Proposing environmental flows based on physical habitat simulation for five fish species in the Lower Duero River Basin, Mexico

Proponiendo el caudal ambiental basado en simulación del hábitat físico para cinco especies de peces en la Cuenca baja del Río Duero, México

Felipe Armas-Vargas[1], Oscar Escolero[2], Diego García de Jalón[3], Luís Zambrano[4], Marta González del Tánago[3] and Stefanie Kralisch[5]

[1]Posgrado en Ciencias de la Tierra, Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria, CDMX, 04510. México
[2]Departamento de Geología Regional, Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria, CDMX, 04510. México
[3]Departamento de Ingeniería Forestal, Unidad Docente de Hidrología, Universidad Politécnica de Madrid, Ciudad Universitaria, Madrid, 28040. España
[4]Departamento de Zoología, Instituto de Biología, Universidad Nacional Autónoma de México, Ciudad Universitaria, CDMX, 04510. México
[5]Department of Applied Geosciences, AGW, Karlsruhe Institute of Technology, Kaiserstr 12, Karlsruhe, 76131. Germany
e-mail: felipejav@geologia.unam.mx

Recibido: 28 de marzo de 2015. ***Aceptado:*** 9 de abril de 2017.

Armas-Vargas F., O. Escolero, D. García de Jalón, L. Zambrano, M. González del Tánago and S. Kralisch. 2017. Proposing environmental flows based on physical habitat simulation for five fish species in the Lower Duero River Basin, Mexico. *Hidrobiológica* 27 (2): 185-200.

ABSTRACT

Background. The concept of "environmental flow" is defined as hydrologic regimes that are required to sustain ecosystem health and functions in rivers. In Mexico, it has become an important topic, not least because a 2012 legal standard (NMX-AA-159-SCFI-2012), establishes procedures for determining instream flow requirements. **Goals.** The aim of this paper is to propose an acceptable environmental flow requirement for a regulated river segment in the Duero River Basin in, Michoacan, Mexico. **Methods.** Of the many methods of establishing environmental flows in rivers, this article is concerned with the habitat simulation method. This is based on the IFIM theoretical framework and the PHABSIM mathematical model, by which the WUA-Q curves were obtained for five species of fish. **Results.** From these curves, we determined that the *Goodea atripinnis* species has the greater habitat area and reached a maximum of 4338 m^2/km for a flow of 5 m^3/s; *Alloophorus robustus* maintained a constant habitat of 2000 m^2/km between flow rates of 5 to 15 m^3/s. With smaller area, *Menidia jordani* had a maximum habitat of 1323 m^2/km for 4.5 m^3/s; and with WUA less than 500 m^2/km the curves of the species *Algansea tincella* and *Aztecula sallaei* were obtained. **Conclusions.** The average regulation in March and April was 3.61 and 3.44 m^3/s and with the EFR proposal it was 5.11 and 5.00 m^3/s for March and April, respectively. In general, the monthly environmental regime is to maintain 80% of the natural flow regime, generating an increase in habitat during the dry season of 24% for *A. robustus* and 23% for *A. sallaei*.

Key words: *Algansea tincella*, Duero River, environmental flows, habitat simulation.

RESUMEN

Antecedentes. El concepto de "caudal ambiental" se define como el régimen hídrico que se requiere para sostener la salud y las funciones de los ecosistemas en ríos. En México, se ha convertido en un tema importante, por la adopción de una norma jurídica en 2012 (NMX-AA-159-SCFI-2012), que establece el procedimiento para determinar caudales ecológicos. **Objetivos.** El objetivo de este artículo es proponer un requerimiento de caudal ambiental aceptable para un segmento de río regulado, en la Cuenca del Río Duero en Michoacán México. **Métodos.** De un gran número de métodos para establecer caudales ambientales en ríos, este artículo aborda el método de simulación del hábitat. Basado en el marco teórico IFIM, y en el modelo matemático PHABSIM, mediante el cual se obtuvieron las curvas WUA-Q para cinco especies de peces. **Resultados.** De estas curvas, se determinó que la especie *Goodea atripinnis* tiene la mayor superficie de hábitat, alcanzando un máximo de 4338 m^2/km para un caudal de 5 m^3/s; *Alloophorus robustus* mantuvo un hábitat constante de 2000 m^2/km entre caudales de 5 a 15 m^3/s. Con un menor área, *Menidia jordani* presentó un hábitat máximo de 1323 m^2/km para 4.5 m^3/s; y con WUA menores a 500 m^2/km las curvas de las especies *Algansea tincella* y *Aztecula sallaei*. **Conclusiones.** La regulación promedio de los caudales en marzo y abril fue de 3.61 y 3.44 m^3/s, con la propuesta de RCA fue de 5.11 y 5.00 m^3/s para marzo y abril, respectivamente. En general, el régimen ambiental mensual está al 80% de conservación del régimen natural de caudales, generando un incremento de hábitat durante el estiaje de 24% para *A. robustus* y 23% para *A. sallaei*.

Palabras clave: *Algansea tincella*, caudales ambientales, río Duero, simulación de hábitat.

INTRODUCTION

Environmental flows are defined as hydrologic regimes that are required to sustain ecosystem health and functions in rivers, wetlands or coastal regions, where there are competing and diverse water uses and flows are regulated. The concept was developed to assure that aquatic ecosystems are left with the necessary water quantity and quality to maintain their biotic structure (Dyson *et al*., 2008). Numerous terms define the same concept: environmental flow (39%), minimum flow (38%), in-stream flow requirement (37%), ecological reserve (23%) and other terms (21%) (Moore, 2004). Different methodologies have been developed to establish the environmental flows in rivers (Dyson *et al*., 2008). E.g., Tharme (2003) registered a minimum of 207 methodologies (29% hydrological, 28% habitat simulation, 17% combination, 11% hydraulic, 8% holistic and 7% others).

The Instream Flow Incremental Methodology (IFIM) is a theoretical framework to evaluate the ecological flow requirement of rivers (Bovee *et al*., 1998; Stalnaker *et al*., 1995; Waddle, 2001). It provides an organizational structure for the evaluation and formulation of water management alternatives that respond to the interests of different water uses (Stalnaker *et al*., 1995). The PHABSIM (Physical Habitat Simulation Model) simulation model (Milhous *et al*., 1989; Waddle, 2001) is used to calculate the available habitat useful in a river segment for different species in different flows. PHABSIM employs a structure defined by stream morphology, hydraulic parameters and habitat suitability criteria (Bovee *et al*., 1998; Milhous, 2007; Stalnaker *et al*., 1995). The IFIM-PHABSIM methodology is based on the concept of Weighted Useable Area (WUA), i.e., the wetted stream area is weighted by empirically derived from fish species' microhabitat preferences (Stalnaker *et al*., 1995). WUA-Q curves provide a measure of the available habitat as a function of stream flow (Waddle, 2001).

The Mexican standard NMX-AA-159-SCFI-2012 (DOF, 2012) establishes the procedure for evaluating ecological flows in basins. This regulation refers to hydrological methodologies as the simplest approach to get results in the short run; as illustrated by the case studies of the River Valley in San Luis Potosi (Santacruz de León & Aguilar-Robledo, 2009) and the Acaponeta River in Nayarit, Mexico (De la Lanza *et al*., 2012). The habitat simulation methodology, on the other hand, requires more detailed information in terms of hydrological, hydraulic and biological data (this IFIM-PHABSIM approach has recently gained significant importance in Mexico). Finally, holistic methods are recommended for basins with highly varying flow regimes and whose characteristics have been significantly altered. They require a greater amount of information and resources (hydrological, hydraulic, biological, ecological, economic, and social). The aim of this paper is to propose an environmental flow requirement in a fluvial segment of the Duero River Basin (DRB) through the habitat simulation method, using five fish species as indicator species.

The DRB. This basin comprises an area of 2198 km^2 (CONAGUA, 2009) and is located in northwest Michoacan state, Mexico (Fig. 1). The Duero River has its source at the springs in the town of Carapan, and flows through the Cañada de los Once Pueblos. Its main tributaries are the Celio River from the south (south of Jacona) and the Tlazazalca River from the northeast (northeast of Tangancicuaro). The flow in Tlazazalca River is regulated by the Urepetiro dam for flood control (Zavala-López, 2011). Further downstream along Duero River, Irrigation District 061 consists of 18,000 hectares of agricultural land and four irrigation modules: I) Urepetiro-Verduzco (20%), II) Principal Chaparaco (30%), III) Río Nuevo (24%), and IV) Peñitas-Estanzuela (26%) (CONAGUA-IPN, 2009). Figure 1 shows that the study area is located at the mouth of the basin. It consists of a river segment of 11.6 km length between the town of San Simon-La Estanzuela and the Camucuato Bridge.

The DRB contains a wide variety of natural resources, i.e., rivers, springs and aquifers, as well as oak and pine forests. The aquatic biodiversity consists of numerous fish species and macroinvertebrates. The hydraulic infrastructure consists of reservoirs and dams, agricultural areas, channels, wells, sewage treatment plants and drinking water systems (Velázquez *et al*., 2005, 2010). The catchments of the DRB face environmental problems such as deforestation, land use change, and the proliferation of invasive species. Other current issues include increasing urbanization, lack of specific sites for solid waste disposal, wastewater discharge into the rivers (CONAGUA-IPN, 2009; Velázquez *et al*., 2005).

Moncayo-Estrada *et al*. (2014) evaluated the index of biological integrity (IBI) for the year 2009 in the Duero River and compared it with indexes obtained in 1986 and 1991. The comparison revealed that the sampling sites of Camecuaro Lake and Camucuato Bridge changed their status from good to fair and poor, respectively. Further, El Capulin, Zamora, La Estanzuela and San Cristobal "A" deteriorated from fair to poor. The environmental degradation that is responsible for this deterioration in biological integrity is attributed to excessive water use and wastewater discharges.

Fish communities. Fish communities are the most common biological group used to assess the environmental quality of freshwater ecosystems in Mexico (Mathuriau *et al*., 2011). The NMX-AA-159-SCFI-2012 (DOF, 2012) also highlights that the experience in selecting target species is more developed for fish (at a national and international level) than for any other animal group. In the DRB, a variety of fish species is to be found. E.g., Ledesma-Ayala (1987) collected 1393 specimens belonging to 16 different species. In this study, the classification of tolerance towards environmental degradation (tolerant, medium-tolerant, sensitive) was the main criterion for the selection of species. Therefore, the ichthyic fauna in the DRB is represented by three families: Atherinidopsidae (species: *Menidia jordani* (Woolman, 1894)), Cyprinidae (species: *Algansea tincella* (Valenciennes, 1844) and *Aztecula sallaei* (Günther, 1868); and Goodeidae (species: *Goodea atripinnis* (Jordan, 1880) and *Alloophorus robustus* (Bean, 1892)). According to Ibáñez *et al*. (2008) and Miller *et al*. (2009) *Menidia jordani* (previously *Chirostoma jordani* (Woolman, 1894)) is a fish that inhabits clear or turbid waters in rivers and channels with depths of 1 m. *Algansea tincella* is found from small streams to large lakes. Spawning occurs from May to July (Barbour & Miller, 1978; Miller *et al*., 2009). *Algansea tincella* lives in water bodies with rocky bottoms to finer sediments (Ledesma-Ayala, 1987). *Goodea atripinnis* is a prolific fish; juveniles appear at the end of January and mid-July, which indicates a prolonged reproductive season (Miller *et al*., 2009). López-Eslava (1988) concluded that *G. atripinnis* reproduces between April and May, whereas Barragán & Magallón (1994) indicate that the reproduction period extends from April to September. The habitat includes clear or turbid waters in streams and it is commonly found in shallow areas (0.5 to 1.7 m). *Alloophorus robustus* is typically found in rivers with clay and gravel beds; the depths range from 1 to 2 m. The juvenile stage occurs in mid-May and June (Miller *et al*., 2009). The reproductive period extends from April to June (Mendoza, 1962).

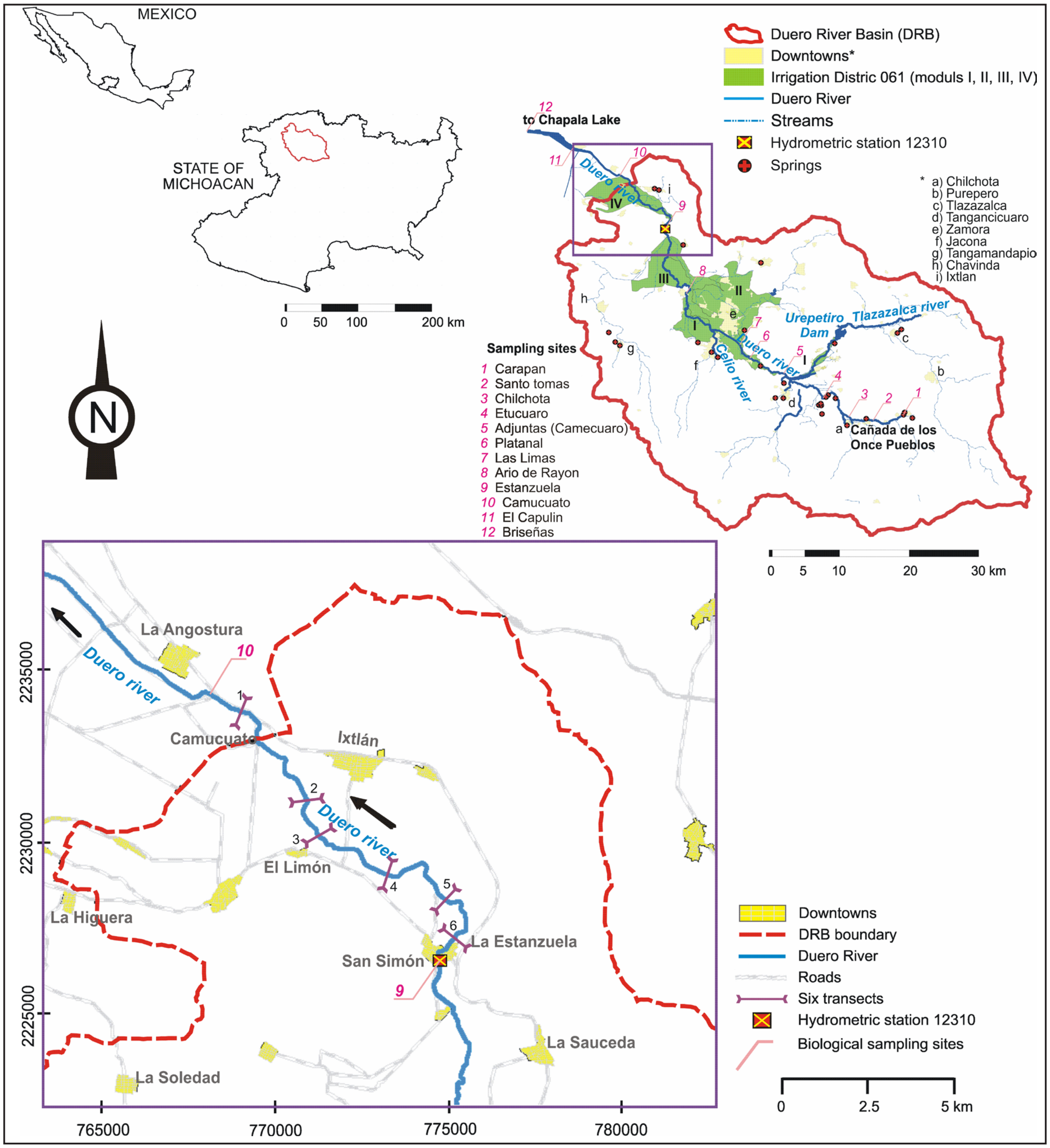


Figure 1. Study area and sections on the Duero River.

However, according to Soto-Galera *et al.* (1990), females experience a simple reproductive cycle from July to August. *Aztecula sallaei* (*Notropis sallei* (Günther, 1868)) inhabits ponds fed by streams and channels, which generally consist of fine-gravelly substrates in depths that range from 0.5 to 1.3 m in the water column. In streams, the preferred current ranges from moderate to quick and occasionally strong. The spawning period most likely occurs from February to April and possibly extends until May (Miller *et al.*, 2009). Although the reproductive period extends from March to September (Sánchez & Navarrete, 1987), June and July have been registered as the months of greatest reproductive intensity (Navarrete & Sánchez, 1987).

Table 1 summarizes some of the ecological attributes of these five fish species and shows four different evaluations of the species' tolerance of environmental degradation, over a period of 17 years. According to Lyons *et al.* (1995[I], 2000[II]), Mercado-Silva *et al.* (2006[III]) and Ramírez-Herrejón *et al.* (2012[IV]) tolerance was evaluated in the following manner: *M. jordani* maintains a 'tolerant' status ([II], [III], [IV]); *A. tincella* changed from 'tolerant' to 'medium-tolerance' ([I], [II], [III], [IV]); *A. sallaei's* assessment changed from 'medium-tolerance' to 'sensitive' ([II], [III]); *G. atripinnis* has maintained a 'high tolerance' over time ([I], [II], [III], [IV]); whereas the *A. robustus* changed from a 'medium-tolerance' to a 'sensitive' evaluation in 2012.

Table 1. Ecological attributes of fish species found in the Duero River, Mexico.

Family	Species	Origin	Habitat	Tolerance				Reproduction	Max. standard length (mm)	Source
				I	II	III	IV			
Atherinidopsidae	*Menidia jordani* (Woolman, 1894)	N[III], I[IV]	WC	–	T	T	T	Ov	91	B1, D4 and N1
Cyprinidae	*Algansea tincella* (Valenciennes, 1844)	N	WC	T	M	M	M	Ov	175	B2, D4 and L6
	Aztecula sallaei [III] (Günther, 1868)	N	WC	–	M	S	–	–	83	A4, D4 and L1
Goodeidae	*Goodea atripinnis* (Jordan, 1880)	N	WC	T	T	T	T	Vi	185	A2, A3 and L6
	Alloophorus robustus (Bean, 1892)	N	WC	M	M	M	S	Vi	200	H1, L6 and S3

Origin (N: native species, and I: introduced); habitat (WC: water column); tolerance (T: tolerant, M: medium-tolerance and S: intolerant/sensitive); reproductive type (Ov: oviparous and Vi: viviparous); max. standard length in mm. Sources: (B1) Barbour (1973); (D4) Díaz-Pardo *et al.* (1993); (N1) Navarrete *et al.* (1996); (B2) Barbour & Miller (1978); (L6) Lyons *et al.* (1995); (A4) Álvarez & Navarro (1957); (L1) López-López & Vallejo de Aquino (1993); (A2) Álvarez (1963); (A3) Álvarez & Cortes (1962); (H1) Hubbs & Turner (1939); (S3) Soto-Galera *et al.* (1990). I and II: Lyons *et al.* (1995, 2000); III: Mercado-Silva *et al.* (2006); IV: Ramírez-Herrejón *et al.* (2012).

MATERIALS AND METHODS

The procedure for proposing the environmental flow requirement (EFR) in the lower basin of the Duero River is the Instream Flow Incremental Methodology (IFIM) (Bovee *et al.*, 1998; Stalnaker *et al.*, 1995; Waddle, 2001), which covers the following steps:

Scope of the study. Currently, the Duero River Basin is subject to various pressures from the agricultural sector and various stakeholders, in addition to being an ecological habitat. Due to regulatory activity, it is necessary to review the status of the river and to propose an environmental flow regime that will continue to support the river ecosystem.

Selection of the hydraulic model. PHABSIM quantifies the habitat, defined as the optimum flow that maximizes the area available for each species (Orth & Leonard, 1990). For each flow, the available habitat is calculated by adding the area of each computational cell that comprises the control section to its corresponding composite suitability index, as expressed by Equation (1) (Bovee *et al.*, 1998; Milhous *et al.*, 1989; Moir *et al.*, 2005; Waddle, 2001).

$$WUA_{Q,s} = \sum_{i=1}^{n} (A_{i,Q})\ (CSI_{i,Q,s}) \qquad (1)$$

where $WUA_{Q,s}$ is the weighted usable area for the given discharge (Q) for target species (*s*), A_i is the area of each computational cell (i), and $CSI_{i,Q,s}$ is the composite suitability of computational cell (i) at discharge (Q) for target species (*s*). WUA is expressed in units of habitat area, m^2 per unitized distance along a stream, 1000 m or 1 km (Waddle, 2001). The CSI is non-dimensional, expressed by Equation (2) (Bovee *et al.*, 1998):

$$CSI_i = (HSIv_i)\ (HSIp_i)\ (HSIs_i) \qquad (2)$$

where HSI is the habitat suitability indices, according to the velocity (v_i), depth (p_i) and substrate (s_i) variables (Waddle, 2001), and expresses the degree of adaptation of an organism to these variables (0 unsuitable to 1 most suitable) (Bovee *et al.*, 1998; Stalnaker *et al.*, 1995).

Hydrologic regime (natural and regulated). Daily flow records were obtained from the hydrometric station (12310) (BANDAS, 2006). We identified two periods: The first period extends from 1936 to 1955 and is named the natural flow regime (NFR); the second period from 1956 to 1999 corresponds to the regulated flow regime (RFR). Figure 2 shows the variation in river flow before and after the hydraulic regulation in the indicated periods. The total annual difference between average monthly flows of the NFR and RFR is less than 10%, whereas the minimum regulated flow regimes (mRFR) show a decrease of 43% relative to the minimum natural flow regimes (mNFR).

The dry season of the NFR curve lasts from January to May, with an average flow of 7.61 to 6.66 m^3/s; except in April, when it is 4.92 m^3/s. The rainy season is reflected by the increased flows from June (8.47 m^3/s) to September (25.79 m^3/s). In the mid-1950s, the DRB experienced flow variations. During the dry season, the RFR curve was reduced by 26% (registering 3.44 m^3/s for April); and during the rainy season, the RFR curve increased 18%, with respect to the natural regime.

In dry season, the mNFR curve shows flows of 3.41 and 3.38 m^3/s, in March and April respectively. Minimum flow rates during March, April, and May have decreased by 80% with regulation, when comparing the mRFR and mNFR curves. In sum, Figure 2 shows that the regulated regime (RFR) now has similar conditions to the natural behavior of the minimum flows (mNFR).

Characterization of the fluvial segment. The slope of the river was defined by tracing a curve every 20 meters in a digital terrain model (DTM) of the area. The measurement sites (transect/cross-section) were identified on the map and in the field; as well as inflows and flow diversions. The model should consider the river reach as a closed system where the continuity equation may be applied (inlet and outlet flows do not vary with time). In addition, the hydrometric station is identified for historical flow records and biological information to generate suitability curves.

River cross-sectionals were generated using a digital theodolite (DTW-10) and a flow meter (GPI-1100) to measure the velocity across the water column. We chose the density of points along the cross section where the depth and velocity of the water column was measured according to the regularity or irregularity of the stream bed and the intensity of the flow; i.e., for uniform beds less detail was given on the measurements, whereas for higher velocities greater detail was applied. That way, six transects were measured along the river reach. According to Payne *et al.* (2004) the total number of transects should be proportional to the complexity of the hydraulic system: 6 to 10 transects for simple reaches and 18 to 20 transects for diverse reaches. The measuring period of the hydraulic variables occurred during February 2011.

Table 2 summarizes the hydraulic characteristics of the six transects (Estanz, sr66, sr63, sr62, sr60, siz68) such as depth, velocity, and

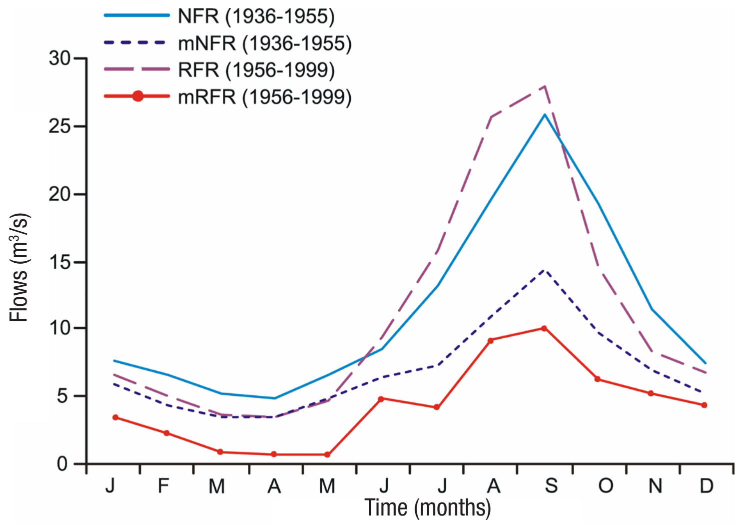


Figure 2. Monthly variation of flow regimes.

dominant substrate; length and average slope of the river. The water surface level (WSL), thalweg, and width of free-surface flow (WFS) was determined through bathymetry of the river transects, displaying the output results on a spreadsheet. The riverbed substrate presented a variety of materials, from fine sediments (clays, silts and sands) to pebbles. According to the standard characterization of substrate values used by PHABSIM (Bovee, 1986), were assigned to the riverbed as a function of the predominant material in the cross section. The type of mesohabitat was identified according to the classification made by Sanz-Ronda *et al.* (2005). The flow volume in the control sections was obtained by applying the central cell division method. The average flow measured in the cross sections was 3.02 m^3/s.

Biological sampling. As mentioned, the NMX-AA-159-SCFI-2012 (DOF, 2012) recommends using fish as target species, in order to build upon previous experience and pre-existing knowledge. For our study, we used the work of Ledesma-Ayala (1987) who had collected ichthyic species in twelve sampling sites along the whole Duero River from Carapan (source) to Briseñas (mouth). The structure of the fish community was analyzed by five samplings conducted from April 1985 to February 1986. More than 50% of the collected specimens (728) corresponded to the five species that we selected as indicators for the generation of suitability curves. Later, López-Eslava (1988) counted 600 specimens of the species *Goodea atripinnis* (also included in the suitability curves). The specimens were obtained using a *seine net* 20 m long by 2 m wide with a mesh size of 1/2 inch; they were immediately fixed and preserved for transportation to the laboratory (Ledesma-Ayala, 1987). Appendix 1 shows a summary of the number of species recorded by Ledesma-Ayala (1987) for each sampling site.

Suitability curves (Category III). These curves were generated for the following fish species: *Menidia jordani*, *Algansea tincella*, *Aztecula sallaei*, *Goodea atripinnis* and *Alloophorus robustus*. The procedure for generating suitability curves was referred to in Bovee *et al.* (1998) and Vargas *et al.* (2010). Sampling stations were characterized by relevant data (length of reach, width of river, substrate, velocity, and depth). A representation factor (RT_i) was obtained from the respective distance between neighboring sampling sites and the total length of the river. The number of class intervals (k) was defined by Sturges' rule, Equation (3)

$$k = 1 + \log_2 N \quad (3)$$

Table 2. Physical characteristics of the study reach, composed of six transects, for use in the PHABSIM model.

Transect key	ID	Reach (km)	Terrain elevation (masl)	WSL (masl)	Thalweg (masl)	Slope of course (m/m)	WFS (m)	Average depth (m)	Average velocity (m/s)	Dominant substrate	Mesohabitat type
Estanz	6	0	1537.2	1533.3	1532.0	0.0029	16.1	0.96	0.19	si-cl-gr	Backwaters
sr66	5	1.8	1535.6	1532.0	1530.8	0.0027	14.1	0.77	0.28	si-cl-gr	Fordable backwaters
sr63	4	2.5	1533.1	1531.9	1530.9	0.0026	18.5	0.52	0.33	cl-si-sa	Slow waters
sr62	3	2.5	1533.0	1529.1	1528.0	0.0025	19.7	0.68	0.21	cl-si-sa	Fordable backwaters
sr60	2	1.2	1531.3	1528.6	1527.0	0.0025	18.9	1.11	0.14	cl-si-gr	Backwaters
siz68	1	3.6	1528.0	1526.4	1525.1	0.0025	18.2	1.16	0.13	cl-si-sa	Backwaters

Cross section (first column); (ID) transect number; length; terrain elevation of the river bank; (WSL) elevation of water surface level of the river; (thalweg) elevation at maximum depth of the cross section; slope of the water length; (WFS) width of free-water surface of the transect; average depth of the water column; average velocity of the water column; dominant substrate clay-silt-sand (cl-si-sa), clay-silt-gravel (cl-si-gr), silt-clay-gravel (si-cl-gr) and mesohabitat identified.

Where N is the number of sampling sites (Scott, 2009). The relative frequency (F_j) was calculated for the class intervals (upper limit) for each variable: depth, velocity, and substrate. Later, F_j was multiplied by RT_i. The availability index (Id_j), was obtained by dividing the product (F_j)(RT_i) value by the sum of total (F_j)(RT_i). Additionally, each (Id_j) value was divided by the maximum value of (Id). The habitat use index (Iu_j) was obtained by dividing the sum of the specimens counted at each sampling site referring to each interval class; i.e., the specimens that belongs within the same class of interval are counted. Thus, stations Estanzuela (with 201) and Capulin (with 426) together sum 627 specimens of *G. atripinnis*, where the depth (1.86 and 2.13 m, respectively) belong to the interval # 4. Therefore, of the 627 specimens obtained it was divided by the total number of specimens (954). Then, the selection index (C_j) is calculated dividing Iu_j by Id_j. Finally, each value of the selection index is divided by the maximum value of C_j (see Appendix 2; example depth).

Appendices 3a-b shows the biological modeling, represented by the habitat sustainability index for the five fish species with respect to each of the habitat variables. E.g., *Aztecula sallaei* prefers variable depths of the water column, with depths ranging from 0.20 to 2.00 m and an optimum depth of 1.00 m. Regarding flow velocity, *A. sallaei* prefers ranges between 0.30 and 0.70 m/s with a suitable velocity of 0.55 m/s (but seeks higher velocities). From Appendix 3c, we observe that the same species prefers coarse substrates such as gravel, but shows a lower preference for finer gravels, sand and silt.

Model implementation. PHABSIM uses hydraulic models to calculate the water surface level (WSL) and the average velocity for each flow rate (Q) to be simulated. The WSL simulation and the hydraulic profiles were performed using the MANSQ model (Manning's stage discharge), which uses the continuity equation (the flow volume is constant throughout the reach) and Manning's equation to determine the depth-flow relationship (WSL-Q) for a cross section, by assuming uniform permanent flow conditions in each section. The velocities simulated for each section were calculated based on the velocities measured in the field by using the calibration model VELSIM (velocity simulation), which is applied when only one measured velocity profile is available (Bovee *et al*., 1998; Waddle, 2001).

Subsequently, calibration curves were estimated for each transect using the least squares method (regression analysis), where WSL is the dependent variable and the independent variable is Q (flow rate). The Manning's roughness coefficient was used to calibrate these curves and later to calibrate the velocity distribution in PHABSIM. As only one measurement was taken, these calibration curves were used to propose other measurement points within the hydraulic section. By combining the hydraulic and biological models, the habitat availability can be quantified using the HABTAE routine of PHABSIM (Milhous *et al*., 1989; Moir *et al*., 2005; Waddle, 2001).

Appendices 4 and 5 show the calibration of the water surface level and the flow velocity (hydraulic modeling) in the "Estanz" transect (ID: 6), which is part of the upstream part of the river reach. Appendix 4a-b shows the results of a minimum of three hydraulic simulations performed with PHABSIM. The continuous line and segmented centerline represent the comparison between the observed (oWSL) and simulated (sWSL) values. The oWSL line is associated with a flow rate of 3.02 m^3/s and a water-column depth of 1.30 m. The lower and upper lines (flows of 0.5 and 11.5 m^3/s), are not associated with the values measured in field, but are a function of the calibration curve of the cross section; i.e., with flow rates 0.5 and 11.5 m^3/s their respective depths (0.7 and 2.6 m) and elevations (1532.7 and 1534.6 masl) were obtained. Similarly, Appendix 5a-b shows that the simulated velocity distribution sVEL is similar to the observed oVEL. For a flow of 3.02 m^3/s, the average oVEL was 0.18 m/s. For flow rates of 0.5 and 11.5 m^3/s average velocities of 0.08 and 0.30 m/s were obtained from the velocity distribution.

RESULTS

Alternatives to determine the optimum flow. Figure 3 shows the WUA-Q curves for the five species in the study area. Since the curve of the species *Goodea atripinnis* has the greatest habitat area, reaching a maximum of 4338 m^2/km for a flow of 5.0 m^3/s, the habitat fluctuates as a function of the flow. The *Alloophorus robustus* curve maintains a constant habitat of 2000 m^2/km from flow of 5 to 15 m^3/s. With a smaller area, the WUA curve of *Menidia jordani* has a maximum habitat of 1323 m^2/km for a flow of 4.5 m^3/s, presenting variable behavior during flow increases.

Finally, the curves of the *Algansea tincella* and *Aztecula sallaei* species trace a smaller useful area (WUA< 500 m^2/km), where the tendency of the curves does not show increases of the area with increased flow. From these curves (WUA-Q), we derived four criteria to determine the optimum flow and thus proposed in Fig. 4 the corresponding EFR for each criterion.

1) The largest WUA curve: The curve corresponding to *Goodea atripinnis* shows the greatest habitat area (4338 m^2/km) with an optimum flow of 5.0 m^3/s. This flow rate is representative for all five species and is set as the minimum flow during the dry season (April). According to García de Jalón & González del Tánago (1998), this situation translates into the best conditions to develop an ecological flow regime: using the natural flow curve, adjusting the optimum flow (obtained from the WUA-Q curve) by the minimum monthly value of the natural curve, and calculating the remaining months proportionally. The proposed environmental flow should fluctuate similarly to the natural regime.

2) Normalizing the WUA curves: The optimum flow provides the maximum habitat percentage for all species studied herein (Leonard & Orth, 1988; Orth & Leonard, 1990). Based on the WUA-Q curves, the axis WUA was normalized by superposing the curves, generating a new habitat optimization curve, which enables the identification of an optimum flow of 5.7 m^3/s corresponding to a value of 75% of the optimum habitat. This flow, which is representative for all the species, was set as the minimum flow during April; it varied proportionally during all remaining months (similar to the previous case).

3) Maximum WUA curve: Table 3 shows the optimum flows for each species. These flows were identified from the maximum values of habitat in the WUA curves (Fig. 3). Table 4 shows the proposed monthly environmental flow regime, and the regulated flow regime to contrast monthly differences. These proposed flows represent a recovery of flows in the months of March and April for *Goodea atripinnis*, *Menidia jordani*, and *Algansea tincella* species, when the regulated flows are below environmental flows. *Alloophorus robustus* and *Aztecula sallaei* prefer higher flows, as in the months of April to October, while the environmental proposal is higher than the RFR, with the exception of July, when the regulated flow is greater than the one proposed.

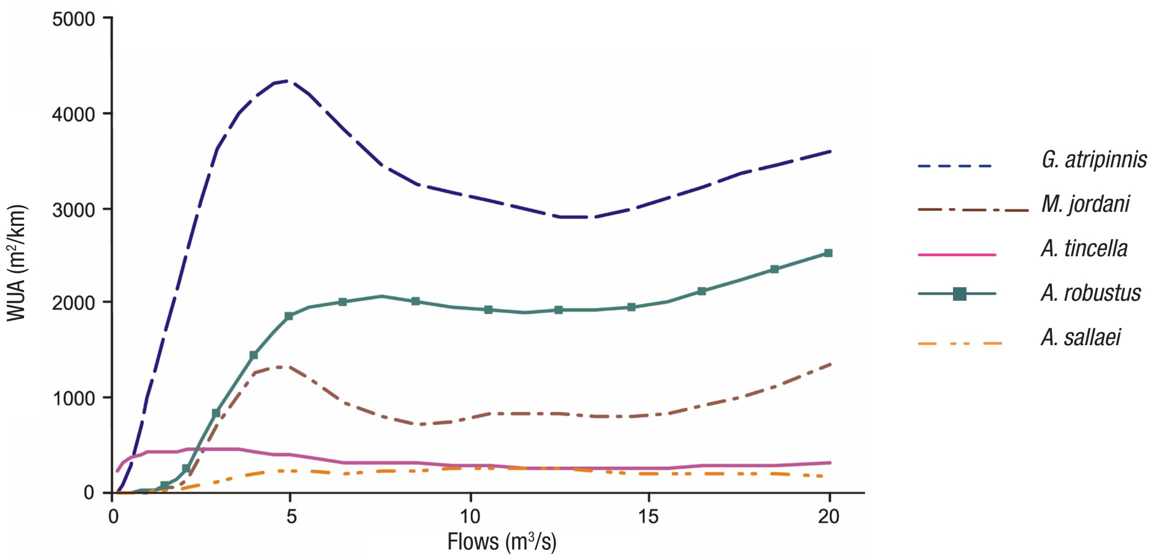


Figure 3. Weighted Usable Area—Flows (WUA-Q) curves for the five fish species.

4) Optimization matrix (Bovee, 1982): Table 5 shows the percentage of the probability of exceedance of historical natural flows. With these flows (Fig. 3), the habitat (WUA) of each species is calculated. Of the five species, the minimum WUA is selected; and later, out of these values the maximum WUA is chosen (214 m^2/km), which corresponds to the probability of exceedance of 50%. In other words, 7.2 m^3/s is the monthly environmental flow that maximizes the habitat with the lowest contribution. This procedure was applied to the remaining months, as is shown in Figure 4. For this technique, a monthly historical series of 20 years was needed to calculate the probability of exceedance in intervals from 50 to 90%.

Monthly variation of habitat. Figure 5 (left column) shows the monthly variation of average WUA for each species: a natural WUA (flows from 1936 to 1955), a regulated WUA (1956 to 1999), and the environmental WUA according to the optimization matrix method. The curves for *Goodea atripinnis* and *Menidia jordani* (Figs. 5a, c) show a significant difference between the regulated habitat and natural habitat in March and April. These variations of habitat oscillate between 10 and 13% for *G. atripinnis* and between 18 and 25% for *M. jordani*. The proposed environmental WUA for both species shows which of them is above the natural WUA during the dry season and which is below the natural WUA curve during the rainy season. Only *Algansea tincella* (Fig. 5e) displays the reverse condition where, during the dry season, the regulated WUA curve lies above the environmental and natural WUA curves (by 14%). In the rainy season, there is not much difference between the regulated and natural WUA curves. *Alloophorus robustus* and *Aztecula sallaei* experience a significant decrease of habitat in March and April with respect to the natural habitat (Figs. 5g, i). These variations range from 33 - 36% for *A. robustus* and 25 - 29% for *A. sallaei*. The environmental WUA in both species is similar to the natural WUA during the dry season. However, for *A. robustus* the proposed environmental WUA is 17% below the natural habitat during the July to October rainy season.

Figure 5 (right column) displays the monthly behavior of the habitat duration curves between the natural WUA curve (reference) and the environmental and regulated WUA curves. The natural habitat for *Goodea atripinnis*, *Menidia jordani*, *Algansea tincella*, *Alloophorus robustus* and *Aztecula sallaei* more frequent or available 90% of time in an average year was 3176 m^2/km, 832 m^2/km, 287 m^2/km, 1818 m^2/km and 204 m^2/km respectively (Figs. 5b, d, f, h, j). With agricultural activities in the region, the flow regime has been altered, which has had effects on the habitat of the species. Larger changes can be observed in the habitat of *A. robustus* with habitat degradation of -33% and for *A. sallaei* with -19%.

For the other three species, minor changes in habitat duration have occurred, with +4% for *G. atripinnis* and *A. tincella*, and +2% for *M. jordani*.

Table 3. Range of optimum minimum flows for each fish species.

Species	Optimum flows* (m^3/s)
Goodea atripinnis	5
Menidia jordani	4.5
Algansea tincella	3
Alloophorus robustus	7.5, 20
Aztecula sallaei	5, 11.5

* The optimum flow was obtained from the WUA-Q curves (see Fig. 3).

Table 4. Proposed environmental flow regime.

Period (months)	Jan-Mar	Apr-Jun	Jul-Oct	Nov-Dec
Optimum flows range (m^3/s)	4 - 5.5	5 - 11.5	7.5 - 20	4 - 5
Regulated flow (1956-1999) (m^3/s)	6.5 - 3.6	3.4 - 9.4	15.8 -14.5	8.4 - 6.7

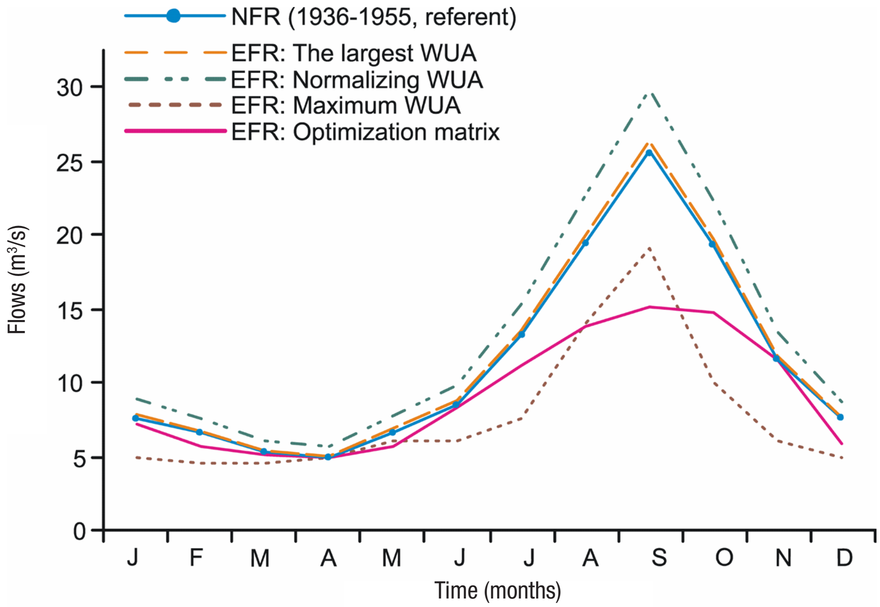


Figure 4. Summary of the four proposals of environmental flow regimes and natural flow regime.

DISCUSSION

Now that these four alternatives have been evaluated to propose EFR curves, we can confirm that all of them have acceptable behavior with respect to the NFR curve; however, only one alternative was selected for this study. By inspection, we discarded the curves obtained by the largest WUA and normalization methods, by overestimating the average natural monthly flow rates. According to Richter *et al.* (2003) and Tharme & King (1998), the assessment of the environmental flow of a river is to evaluate how much water of that original regime can continue to flow without compromising the integrity of ecosystems. The EFR curve (maximum WUA) has a downward behavior with respect to the natural referent curve; however, before proposing the EFR curve, not all WUA-Q curves were clear enough to identify the optimum flow for the species. According to Wilding (2007), this criterion for an inflection point is the most commonly used procedure; however, they are not always clearly present. Finally, the optimization matrix curve presented a downward behavior in the dry and rainy season, with respect to the NFR curve. According to Richter *et al.* (2003), it seeks a balance between the limit of the amount of water that can be withdrawn from a river and a limit on the shape to which the natural flow regime can be altered. This fourth alternative was selected to propose the environmental flow regime.

The intensive reduction of flows in the river will cause loss of habitat for fish and other aquatic organisms (Welcomme, 1992). The flow regulation in the Duero River is mainly reflected in March and April. Contrasting the habitat variation curves, Figure 5 (left column) shows that the flow regulation has affected four of the five fish species. We should note that *Goodea atripinnis* and *Menidia jordani* have decreased habitat from March to April, partially affecting the reproductive period of both; however, the reproduction period of *G. atripinnis* has been extended from April to September (Barragán & Magallón, 1994) and from February to August for *M. jordani* (Miller *et al.*, 2009). Despite this partial affectation of habitat, Lyons *et al.* (1995, 2000), Mercado-Silva *et al.* (2006) and Ramírez-Herrejón *et al.* (2012) depict both species as tolerant of environmental degradation, being prolific species with an annual presence. The preferred habitat of both species occurs in the dry season, with optimum minimum flow of 4 to 5.5 m^3/s; however, they also adapt well to flow rates in the rainy season (between 18 to 20 m^3/s). The proposed environmental WUA curve (optimization matrix method) shows a slight increase

Table 5. Application of matrix optimization to select the average environmental flow per month (for this example, January).

Month	Species	Q_n 50%	Q_n 60%	Q_n 70%	Q_n 80%	Q_n 90%	WUA	Average monthly environmental flow
		7.2 (m^3/s)	7.1 (m^3/s)	7.0 (m^3/s)	6.6 (m^3/s)	6.4 (m^3/s)		
January	*Goodea atripinnis*	3555	3592	3630	3778	3854	m^2/km	
	Menidia jordani	845	860	874	932	973	m^2/km	
	Algansea tincella	319	320	321	325	330	m^2/km	
	Alloophorus robustus	2042	2037	2031	2009	1998	m^2/km	
	Aztecula sallaei	214	213	211	206	207	m^2/km	
	Minimum WUA	214	213	211	206	207	m^2/km	7.2 m^3/s

The maximum value of the minimum WUA for January is 214 m^2/km and the range of natural flow (Q_n) is associated with the probability of exceedance (50 to 90%).

in habitat during the dry season and decreased habitat during the rainy season, indicating a probable natural limit.

River regulation resulted in more habitat decline from January to May for *Alloophorus robustus* and *Aztecula sallaei*, affecting various stages of life. E.g., the juvenile stage of *A. robustus* is from February to March. The spawning period of *A. sallaei* is from February to April, and maybe until May (Miller *et al*., 2009), and the reproduction period lasts from April to August for *A. robustus* (Mendoza, 1962; Soto-Galera *et al*., 1990) and from March to September for *A. sallaei* (Sánchez & Navarrete, 1987). Considering the habitat duration curves, the contrast between NFR and RFR was evident for 50% of the time. The useful habitat of both species is mostly in the rainy season; though with a different range of the optimum minimum: 7.5 to 20 m^3/s for *Alloophorus robustus* and 5 to 11.5 m^3/s for *Aztecula sallaei*. However, both species also find favorable habitat in the dry season, while *Alloophorus robustus* is normally found in lentic water and *Aztecula sallaei* prefers moderate to strong currents (Miller *et al*., 2009). According to Lyons *et al*. (1995, 2000), Mercado-Silva *et al*. (2006), and Ramírez-Herrejón *et al*. (2012), both species are sensitive or intolerant towards habitat deterioration.

Finally, regarding *Algansea tincella*, with medium tolerance status (Lyons *et al*., 1995, 2000; Mercado-Silva *et al*., 2006; Ramírez-Herrejón *et al*., 2012), the available habitat area has increased with flow regulation and life stages (spawning and reproduction) do not seem to be compromised, but the reproduction season in April benefits from regulation. According to Welcomme (1992) the aquatic organisms in rivers usually adapt to the regimes of the flow. The preferred habitat of *Algansea tincella* is at the flow rates that corresponding to the dry season, with an optimum flow of 3 to 4 m^3/s; however, it also prefers 8 m^3/s in the rainy season (November). As for the proposed EFR, the habitat in the rainy season decreases below the natural reference, which can be considered a new limit capable of maintain the integrity of the ecosystem.

EFR proposal. Figure 6 shows the proposed environmental flow requirement, the regulated flow regime (RFR) and the minimum regulated flow regime (mRFR) in order to compare the monthly flow variation. In the dry season, environmental flows from January to May are greater than the regulated flow (RFR curve), being March and April the most critical with RFR at 30% below the environmental proposal. According to García de Jalón & González del Tánago (1998), the environmental flows must be greater in periods of low flow. In the rainy season, the EFR curve shows an increasing trend from June to August, reaching a maximum in September and decreasing from October to November. According to Richter *et al*. (2003), there are limits to the amount of water that can be withdrawn from rivers before severely degrading their natural functions and the services they provide.

The average annual flow rate under the NFR is 11.36 m^3/s, for regulated flow it is 10.98 m^3/s and for the proposed EFR it is 9.09 m^3/s. From this we can assume that annual regulation has not significantly affected the flow behavior of the river, reported at only 5% below natural conditions (NFR curve). However, with monthly regulation (during the dry season), the data shows a different perspective. Figure 6 now shows that the proposed EFR lies above the RFR curve from January to May (e.g., see Table 6). During the dry season, the current average flow rates (RFR curve) resemble the conditions of the mNFR curve; i.e., the minimum flows during the natural regime. Consequently, the minimum regulated flows (mRFR) have reached levels not yet registered in the 1936-1955 period. For example, Table 6 shows the variation of February, March, and April.

Table 6. Comparison between flows: environmental vs regulated, and natural minimums vs regulated minimums.

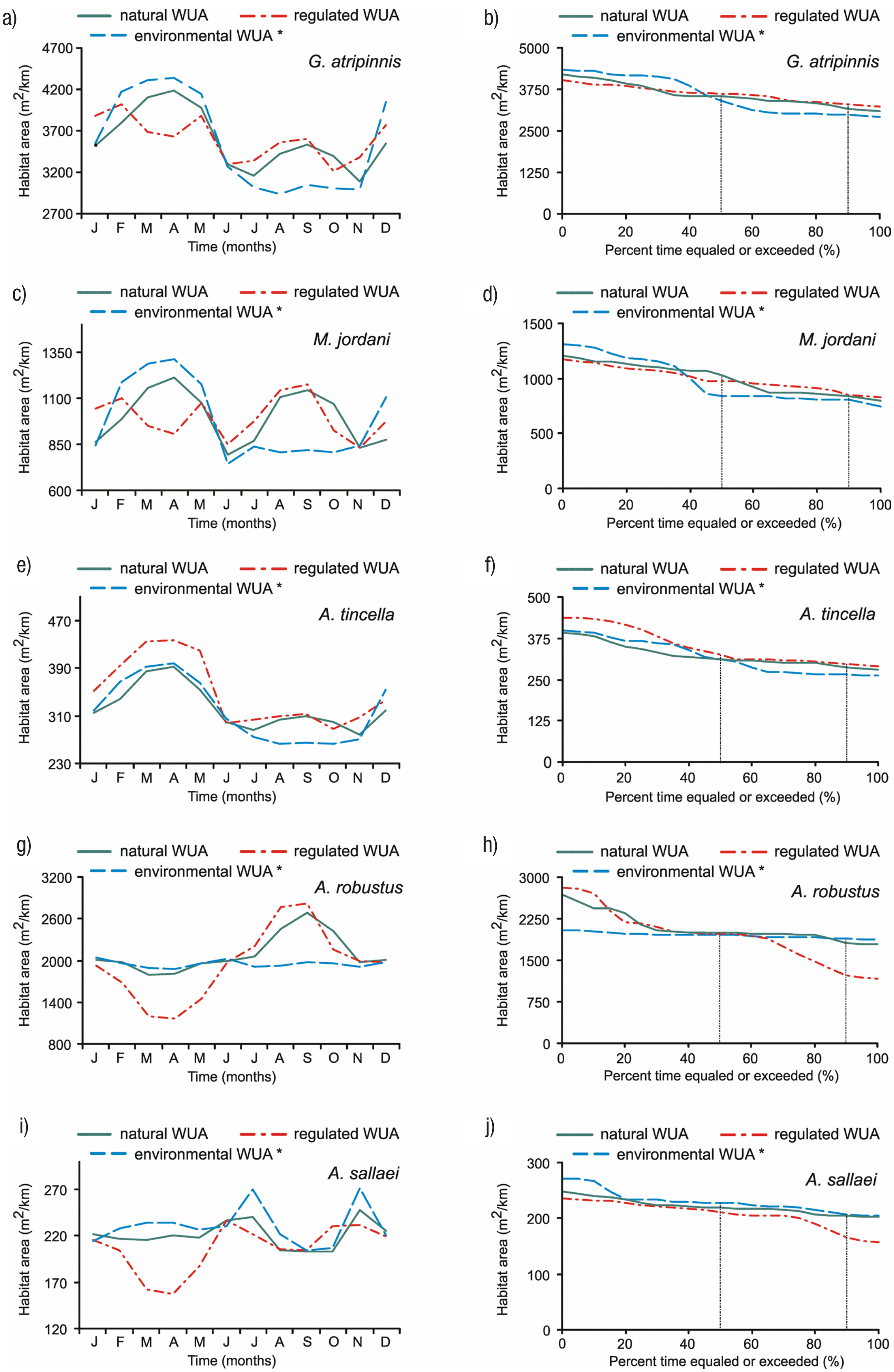
Dry season	EFR flow greater to RFR flow	mNFR flow greater to mRFR flow
February	5.59 - 4.96 m^3/s	4.38 - 2.29 m^3/s
March	5.11 - 3.61 m^3/s	3.41 - 0.80 m^3/s
April	5.00 - 3.44 m^3/s	3.38 - 0.73 m^3/s

García de Jalón & González del Tánago (1998) point out that the flow and habitat requirements of different fish species can vary widely throughout the year. In case of the Duero River, *Alloophorus robustus* and *Aztecula sallaei* require greater flow rates during the dry season, implying loss of habitat and stress to their life stages (spawning and reproduction, Fig. 6). The proposed environmental flow regime can benefit their life cycle, due to the natural tendency of the proposed curve. In other words, if the habitat is unfavorable to these species, *Algansea tincella* finds it favorable. Similarly, *Goodea atripinnis* and *Menidia jordani* found favorable habitat and flows throughout the year.

Regulation on the Duero River resulted in an average annual variation of less than 10% between the natural (NFR, 1936-1955) and the regulated flow regime (RFR, 1956-1999); for the annual average minimum flow (mNFR and mRFR curves) this difference was 40%. However, looking at monthly data, during the dry season from January to May the difference between the minimum flows (regulated vs natural) was a 66% decrease; showing that the effect of the regulation is most noticeable in the dry season. The difference between the annual average NFR curve and the EFR curve is 20%; i.e., the environmental flow preserves up to 80% of the natural flow regime. This EFR proposed for the lower reach of the Duero River during the dry season generates a favorable effect on the available habitat areas of the five target fish species, with a 11% increase of WUA for *A. tincella*, and a recovery of degraded habitat area for *G. atripinnis* (with 10%), *M. jordani* (18%), *A. robustus* (24%) and for *A. sallaei* (23%).

The management of environmental flows should be a fundamental part of the integrated water resources management approach in the Duero River, due to its beneficial mitigation impacts on the constant pressure of regulatory activity. It would be convenient to discontinue decreasing this activity from March and April (3.61 to 3.44 m^3/s), thus avoiding the occurrence of minimum regulated flows; we also recommend establishing the proposed average environmental flows from 5.11 to 5.00 m^3/s (for March and April, respectively).

The regulation of the river has direct implications on the available habitat of the target species, mainly in March and April; *Alloophorus robustus* and *Aztecula sallaei* are the most affected, while *Algansea tincella* benefits with an increase in habitat. However, in the rainy season regulation has not affected the habitat of the species. We should mention that this analysis of the habitat variation curves was done with monthly average information. Thus, it is necessary now to analyze habitat variation with minimum flows. Flow rates lower than 1 m^3/s during March, April, and May increase habitat degradation in the river and diminish ecosystem resilience. With an environmental proposal of 80% conservation of the NFR, we recommend identifying other lower thresholds to observe the variation in the fluvial habitat.



Figures 5a-j. Variation in the monthly habitat (left) and habitat duration curves (right) for each fish species (* = Optimization matrix method).

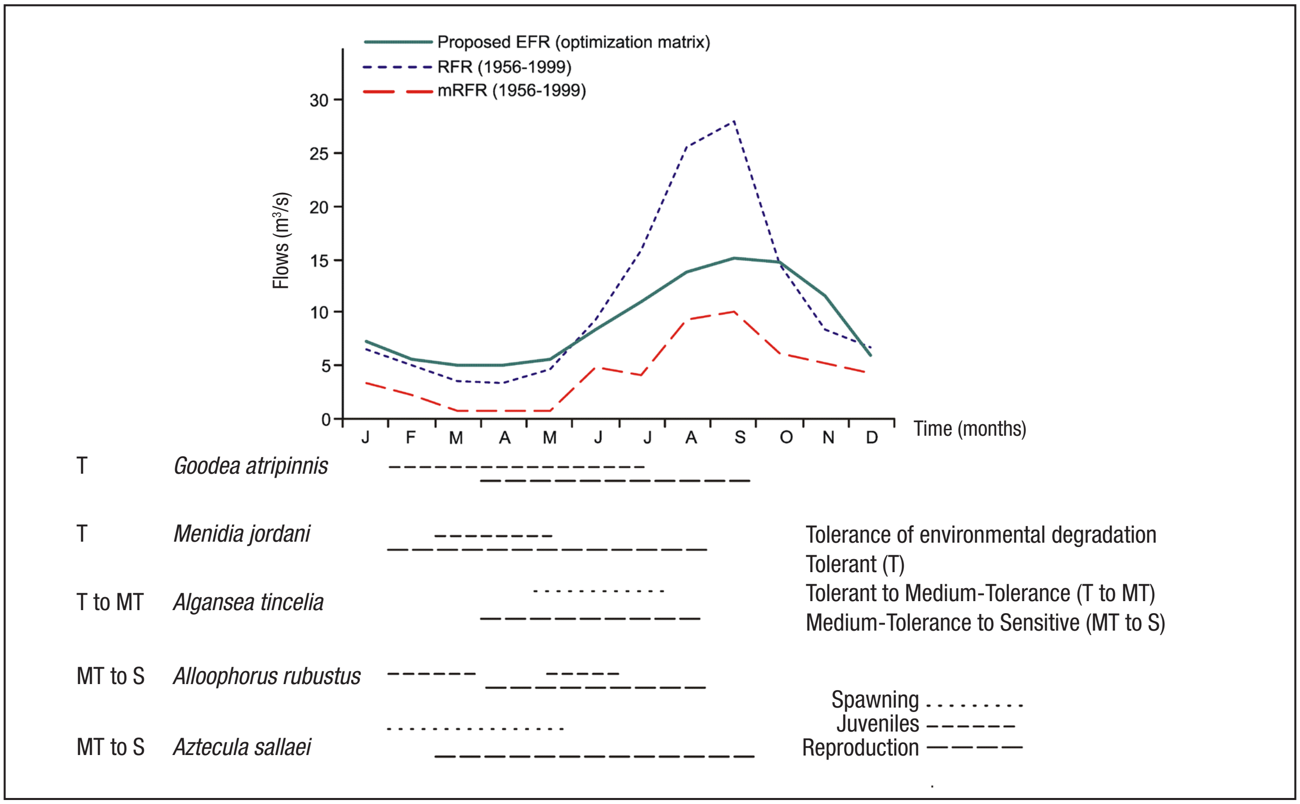


Figure 6. Proposal environmental flow requirement (EFR) in the study area, contrasting with flows regulated and life stages. Note: The life stages with information: Barbour & Miller (1978), Barragán & Magallón (1994), Ledesma-Ayala (1987), López-Eslava (1988), Mendoza (1962), Miller *et al.* (2009), Navarrete & Sánchez (1987) and Soto-Galera *et al.* (1990). Tolerance of environmental degradation with information from Lyons *et al.* (1995, 2000), Mercado-Silva *et al.* (2006) and Ramírez-Herrejón *et al.* (2012).

We believe that this research will be relevant at the national level, since it is one of the first studies to apply this methodology to a Mexican river. The study focuses on only one reach of the river, on the lower basin where the instream water demand competes with irrigation infrastructure. Therefore, water management plays an important role in the allocation and/or implementation of environmental flows, for care and conservation of the aquatic ecosystems in the DRB.

ACKNOWLEDGMENTS

The Universidad Nacional Autónoma de México (UNAM), through the PAPIIT Program (IN111312), financially supported this study. CONACYT granted scholarships (210354) that allowed graduate studies and approved a scholarship supplement for an academic exchange with the Laboratorio de Hidrobiología at the Universidad Politécnica de Madrid, Spain. We thank the Graduate Program in Earth Sciences, within the Instituto de Geología, UNAM. We thank Norman Mercado-Silva (CIByC, UAEM), John Lyons (DNR, University of Wisconsin-Madison), and Omar Domínguez-Domínguez (LBA, Fac. Biol., UMSNH) for suggestions on selecting species. We also wish to thank Luzma Fabiola Nava (International Institute for Applied Systems Analysis) for constructive comments on the manuscript.

REFERENCES

Álvarez, J. 1963. Michoacán ichthyology. III. The fishes of San Juanico and Tocumbo, Mich. *Anales de la Escuela Nacional de Ciencias Biológicas México* 12 (1-4): 111-138.

Álvarez, J. & M. T. Cortes. 1962. Ictiología michoacana I. Claves y catálogo de las especies conocidas. *Anales de la Escuela Nacional de Ciencias Biológicas México* 11 (1-4): 86-142.

Álvarez, J. & L. Navarro. 1957. *Los peces del valle de México.* Secretaría de Marina, Instituto Nacional de Pesca, Dirección de Pesca e Industrias Conexas, México, D.F. 62 p.

BANDAS (Banco nacional de datos de aguas superficiales). 2006. Comisión Nacional del Agua. Disponible en línea en: http://www.imta.gob.mx/index.php?Itemid=145&option=com_wrapper&view=wrapper (consultado el 18 Mayo 2013).

Barbour, C. D. 1973. The systematics and evolution of the genus *Chirostoma* Swainson (Pisces, Atherinidae). *Tulane Studies in Zoology and Botany* 18: 97-141.

Barbour, C. D. & R. R. Miller. 1978. A revision of the mexican cyprinid fish genus *Algansea*. *Miscellaneous Publications Museum of Zoology, University of Michigan* 155: 1-72.

Barragán, J. & B. S. Magallón. 1994. Peces dulceacuícolas mexicanos X. *Goodea atripinnis* (Cyprinodontiformes: Goodeidae). *Zoología Informa* 28: 27-36.

Bovee, K. D. 1982. *A guide to stream habitat analysis using the instream flow incremental methodology*. FWS/OBS-82/26, Instream Flow Information Paper 12. U.S. Fish and Wildlife Service. Annapolis, MD. 248 p.

Bovee, K. D. 1986. *Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology*. FWS/OBS-86/7, Instream Flow Information Paper 21. U.S. Fish and Wildlife Service. Washington, DC. 235 p.

Bovee, K. D., B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, J. Taylor & J. Henriksen. 1998. *Stream habitat analysis using the instream flow incremental methodology*. Report USGS/BRD-1998-0004. U.S. Geological Survey, BRDIT. Fort Collins, CO. 131 p.

CONAGUA (Comisión Nacional del Agua). 2009. *Programa Hídrico Visión 2030 del Estado de Michoacán de Ocampo*. Secretaría de Medio Ambiente y Recursos Naturales. 170 p.

CONAGUA-IPN (Comisión Nacional del Agua-Instituto Politécnico Nacional). 2009. *Programa detallado de acciones para el proyecto emblemático: Saneamiento Integral de la Cuenca del Río Duero*. Convenio CNA-MIC-SCCGSAE-01/2008. Informe Final. 142 p.

De la Lanza Espino, G., J. L. Carbajal Pérez, S. A. Salinas Rodríguez & J. E. Barrios Ordóñez. 2012. Medición del caudal ecológico del río Acaponeta, Nayarit, comparando distintos intervalos de tiempo. *Investigaciones geográficas* 78: 62-74. DOI: 10.14350/rig.35269

Díaz-Pardo, E., M. A. Godínez-Rodríguez, E. L. López-López & E. Soto-Galera. 1993. Ecología de los peces de la cuenca del río Lerma, México. *Anales de la Escuela Nacional de Ciencias Biológicas México* 39: 103-127.

DOF (Diario Oficial de la Federación). 2012. *NMX-AA-159-SCFI-2012. Norma Mexicana. Que establece el procedimiento para la determinación del caudal ecológico en cuencas hidrológicas*. Diario Oficial de la Federación. México, D.F. Septiembre 20: 96 p.

Dyson, M., G. Bergkamp & J. Scanlon (Eds.). 2008. Flow: the essentials of environmental flows. International Union for Conservation of Nature. Gland, Switzerland. 134 p.

García de Jalón, D. & M. González del Tánago. 1998. El concepto de caudal ecológico y criterios para su aplicación en los ríos Españoles. Disponible en línea en: http://www.fnca.eu/biblioteca-del-agua/documentos/documentos/308.pdf (consultado el 3 Octubre 2016).

Hubbs, C. L. & C. L. Turner. 1939. Studies of the fishes of the order Cyprinodontes. XVI. A revision of the Goodeidae. *Miscellaneous Publications Museum of Zoology, University of Michigan* 42: 1-90.

Ibáñez, A. L., J. L. García-Calderón & B. R. Torres-Orozco. 2008. Reproductive features of the “charal” *Menidia jordani* (Woolman) from Lake of Metztitlán, Hidalgo. *Hidrobiológica* 18 (1): 1-9.

Ledesma-Ayala, C. L. 1987. Estudio ictiologico del rio Duero, Michoacán. Tesis Profesional en Ciencias (Biología), Facultad de Ciencias Biológicas, UANL, México. 105 p.

Leonard, P. M. & D. J. Orth. 1988. *Habitat-use guilds and selection of instream flow target species*. Biological Report 88 (11). U.S. Fish and Wildlife Service. Annapolis, MD. 18 p.

López-Eslava, S. 1988. Ecología y biología de *Goodea atripinnis* en el Río Duero, Michoacán. Tesis Profesional en Ciencias (Biología), Facultad de Ciencias, UNAM, México. 70 p.

López-López, E. & P. Vallejo de Aquino. 1993. Peces dulceacuícolas mexicanos VIII. *Notropis sallei* (Cypriniformes: Cyprinidae). *Zoología Informa* 25: 12-24.

Lyons, J., A. Gutiérrez-Hernández, E. Díaz-Pardo, E. Soto-Galera, M. Medina-Nava & R. Pineda-López. 2000. Development of a preliminary index of biotic integrity (IBI) based on fish assemblages to assess ecosystem condition in the lakes of central Mexico. *Hidrobiológica* 418 (1): 57-72.

Lyons, J., S. Navarro-Pérez, A. P. Cochran, C. E. Santana & M. Guzmán-Arroyo. 1995. Index of biotic integrity based on fish assemblages for the conservation of streams and rivers in west-central Mexico. *Conservation Biology* 9 (3): 569-584.

Mathuriau, C., N. Mercado-Silva, J. Lyons & L. M. Martínez-Rivera. 2011. Fish and macroinvertebrates as freshwater ecosystem bioindicators in Mexico: current state and perspectives. *In*: Oswald, S. U. (Eds.). *Water Resources in Mexico*. Springer-Verlag, Berlin, pp. 251-261. DOI: 10.1007/978-3-642-05432-7_19

Mendoza, G. 1962. The reproductive cycles of three viviparous teleosts, *Alloophorus robustus*, *Goodea luitpoldi* and *Neoophorus diazi*. *The Biological Bulletin* 123: 351-365.

Mercado-Silva, N., J. Lyons, E. Díaz-Pardo, A. Gutiérrez-Hernández, C. P. Ornelas-García, C. Pedraza-Lara & M. J. Vander-Zanden. 2006. Long-term changes in the fish assemblage of the Laja River, Guanajuato, central Mexico. *Aquatic Conservation: Marine and Freshwater Ecosystems* 16 (5): 533-546. DOI: 10.1002/aqc.737

Milhous, R. T. 2007. Application of Physical Habitat Simulation in the Evaluation of Physical Habitat Suitability. *U.S. Geological Survey professional paper* 1651 (2): 873-888.

Milhous, R. T., M. A. Updike & D. M. Schneider. 1989. *Physical habitat simulation system reference manual, version II*. Biological Report 89 (16). U.S. Fish and Wildlife Service. Annapolis, MD. 403 p.

Miller, R. R., W. L. Minckley & S. M. Norris. 2009. *Peces Dulceacuícolas de México*. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad/El Colegio de la Frontera Sur/Sociedad Ictiológica Mexicana, A.C./Desert Fishes Council. México. 559 p.

Moir, H. J., C. N. Gibbins, C. Soulsby & A. F. Youngson. 2005. PHABSIM modeling of Atlantic salmon spawning habitat in an upland stream: testing the influence of habitat suitability indices on model output. *River Research and Applications* 21: 1021-1034. DOI: 10.1002/rra.869

Moncayo-Estrada, R., J. Lyons, J. P. Ramírez-Herrejón, C. Escalera-Gallardo & O. Campos-Campos. 2015. Status and Trends in Biotic Integrity in a Sub-Tropical River Drainage: Analysis of the Fish Assemblage Over a Three Decade Period. *River Research and Applications* 31 (7): 808-824. DOI: 10.1002/rra.2774

Moore, M. 2004. Perceptions and interpretations of environmental flows and implications for future water resource management. Master's thesis, Department of Water and Environmental Studies, Linköping University, Sweden. 67 p.

Navarrete, S. N. A. & M. R. Sánchez. 1987. Ictiofauna del embalse Trinidad Fabela. *Memorias del IX Congreso de Zoología. Sociedad Mexicana de Zoología* 2: 31-34.

Navarrete, N. A., R. Sánchez & M. L. Rojas. 1996. Selección del zooplancton por el charal *Chirostoma jordani* (Atheriniformes: Atherinidae). *Revista Biología Tropical* 44 (2): 757-761.

Orth, D. J. & P. M. Leonard. 1990. Comparison of discharge methods and habitat optimization for recommending instream flows to protect fish habitat. *Regulated Rivers: Research & Management* 5: 129-138. DOI: 10.1002/rrr.3450050204

Payne, T. R., S. D. Eggers & D. B. Parkinson. 2004. The number of transects required to compute a robust PHABSIM habitat index. *Hydroécologie Appliquée* 14: 27-53. DOI: https://doi.org/10.1051/hydro:2004003

Ramírez-Herrejón, J. P., N. Mercado-Silva, M. Medina-Nava & O. Domínguez-Domínguez. 2012. Validación de dos índices biológicos de integridad (IBI) en la subcuenca del río Angulo en el centro de México. *Revista Biología Tropical* 60 (4): 1669-1685.

Richter, B. D., R. Mathews, D. L. Harrison, & R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological applications* 13 (1): 206-224.

Sánchez, M. R. & S. N. A. Navarrete. 1987. Aspectos ecológicos y utilización de *Notropis sallei* del embalse la Goleta, Estado de México. *Memorias del IX Congreso de Zoología. Sociedad Mexicana de Zoología* 2: 104-107.

Santacruz de León, G., & M. Aguilar-Robledo. 2009. Estimación de los caudales ecológicos en el Río Valles con el método Tennant. *Hidrobiológic*a 19 (1): 25-32.

Sanz-Ronda, F. J., A. Martínez de Azagra & G. E. Arenal. 2005. Evaluación del método del tramo representativo en la cuantificación del hábitat fluvial. *Ecología* 19: 283-302.

Scott, D. W. 2009. Sturges' rule. Wiley Interdisciplinary Reviews: *Computational Statistics* 1 (3): 303-306. DOI: 10.1002/wics.035

Soto-Galera, E., E. Díaz-Pardo & C. Guerra-Magaña. 1990. Peces dulceacuícolas mexicanos III: *Alloophorus robustus* (Cyprinodontiformes: Goodeidae). *Zoología Informa* 19/20: 21-29.

Stalnaker, C. B., B. L. Lamb, J. Henriksen, K. Bovee & J. Bartholow. 1995. *The instream flow incremental methodology: a primer for IFIM*. Biological Report 29. U.S. Geological Survey. Washington, DC. 45 p.

Tharme, R. E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19 (5-6): 397-441. DOI: 10.1002/rra.736

Tharme R. E., & J. M. King. 1998. *Development of the Building Block Methodology for instream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems*. Water Research Commission Report 576/1/98. 452 p.

Vargas, P. V., I. Arismendi, G. Lara, J. Millar & S. Peredo. 2010. Evidencia de solapamiento de micro-hábitat entre juveniles del salmón introducido *Oncorhynchus tshawytscha* y el pez nativo *Trichomycterus areolatus* en el río Allipén, Chile. *Revista de Biología Marina y Oceanografía* 45 (2): 285-292. DOI: 10.4067/S0718-19572010000200010

Velázquez, M. M. A. 2005. Diagnóstico para el saneamiento del río Duero. Informe Técnico para el Consejo Estatal de la Fresa de Michoacán, A.C. 198 p.

Velázquez, M. M. A., J. L. Pimentel & M. Ortega. 2010. Estudio de la distribución del boro en fuentes de agua de la cuenca del río Duero, México, utilizando análisis estadístico multivariado. *Revista Internacional de Contaminación Ambiental* 27 (1): 19-30.

Waddle, T. J. (Ed.). 2001. *PHABSIM for Windows user's manual and exercises*. Open-File Report 340. U.S. Geological Survey. Fort Collins, CO. 288 p.

Welcomme, R. L. 1992. *Pesca fluvial*. FAO. Documento Técnico de Pesca 262. Roma, FAO. 303 p.

Wilding, K. T. 2007. *Minimum flows for ecosystem health in the Whakapipi Stream (Pukekohe)*. Environment Waikato Technical Report 2007/28. National Institute of Water & Atmospheric Research Ltd. Hamilton New Zealand. 64 p.

Zavala-López, L. 2011. Inventario y caracterización de los manantiales en la Cuenca del Río Duero, Michoacán. Tesis Profesional Ingeniero Agrónomo. Departamento de Irrigación, UACh, México. 142 p.

Appendix 1. Total number of fish caught by species, sampling sites of the Duero River, Mexico (Ledesma-Ayala, 1987; López-Eslava, 1988).

Station	Carapán	Santo Tomás	Chilchota	Etúcuaro	Adjuntas	Platanal	Las Limas	Ario de Rayón	Estanzuela	Camucuato	Capulín	Briseñas
# station	1	2	3	4	5	6	7	8	9	10	11	12
A. tincella	0	28	0	0	0	14	3	0	4	2	0	0
A. sallaei	0	0	0	10	12	0	58	0	39	29	4	3
A. robustus	0	0	0	0	1	0	0	0	5	2	3	11
G. atripinnis	0	0	0	0	137	0	0	1	201	75	426	114
M. jordani	0	0	0	0	0	0	0	0	0	1	91	54
Abundance	0	28	0	10	150	14	61	1	249	109	524	182

Appendix 2. Characteristics and calculation of the representativity index (RT_i) of the Duero River, Mexico.

#	Sampling site	Reach (m)	Width (m)	Depth* (m)	Velocity* (m/s)	Substrate key	Substrate	Flow* (m^3/s)	Manning's Roughness	Representativity reach, RT_i
1	Carapan	1368	3.2	0.18	0.15	13	large pebbles	0.09	0.18	0.01
2	Santo tomas	6610	5.9	0.17	0.14	12	small pebbles	0.14	0.15	0.07
3	Chilchota	4557	7.2	0.32	0.28	12	small pebbles	0.63	0.08	0.05
4	Etucuaro	8680	6.5	1.52	0.34	11	very coarse gravel	3.3	0.13	0.09
5	Adjuntas (Camecuaro)	8350	9.8	2.59	0.39	10	coarse gravel	9.8	0.23	0.09
6	Platanal	6690	9.1	0.64	0.30	9	medium gravel	1.7	0.12	0.07
7	Las Limas	4574	21.0	0.55	0.63	9	medium gravel	7.2	0.03	0.05
8	Ario de Rayon	13,940	7.2	1.01	0.28	7	very fine gravel	2.0	0.13	0.15
9	Estanzuela	17,130	16.1	1.86	0.30	6	sand	9.1	0.16	0.18
10	Camucuato	13,400	18.2	2.16	0.24	5	silt	9.6	0.23	0.14
11	El Capulin	7710	35.0	2.13	0.18	4	clay	13	0.35	0.08
12	Briseñas	3127	75.0	2.50	0.13	4	clay	23	0.36	0.03
	Total distance (Duero River)	96,136								

* Depth, velocity, and flow are average values for 1985-1986.

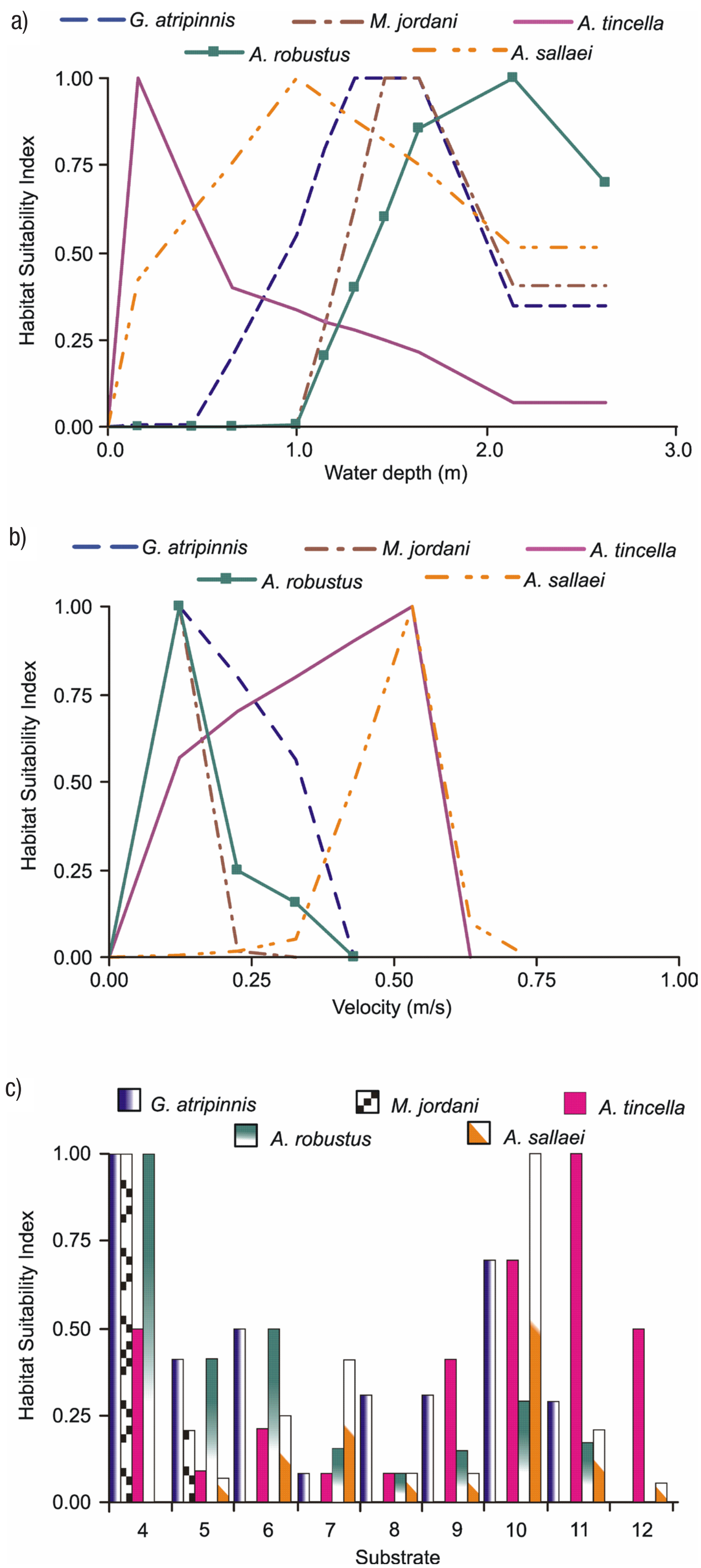
Appendix 2. (Continuation) Calculation of the index of availability (Id_j) for the depth variable.

Intervals	Lower Lim.	Upper Lim.	Classmark	F_j	fa	F_j*RT_i	Id_j, Availability index	Normalized index
1	0.16	0.64	0.40	5	5	1.24	0.45	1.00
2	0.65	1.14	0.90	1	6	0.15	0.05	0.12
3	1.15	1.63	1.39	1	7	0.09	0.03	0.07
4	1.64	2.13	1.89	2	9	0.52	0.19	0.42
5	2.14	2.62	2.38	3	12	0.78	0.28	0.63
Summation						2.8	1.0	

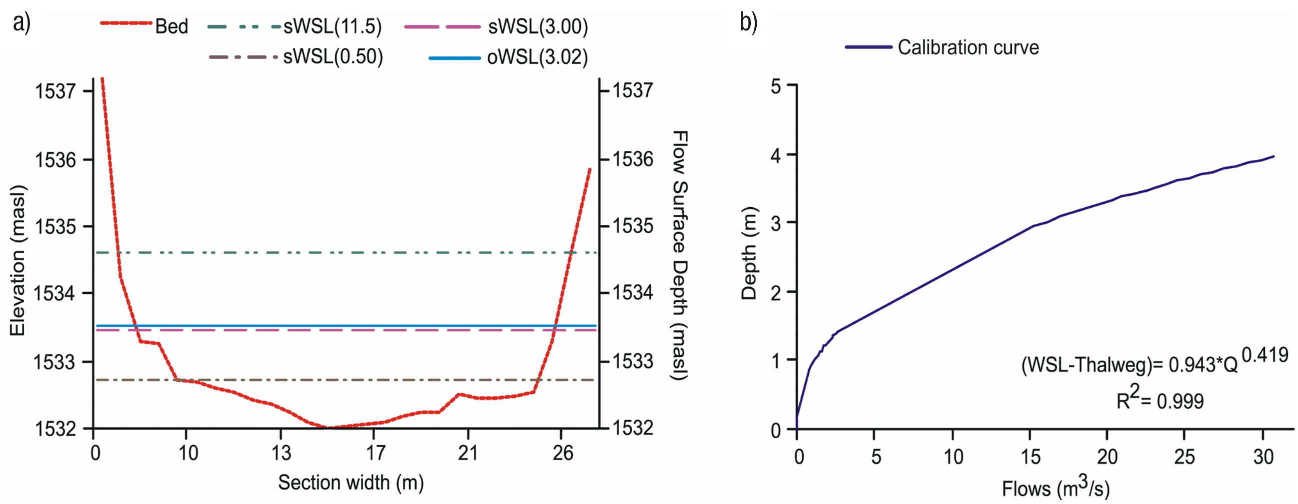
Intervals: $K=1+Log_2 N$; where N is number of sampling sites.

Appendix 2. (Continuation) Calculation of the usage index (Iu_j) for the species *Goodea atripinnis*.

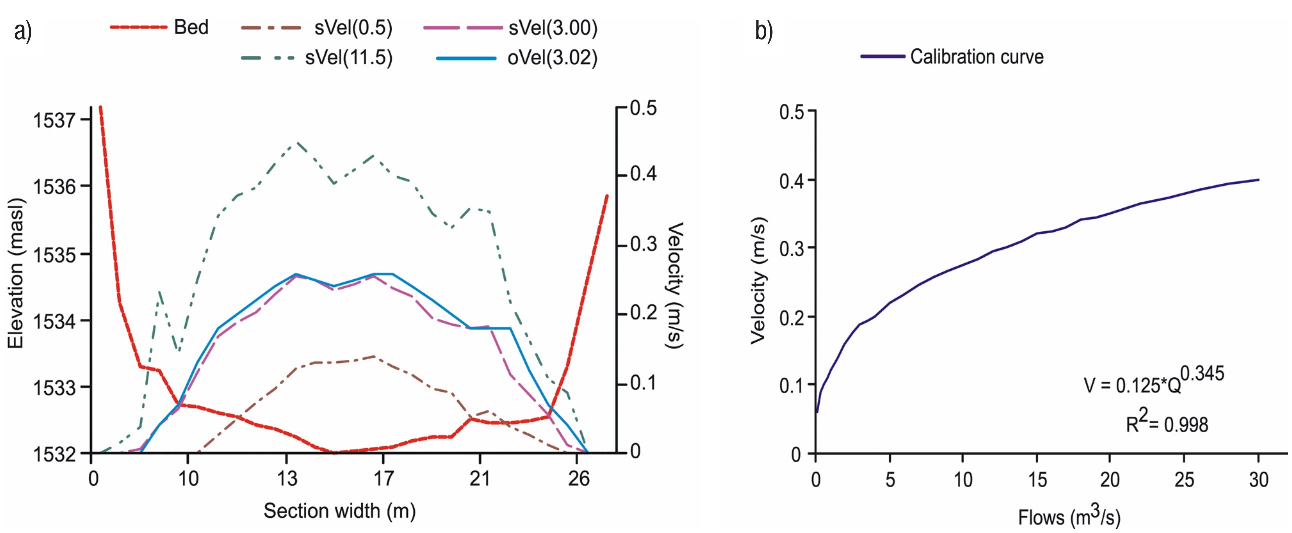
Intervals	# of specimens per site	Iu_j, Use index	$C_j=Iu_j/Id_j$	C_j Normalized
1	–	–	–	0
2	1	0.001	0.020	0.01
3	–	–	–	1.00
4	627	0.66	3.52	0.35
5	326	0.34	1.22	0
Total sum of specimens	954			



Appendix 3a-c. Suitability curves for the five ichthyic species: a) depth, b) velocity and c) substrate. (4-clay, 5-silt, 6-sand, 7-very fine gravel, 8-fine gravel, 9-medium gravel, 10-coarse gravel, 11-very coarse gravel and 12-small pebbles).



Appendix 4a-b. a) Simulation of the water surface level for section "Estanz". b) Calibration curve of "Estanz" section (depth).



Appendix 5a-b. a) Simulation of the velocity distribution for section "Estanz". b) Calibration curve of the "Estanz" section (velocity).