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Differences in physical habitat simulation system modelling results using benthic or pelagic fish species as indicators in Peruvian Andes–Amazon rivers

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Abstract

Aquatic organisms with different adaptations are used as indicators in physical habitat simulation system models. Those adaptations are critical for determining the shape of the weighted usable area/width curve and for recommending values of environmental flows. The main objective of this study is to compare the use of benthic native species (*Astroblepus taczanowskii* and *Astroblepus vanceae*) versus the introduced *Oncorhynchus mykiss* (rainbow trout) as target indicators for PHABSIM modelling in the Andean–Amazon piedmont rivers. We used adjusted probability distribution functions with L-moments analyses for developing curves of use and preference to evaluate the efficiency of each indicator. Two hydraulic modelling sections were established in the Ulcumayo River with 21 and 27 cross sections, respectively. Native benthic species are usually dominant but scarcely used as focus organisms for environmental flows modelling. These species are associated with fast running and shallow waters, which makes them potentially more sensitive to the effects of flow reduction. Our results indicated that the native species were more restricted to velocity and depth than *O. mykiss*. Using selection curves in PHABSIM modelling, it is required between 10% to 94% of the mean monthly flow to preserve 90% of the available habitat for *Astroblepus* during the dry season (May to November). In contrast, rainbow trout requires 5% to 88% of the mean monthly flow. We conclude that a multispecies approach is useful for determining the required environmental instream flows contributing to a better sustainable condition for the Neotropical mountain rivers.

KEYWORDS

Astroblepus, environmental flows, habitat suitability curves, PHABSIM, rainbow trout, target species

1 | INTRODUCTION

Dams, impoundments, and population growth threat rivers functioning worldwide. The rapid growth rate of human populations living along rivers and the accelerated land use changes in the catchment area are driving a rapid degradation of water bodies. An intense hydrologic modification reduces the connectivity and migratory routes for biota and the overall quality of aquatic ecosystems. (Arthington, 2012; Arthington, Naiman, McClain, & Nilsson, 2010; Postel & Richter, 2003; Vörösmarty et al., 2003). South America possesses the largest available freshwater resources of all the continents (29.7% according to FAO, 2003), which are principally distributed in Amazon, Paraná–La Plata, Orinoco, Magdalena, and São Francisco river systems. Unlike Europe and North America, where water courses have been extensively altered (Alcamo, Vörösmarty, Naiman, Lettenmaier, & Pahl-Wostl, 2008; Vörösmarty et al., 2003), many South American rivers remain closer to their natural condition. However, this situation could change as new hydropower and waterway projects are constructed in the headwaters (Finer & Jenkins, 2012; Rubio et al., 2017).

The Peruvian National Water Authority (ANA) worked in a proposal to apply environmental flow regulations (National Environmental Flows Guidelines, Resolutions 154-2016-ANA, 118-2019-ANA). These guidelines are based largely on the use of physical habitat simulation system (PHABSIM) approach (Stalnaker, 1994; Stalnaker et al., 1995) and the development of hydraulic simulations to quantify current and future habitat availability. This method has been used extensively in Peru (even before the guidelines approval) for environmental analyses of hydropower or agriculture water diversion proposals. In more than 50% of Peruvian hydropower projects, the environmental studies (http://www.minem.gob.pe/_sector.php?idSector=2, Ministerio de Energía y Minas, 2010 accessed March 2019) contained analyses of "environmental flows." PHABSIM was the preferred methodology used in these studies for developing recommended flows. A majority of these studies used pelagic fishes, particularly rainbow trout, as the target species, and a few used other fish species and aquatic insects.

PHABSIM (Bovee, 1982; Bovee & Milhous, 1978; Milhous, 1979) is a coupled model that serve as biological input in the negotiation process conceived for the instream flow incremental methodology (Stalnaker et al., 1995). The PHABSIM was developed as the interaction between one-dimensional hydraulic model (and currently two dimensional; Steffler, Ghanem, Blackburn, & Yang, 2009) and the habitat suitability curves (HSCs) for a set of target species (or indicators). The model simulates the situation for a group of hydraulic geometry variables (velocity, depth, wetted substrate, and cover) at different flows. As a result, PHABSIM showed a prediction of the amount of available habitat for the indicator species at different flows. Biological information for the modelling (HSC) is critical for defining the requirements to sustain and preserve aquatic biota. In its univariate form, the HSC represents the habitat use or habitat preference of stream organisms (Conklin, Canton, Chadwick, & Miller, 1996). Bovee (1986) defined three types of HSC as PHABSIM model input: type I based on professional experience, type II HSC based on frequency distributions of habitat use, and type III based on selection analysis relating use and availability data. The use of inappropriate curves may result in poor estimation of the required environmental flows. For example, the use of single curves for the selection of suitable physical characteristics for one species could not be the suitable for the conservation of the entire community (Rosenfeld & Ptolemy, 2012).

Many factors can affect the performance of PHABSIM such as not using uncertainty analyses (weighted usable area/width; Gard, 2005, 2009; Williams, 2010), HSC development and application (Ayllón, Almodóvar, Nicola, & Elvira, 2012), the use of only one species for modelling, avoiding the connectivity between functional and trophic levels (Rosenfeld & Ptolemy, 2012), or the use of coarse taxonomical categories (Gore, Crawford, & Addison, 1998; Gore, Layzer, & Mead, 2001; Gore & Nestler, 1988). Some authors have suggested that PHABSIM is obsolete, and it should be replaced by other methods (Railsback, 2016) as the mesohabitat modelling approaches (Parasiewicz, 2007) or two- and three-dimensional hydraulic modelling (Waddle, 2010; Waddle & Holmquist, 2011). However, PHABSIM is a useful tool used by numerous trained technicians, the model remains widely used, and it is officially required in many regions of the world including South America. It possesses a series of practical attributes including predictive measurements of future habitat availability and the interoperability and transferability between similar basins and species (Stalnaker, Chisholm, & Paul, 2017). Nevertheless, there are a series of recommended steps to improve its performance (Beecher, 2017).

The quality of HSCs can affect PHABSIM results in several ways. For example, if the functions are developed for organisms that occupy primarily river pools the results could underestimate the instream flows needed for the biota that occupy the riffles or other habitats. On the other hand, if the used curves are based on organisms that live in fast and shallow rivers, the effects of a similar reduction in flow may be higher due to the reduction in river stage and water velocities (Ayllón et al., 2012; Thomas & Bovee, 1993). Determinant factors could include the type of river, dominant type of habitat, resident species, or conservation objectives. Constructing complete models are critical in Neotropical region, where suitability curves are not extensively developed, especially for small native fish species like *Astroblepus* (Astroblepidae: Siluriformes), *Trichomycterus* (Trichomycteridae: Siluriformes), and *Orestias* (Cyprinodontidae: Cyprinodontiformes) that dominate Andean–Amazon piedmont rivers above 1,000 msl (Ortega, 1992). These taxa are strongly influenced by predation and competition from *Oncorhynchus mykiss* (rainbow trout), a salmonid species introduced in Peru at the beginning of the 20th century (Ortega, Guerra, & Ramírez, 2007; Oyague & Franco, 2013; Vera & Berger, 1977).

Astroblepids are among the most important fishes in the Andes' montane region (Ortega, 1992) with adaptations for fast flowing water at the headwaters, as an oral suction cup and the absence of pelvic bones (Maldonado-Ocampo et al., 2005; Schaefer & Buitrago-Suarez, 2002; Vélez-Espino, 2006). However, despite their representativeness, these fishes are rarely used as indicators in ecological flow models, due to their small size, unknown biology, and reduced economic importance. Furthermore, benthic organisms, especially those with adaptations to live in fast-running parts of the river (e.g., flat bodies, claws, suction cups, or very flexible bodies), some aquatic insects, and benthic fishes (usually Siluriformes) are the biota potentially most impacted by the reductions in flow (Gore et al., 2001). Flow reductions affect water level, river velocity, and sediment deposition, mainly impacting the rapids not the pools.

Some concerning factors about the environmental flows regulation and practice in South American countries were (a) the lack of knowledge about the biology—including preferences for eco-hydrological and eco-hydraulic features—of regional aquatic species (in a highly biodiverse region with numerous species with unique adaptations); (b) the incorrect use of methods, confusing the specific utility of some of them (as the use of PHABSIM as environmental flow method, when it is mainly used as a negotiation element in the context of the instream flow incremental methodology); and (c) the current interest to develop projects related with water courses modification along the Andean–Amazon ecosystems

(Finer & Jenkins, 2012; Rubio et al., 2017). In this context, the main purpose of this study is to contribute to the regional knowledge about the utility of a widespread and very characteristic family of mountain fishes (Astroblepidae) as potential tools to evaluate the impacts generated by a proposed project intervention. To reach this objective, we assessed how the differences obtained in use/preference curves for native Astroblepids and introduced Salmonids can affect the recommended flows from PHABSIM simulations at Andes–Amazon piedmont rivers. Our hypothesis indicated that the characteristics of benthic organisms define different responses than those obtained using only pelagic species. Based on these differences, the recommended flows can be increased or reduced depending on the type of indicators used. To obtain the best estimation of environmental flows, the use of a combined approach can be required, in order to preserve more efficiently the water resources and services provided by the rivers in this region.

2 | METHODS

2.1 | Study site

The data was collected in the Ulcumayo River, a subbasin of the Perene watershed, on the eastern slopes of the Andes in central Peru (Figure 1a). Eight stream reaches were sampled at 2,200 to 2,800 msl (Figure 1b). The study area corresponds to mean order rivers (Order 3–4 based on Strahler, 1957), distant 40–50 km from its origin, medium basin size (up to 1,200 km^2), and 16 to 25 m in width (21.4 m as mean value; Rosgen, 1994; Rosgen & Silvey, 1996; Sutfin, Shaw, Wohl, & Cooper, 2014). To define the gradient category of the studied reaches, we used the Rosgen's criteria (1994) to define channel types: low gradient <2%, 2–4% medium gradient, and >4% high gradient. Following this classification all the sampling sites correspond to medium to high reach gradient (measured values between 2% and 7%). In all the studied places, the channel has low to medium width/depth ratio and low sinuosity (Table 1; Rosgen, 1994; Shaw, Cooper, & Sutfin, 2018). The sampled river has mean monthly flows varying between 5 to 30 m^3/s. The eight sampling locations were selected based on two main factors (as recommended by Bovee, 1997): representatively and access.

Based on the slope and altitude, the sampling sections were divided into two main fluvial sectors: (a) four upper-reach sections with medium to high gradient (3–7%), dominated by riffle-pool hydromorphologic units at 2,500 to 2,800 msl, and (b) four lower-reach sections at 2,200 to 2,500 msl. All in medium gradient reaches (2–4%), with presence of riffles, pools, and glides.

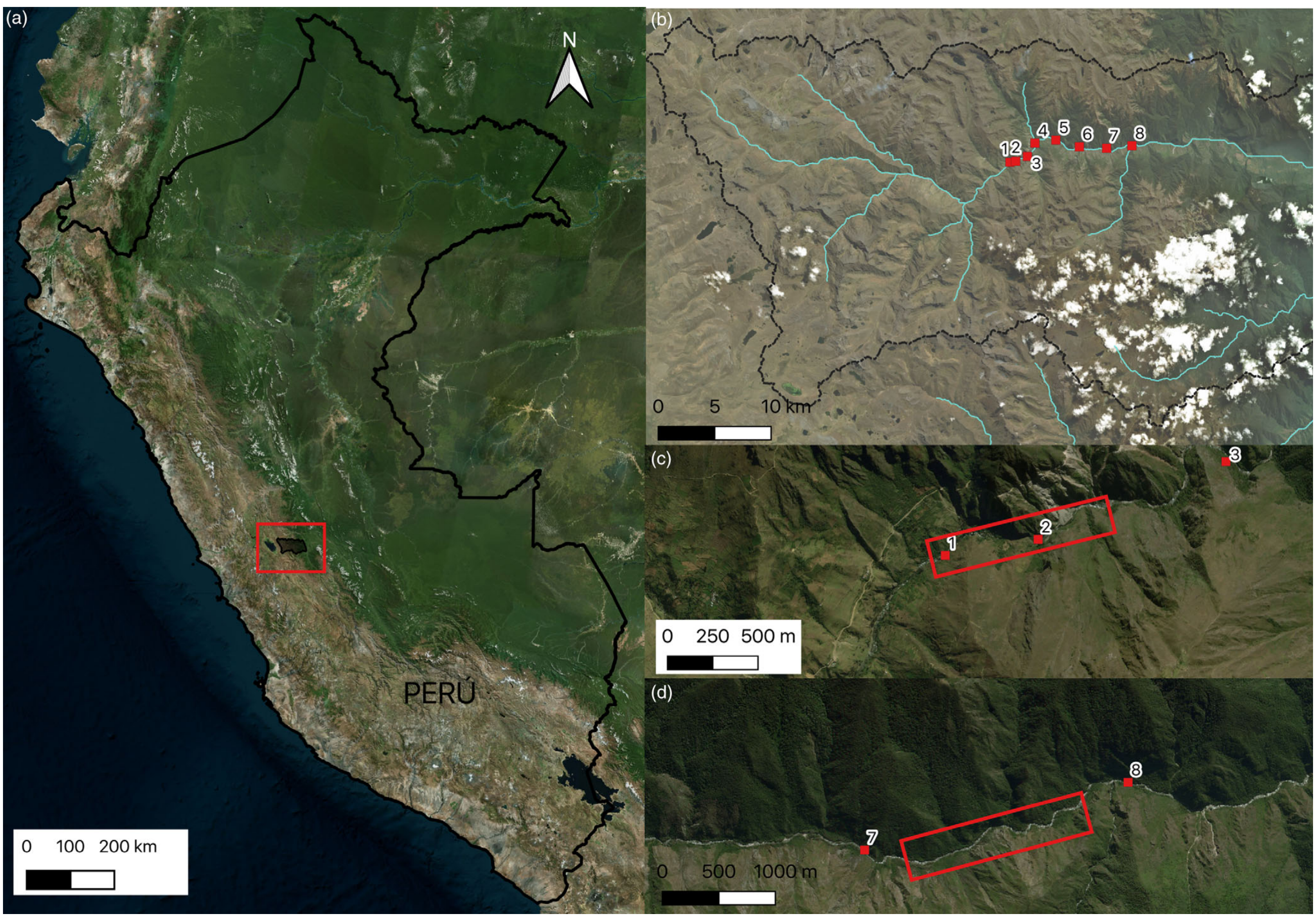

FIGURE 1 Map showing the Ulcumayo watershed (a), sampling locations (b), and Simulation Reaches 1 and 2 (c and d, respectively)

TABLE 1 Location and some general morphological features of the sampling points

Point ID	Longitude	Latitude	Average width	Altitude	Entretchment	Width/depth	Slope	Sinuosity
1	75.698° W	10.971° S	16.3	2,828	1.23	25.87	0.07	1.13
2	75.694° W	10.969° S	22.3	2,789	1.20	22.76	0.05	1.08
3	75.684° W	10.965° S	22.4	2,725	1.22	23.83	0.06	1.23
4	75.678° W	10.954° S	21.4	2,565	1.03	19.45	0.03	1.10
5	75.661° W	10.952° S	20.9	2,492	1.04	18.66	0.04	1.10
6	75.642° W	10.957° S	23.5	2,403	1.06	23.98	0.02	1.11
7	75.621° W	10.959° S	25.8	2,346	1.36	25.80	0.04	1.25
8	75.599° W	10.957° S	27.1	2,237	1.38	24.64	0.03	1.42

Note: Entrenchment, width/depth, and sinuosity are defined as by Leopold and Maddock (1953) and Rosgen (1996).

TABLE 3 Types of substrate, cover, and combinations founded during the sampling work

Substrate		Cover		Founded combinations (channel index)	
ID	Type	ID	Type	ID	Combination
0	Bedrock	0	Absent	0	Bedrock—no cover
1	Boulder	1	Fines—OM	1	Boulder—no cover
2	Cobble	2	Periphyton	2	Boulder—fines/OM
3	Gravel	3	Mosses	3	Boulder—periphyton
4	Sand	4	Macrophytes	4	Boulder—mosses
5	Silt—clay			5	Boulder—macrophytes
				6	Cobble—fines/OM
				7	Cobble—periphyton
				8	Gravel
				9	Sand
				10	Silt—clay

Note: Types of substrate, cover, and combinations based on Bovee (1986, 1997) and Chovanec et al. (2000).

The study area was located in the Yungas (Olson et al., 2001), an ecoregion in South America with high humidity, forest cover, and biodiversity but currently under intensive human pressure. In Peru, the Yungas has two main climatic seasons: the dry season extends between May to November and the rainy season from December to April.

2.2 | Fish sampling

Fish samples were collected at our eight sampling sites during the dry season in August 2010 and July 2012. In the high-water season (March 2011), it is possible to register the hydraulic variables in cross sections using strong security gear, but the river conditions made impossible to practice systematic fishing.

Each fishing site was 100-m long and stratified into mesohabitats as rapid, run, riffle, glide, pool, backwater (Parasiewicz, 2001, 2007; Parasiewicz & Dunbar, 2001). We sampled 20 to 30 discrete collecting points per site in proportion to the rate of the mesohabitats. Fishes were sampled using a battery backpack electrofisher (Smith-Root 12B POW). Following the recommendations of Bain, Finn, and Booke (1985) and Ensign, Temple, and Neves (2002), we applied a prepositioned electrode sampling. For each discrete collecting point, we prelocate the electrofisher electrodes (anode and cathode) at all the possible mesohabitat types, immediately an appropriate discharge (depending on the water conductivity) was liberated for 30 s, collecting all the removed individuals. All fishes with length >20 mm were measured using an ichthyometer and a precision scale (Ohaus Adventurer, 0.001 g precision). In order to obtain data to construct the use and selection curves, at all sampling points, three physical parameters (microhabitat parameters) were measured: mean water column velocity (m/s), total water depth (m), and the combination between substrate and cover (channel index, Table 3). When it was possible, we identified two developmental stages, adult and juvenile, based on biological characteristics such as size, presence of particular marks, gonadal development, and structures (Alexiades & Encalada, 2017; Gall & Crandell, 1992; Schaefer, 1990).

2.3 | Habitat modelling data collection

Two reaches (Figure 1c,d) were selected as PHABSIM simulation units, based on criteria recommended by Bovee (1997) and

TABLE 2 Total amount of fish captured by species at the two dry seasons

	Total		Adult		Juvenile		Fast-shallow habitats		Slow-deep habitats	
Fish species	August 10	July12	August 10	July 12	August 10	July 12	August 10	July 12	August 10	July 12
Oncorhynchus mykiss	227	193	121	83	106	110	68	46	159	147
Astroblepus taczanowskii	249	184	103	66	146	118	167	151	82	33
Astroblepus vanceae	198	209	117	124	81	85	101	133	97	76
Astroblepus peruanus	42	36	28	11	14	25	27	24	15	12
Astroblepus sp.	3	18	3	14	0	4	2	15	1	3
Creagrutus sp.	5	2	3	2	2	0	0	0	5	2
Hemibrycon sp.	12	26	10	21	2	5	3	5	9	21
Chaetostoma sp.	21	19	4	9	17	10	14	10	7	9

Note: Fast-shallow habitats: run, rapid, and riffle. Slow-deep habitats: pool, backwater, and glide.

Parasiewicz (2007): representativeness about the habitats and absence of tributaries that increased the flow downstream more than 10%.

At each simulation unit, data were collected following Bovee (1997), Gard (2005), and Williams (2010) recommendations. Modelled Reach 1 was 718-m long in the upper part of the Ulcumayo River, a characteristic sector of "upper basin high gradient river," with an elevation gradient of 36 m (2,766 to 2,802 msl). Reach 2 was 1,442-m long between 2,207 to 2,241 msl, just below the junction of the Cajas and La Sal rivers. The dominant mesohabitats in Reach 1 were riffles and pools, with some cascades and rapids, and a small presence of glides, whereas in Reach 2, glides were more important because the average slope was lower.

At Simulation Reach 1, 21 cross sections (XS) were performed, meanwhile Simulation Reach 2 was constituted by 27 cross sections. To select the XS number and position, we used the mesohabitat characterization of our simulation units (Bovee, 1997), locating one or two XS (depending on the length) at each mesohabitat unit. In this form, our modelling process is based on cross-sectional data (microhabitat features) representing all the typological variability of the reach. The first geographic point for each simulation unit (lower—left margin point) was defined using a Real-Time Kinetic navigation system (RTK South Galaxy G1). Based on that point, all the cross-sectional data (location and level) were collected using a Leica Futura TS-100 Total Station. The cross-sectional profile data were registered at 1-m intervals, and the velocity values were measured at two vertical levels (0.2 and 0.8 units with respect to the water depth) using an OTT C31 current meter.

2.4 | Univariate suitability curves development

Eight fish species were collected: rainbow trout (*O. mykiss*), four species of the native catfish genus *Astroblepus* (*Astroblepus taczanowskii*, *Astroblepus vanceae*, *Astroblepus peruanus*, and *Astroblepus* sp.), and three unidentified native species belonging the genera *Creagrutus*, *Hemibrycon* and *Chaetostoma*. Five of the registered species were scarce, with less than 50 individuals by season (Table 2). Considering the species abundance, the habitat suitability curves were developed only for three species: *A. taczanowskii*, *A. vanceae*, and *O. mykiss*. The three selected species showed some differences in the ecological niche and habitat uses: both *Astroblepus* species are benthic fishes, usually founded in shallow and fast water zones (rapids and riffles), using spaces behind rocks and consuming aquatic insects. Meanwhile, *O. mykiss* is a typical pelagic species that moves constantly between rapids (principal food provision zones) and pools (where spends the higher amount of time).

Two type of microhabitat preference curves were developed using the depth and velocity data collected during the first dry season (2010): use (type II) and selection (type III) HSCs. For the use curves we followed the procedures proposed by Som, Goodman, Perry, and Hardy (2015), using a frequency table of microhabitat data (velocity and depth) and performing L-moments nonlinear analysis to test the adjustment of probability distribution functions (PDFs) to our data. Type III (selection) curves were generated using a similar process, but the selection values were calculated using the Ivlev algorithm (Equation 1).

$$S = \frac{ri - pi}{ri + pi}, \tag{1}$$

where S is the selectivity value, ri the relative abundance of the fish in the ith frequency class (interval of values) for each physical variable (depth and velocity), and pi is the relative abundance of class i (Strauss, 1979). To apply this algorithm, we estimated pi based on the depth and velocity values obtained at all the cross sections performed for the hydraulic simulation (N = 478 measurements).

Six PDFs were tested as potential predictors: Gumbel, Weibull, Pearson type III, Gamma, Rice, and Rayleigh. The selection of the best PDF was based on R^2, Akaike information criteria, and mean square error indicators (Ahmadi-Nedushan et al., 2006). With the fish data obtained during the second dry season (2012), a transferability analysis was performed, reconstructing the curves and evaluating the goodness of fit with two efficiency estimators (Zambrano-Bigiarini, 2017): Nash–Sutcliffe (NSE) and Kling–Gupta (KGE) efficiency indices.

TABLE 4 Selected PDFs, selection criteria, and transferability for HSCs created using fishes collected during 2010 dry season

				Selection criteria			Transferability GOF	
Hydraulic feature	HSC type	Target species (stage)	Selected PDF	R^2	AIC	*MSE*	NSE	KGE
Velocity	II (use)	*Astroblepus taczanowskii* (adult)	Pearson III	.92	−39.48	0.01	0.83	0.66
		A. taczanowskii (juvenile)	Gumbel	.80	−22.31	0.02	0.67	0.63
		Astroblepus vanceae (adult)	Gumbel	.96	−31.60	0.01	0.91	0.94
		A. vanceae (juvenile)	Rice	.90	−21.47	0.02	0.89	0.83
		Oncorhynchus mykiss (adult)	Weibull	.96	−55.37	0.01	0.95	0.92
		O. mykiss (juvenile)	Gamma	.95	−49.18	0.01	0.95	0.92
	III (selection)	*A. taczanowskii* (adult)	Weibull	.88	−23.01	0.02	0.88	0.91
		A. taczanowskii (juvenile)	Weibull	.88	−22.72	0.02	0.85	0.88
		A. vanceae (adult)	Rice	.85	−11.78	0.02	0.85	0.86
		A. vanceae (juvenile)	Weibull	.91	−23.17	0.01	0.90	0.87
		O. mykiss (adult)	Gamma	.87	−30.44	0.02	0.78	0.71
		O. mykiss (juvenile)	Weibull	.49	2.72	0.08	0.43	0.56
Depth	II (use)	*A. taczanowskii* (adult)	Pearson III	.91	−36.12	0.01	0.85	0.71
		A. taczanowskii (juvenile)	Gumbel	.65	−13.56	0.06	0.58	0.65
		A. vanceae (adult)	Rayleigh	.85	−24.34	0.03	0.66	0.54
		A. vanceae (juvenile)	Pearson III	.86	−25.51	0.01	0.86	0.86
		O. mykiss (adult)	Pearson III	.79	−10.83	0.03	0.78	0.84
		O. mykiss (juvenile)	Pearson III	.82	−22.38	0.03	0.58	0.54
	III (selection)	*A. taczanowskii* (adult)	Rayleigh	.64	6.01	0.06	0.63	0.76
		A. taczanowskii (juvenile)	Gamma	.57	7.46	0.07	0.64	0.62
		A. vanceae (adult)	Pearson III	.61	8.07	0.07	0.61	0.74
		A. vanceae (juvenile)	Weibull	.58	9.31	0.09	0.49	0.55
		O. mykiss (adult)	Rayleigh	.48	8.55	0.09	0.31	0.54
		O. mykiss (juvenile)	Weibull	.57	0.39	0.06	0.44	0.71

Note: Transferability was evaluated comparing the relative frequency of use or selection of fishes in 2012 dry season, with the expected probability based on the HSC.
Abbreviations: AIC, Akaike information criteria; HSC, habitat suitability curve; GOF, goodness of fit; KGE, Kling–Gupta efficiency; MSE, mean square error; NSE, Nash–Sutcliffe efficiency; PDFs, probability distribution functions.

In the case of functions for the combination of substrate and cover (channel index, codes detailed in Table 3), we used an approach based on relative use patterns and do not adjust those values to any probability function.

2.5 | PHABSIM procedures and recommended flows

The PHABSIM modelling was performed for each cross section using the HSCs developed for the target species (*A. taczanowskii*, *A. vanceae*, and *O. mykiss*) and hydraulic data collected under different flow conditions (dry season 2010, wet season 2011, and dry season 2012). We used hydraulic data from wet season in order to perform the physical model under a wide set of potential hydrological and hydraulic conditions, but our final analyses were based only in the habitat availability estimations for the dry season (May to November). In this work, we used WUW (weighted usable width) instead of weighted useable area (the most commonly used product of PHABSIM), in order to generate confidence intervals using a randomization procedure for the obtained results with each indicator species. With the relative mean WUW, we developed a time-series analysis to estimate the required flows to preserve 90% and 75% of the available physical habitat in natural conditions during the dry season. Based on these estimations the performance of each target species was compared.

3 | RESULTS

3.1 | Habitat suitability curves

Using the criteria values (R^2, Akaike information criteria, and mean square error), we selected the best probability function for each velocity and depth of the HSC created with the fish data collected in August 2010 (Table 4). Then, two goodness of fit indicators were calculated (NSE and KGE) for the transferability of these HSCs to July

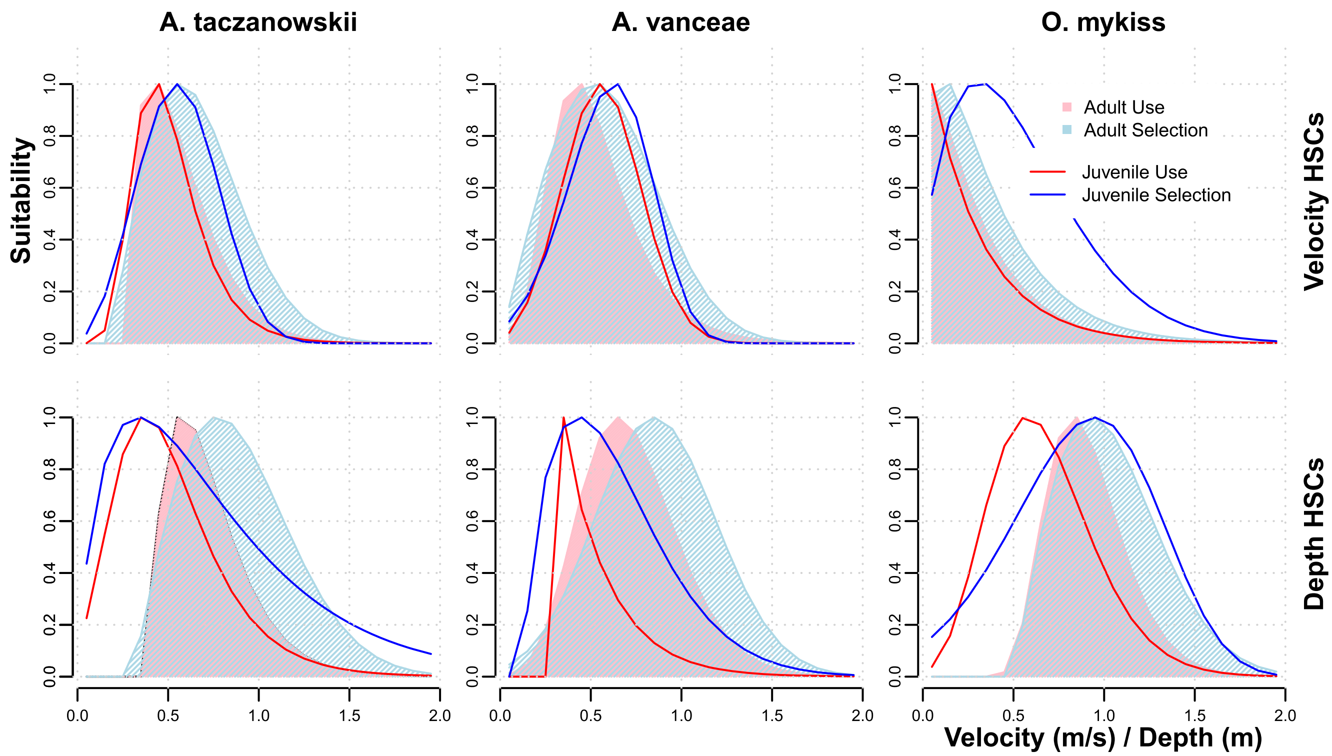

FIGURE 2 Selected HSCs for velocity and depth; Shadowed areas: Adults; Lines: Juveniles; Red: Type II HSC (use); Blue: Type III HSC (selection). HSC, habitat suitability curve

2012 data, showing in most cases an acceptable adjustment between simulated and validated data (Hall, 2001; Verberk, van der Velde, & Esselink, 2010).

Velocity and depth of the HSCs (Figure 2) are expected for each type of habitat use. The species of native catfishes (*A. taczanowskii* and *A. vanceae*) exhibit a remarkable preference for mid values of velocity (the optimum was around 0.5 m/s) at both identified life stages (adults and juveniles). This result is explained because a large number of these organisms were captured from medium to fast water zones, as rapids or riffles. For rainbow trout (*O. mykiss*), a species related to zones with slow movement such as pools or glides, the curve obtained shows a noticeable shift to lower ranges of velocity (with an optimum around 0.2–0.3 m/s for adults).

The preference patterns for depth showed differences between life stages (adults and juveniles) and between species. Both *Astroblepus* species preferred shallow to medium depth values, whereas *O. mykiss* preferred deeper parts of the river. The adults of *Astroblepus* spp. preferred depths located between 0.5 and 1 m below the surface, whereas the juvenile specimens tended to be located at depths between 0.1 and 0.5 m. In the case of *O. mykiss*, the adults are usually found at 0.5 to 1.5 m, and the juveniles around 0.4 to 0.75 m.

For the channel index use (Figure 3), none of the collected specimens of fishes during the field work were captured at locations, where the substrate was constituted only by bedrock ("0" as channel index code). The individual value of suitability for each of the five categories that included boulders ("1" to "5") can be low (less than 0.6 usually); nevertheless, both *Astroblepus* species showed an important association with this substrate, using all the possible combinations with rocks of that dimension. In the case of *O. mykiss*, the use of boulder substrate is very limited, never using boulders without cover (Code "1") and only using Categories "2" to "5" with low frequency. The preferred type of substrate is cobble, the Categories "6" and "7" represented the optimum substrate for both stages of *A. taczanowskii*, juveniles of *A. vanceae* and adult *O. mykiss*. Finally, gravel (without cover, Category "8") constituted the preferred substrate for *A. vanceae* adults and *O. mykiss* juveniles.

3.2 | Physical habitat simulations and recommended flows

Using all selected HSCs, the PHABSIM habitat modelling was conducted (Figures 4 and 5). The results generally showed two trends: (a) the values of maximum habitat availability for juveniles occur at lower flow values in contrast of those observed for adults and (b) the maximum habitat availability value for the native *Astroblepus* species at juvenile or adult life stages generally occurs at higher flow values than the observed for the adult *O. mykiss*. Nevertheless, some deviations of these patterns can be observed. Using the type II HSC (use criteria) at the upper reach (Simulation Reach 1), the obtained results for adults of *O. mykiss* were similar to those obtained for *A. vanceae* but were lower (maximum habitat availability occurs at lower flow) for *A. taczanowskii*. When the juvenile stage is analysed, *O. mykiss* showed a right-displaced WUW curve relative to both *Astroblepus* species.

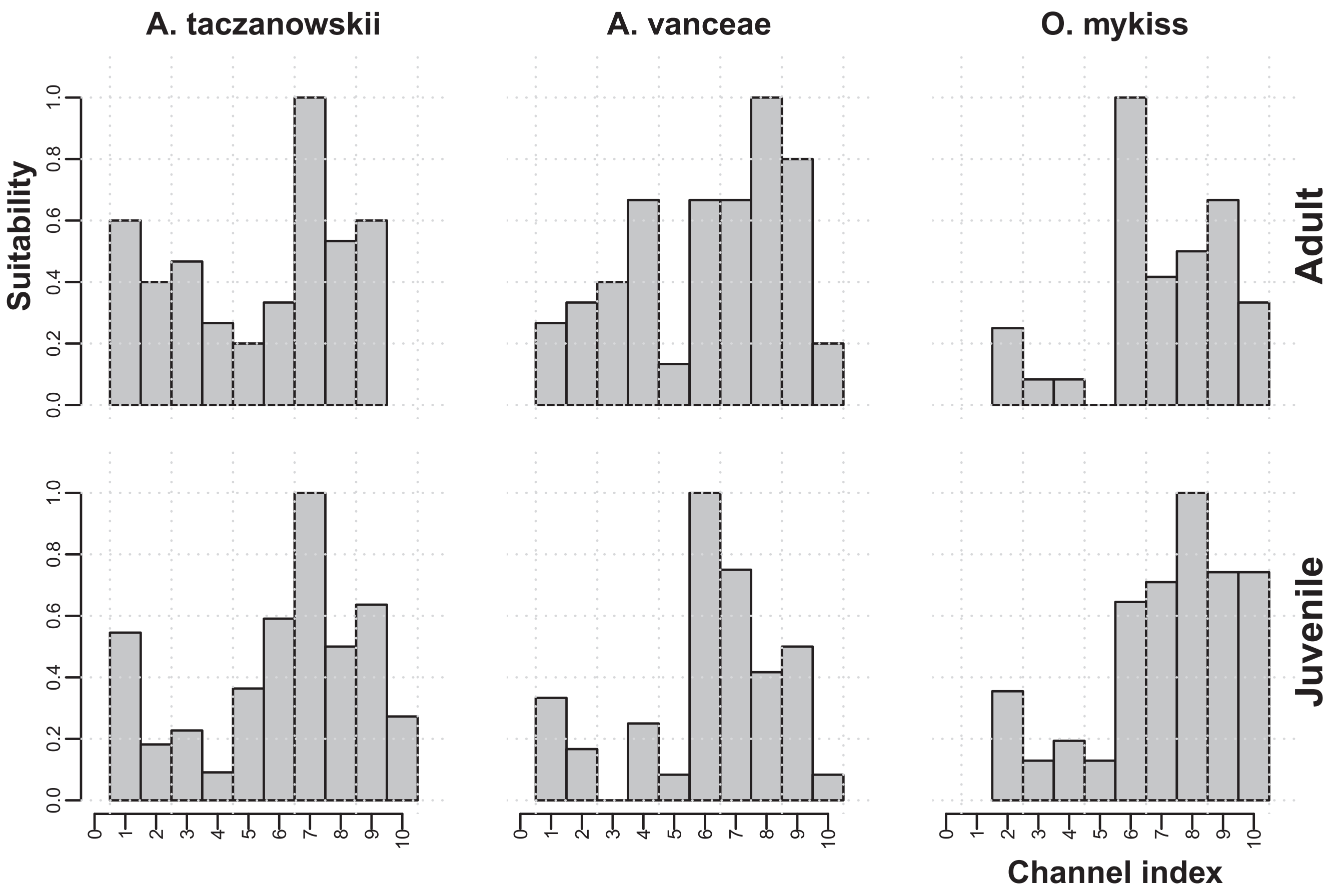

FIGURE 3 Selected habitat suitability curve for channel index (combination of substrate and cover, based on Table 3)

The observed displacement means that the maximum habitat availability for juvenile trout at this area occurs at higher flows. Meanwhile, in the case of the lower part of the study area (Simulation Reach 2), both *O. mykiss* life stages results showed lower flow values for maximum habitat availability than *Astroblepus* species (the WUW curves for *O. mykiss* is left-located in comparison with curves for *Astroblepus* spp. in all the cases). When type III HSC was used (selection curves, Figure 5), the behaviour of the WUW was similar to the observed results of type II, with small differences: in the case of adults the results showed a left displacement for *O. mykiss* at both simulation reaches. This indicates that the values for maximum habitat availability for this species occur at lower flow values in comparison to *Astroblepus* species. Juvenile *O. mykiss* showed the same pattern as adults for the Simulation Reach 1 (upper part of the study area), with lower values of flow required for the maximum available habitat. In the case of the Simulation Reach 2, the results were similar for all three indicators.

The position and form (amplitude and slope) of the WUW curve obtained in one-dimensional habitat modelling defined the response of each single indicator species to change in flow. The WUW curves obtained in this work suggested that the equal reductions in flow could produce higher detrimental effects in the habitat availability for adult *Astroblepus* spp. than for the adult rainbow trout at both places. Juvenile rainbow trout could be affected in the same way as *Astroblepus* in some cases, depending on the type of curve used and the simulation reach evaluated. But generally, in most of potential combinations, the rainbow trout showed left-displaced curves as opposed to benthic native catfishes, and this could have a clear effect on the amount of recommended water preservation for ecological purposes.

To assess whether the WUW results (by species and HSC type) affect the recommended environmental flows, we compared the obtained values for two levels of habitat preservation during the dry season (Table 5). Only for the type II HSC (habitat use) and the Simulation Reach 1 (upper Ulcumayo). The pelagic *O. mykiss* showed a required range of preservation flow values higher than that obtained for both species of *Astroblepus*. All the other cases, *Astroblepus* spp. were more demanding in the amount of preserved flow to ensure the conservation of important physical features used by the species.

At both simulation reaches, the lowest values of preserved flows to ensure the conservation of a specific amount of habitat correspond generally to *O. mykiss*, the pelagic species. Both *Astroblepus* species (benthic fishes) showed remarkably higher needs of preserved flows (Figure 6). The exception (*O. mykiss* are higher than *Astroblepus* spp.'s needs) is when the recommended flows were estimated using the type II HSC in the upper section of the Ulcumayo River (Simulation Reach 1).

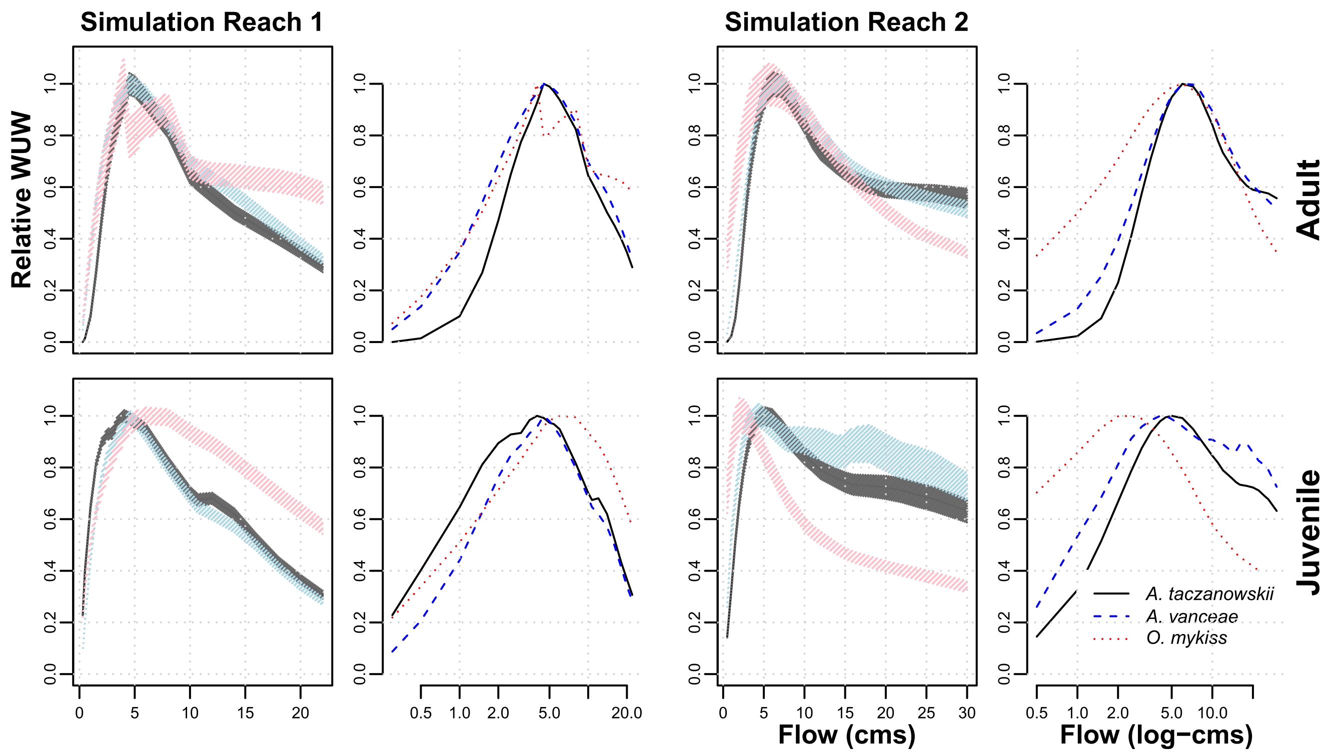

FIGURE 4 Relative (normalized) weighted usable width (WUW) obtained for both simulations reaches, based on type II habitat suitability curve (use). Shadowed areas represent the 95% confidence interval of 10,000 randomization procedure based on permutations of 12 and 15 cross sections on Simulations Reaches 1 and 2, respectively. Lines represent the average value based on the previous randomization procedure, the X-axis on logarithmic units to show more clearly the lower flows differences between benthic (*Astroblepus* spp.) and pelagic (*Oncorhynchus mykiss*) fish species. Black area/line: *Astroblepus tackzanowskii*; Blue area/line: *Astroblepus vanceae*; Red area/line: *O. mykiss*

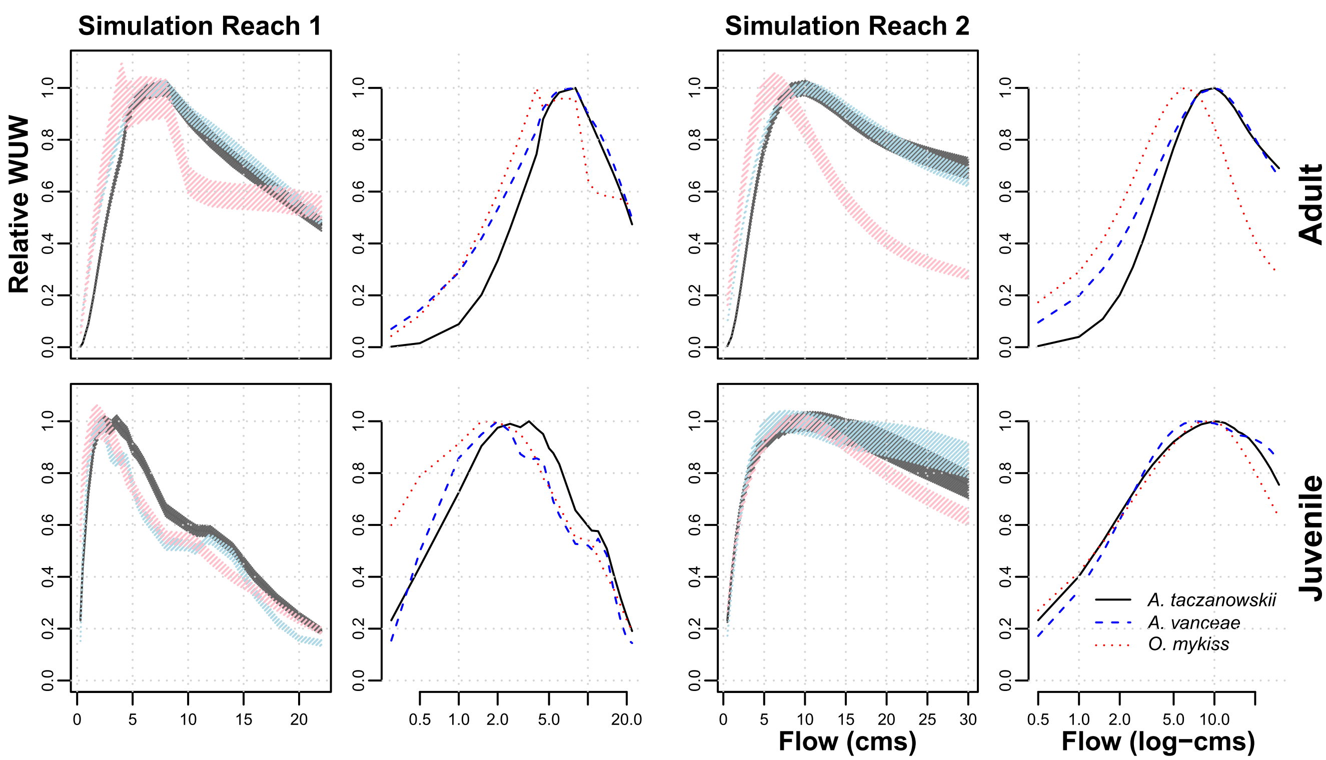

FIGURE 5 Relative (normalized) weighted usable width (WUW) obtained for both simulations reaches, based on type III habitat suitability curve (selection). Shadowed areas/lines, colour codes, and axis representation are the same described in Figure 4

TABLE 5 Range of required instream flow proportion to ensure two levels of habitat conservation (90% and 75%), during the dry season (May to November)

Simulation reach	Habitat suitability curve type	Target species (stage)	90% habitat	75% habitat
Simulation Reach 1 (upper Ulcumayo)	II (use)	*Astroblepus taczanowskii* (adult)	0.84–0.94	0.66–0.85
		A. taczanowskii (juvenile)	0.50–0.74	0.32–0.54
		Astroblepus vanceae (adult)	0.74–0.88	0.53–0.72
		A. vanceae (juvenile)	0.67–0.86	0.45–0.68
		Oncorhynchus mykiss (adult)	0.79–0.88	0.46–0.55
		O. mykiss (juvenile)	0.54–0.61	0.45–0.51
	III (selection)	*A. taczanowskii* (adult)	0.80–0.88	0.58–0.71
		A. taczanowskii (juvenile)	0.36–0.60	0.19–0.34
		A. vanceae (adult)	0.68–0.77	0.40–0.52
		A. vanceae (juvenile)	0.27–0.60	0.17–0.36
		O. mykiss (adult)	0.67–0.74	0.40–0.48
		O. mykiss (juvenile)	0.24–0.57	0.15–0.34
Simulation Reach 2 (middle Ulcumayo)	II (use)	*A. taczanowskii* (adult)	0.45–0.89	0.38–0.76
		A. taczanowskii (juvenile)	0.29–0.73	0.23–0.55
		A. vanceae (adult)	0.46–0.86	0.37–0.71
		A. vanceae (juvenile)	0.23–0.58	0.17–0.42
		O. mykiss (adult)	0.31–0.71	0.31–0.48
		O. mykiss (juvenile)	0.20–0.62	0.05–0.13
	III (selection)	*A. taczanowskii* (adult)	0.65–0.84	0.46–0.66
		A. taczanowskii (juvenile)	0.51–0.71	0.22–0.28
		A. vanceae (adult)	0.55–0.72	0.32–0.45
		A. vanceae (juvenile)	0.21–0.38	0.10–0.26
		O. mykiss (adult)	0.23–0.54	0.20–0.44
		O. mykiss (juvenile)	0.17–0.43	0.07–0.28

4 | DISCUSSION

The shape of the constructed HSCs and the obtained results for modelling were consistent with the characteristics and adaptations of the species. *O. mykiss* is a pelagic fish strongly associated with pools and backwaters (Raleigh, Hickman, Solomon, & Nelson, 1984). Its capture rate was higher in those habitats as a result of the individuals' behaviour. They spend a considerable amount of time resting in pool areas, because moving through fast waters demands more energy consumption (Ellerby, 2010; Tudorache, Viaene, Blust, Vereecken, & De Boeck, 2007; Webb, 1971). Despite this, fast flow mesohabitats of the river are the most important feeding places for this species (Turner et al., 2016). On the other hand, both *Astroblepus* species showed preference for fast flow habitats because an evolutionary reason: these species are adapted to stay within the rapids flow at a low energy consumption (Alexiades & Encalada, 2017; Velez-Espino, 2003). These adaptations are important from a biogeographical perspective, due to the species capacity to move freely across the stream, from the lower parts to the higher areas of the basins. Therefore, *Astroblepus* species can colonize many of the upper areas of the Andean watersheds, where other South American taxa cannot naturally reach (Albert & Reis, 2011; Lujan et al., 2013; Maldonado-Ocampo et al., 2005). In addition, life-stage differences were identified and related to the potential age segregation (Ayllón et al., 2012; Ayllón, Almodóvar, Nicola, & Elvira, 2009; Bremset & Berg, 1999; Picard, Dodson, & FitzGerald, 2011; Walters & Wilson, 1996) and the previously observed specific preferences.

Mountain rivers have a continuum longitudinal profile dominated by two mesohabitats: rapids and pools (Dingman, 2009). When the analysis includes the typical hydromorphology of mountain rivers (such as the Ulcumayo River) and its inherent hydraulic behaviour (Jarrett, 1984, 1988; Sieben, 1993; Statzner, Gore, & Resh, 1988), the results can be predictable. For example, if those changes are assessed as a reduction in flow, the effects could be strongly evidenced in the water level changes, velocity, and sedimentation in fast and shallow mesohabitats (rapids, runs, riffles, and cascades). If those changes are assessed through a combination of hydraulic and biological models such as PHABSIM, the variability in available habitat will be more noticeable for species with preference for these types of river mesohabitat. Conversely, if the analysis is carried out based on species that prefer slow flow habitats and greater depth, the loss of registered habitat tend to be less dramatic. However, the last results may be unreal because the loss of the rapid's functionality could affect the entire community limiting the food source availability as well as

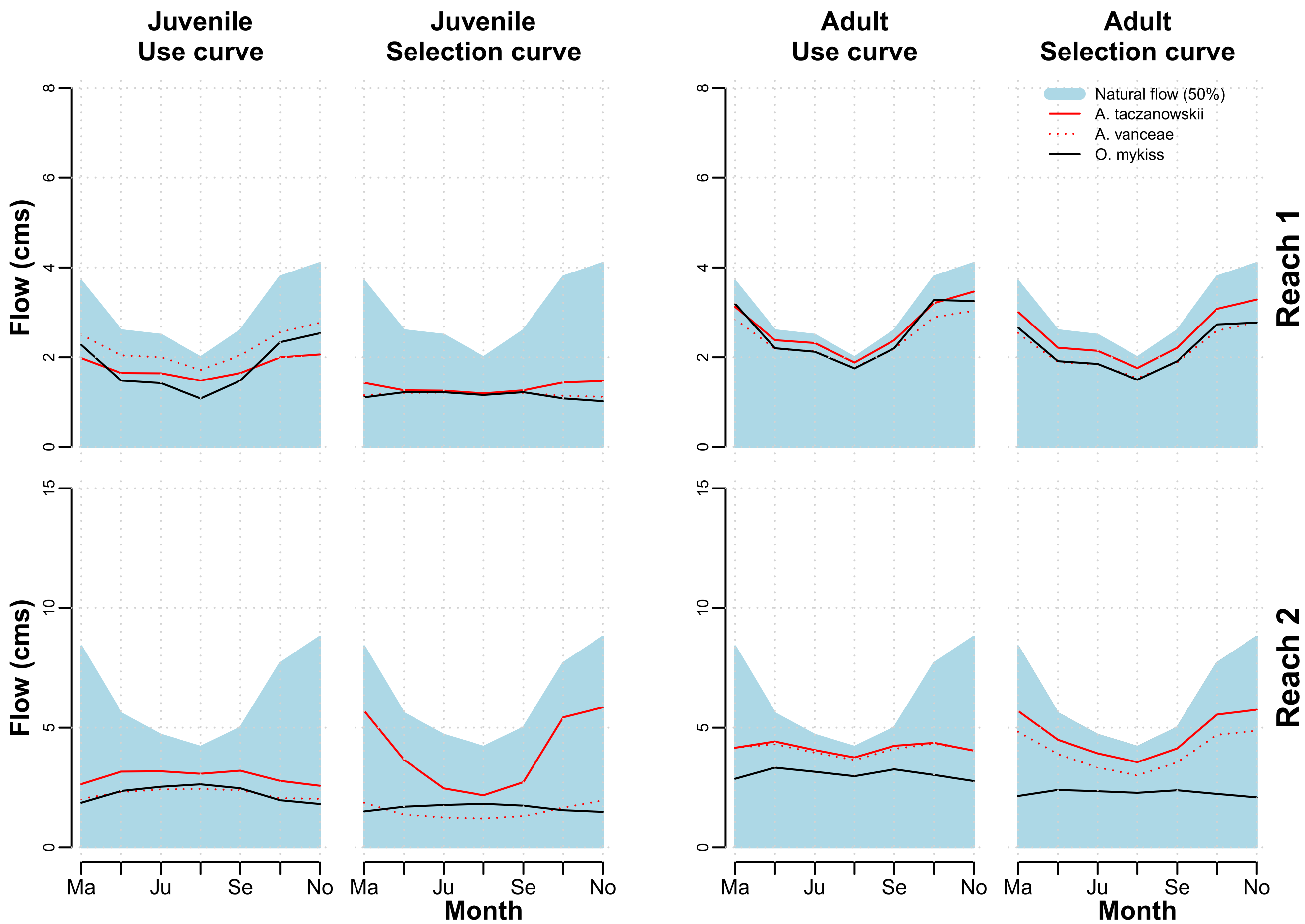

FIGURE 6 Mean monthly flow during dry season (May to November) under natural conditions (50% persistence) and the recommended values to preserve 90% of the habitat availability

impacting on the displacement capacity for organisms along the longitudinal gradient (Rosenfeld & Ptolemy, 2012). These detrimental effects tend to not be considered when given recommendations for the environmental studies of the hydropower projects in Peru, mainly because the models are designed with pelagic species.

The differences obtained in preference patterns (habitat suitability indexes) between species and life stages are in line with similar previous works. Ayllón et al. (2012) showed that trout preference curves for velocity exhibits, in general, a typical behaviour where the juvenile stages tend to select slightly lower velocities than the adults. da Costa, Mattos, Borges, and Araújo (2013) found higher velocity preferences for small catfish species than some characins. Velez-Espino (2003) reports that the minimum velocity value for *Astroblepus ubidai* is 0.139 m/s, which means that at lower velocities it would be difficult to find this species. The last is a common behaviour for the Astroblepidae family, which is well adapted to live in mountain environments and particularly in fast and shallow river mesohabitats (Burgess, 1989; Maldonado-Ocampo et al., 2005). Correspondingly, differences in HSCs velocity is the most important factor for preserving the habitat when considering age range (adult stage over juvenile) and species (*Astroblepus* over rainbow trout). The HSCs for depth showed a not clear tendency related to the habitat displacement for different age stage (Ayllón et al., 2009, 2012; Bremset & Berg, 1999; Picard et al., 2011; Walters & Wilson, 1996), at least, not as defined as velocity variable. The third element for the model including the combination of cover and substrate (so-called channel index) is considered invariable over time and flow regimes. Due to this, it can show specific influences in selectivity by species.

Our results showed the weakness point of using a single indicator for the physical habitat modelling in Neotropical mountain rivers. Hence, to estimate and recommend flow regime, multitaxon approach (combination of groups of indicators as macroinvertebrates and fishes) is needed to enhance the results. Each potential indicator of habitat preference is influenced by specific adaptations. The functionality of the entire community depends on the presence and viability of its biotic components, particularly in a highly rich scenario like a Neotropical river. The latest is consistent with Rosenfeld and Ptolemy (2012) or Hayes et al. (2018) statements, highlighting the importance to consider different components of energy flux, to accurately estimate the real requirements of populations and communities. If the resources or controllers are not considered in the model, the results have low probabilities to ensure a good environment for the objective organisms. In this way, Gore and Nestler (1988) emphasized the relevance of the effects of biological interactions. Further, Gore et al.

(2001) suggested the use of macroinvertebrates as indicators for instream studies, results in line with our recommendations on the use of individuals of the native benthic fishes for modelling in Andean–Amazon piedmont rivers.

These recommendations are not limited to benthic and pelagic fishes. As suggested by Gore et al. (1998, 2001) and other authors (Kelly, Hayes, Allen, West, & Hudson, 2015; Orth, 1987; Rosenfeld & Ptolemy, 2012), the benthic invertebrates are an important group of organisms. They are fundamental in the secondary production patterns of the river habitats (Downing, 1991; Downing & Rigler, 1984) as well as resources for organisms that occupy other trophic levels (Vélez-Espino, 2006; Vera, Oyague, Castañeda, & Quinteros, 2013). Their use as indicators for aquatic habitat modelling would be useful for considering the entire energy flux structure. In the same way, the use of aquatic birds or mammals is possible and (considering particular objectives and tools) recommendable in some cases.

Notwithstanding, it is important to remind the challenges in the South American context. Among the main limitations is the lack of specific information about the biology of the numerous species of fishes and other aquatic organisms (Reis, Kullander, & Ferraris, 2003) and the scarcity of habitat suitability curves available for regional and local species. The last issue is particularly difficult to address in a highly biodiverse region, where many species show unique adaptations to very particular habitat conditions (Albert et al., 2011). Some authors suggested that it is possible to transfer the created HSCs for similar species in different ecosystems, but this includes a series of risks, especially considering the particularity of habitats and species in the Neotropics. To sum up, the best way to improve the science and practice of ecological flows in Peru (and in South America) is—probably—the proper application of existing techniques in joint with generation of local information to obtain complete results.

5 | CONCLUSIONS

The development of environmental flow studies for sustainable managing of mountain rivers in South America is challenging. Human threat, incomplete data, and limited knowledge about the local species and processes are the main constrains. Nevertheless, governments and private companies are engaged in enhancing the development of complete studies and reduce the knowledge gap. Our literature review was limited to the Peruvian context. Yet based on the lack of regional published works about the topic and the scarce accessible data with the methods used, it is likely that the situation is replicable in the entire region. The extended use of PHABSIM as the main tool for recommending environmental flows shows some misuses. First, the application of the model based only in one species (in many cases this species is introduced as *O. mykiss*); second, the use of data collected only in one season; and third, the incorrect transference of use/preference curves (situation particularly difficult and not recommendable in a highly biodiverse region with unique adaptations). Our study demonstrates clearly the differences that can be obtained using only one indicator. If this indicator is strongly associated to slow-deep habitats (pools or backwaters) as pelagic fishes, the recommended flows can be lower for maintaining the viability of habitats such as rapids or riffles, affecting the communities using these river areas. On the other hand, if the species selected uses preferably the fast-shallow habitats (runs, rapids, and riffles), the recommended flows can be very conservative, and the potential project could be not feasible. An equilibrium between the conservation objectives and the socio-economic requirements for projects development is optimal. Therefore, to obtain the most fitting results with PHABSIM model, it is recommended the use of a group of organisms with different adaptations, niches, trophic functions, and ecological traits.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Eduardo Oyague, upon reasonable request.

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