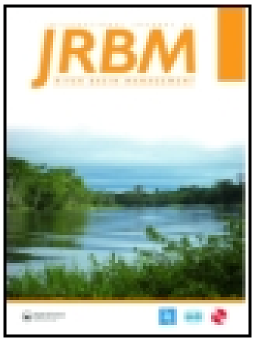

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RESEARCH PAPER

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Target species selection and design of fish habitat suitability curves in the Ayuquila-Armería River, western Mexico

Demetrio Meza Rodríguez [a], Luis Manuel Martínez Rivera [a], Norman Mercado-Silva [b], Diego García de Jalón Lastra[c], Carlos Alonso González [a] and Ángel Aguirre García[a]

[a]Departamento de Ecología y Recursos Naturales, Universidad de Guadalajara, Autlán de Navarro, México; [b]Centro de Investigación en Biodiversidad y Conservación, Universidad Autónoma del Estado de Morelos, Cuernavaca, México; [c]Escuela de Ingenieros Forestales y del Medio Natural, Laboratorio de Hidrobiología, Universidad Politécnica de Madrid, Madrid, España

ABSTRACT
The implementation of hydroecological models requires an understanding of the biological attributes and habitat requirements of the local stream fauna. We describe a procedure for selecting target (fish) species and calculating habitat fitness curves based on depth and velocity and substrate type data in the Ayuquila-Armería river in central-western Mexico. The selected target species were *Sicydium multipunctatum*, *Agonostomus monticola* and *Allodontichthys zonistius*, and selection of these species was based on their endemism, vulnerability and sensitivity. Eighty-four samples from nine sites monitored over 14 years were used to calculate category III univariate curves. The suitability curves proposed for each target species describe their habitat suitability values in terms of depth (m), velocity (m s^{-1}) and substrate type (mm). These curves allow the construction of eco-hydraulic models necessary to define the minimum ecological flow in the Ayuquila-Armería river.

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Ecological flow; aquatic habitat; univariate curves; *Sicydium multipunctatum*; *Agonostomus monticola*

1. Introduction

Freshwater species are non-randomly distributed among the different habitats of a river, preferentially occupying areas that are suitable for feeding, reproduction and survival (Grinnell, 1917; Hutchinson, 1957; Karr et al., 1983). This constitutes the basis for the development of predictive models of species distribution across environmental gradients (Ahmadi-Nedushan et al., 2006). However, the efficiency of such models depends on our knowledge of the response of species to these gradients. This specific information can be analyzed through the development of habitat suitability criteria based on different factors (for example, depth, velocity and substrate type) (Bovee, 1982, 1986). Suitability criteria help to evaluate the degree of preference for different habitats exhibited by a particular species (Bovee et al., 1998). Efforts to develop habitat suitability criteria for multiple species have increased as a result of the degradation of water resources and growing concern regarding biodiversity loss (Bovee, 1986; Bovee et al., 1998; Hirzel & Le Lay, 2008; Lamouroux et al., 1999; Leonard & Orth, 1988; Macura et al., 2018; Mayo et al., 1995; Milhous et al., 1981; Muñoz-Mas et al., 2012, 2014; Rodrigues et al., 2013; Stalnaker, 1979; Strakosh et al., 2003; Teresa & Casatti, 2013; Vadas & Orth, 2001; Vilizzi et al., 2004).

Habitat suitability criteria constitute a fundamental component of many hydroecological methods (Stalnaker et al., 1995). Currently, one of the most recognized methods is the Instream Flow Incremental Methodology (IFIM) for quantification of fish habitat as a function of water flow (Armour et al., 1984; Bovee et al., 1998; Bovee & Milhous, 1978; Glova, 1988; Stalnaker, 1979). IFIM includes the development of hydraulic and habitat simulation models based on depth, velocity, shear stress, roughness, channel size and movement. The models of habitat requirement are also known as indices of habitat suitability. In particular, the suitability of habitat traits to the habitat requirements of the target fish can be expressed in the form of suitability curves (Bovee, 1982; Bovee et al., 1998; Milhous et al., 1981; Orth & Maughan, 1982; Waters, 1976). Waters (1976) first suggested the use of continuous curves representing suitability in an index with a range from 0 to 1, representing minimum and maximum suitability, respectively. Since then, habitat suitability curves (HSC) have become by far the most common method employed in studies related to the simulation of physical habitat (Payne & Allen, 2009).

The term generally accepted by Orth and Maughan (1981) and Bovee (1986) is 'habitat suitability curve', but there are several different references in the literature that relate to this concept, including habitat preference by Briggs (1953), physical criteria by Chambers et al. (1955), table of standards or norms by Westgate (1958), probability of use by Bovee and Cochnauer (1977) and preference curve by Bovee (1982). Nestler et al. (2019) describe the origin and meaning of the habitat suitability curve. The present study uses the term 'habitat suitability curve'.

Suitability curves are usually grouped into four categories (Tharme, 2003). Category I suitability curves are based on expert judgment or on literature review of fish habitat requirements (Bovee, 1986; Bovee et al., 1998; Mohedano, 2008; Scheele, 1975; Zuboy, 1981). Those of category II (known specifically as habitat suitability curves) are based upon frequency of use by fish for habitat variables and are obtained by measurement of habitat attributes in points occupied by the organisms through field sampling efforts that must represent an equal proportion of the different habitat types present (Bovee, 1986; Bovee et al., 1998; Collings et al., 1972; Johnson, 1980; Waters, 1976). Category III suitability criteria come from habitat use data corrected by habitat availability for the target species. These are also known as

CONTACT Luis Manuel Martínez Rivera lmartinez@cucsur.udg.mx

habitat preference curves, since the use is weighted according to habitat availability in the ecosystem (Bovee et al., 1998; Manly et al., 1993; Martínez-Capel & García de Jalón, 1999). Curves in category IV reflect the synergy among two or more variables, since the habitat preferences of individual species can change when considering two variables together (Hamilton & Nelson, 1984; Mayo et al., 1995; Valdez et al., 1990).

Suitability curves are expressed as suitability functions, which can be classified into four indices: (1) binary (Bovee et al., 1998), (2) univariate (Waters, 1976), (3) multivariate (Boavida et al., 2014; Pouilly et al., 1994) and (4) fuzzy rule-based (Adriaenssens et al., 2004; Jorde et al., 2001; Mouton et al., 2008; Silvert, 2000). Of these, the univariate indices proposed by Waters (1976) have become the most widely known and utilized criteria worldwide (Bovee et al., 1998), although development of these indices in Latin America is still incipient.

Recently, Mexico published the Mexican official norm NMX-AA-159-SCFI-2012, which defines the procedure for determination of ecological flows in hydrological basins. The norm incorporates a hydrobiological methodology through habitat simulations, in order to define the minimum ecological flow from a study of all habitat factors and conditions for one or several target species of the fluvial ecosystem (DOF, 2012). The first step in the habitat simulation procedure is selection of the target species. While this may seem straightforward, suitable species selection can depend on a range of factors (*e.g.* biological parameters, economic importance and the availability of pertinent data), and it is important to have a clear process of data selection.

The Ayuquila-Armería River is one of the most important in western Mexico (Graf et al., 2006; Martínez et al., 2000). Its location in the transition zone between the Nearctic and Neotropical biogeographic regions confers particular biological characteristics (Jardel et al., 1996). The river hosts more than 29 native fish species, of which 15 are found within the Sierra de Manantlán Biosphere Reserve (SMBR) and three are endemic to Mexico (Santana et al., 1993). Among other factors, deviation and retention of the water have affected the biota of the river (Lyons & Navarro-Pérez, 1990; Santana et al., 1993).

Considering the normative requirements described above and utilizing the knowledge that already exists regarding the ichthyofauna of the Ayuquila-Armería River, we used field data gathered over a period of 14 years to construct category III habitat suitability curves. Derived from frequency analyses of field data, these curves are fitted to a frequency histogram, with each curve describing the observed utilization of a habitat variable for the selected species. The results serve as a basis for an eco-hydraulic design to estimate the minimum ecological flow in the Ayuquila-Armería River.

2. Materials and methods

2.1. Study area

The Ayuquila-Armería River (States of Jalisco and Colima, Mexico; 18°51'05″–20°28′03″N, 104°38′17″–103°34′41″W) (Figure 1) drains 9864 km^2 of very mountainous terrain with average annual precipitation and temperature values of 836 mL and 21°C, respectively. The river is 321 km in length and presents an extremely variable flow, but one that remains permanent throughout the year (Meza-Rodríguez et al., 2017a, 2017b).

2.2. Sampling and selection of target species

2.2.1. Sampling

Target species were selected based on information contained in the databases of the project 'Manejo y Conservación de los Recursos Naturales de la Cuenca del Río Ayuquila-Armería' at the Ecology and Natural Resources Department, Universidad de Guadalajara (L.M. Martínez, coauthor). This project was conducted with information generated in the field, implementing a standardized sampling method over the period 1998–2011. For the present study, we used data from 78 field trips conducted bimonthly (Dry season – February, April, June, December; Rainy season – August, October), and six sampling trips outside of the periods defined above, in nine permanent sites that covered 70 kilometres of the course of the river (Figure 1).

The field sampling utilized various techniques to capture fish (mainly using a gill net of 2 m in width and 5 m in length) along a 150–200 m length of the river at each of the sampling sites. In each case, all the available habitats (riffle, rapids, pools, backwater and turbid waters) at the site were sampled for a period of approximately one hour using the method of equal effort (Petrere *et al.* 2010). The captured fish were identified *in situ*, recorded and released. In general, these captured specimens varied in size (total length) from 30–350 mm, while their abundance in the samples was considered to reflect their abundance in the communities (Juncos et al., 2006). In this study, we did not consider fish size classes; however, the range of sizes of three species was relatively narrow.

In each site and sampling event, measurements were taken of depth (m) and the average flow velocity (± 0.1 m s^{-1}) (with a *Global Water* FP111 flow probe) at 0.6 times the depth of the water, as established by Chow (1959). The dominant granulometry was specified per site using a transect perpendicular to the flow direction, from one side of the river to the other. Substrates were classified according to the American Geophysical Union, silt (<0.062 mm), sand (0.062–2 mm), fine gravel (2–8 mm), coarse gravel (8–64 mm), cobbles (64–256), boulder (256–1024 mm), rocks (>1024 mm), bedrock (continuous rock), translated by García de Jalón and Schmidt (1995) and Martínez-Capel and García de Jalón (1999).

2.2.2. Target species selection

Some water bodies harbour several species that can be considered as target species; in some cases, all species show similar suitability curves and any of these species could represent the habitat requirements of all other species, since the difference in values between alternatives is low. However, in other cases, multiple species show different suitability curves and it is therefore difficult to select target species to represent all of the community requirements. Selection of the target species should be attributed to native species, especially where these are autochthonous, endemic, endangered, vulnerable, sensitive or of special interest (Bovee, 1986; Freeman, 1998).

The aptitude of a species for use as a target species also depends on its life history and on the knowledge of its requirements (e.g. feeding, growth, reproduction and habitat) (Bain & Meixler, 2008). In addition, selected target species should be sufficiently common in the field records, and we

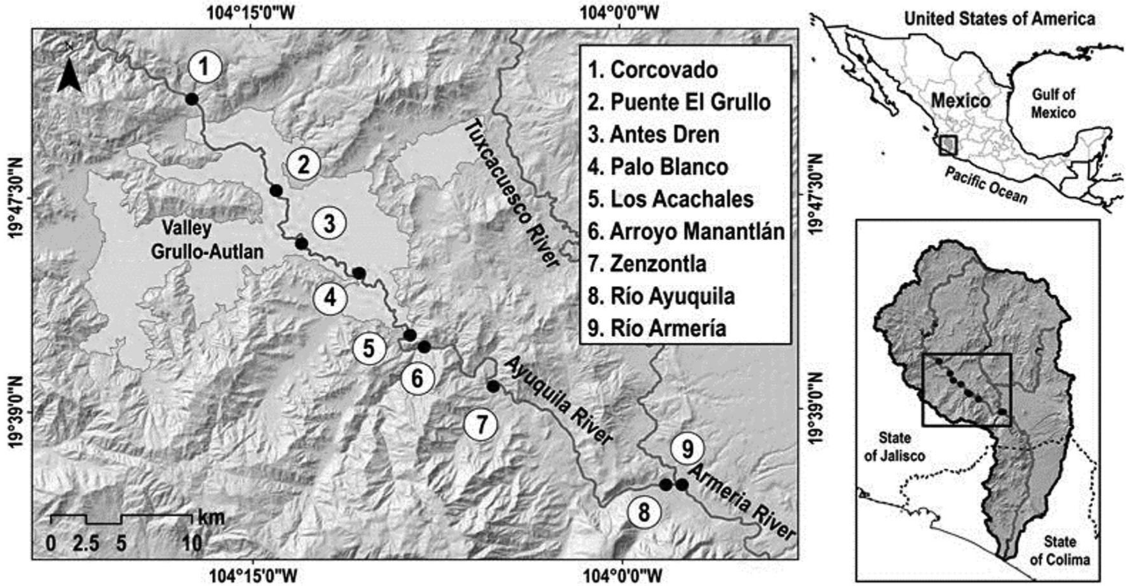

Figure 1. The Ayuquila-Armería River basin (States of Jalisco and Colima), Mexico. Sampling sites are labelled 1–9.

therefore only considered those that exceeded 150 individuals collected over all of the field trips. This threshold is necessary in order to allow frequency analyses (Bovee et al., 1998).

2.3. Construction of suitability curves (Category III)

Once the target species were selected, three suitability curves were constructed for each species based on the habitat variables of depth, velocity and substrate type. For this, and based on the information obtained from fieldwork, we analyzed the data distribution for each habitat variable, that was the base used to construct the availability curves. The first step was to divide the range of values found into intervals, using the formula of Sturges (1926) and an analysis of the frequency (F*j*) for each. For each interval class, *j* was carried out. Classification of the substrates utilized the categories according to García de Jalón and Schmidt (1995) and Martínez-Capel and García de Jalón (1999), as described above.

The index of availability (Id_j) was calculated by aggregating the sites occupied and unoccupied by the species for each interval in the ratio between the weighted frequency of the class F_j and the sum of the weighted frequencies for all classes (ΣFj). The result was normalized, obtaining values in a range from zero to one, the graphic representation of which provided the habitat availability curve for each variable (Martínez-Capel & García de Jalón, 1999).

Once the quantity of available habitat and variability for each parameter were determined, the frequency of use of these habitats by the target species was analyzed. The index of use (Iu_j) was established by grouping the sites where the target species were recorded (Bovee et al., 1998). To calculate the Iu_j for each interval; Iu_j= number of individuals (*e.g.* fish of a species) associated with the class *j* divided by the total number of individuals of the same species collected during fieldwork. This value was normalized, producing values ranging from zero to one (García de Jalón & Schmidt, 1995).

These two indices were defined within the representative river section, corresponding to 70 km of the Ayuquila-Armería River, along which the nine field sites were distributed. Within this stretch of the river, the selected target species can be considered representative of the study area (D. García de Jalón, *pers. comm.*).

To estimate the index of suitability (IS) for category III curves, we calculated he relationship between the proportional use of the habitat (Iu_j) and habitat availability (Id_j), through the (Iu_j / Id_j) ratio method, the ratio was calculated within each class (range) of a variable, considering the proportion at which this class is utilized and the percentage of the available environment it represents. With this ratio, the IS was obtained (Bovee et al., 1998; Martínez-Capel & García de Jalón, 1999). The IS was normalized (by dividing the value of each class by the highest value within all classes), with values ranging from zero (minimum value, unacceptable) to one (maximum value, suitable), and its graphic representation defined the suitability curve for each species.

3. Results

3.1. Samples

Fifteen species of fish (of nine families) were identified (Table 1) from a total of 73,023 individuals captured during all sampling periods. Only juveniles and adults were included. The highest number of individuals belonged to the family Poeciliidae, while Ictaluridae and Cyprinidae presented the lowest number of individuals collected (Table 1).

The most abundant species were *Ilyodon furcidens* and *Poecilia butleri* (92% of the total of the individuals collected). The species with the lowest number of individuals collected were *Ictalurus dugesii*, *Awaous banana*, *Algansea aphanea*, *Poeciliopsis infans*, *Xenotoca melanosoma*, *Moxostoma austrinum* and *Goodea atripinnis*. The sites with the highest number of individuals were Los Acachales, Palo Blanco, and Puente El Grullo. The sites with the lowest number of individuals were El Corcovado and Zenzontla (Table 1).

Along the 70 km length of the representative stretch of river, three endemic species were identified: two at national level, *A. aphanea* and *G. atripinnis*, and one at regional level, *Allodontichthys zonistius*. This latter species has only been recorded in the rivers Ayuquila-Armería and

Table 1. Number of fishes captured in each sampling site during long-term monitoring of the river Ayuquila-Armería (1998–2011).

Sampling site	El Corcovado	Puente El Grullo	Antes dren	Palo Blanco	Acachales	Antes Manantlán	Zenzontla	Río Ayuquila	Río Armería	Total
Family/Species										
Catostomidae										
Moxostoma austrinum Bean, 1880	9	1	0	0	0	12	4	8	8	42
Characidae										
Astyanax cf. aeneus Günther, 1860	21	218	13	12	62	319	325	478	230	1678
Cichlidae										
Nandopsis istlanum Jordan and Schneider, 1899	7	18	0	0	11	2	28	34	40	140
Cyprinidae										
Algansea aphanea Barbour and Miller, 1978	0	0	0	0	0	0	0	12	0	12
Gobiidae										
Sicydium multipunctatum Regan, 1905	0	0	0	0	0	13	108	21	25	167
Awaous banana Valenciennes, 1837	0	0	0	0	1	0	1	1	0	3
Goodeidae										
Allodontichthys zonistius Hubbs, 1932	79	62	22	2	37	105	119	125	119	670
Goodea atripinnis Jordan, 1880	0	1	0	26	17	0	0	0	0	44
Xenotoca melanosoma Fitzsimons, 1972	1	5	5	7	71	0	1	2	5	97
Ictaluridae										
Ictalurus dugesii Bean, 1880	6	0	0	0	0	0	3	0	1	10
Mugilidae										
Agonostomus monticola Bancroft, 1834	32	4	2	6	7	95	58	48	105	357
Poeciliidae										
Ilyodon furcidens Jordan and Gilbert, 1882	1126	6167	2187	1100	4865	6166	1842	3107	2913	29,473
Poeciliopsis baenschi Meyer, Radda, Riehl and Feichtinger, 1986	43	213	372	12	327	5	148	1373	241	2734
Poecilia butleri Jordan, 1889	850	4035	6834	10,560	11,327	422	558	1830	1155	37,571
Poeciliopsis infans Woolman, 1894	0	2	0	0	0	0	0	15	8	25
Total	2174	10,726	9435	11,725	16,725	7139	3195	7054	4850	73,023

Coahuayana (Lyons & Mercado-Silva, 2000). The three described above and twelve native species were identified, including *Agonostomus monticola, A. banana, Astyanax cf. aeneus*, *I. dugesii*, *M. austrinum*, *Nandopsis istlanum*, *Sicydium multipunctatum*, *P. infans*, *X. melanosoma*, *I. furcidens*, *P. butleri* and *Poeciliopsis baenschi* (Table 1).

3.2. Target species selection

Three species were selected for being native, endemic and indicators of good water quality, as well as for their migratory characteristics and good representation of the characteristics of the native species of the basin. These selected species were *Sicydium multipunctatum*, *Agonostomus monticola* and *Allodontichthys zonistius*.

Sicydium multipunctatum: This species belongs to the family Pisces: Gobiidae and its common name is the multi-spotted goby (Castro-Aguirre et al., 1999; Rush, 2009). It is a native species that reaches a size of (±) 250 mm. Its habitat is rocky rapids with boulders, in both high and low areas and in clear waters. It is fast and located among the rocks at a depth of up to around 2 m (Carr & Giovannoli, 1950; Lyons & Mercado-Silva, 1999; Rush, 2009). Its main characteristic is that it is a diadrome fish, in which all stages of the life cycle, except the larval stage, take place in freshwater (Rush, 2009). Sicydium goby are sensitive to environmental degradation and is a good indicator of environmental quality (Lyons, 2005; Lyons *et al.* 1995).

Agonostomus monticola: This species belongs to the family (Pisces: Mugilidae) and its common name is mountain mullet. It is a native species that reaches a size of (±) 360 mm (Anderson, 1957; Espinosa-Pérez et al., 1998; Fischer et al., 1995; Rush, 2009; Torres-Navarro & Lyons, 1999). It is a catadromous species, the juveniles and adults inhabit the rivers in which they feed, gain weight and begin sexual maturation, then go to the sea to reproduce (Anderson, 1957; Carr & Giovannoli, 1950; Castro-Aguirre et al., 1999; Torres-Navarro & Lyons, 1999). The species feeds opportunistically and is mainly carnivorous. It eats crustaceans, various insects (especially aquatic) and algae (Torres-Navarro & Lyons, 1999). Its habitats are the rapid currents of rivers with rocky substrates and well-oxygenated, turbulent water. Its niche seems to be 'eddies, with strong currents and large boulders' and it is a rheophilic species (Anderson, 1957; Carr & Giovannoli, 1950; Lyons & Mercado-Silva, 1999; Rush, 2009) This species spawns at sea, where the juveniles stay until reaching 30–35 mm in length, when they return once again to the mountains of the basin (Anderson, 1957).

Allodontichthys zonistius: This species belongs to the family (Pisces: Goodeidae) and its common name is bandfin splitfin. It is an endemic benthic carnivorous species, with a status of vulnerable-endangered in the Ayuquila-

Armería River (Lyons & Mercado-Silva, 1999, 2000; Lyons & Navarro-Pérez, 1990; Rush, 2009; Webb, 2002). The species reaches a size of (±) 70 mm, and members of its genus are bottom-dwelling fish; they have adapted to live on rocky bottoms through a reduction of the bladder and modification of their body shape (Lyons & Mercado-Silva, 2000). The habitat in which it develops are areas of rapids with clear waters, on gravel bottoms with rocks and boulders, reaching depths of up to 1.0 m, but usually 0.5 m or less, and with flow velocities of between 0.50 and 0.70 m s^{-1}. The species avoids flow velocities higher than 0.75 m s^{-1} (Lyons & Mercado-Silva, 2000; Lyons & Navarro-Pérez, 1990; Miller & Uyeno, 1980). The species requires good water quality, with at least 3 mg/L of dissolved oxygen. The species is a good indicator of environmental quality, since its presence implies that the environmental quality is good (Lyons & Mercado-Silva, 2000).

3.3. Use and availability of habitat (Category III curves)

For the species *S. multipunctatum*, the curves of use and the habitat availability related to depth coincided at 0.43 m. At depths <0.33 m and >0.60 m, this species appeared low in the index of availability. The index of fish use and habitat availability related to water velocity for S. *multipunctatum* coincided with an optimum value of 0.71 m s^{-1}; at velocities <0.55 m s^{-1} and >0.80 m s^{-1}, the index of use decreased relative to the velocity (Figure 2).

The highest habitat availability and use of habitat related to depth for *A. monticola* was found between 0.40 and 0.50 m, with use decreasing considerably at depths greater than 0.80 m. *Agonostomus monticola* was found in sites with flow velocities of between 0.40 and 0.50 m s^{-1}. At <0.25 m s^{-1} and >0.90 m s^{-1}, the index of use decreased relative to velocity. The availability of optimum flow velocity for *A. monticola* peaked between 0.25 and 0.40 m s^{-1}. Velocities of <0.25 and >0.74 m s^{-1} decreased the habitat availability compared to velocity (Figure 2). The highest flow velocity for *A. monticola* was 1.21 m s^{-1}.

The *A. zonistius* curves of use and availability coincided at a depth of 0.46 m. The index of use for depth decreased at depths <0.27 m and >0.70 m. In the index of flow velocity for this species, the optimum value was 0.46 m s^{-1}. At flow velocities <0.13 and >0.76 m s^{-1}, the index of use and availability for velocity decreased (Figure 2).

Sicydium multipunctatum was found predominantly among boulders (of diameter 256–1024 mm) and presented an index of availability corresponding to fine gravel (2–8 mm) (Figure 2). *Agonostomus monticola* was generally found on cobble (64–256 mm) and boulder (256–1024 mm) substrates and had an index of availability dominated by silts (<0.062 mm). The indices of use and availability for *A. zonistius* coincided with the boulder category.

3.4. Habitat suitability curves (Category III)

For *S. multipunctatum* were similar to those of use and availability for depth (0.43 m) and velocity (0.71 m s^{-1}) (Figure 3); the intervals of suitability for species varied with depth (0.43–0.87 m) and velocity (0.56–0.90 m s^{-1}).

The depth suitability curve of *A. Monticola* included zones from 0.73 to 0.87 m, which were deeper than the areas found using the curves of use and availability. The velocity suitability curve for this species also identified zones of greater velocity (of between 0.74 and 0.90 m s^{-1}) than the curves of use and availability. The suitability curves for *A. zonistius* indicated suitable habitats for this species at a depth of 0.56 m and flow velocity of 0.56 m s^{-1} (Figure 3).

Regarding substrate selection, the suitable habitat for *S. multipunctatum* was located on coarse gravel (8–64 mm), with adequate conditions of suitability also found among rocks and boulders. The least optimal substrates were defined as silts, sands (<0.062–2 mm) and fine gravel (2–8 mm) (Figure 3). *Agonostomus monticola* finds a suitable substrate in areas of boulders (256–1024 mm), with adequate conditions of suitability in cobbles (64–256 mm), and with the least suitable substrates including silts, sands, fine gravel and coarse gravel (8–64 mm) (Figure 3). For *A. zonistius*, the suitable substrates were cobbles (64–256 mm), with appropriate conditions of suitability on coarse gravels and boulders, while the least suitable categories were silts, sands and fine gravels (Figure 3).

4. Discussion

This is one of the first studies to identify Neotropical fish species for the purpose of research related to ecological flows in Mexico. The use of the proposed curves of habitat suitability may not be limited to predictive models of eco-hydraulic simulation in aquatic environments in Mexico, since the information of the target species found in this study will be valuable for future ecohydraulic modelling along the coastline (Atlantic; southeast of North Carolina in the USA to the south of Venezuela, and Pacific; close to Mazatlán, in Sinaloa, Mexico, to the south of the Choluteca river basin in Honduras) where these species develop (Rush, 2009). It will also contribute to the improved conservation of aquatic resources in Latin America through the estimation of ecological flows from a more ecological perspective. However, our results must be used carefully in terms of their transferability to other areas.

It is important to clarify that it is not recommended to use criteria designed in one basin to define the criteria of ecological flows in another (Bovee, 1986). For example, the suitability curves of the species *A. monticola* and *S. multipunctatum* could be used in basins with similar characteristics to those of the Ayuquila-Armería River, but it is recommended to conduct studies of the transferability of all of these characteristics to other basins from a regional perspective, such as the studies conducted by Thomas and Bovee (1993), Freeman et al. (1997), Teresa and Casatti (2013), and Papadaki et al. (2017). Suitability curves could be validated in similar fluvial systems that contain the same species and present a similar flow regime (Parasiewicz et al., 2013).

One important contribution of this study is the identification of *P. butleri, G. atripinnis* and *X. melanosoma*, which are ecologically important species within the river. However, their relationship with the flow dynamic is relatively low (by preferentially inhabiting environments of slower flow velocity) (Rush, 2009; Soto et al., 1998), or they present low specificity for some of the variables (depth, velocity, substrate type, dissolved oxygen, turbidity, salinity) (Flores-Kehn et al., 2008), which would limit their utility in future proposals of ecological flows in Mexican rivers.

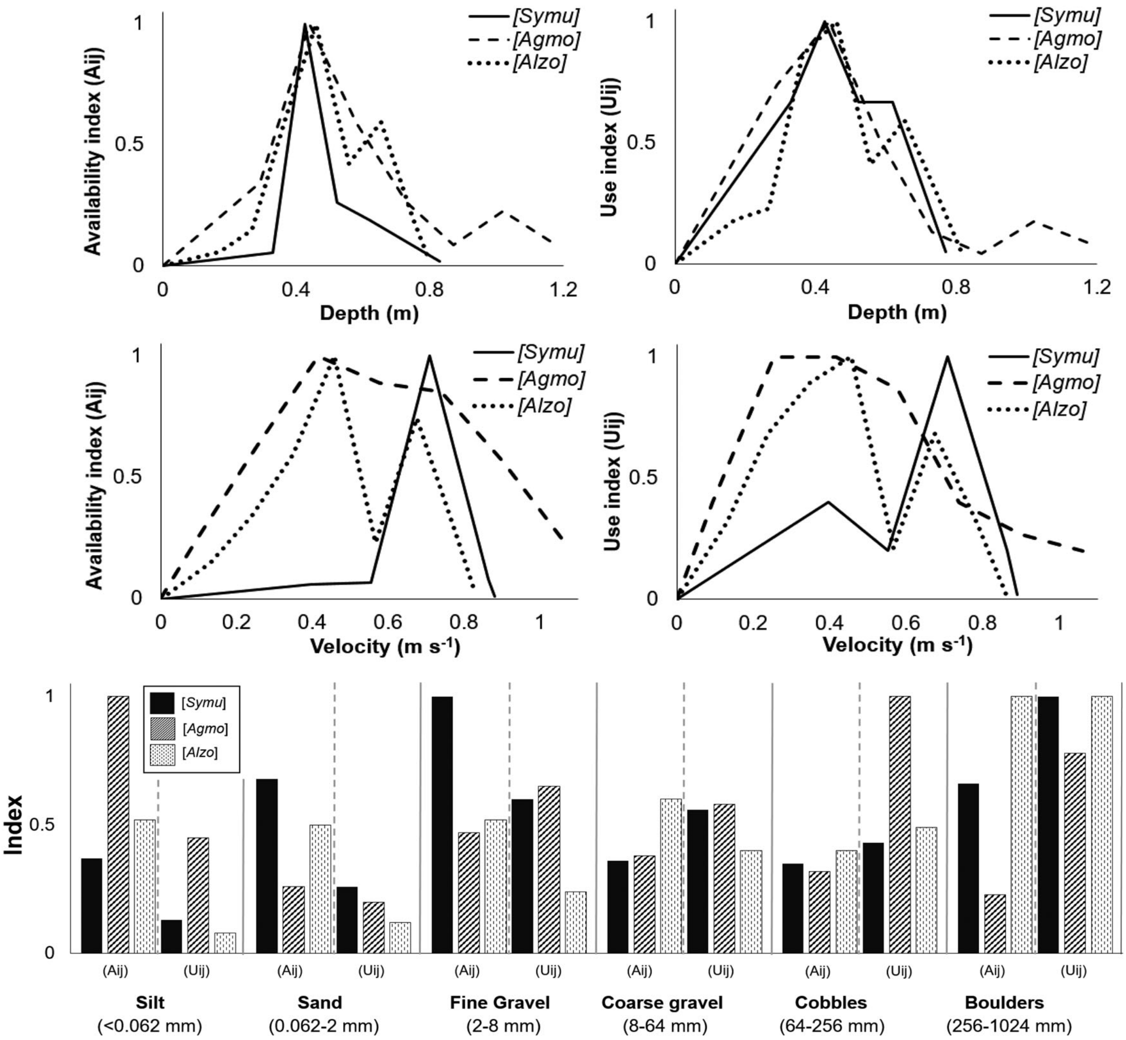

Figure 2. Habitat availability index (Aij) and habitat use index (Uij) curves for velocity, depth and substrate type for three target fish species: *S. multipunctatum* [*Symu*], *A. monticola* [*Agmo*] and *A. zonistius* [*Alzo*].

The proposed suitability curves for the three species showed differences related to adaptations for the use of habitat. *Agonostomus monticola* preferred zones that were deeper and with faster flows than the other two species. Such zones are characteristic of areas of rapids found on the river. The curves of *A. zonistius* for depth (0.56 m) and velocity (0.57 m s^{-1}) presented lower values than those of *A. monticola*. Previous studies conducted by Lyons and Mercado-Silva (2000) indicated that *A. zonistius* avoids areas with velocities greater than 0.75 m s^{-1}, and the results of this study suggest that this species is found in depths from 0.42 to 0.73 m and flow velocities from 0.60 to 0.68 m s^{-1}. The depths and velocities defined for this species match the characteristics of riffle zones and shallow rapids in the river.

Sicydium multipunctatum is located in shallower and less rapid zones than *A. monticola*; it finds suitable habitats in areas of 0.4 m in depth and with flow velocities > 0.55 m s^{-1}. The velocity values suggest that *S. multipunctatum* may co-occur with *A. zonistius*. All three species are found using coarse gravels, boulders, and rocks as substrate. In particular, *A. zonistius* is found below large rocks in rapid flowing zones, probably as a strategy to obtain food (Lyons & Mercado-Silva, 2000).

Knowledge of the interactions among different variables of the physical environment is important since it leads to the improvement of eco-hydraulic simulations by means of suitability functions, according to Bovee (1986). For example, some fish choose vegetated shallower areas as refuge from predation, or they seek deeper zones when no such protection is available. Moreover, as the fish grow in size, they use deeper zones since they are developing their swimming abilities and require greater depths in which to swim freely (Grossman et al., 1987). In contrast, smaller individuals often occupy zones that imply a lower energetic cost (close to the banks or in shallow zones), in contrast to the behaviour presented by the adults.

Other factors that can explain why fish do not use their ideal habitats include changes in food availability, depredation, competition, pollution (Freeman et al., 1997; Heggenes, 1996) and elimination of the riparian vegetation, which is very unfavourable for the fish as it increases the insolation of the water, raising the temperature and reducing the level of dissolved oxygen (Espinosa-Pérez et al., 1998; García de Jalón et al., 2002). In this way, where optimal conditions are unavailable for the reasons described above, individuals are forced to use less suitable zones (outside their optimum) and thus appear to present optimal conditions that are in fact merely tolerable, according to Manly et al. (1993).

While the criteria of suitability have been defined for three of the species that inhabit the basin of the Ayuquila-Armería River, it is necessary to clarify that these fish have a considerable capacity for adaptation to changes that can take place in

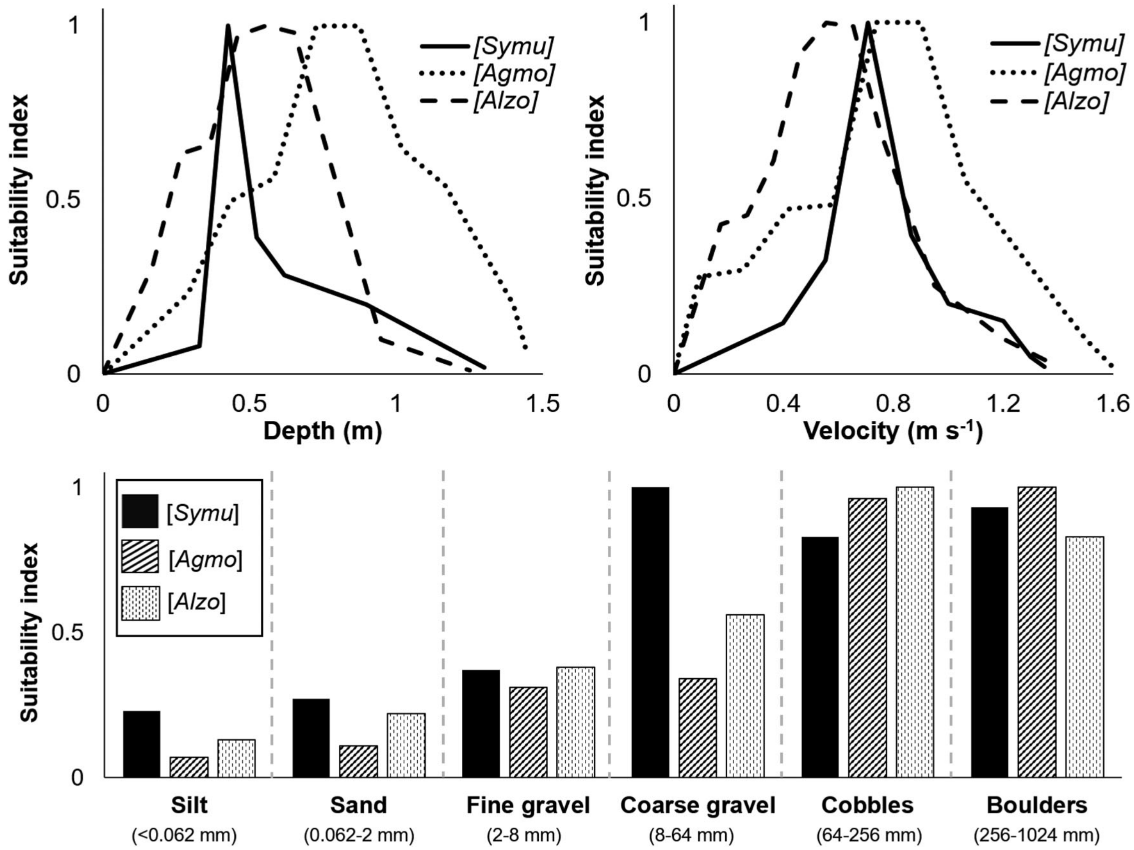

Figure 3. Habitat suitability curves (Category III) for velocity, depth and substrate type histograms for the three target species: *S. multipunctatum* [*Symu*], *A. monticola* [*Agmo*] and *A. zonistius* [*Alzo*].

their environment (García de Jalón & Schmidt, 1995; Rodrigues et al., 2015). In the rainy season, the geomorphology of the river changes due to the increased flow and the species exhibit a range of responses relative to their suitable habitat (Rodrigues et al., 2015). For example, *A. monticola* and *S. multipunctatum* have hydrodynamic advantages (Anderson, 1957; Lyons, 2005) in the rapid currents during the rainy season.

At present, habitat suitability curves in Mexico are only available for a few species that could be used to establish comparisons (González & Banderas, 2015). More studies are therefore required to address the development of suitability curves for different species in Neotropical environments, based on experimental data and specialized knowledge. For example, Rodrigues et al. (2015) in southeastern Brazil found specialization in the use of habitat between species; some fish were found in almost all sites, while others have preferences for very specific conditions, such as a particular substrate or a narrow range of depths or water flow velocities.

Spatial and temporal variations of the aquatic environment are very important factors to consider when conducting suitability studies as described by Manly et al. (2004). Although the velocity, depth and substrates can explain the variation observed in the fish within the river, it is necessary to correct these models and explore other habitat variables, such as water quality, temperature and plant coverage, which would allow a better understanding of the functioning of the fish communities. For future research, it will be necessary to consider changes in the habitat use related to fish ontogeny. For example, this type of study has been conducted by Martínez-Capel and García de Jalón (1999) for the species *Leuciscus pyrenaicus* Günther, 1868 and *Barbus bocagei* Steindachner, 1864, in the Jarama River, in Spain. These authors found that depth is a differentiating variable in terms of different fish sizes (usually increasing with the size of the fish) and that the substrate is of very little relevance and has does not reflect interspecific differences or dependence on the state of development.

Finally, the present study demonstrates the advantages of selecting and generating suitability curves to establish the ecohydraulic models necessary to define the minimum ecological flow for the Ayuquila-Armería River, as established in the methodology of the Mexican norm NMX-AA-159-SCFI-2012, presented in appendix E, for estimation of ecological flows.

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ORCID

Demetrio Meza Rodríguez http://orcid.org/0000-0002-5855-6939
Luis Manuel Martínez Rivera http://orcid.org/0000-0002-7050-9385
Norman Mercado-Silva http://orcid.org/0000-0001-7764-8161
Carlos Alonso Gonzálezc http://orcid.org/0000-0002-2395-4259

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