (Fig. 4). In other words, a connection of adequate environments was observed for the species along 90 % of the Cauca River basin.

We recommend the protection of nine sub-basins (Fig. 5): (1) the sub-basin of Timba River, which complements the Farallones PNN in Cali, forming a corridor between the Cauca and Pacific basins, (2 and 3) the sub-basins of La Vieja and Risaralda Rivers which connect the middle and upper Cauca basin, and also complement and connect with Los Nevados PNN, Tatamá, the Integrated Handling District of the upper Quindío River in Salento, Campo Alegre, Barbas Bremen, and La Cuchilla del San Juan. In the middle and lower Cauca basin (4, 5, 6, 7, and 8), the sub-basins of the Arma, Porce, and lower Nechí Rivers generate a corridor that connects the upper protected parts of the El Sapo and Hoyo Grande marshes, and the Ayapel wetland complex. The sub-basins of Arma and Risaralda Rivers complement the connection of the middle and upper parts of the Cauca River with the La Cuchilla de San Juan, Cuchilla de Jardín and Támesis Integrated Handling District, which also connect the canyons of the Melcocho River, Santo Domingo, and the Alto de San Miguel (RFP) with the San Nicolás and San Miguel hills (DMI). (9) The sub-basin of San Bartolo River that drains into the Magdalena River generates a corridor that connects the Barbacoas marsh and the Alicante River canyon (DMI).

This spatial prioritization seems robust to slight changes in the input metrics and changes in the weights assigned to each criterion (Fig. A2). In any alternative scenario, at least six of the nine originally proposed sub-basins (66 %) are kept, and four sub-basins (Timba, Risaralda, Arma and upper Nechí Rivers) appear in all alternatives (Fig. A3).

4. Discussion

We present a simple method to identify and prioritize protection areas (sub-basins) for freshwater fish by implementing four criteria: representativeness, viability, connectivity, and complementarity, as well as a proposal to establish protected areas in nine sub-basins for the conservation of Sabaleta (*Brycon henni*), a native species to Colombia. One of the main challenges in the conservation biogeography of freshwater fishes is the improvement of conservation planning strategies (challenge number 10, according to Olden et al., 2010). Although conservation planning guidelines have long existed (Margules and Pressey, 2000), most implementations of these methods have been in terrestrial systems, limiting the conservation of freshwater organisms to the priorities of land biodiversity protection (Abell et al., 2007; Nel et al., 2009). Despite important conservation efforts of freshwater bodies and their associated biodiversity (i.e., Jaramillo et al., 2015), our results emphasize worrying gaps and important opportunities of complementing the current protected area network with a more comprehensive strategy based on explicit criteria directed toward the conservation of freshwater organisms.

The methodology proposed in this study could be sensitive to changes in any of its incomes including the focal species, the data supplied to establish the criteria, and the relative weight of each criterion. The debate on whether to implement single vs multiple species approaches in conservation is old (Beier, 2009; Block et al., 1995; Correa Ayram et al., 2019; Lambeck, 1997) and is justified on economy (i.e., shortage of funding to protect biodiversity) and urgency, rather than on knowledge that the majority of species respond in a similar fashion. For example, if we were to choose Andean species with a highly restricted range, the challenges faced by each one would differ. We encourage exercises with both approaches as long as there is high quality available data to implement them. We included various methodological alternatives to assess sensitivity of our results to modifications of the income data and changes in the relative weight given to each criterion. Supplementary Fig. A2 shows how spatial prioritization changes with slight modifications of the protocol. In general, there are important changes to the original proposal, for example, addition and exclusion of sub-basins (Fig. A2). Nonetheless, various sub-basins remain with high conservation priority despite alternative strategies and four sub-basins (Timba, Risaralda, Arma and upper Nechí Rivers) appear in all alternatives (Fig. A3). This information in itself can be used to guide conservation decisions. Additional incomes might be considered in single species approaches such as information about abundance, and in multiple species approaches, phylogenetic and functional information may also be included (Strecker et al., 2011; Stuart-Smith et al., 2013).

The four criteria implemented in the methodology proposed are standard in conservation planning (Harris et al., 2019), but its relative importance may vary depending on each situation (Zhu et al., 2021). In our case, the results indicate that the criteria with the greatest contribution were complementarity and viability, while the criteria with the largest variances were representativity and connectivity (Fig. 3). Given the extremely poor coverage of freshwater systems in the current protected area network (Fig. 2), the complementarity criterion is expected to contribute largely in most if not all sub-basins, and thus might not be a highly informative criterion in this particular case (Fig. A4). We do not expect all four criteria to be useful in all situations, and the relative weight of each could be modified accordingly. For *B. henni*, we believe representativity, viability and connectivity were all informative criteria and should be maintained. For example, Timba, La Vieja River and upper Nechí sub-basins contribute to connectivity; while Porce, lower Nechí and Nare River did it for representativeness, and in the case of viability Taraza, Arma River and San Juan sub-basins. These criteria allow the identification of corridors of environmentally similar habitats that maintain (and may help restore) the connections between sub-basins (Correa Ayram et al., 2019; Mohammadi et al., 2022). On the other hand, the extent and resolution of spatially explicit information can also affect decisions (Du Toit, 2010) and it is important to adjust the scale of the planning exercise to the biology of the organisms. However, this is still a significant challenge since, for a single organism, certain aspects, such as connectivity, can be handled on a certain scale, while other aspects, such as reproduction, may require the use of different scales (Schneider, 2001). Therefore, we suggest conducting sensitivity analyses that make it possible to establish which supplies are relevant and at which scales, as well as explaining why they were used.

The effectiveness of a protected area greatly depends on those involved in its delineation and meeting these conservation objectives depends on the participation and commitment of the local population, the managers, and the academics (Somuah et al., 2021). Therefore, we consider this proposal to be a good starting point to initiate the dialogue and agreement amongst actors (human population, state holders, government authorities, and the academy) regarding the protection of aquatic systems and their species. It is necessary to establish legislative regulations and policies that are more closely in accordance with conservation strategies oriented toward freshwater systems, allowing rivers to maintain their functionality to support the populations of freshwater species, without hindering their use by local communities (Abell et al., 2007). A few examples include the proposal for quantitative conservation targets, which allows to select areas that meet these objectives (Chávez González et al., 2018; Rondinini and Chiozza, 2010), the implementation of a system of protected areas that is specific for freshwater fish and includes areas for protection, management, and fishing (Abell et al., 2008), and the implementation of connectivity measures oriented toward fluvial networks (Hermoso et al., 2011;

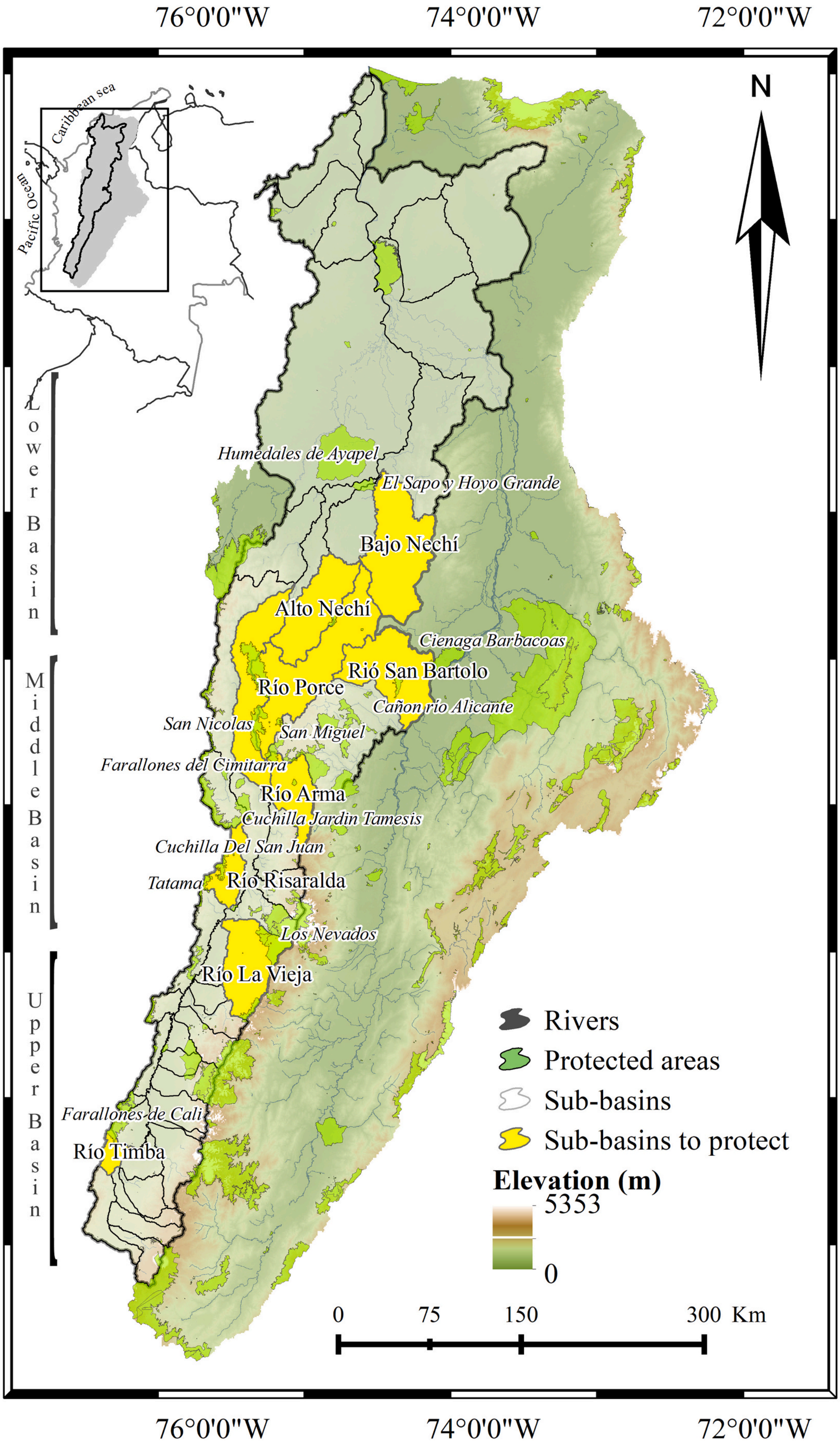

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Fig. 5. Sub-basins with a high conservation priority. The nine sub-basins identified as high priority for the implementation of conservation strategies for *B. henni* are delineated and named in yellow. The names of the protected areas that complement the proposal are in cursive. The digital elevation model (SRTM, 1 arc sec) was obtained from USGS Earth Explorer (https://earthexplorer.usgs.gov), the shapefiles of rivers and basins were obtained from IGAC (https://geoportal.igac.gov.co/), and that of national protected areas was obtained from http://www.parquesnacionales.gov.co. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Moilanen et al., 2008).

In our study, we used *B. henni* as a model system to promote protection strategies for freshwater organisms. The Sabaleta is widely distributed along the Andean mountains, and it is important for subsistence fishing and feeding; its protection would promote the presence of protein in the diet of the inhabitants of the upper mountain region, the economy of the fishing population, and recreational fishing in this region (Jiménez-Segura et al., 2016). It would be a challenge to protect an entire sub-basin without considering the needs of its inhabitants; thus, conservation strategies must be implemented that both protect and allow a certain amount of use (Abell et al., 2007). Freshwater systems face inherent challenges, such as those caused by hydroelectric power plants (Finer and Jenkins, 2012) and by the exploitation or use of natural resources for human subsistence (Boron et al., 2019; Castiblanco et al., 2013), which are especially difficult to handle considering protected areas allow no human intervention (Abell et al., 2008). Some of the conservation efforts for this species have suggested to conduct reintroductions, but these proposals are expensive, tedious, and ineffective (Mancera-Rodríguez, 2017). Little has been done to promote in-situ protection, as reflected in the national system of protected areas (Parques Nacionales Naturales, 2019; Fig. 3). Thus, we believe that complementing the system of protected areas with methodological proposals such as presented in this document would improve the system and contribute to conserving and protecting rivers and streams along the basin. The suggested guidelines for the methodology proposed in this study promote connectivity amongst sub-basins, and would result in the protection of a considerable percentage of freshwater fish, slightly over 70 % of the diversity of fish species in the macrobasin and which co-occur with this species (Jiménez-Segura et al., 2016; Román-P et al., 2014).

The main objective of this proposal was to identify conservation areas for a single freshwater fish species. As a result, many solutions could arise, with varying spatial configurations, providing design options that meet both ecological and socioeconomic objectives; for example, the development of mechanisms that ensure that hydroelectric plant operations keep their commitments in a responsible manner, thus, guaranteeing conservation strategies while balancing economic development (Ascher, 2021). Considering our analysis, we suggest the protection and conservation of nine sub-basins as strategic river corridors that would promote the connection between aquatic systems and the areas that are currently protected by the national parks system. Although this focus could connect highlands with floodplains; it is crucial to conduct this same protocol with multiple species, including migratory fish, due to their abundance and production, they are of great social, economic, and cultural importance (López-Casas et al., 2016; The Nature Conservancy et al., 2014). Finally, we conclude that despite the limitations, our work not only provides useful information for the ecological planning of water bodies, but also provides a replicable spatial approach, and its products can serve as key information for decision-making about biodiversity conservation.

CRediT authorship contribution statement

Daniel Valencia-Rodríguez: Conceptualization, Methodology, Formal Analysis, Data Curation, Writing-Review and Editing. **Luz Jiménez-Segura**: Resources, Supervision, Writing-Review and Editing, Project Administration. **Carlos A. Rogéliz**: Conceptualization, Writing-Original Draft Preparation. **Juan L. Parra**: Conceptualization, Investigation, Methodology, Supervision, Resources, Writing-Review and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109672.

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