Fish as Ecological Indicators in Mediterranean Streams: The Catalan Experience

Chapter · September 2015

DOI: 10.1007/698_2015_345

Lluís Benejam
University of Vic

Marc Ordeix
University of Vic - Central University of Catalonia

Nuno Caiola
IRTA Institute of Agrifood Research and Technology

Antoni Munné
Catalan Water Agency. (Generalitat de Catalunya)

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Lluís Benejam, Marc Ordeix, Frederic Casals, Nuno Caiola, Adolf de Sostoa, Carolina Solà, and Antoni Munné

Abstract The Water Framework Directive includes fish fauna as one of the biological elements, jointly with aquatic flora and benthic invertebrates, to assess and monitor water and habitat quality. Successful implementation of the Directive depends in part on the development of reliable, science-based tools to directly assess biological conditions. Although fish have been used as ecological indicators for more than 30 years around the world, mainly in North America and more recently in Europe, few studies have been done in Mediterranean streams. Fish assemblages of the Mediterranean basin, similarly to other Mediterranean areas such as California, have particular characteristics that hamper IBI's development: few native species, poor knowledge of their ecological requirements, high number

L. Benejam (✉)
BETA Technology Centre, Aquatic Ecology Group, University of Vic – Central University of Catalonia, Vic, Spain
e-mail: lluis.benejam@uvic.cat

M. Ordeix
Center for the Study of Mediterranean Rivers – Ter River Museum, Passeig del Ter, 2., 08560 Manlleu, Spain

F. Casals
Department of Animal Production, University of Lleida, Avda. Rovira Roure 177, 25198 Lleida, Spain

N. Caiola
IRTA Aquatic Ecosystems, Carretera Poble Nou Km 5.5, Sant Carles de la Ràpita, 43540 Catalonia, Spain

A. de Sostoa
Department of Animal Biology (Vertebrates), University of Barcelona, Avda. Diagonal 645, 08028 Barcelona, Spain

C. Solà and A. Munné
Catalan Water Agency (ACA), Provença 204-208, 08036 Barcelona, Spain

A. Munné et al. (eds.), *Experiences from Surface Water Quality Monitoring: The EU Water Framework Directive Implementation in the Catalan River Basin District (Part I)*, Hdb Env Chem, DOI 10.1007/698_2015_345,

of endemisms with a wide range of tolerance to environmental variations and many exotic species. This chapter summarizes our experience in developing fish-based tools in Catalonia. We discuss the challenges and difficulties to develop these approaches in Mediterranean streams. We show the IBICAT2010 as a fish-based assessment method suitable for the evaluation of the ecological status of Catalan rivers. Moreover, we assess size-related variables as a bioassessment tool because population size structure can provide insights into species-specific applications and management. Finally, we analyse the longitudinal connectivity throughout Catalan rivers and fish passes by using the index of river connectivity (ICF) specially designed to Catalan rivers.

Keywords Biological indices, Ecological status, Freshwater fish, Human pressure, Monitoring program, River connectivity, Water Framework Directive

Contents

1 Fish as Ecological Indicators

Fish have some particular features and advantages as indicators of the health of freshwater ecosystems [1]. Fish continually inhabit the receiving water and integrate the chemical, physical and biological histories of the waters. Most fish species have long lifespans (about 2–10 years) and can both reflect long-term and current water quality. The sampling frequency needed for trend assessment is less than for short-lived organisms, and the taxonomy of fishes is well established, enabling professional biologists the ability to reduce laboratory time by identifying most specimens in the field. Fish have large ranges and are less affected by natural microhabitat differences than smaller organisms, making them extremely useful for assessing regional and macrohabitat differences. Moreover, fish are highly visible and valuable components of the aquatic community to the public, making communication easier.

It is widely known that exposure to environmental stressors (e.g. pollution or low oxygen) causes detrimental effects on important fish features such as metabolism, growth, resistance to diseases, reproductive potential and, ultimately, the health, condition and survival of fish [2–4]. Depending on the intensity and duration of stress exposure and species-specific features these negative effects may be transferred from the individual to population or community levels [5]. The knowledge, for each species, of their functional attributes, range of tolerance and responses in front of different kinds of stress will permit to use freshwater fish as ecological indicators. The biological indicators complement the traditional physicochemical indicators, facilitating a better assessment and management of freshwater ecosystems.

Although the study of fish as ecological indicators started at the beginning of the twentieth century [1], it is not until the year 1981 that James Karr proposed [6] the first biological index based on fish, namely the Index of Biotic Integrity (IBI). James Karr defined biological integrity as "the ability to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity and functional organization comparable to those of natural habitats within a region" [7]. Different factors (both biotic and abiotic) may affect this biotic integrity: chemical variables, flow regime, biotic factors, energy source and habitat structure (Fig. 1). The original IBI consists of 12 fish-assemblage attributes (called metrics) that reflect predominant anthropogenic effects on streams. Each metric describes a particular taxonomic, trophic, reproductive or tolerance feature of the assemblage. An IBI score represents comparisons between metric values at a sampling site and those expected under conditions least affected by anthropogenic disturbance.

The utilization of the fish as bioindicators has spread all over the planet, and the original version of the IBI has been modified in numerous ways for application in many different regions and habitat around the world [8–11]. These new versions maintain a multimetric structure but they incorporate different typologies, number of metrics and values. A European project (FAME: Fish-based Assessment Method for the Ecological Status of European Rivers) developed the European Fish Index (EFI), the first standardized fish-based assessment method applicable across a wide range of European streams [12, 13]. Because of several limitations observed in the performance of the index, a new version (EFI+) was developed [14]. Although many IBIs have been adapted for different European countries and specific rivers basins [15, 16], few of them are used on Mediterranean streams because they present a number of potential difficulties.

2 Challenges and Difficulties in Mediterranean Streams

The fish assemblages of the Mediterranean basin, similarly to other Mediterranean areas such as California, have particular characteristics that hamper IBI's development: few native species, poor knowledge of their ecological requirements, high number of endemisms with a wide range of tolerance to environmental variations and many exotic species [17, 18]. The Index of Biotic Integrity mainly has been developed in areas with complex fish communities: many native species with different trophic levels. The IBIs characterize by having many metrics (normally around 12), independent among them (metrics with redundant information should

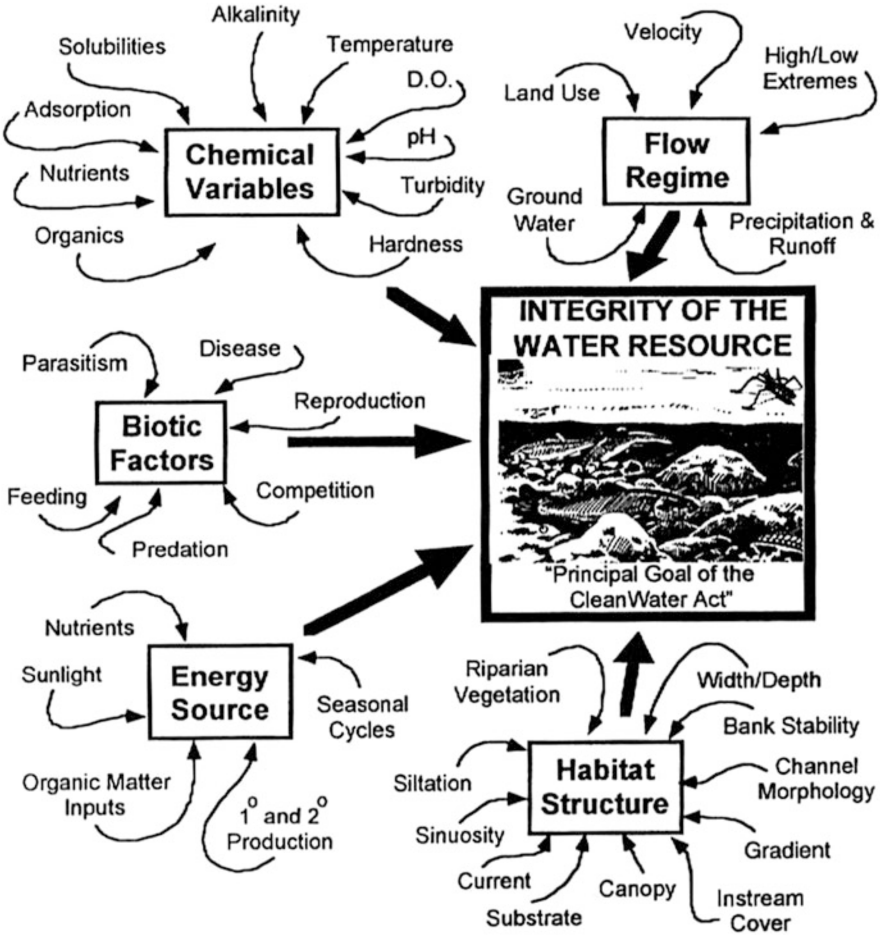

Fig. 1 The five principal factors, with some of their important chemical, physical and biological components that influence and determine the integrity of water resources. From [1]

be avoided) and of different levels of organization (individual, population, community, ecosystem and landscape) [8, 19]. In order to correctly detect different kinds of ecosystem alterations, Karr and Chu [19] emphasized that IBIs should have metrics for each organization level.

Developing enough metrics for IBIs is difficult in Mediterranean rivers due to low fish richness [20]. Miller et al. [8] suggested that although an IBI with less than 12 metrics may work, it may be less responsive to a broad spectrum of degradation. The low fish richness in the Mediterranean basin hinders the use of very common fish metrics such as: diversity of species, trophic specialization and reproductive strategies. This low richness is especially problematic in headwater sites, where often there are only one or two species and sometimes one is an introduced or translocated salmonid [17]. In a project in the Tordera River, in

Catalonia, we studied this situation and recommend that this low richness could be compensated assessing metrics based on age or size structure, fish individual state or including other aquatic biota [21]. For instance, there are IBIs that combine fish metrics with benthic invertebrates [22] and both adults and tadpoles of amphibians [17]. With regard to individual health, although DELT anomalies (deformities, eroded fins, lesions and tumors) are incorporated in many IBIs [23], the presence of ectoparasites or fish condition is not included. Both metrics have been shown as a good bioindicator in different studies in Catalonia watersheds in cases with high contamination with heavy metals [24], anoxic situation [25] and alteration of natural flow regime [26]. These fish metrics could help to increase the number of metrics in Mediterranean IBIs, concretely at individual health level [19], because they have responded significantly in front of habitat degradation and poor quality of water.

Hydrological variability of Mediterranean-type regions profoundly determines the life forms and life cycles of aquatic organisms, as well as ecological processes [27, 28]. Fish fauna from these heterogeneous ecosystems must frequently survive under alternating scenarios of too much or too little water with a few intermediate but crucial periods of investment in recruitment and growth [20]. Under these conditions, fishes tend to have short life spans, rapid growth rates, high fecundity and early sexual maturity and spawning, as well as generalist and opportunistic feeding strategies [29, 30]. The native species of Mediterranean streams have a wide range of tolerance to environmental variations and are habitat and feeding generalists, well adapted to survive in changing environments [20, 31]. Many metrics of IBIs describe a particular trophic, reproductive or tolerance guilds of fish species. In Mediterranean streams, sometimes it is difficult to classify the species due to its wide range of tolerance and in many cases relatively little is known about the ecology of many fishes in Mediterranean areas [32, 33]. More basic studies of the ecological requirements of Mediterranean species are needed to fill this information gap. Long-term studies monitoring both fish assemblages and physicochemical parameters could be invaluable in this regard.

The introduced species are a serious environmental problem in Mediterranean freshwater ecosystems and a challenge to develop an IBI [34, 35]. Some authors suggest that exotic species should not be included in the absolute richness metrics of IBIs [36, 37] but could be a reliable indicator of poor river health [38]. Moreover, other authors indicate that although exotic species are a loss of biotic integrity they might provide a great deal of information about water and habitat quality [17]. This represents a conflict between using an IBI to measure diversity and abundance of native organisms and using an IBI to measure water and habitat quality. Exotic species have been incorporated in metrics of different IBIs applied in Mediterranean basins [20, 39, 40]. Although Ferreira et al. [41] included exotic species in the metric of absolute richness, in other works where this metric was present only native species were considered [20, 39]. While Sostoa et al. [39] and Magalhães et al. [40] suggest some metrics exclusively for native species (e.g. number of native insectivores), in general exotic and native species are pooled in metrics of trophic and reproductive functions. Although to take the information about water and habitat quality that exotic species provide this could be a solution in front of the problem of low native species in Mediterranean basin. In our opinion valuing positively the abundance and richness of exotics fish is counterproductive. Nevertheless, in Catalonia that could constitute a problem since the number of native fish species currently sampled (Table 1) is similar to the exotic ones (Table 2). A total of 16 native species were sampled (2007–2008) in front of 16 exotic species.

Table 1 List of native fish species in the Catalan rivers and their IUCN Red List categories

Species	UICN categories
Petromyzon marinus[a]	VU
Acipenser sturio[a]	CR
Anguilla anguilla	VU
Alosa alosa[a]	VU
Alosa fallax[a]	VU
Atherina boyeri[a]	VU
Platichthys flesus[a]	LC
Syngnathus abaster[a]	LC
Salmo trutta	VU
Cottus hispaniolensis[a]	CR
Gasterosteus aculeatus	EN
Barbatula quignardi	VU
Cobitis calderoni[a]	VU
Cobitis paludica[a]	VU
Achondrostoma arcasii	VU
Barbus haasi	VU
Barbus meridionalis	VU
Gobio lozanoi	LC
Luciobarbus graellsii	NT
Parachondrostoma miegii	NT
Phoxinus bigerri	VU
Squalius laietanus	VU
Tinca tinca[a]	LC
Aphanius iberus[a]	EN
Valencia hispànica[a]	CR
Salaria fluviatilis	VU
Pomatoschistus microps	LC
Chelon labrosus[a]	LC
Liza ramada	LC
Mugil cephalus	LC

[a]Absent in the last sampling period carried out in Catalan rivers, 2007–2008. Taxonomy and status of species are assigned following [32]

Table 2 List of introduced fish species in the Catalan rivers and their origin

Species	Origin
Acipenser baerii[a]	Europe
Oncorhynchus mykiss	North America
Salvelinus fontinalis[a]	Europe
Abramis brama[a]	Europe
Abramis bjoerkna[a]	Europe
Alburnus alburnus	Europe
Carassius auratus	Asia
Cyprinus carpio	Asia
Pseudorasbora parva	Asia
Rutilus rutilus	Europe
Scardinius erythrophthalmus	Europe
Misgurnus angillicaudatus	Asia
Esox lucius	Europe
Lepomis gibbosus	North America
Micropterus salmoides	North America
Perca fluviatilis	Europe
Sander lucioperca	Europe
Ameiurus melas	North America
Ictalurus punctatus[a]	North America
Silurus glanis	Europe
Gambusia holbrooki	North America

[a]Absence in the last sampling period carried out in Catalan rivers, 2007–2008). Taxonomy and status of species are assigned following [32]

Finally, another difficulty to develop metrics and IBIs in the Mediterranean basin is the lack of reference areas to test the metrics. In order to know the ecological status the current condition has to be compared to the natural conditions (structure, composition, function, diversity) in the absence of human disturbance or alteration (reference condition) [42]. Chovarec et al. [43] suggest that “reference condition is the state that has existed before the human interferences, or at least without human influences that have altered significantly their natural characteristics”. Owen et al. [44] consider that the “reference condition is when physical-chemical, hydromorphologic and biological values corresponding to the area without human alteration”. The concept of reference condition is widely known and used. For example the EPA (US Environmental Protection Agency) in the United States [45], the “National River Health Program” in Australia [46], the “River Health Programme” in South Africa [47] and the “Water Frame Directive” in Europe use the concept of reference condition to assess the ecological status and to develop fish metrics and indices. The problem in many regions of the world, and especially in the Mediterranean basin, is that pristine sites are unavailable due to an intensive human activity during many centuries [48, 49]. Not only are undisturbed sites unlikely to exist but the rate of stream modification has been accelerating in recent decades [33]. While the “least disturbed” or “best available” sites are sometimes used as alternatives to reference sites [50], the WFD requires pristine or near pristine reference sites [51]. However, it is almost impossible to find Mediterranean stream reaches where native fish assemblages have not been altered. Especially in areas as river mouths it can be difficult to know the original biota composition and also the natural flow regime, because reservoirs and water abstraction have profoundly altered them. In these cases biologists have to use different methods to select the reference conditions. One of the methods is the “expert criterion”, which is easy but requires an exhaustive validation [44]. In other cases, researchers may use predictable models and paleolimnology information or in some cases must rely on historical data, collected when human activity was low, to define reference condition [19, 52, 53].

One extreme case of the problem in reference conditions is the case of reservoirs. Due to their artificial nature natural reference conditions do not exist for reservoirs. For this reason different authors have adapted the original fish metrics of Karr et al. [36] and suggested to name it the RFAI (Reservoir Fish Assemblage Index) [54, 55]. In Catalonia, the fish assemblages of 14 reservoirs were sampled by boat electrofishing in the littoral and multi-mesh gillnets in the limnetic zone [56]. Most eutrophic reservoirs were dominated by common carp (*Cyprinus carpio*) whereas oligotrophic reservoirs presented other fish species intolerant to pollution rather native (such as brown trout, *Salmo trutta*). The absolute and relative abundance of common carp was strongly related to the trophic state of the reservoir and 40% of its variation was explained by total phosphorous concentration. Despite clear changes in species composition, there was no significant effect of water quality on overall fish richness or Shannon’s diversity, suggesting that for such low richness assemblages species composition is a better indicator of cultural eutrophication of reservoirs than fish diversity. WFD considers reservoirs as artificial water bodies or heavily modified water body, therefore in these cases the aim is to obtain a good ecological potential before 2015. In the WFD the good ecological potential of one artificial water body is defined as the nearest values to the most similar natural water body.

3 Features of Fish in Catalonia

Mediterranean streams have flow patterns strongly seasonal: low flow in the hot summer drought and flash floods during autumn and spring storms [27]. During the summer, some parts of the stream can remain reduced as a series of pools. Interannual variability in precipitation is high while lengthy periods of drought are common [27]. This hydrological variability of Mediterranean-type regions profoundly determines the life forms and life cycles of aquatic organisms, as well as ecological processes [20]. Besides these natural factors, the water resources of the Mediterranean basin suffer a high human pressure because it is a highly populated area with urban and industrial growths, especially in the last 50 years [57–59]. Apart from the direct pressure on the water resources, Catalan rivers, and other rivers in the Mediterranean basin, also suffer from alterations in natural hydromorphology and riparian vegetation [60, 61]. Although the pollution from industrial and urban waste has in general decreased thanks to entry in operation of many treatment plants [62], there is an increase in the number of contaminants of emerging concern, particularly from pharmaceuticals, personal care products and perfluorinated compounds among others [63].

In Catalonia, with the exception of the Ebro, rivers have a basin area of intermediate dimensions (from 312 km^2 of Foix to 4,948 km^2 of Llobregat) and average streamflows that oscillate between 1.5 m^3/s of Francolí and 20 m^3/s of Llobregat. Most rivers are strongly regulated in middle and lower reaches but even in upper parts. In Catalonia there exist more than 20 big dams and nearly 8,000 of big obstacles according to the database of the Catalan Water Agency. Current information of fish populations in Catalonia comes from two periods of sampling programme (2002 and 2007–2008) to develop some fish based IBI during the implementation of the WFD [39, 64]. For the historical data we are based on many published and unpublished records of other authors and ourselves. At present, the icthiofauna of Catalonia is formed by a total of 51 species of which 30 are native (14 of them endemic for the Iberian Peninsula) and 21 are non-native or exotic (Tables 1 and 2). Many of native species are migratory: four anadromous, one catadromous and seven amphidromous. Fourteen of the native species are absent during last sampling period (2007–2008) [64] due to different situations. Sampling was made on riverine water bodies, but not in transitional or coastal waters, which means that the four amphidromous species less tolerant to freshwater were not present. The absence of *A. iberus* and *V. hispanica* may be explained by the same reason because both species live in freshwater and brackish littoral lagoons. But the absence of the other eight native species is related to the high number of threatened for freshwater fish commonly found in Mediterranean basins [18].

There is a threat of extinction for most part of the native fish species of the Catalan rivers, and two of them (*A. sturio* and *P. marinus*) are locally extinct. Other species are closer to local extinctions, for example *C. paludica*, and some others have patchy distributions, *G. aculeatus* or *S. fluviatilis*, which present fragmented populations with smaller distribution areas than historical ones. According to the evolution of their distribution, we can compare the number of basins with the presence of native species (Table 3). Just for one species (*B. haasi*) the number of basins with presence shows no changes comparing to their historical range. Many others are present in a smaller number of basins. *G. aculeatus* is of particular concern for their extremely reduced distribution and *S. laietanus* due to their long-term decline. A particular case for native species is the group of species which are increasing the presence on more basins as a consequence to translocate to others basins for sport fishing purpose (*B. barbatula*, *G. lozanoi*, *L. graellsii*, *P. miegii* and *P. bigerri*).

Table 3 Evolution of fish distribution by basins according to the historical presence, for the period 2002–2003 [39] and for the period 2007–2008 [64]

	Number of basins (historical)	Number of basins (2002–2003)	Number of basins (2007–2008)
Native species			
Anguilla anguilla	14	8	10
Barbatula barbatula	1	2	2
Barbus haasi	7	7	7
Barbus meridionalis	7	6	6
Gasterosteus aculeatus	5	3	2
Gobio lozanoi	1	4	4
Luciobarbus graellsii	1	4	5
Parachondrostoma miegii	2	4	5
Phoxinus bigerri	2	6	6
Salaria fluviatilis	4	2	3
Squalius laietanus	11	9	7
Salmo trutta	3	10	8
Exotic species			
Misgurnus anguillicaudatus	0	0	2
Alburnus alburnus	0	4	6
Ameiurus melas	0	1	2
Carassius auratus	0	3	4
Cyprinus carpio	0	8	10
Esox lucius	0	1	1
Gambusia holbrooki	0	5	5
Lepomis gibbosus	0	6	6
Micropterus salmoides	0	2	2
Oncorhynchus mykiss	0	5	3
Pseudorasbora parva	0	1	2
Rutilus rutilus	0	1	5
Sander lucioperca	0	1	1
Scardinius erythrophthalmus	0	3	4
Silurus glanis	0	1	2

Related to exotic species (Table 2), Catalan rivers are a hot spot and the main origin and introduction route to the Iberian Peninsula [34, 65]. Some of the previously detected species are not established (e.g. *A. baerii* or *I. punctatus*) but there are new additions to the exotic fishes like *M. anguillicaudatus* [66]. More than 50% of the exotic species have increased their distribution with respect to the previous period like *R. rutilus* (present in four more basins) or *A. alburnus* (present in two more basins). Some other species maintain their presence in the previously detected basins (*E. lucius*, *G. holbrooki*, *M. salmoides* or *S. lucioperca*). All exotic fishes are more related to lotic conditions present in reservoirs of Catalan rivers

[56]. Most of the species collected in Catalan reservoirs are exotics (11 species), from which *C. carpio* and *R. rutilus* are the most abundant in the lowest altitude reservoirs [56]. Fish introductions are still growing with new species on the list and in expansion for the naturalized exotics. For that reason, many river stretches are far away from the biotic integrity (just about one third of sampled localities) and many others are dry without fish live (another third of the sampled localities) [39, 64]. On the other hand, some improvements, mainly in water quality, imply an increase of native fish density. The recovery of the population of *A. fallax* in the Ebro river during last years could confirm this idea [67].

4 IBICAT 2010

The $IBICAT_{2010}$ is a fish-based assessment method suitable for the evaluation of the ecological status of Catalan rivers [64]. It is an improved version of the IBICAT [39]. The $IBICAT_{2010}$ is a type-specific method that is based on eight environmental variables (altitude, slope, Strahler river order, mean annual air temperature, mean July air temperature, mean annual rainfall, mean July rainfall, distance to river mouth) that were selected as the best descriptors of a river classification based on the historical fish distribution. A discriminant analysis classification was used for the classification of each site. The overall misclassification rate was 0.16. A total of six river types were defined: type 1 – coastal streams; type 2 – humid mountain; type 3 – main courses; type 4 – Mediterranean lowland; type 5 – high mountain; type 6 – main courses of large rivers. Metrics describing the composition, abundance, functional traits, age structure and health condition of the fish fauna were first screened through a Pearson correlation analysis between each metrics and a synthetic pressure index based on water quality, hydromorphological alteration and habitat quality variables. Non-significant correlations were not allowed. Then, to evaluate the response of the candidate metrics to pressures a graphical analysis (boxplots) supported by statistical tests (ANOVA) was performed. Finally, redundant metrics were removed based on Spearman correlations: metrics pairs with $\rho \geq 0.9$ were not allowed. The whole screening process was performed for each river type. A total of 17 metrics were selected: density of alien species, density of native marine migratory fish, density of native piscivorous, density of intolerant species with less than 15 cm total length, density of invertivorous, density of omnivorous, density of rheophilics, number of alien tolerant species, number of native intolerant species, number of lithophilic native species, percentage biomass of native benthic, percentage individuals with injuries/deformities/parasites, percentage of intolerant species, percentage of omnivorous species, percentage of introduced invertivorous species, percentage of native lithophilic species and percentage of native tolerant species.

The $IBICAT_{2010}$ is computed with a specific metric subset per river type using the formula:

$$\mathrm{IBICAT}_{2010} = -\sum (Mt \times R) + K,$$

where Mt is the value of the metric, R is the correlation coefficient between the metric and the global pressure and K is the constant of the river type that allows a minimum IBICAT_{2010} value that is not negative but near zero.

Finally the IBICAT_{2010} value is categorized into five quality classes, as defined in the EU WFD. The scoring criteria used to define the classes followed the procedure proposed by the European working group REFCOND [68].

5 Size-Related Variables as a Bioassessment Tool

As we discussed in second section of this chapter, the difficulties to develop enough fish metrics in IBIs on Mediterranean streams could be compensated by assessing metrics based on age or size structure. In particular, body size is a key property of organisms and arguably the most important trait affecting the ecological performance of individuals [69]. The implications of body size on growth, mortality and trophic interactions highlight the importance of size structure for population and community functioning [70–72]. Population and community size structure is considered a good health indicator because it has the potential to inform on whether disturbance is affecting the population and, moreover, it can help to identify the complex effects of biotic and abiotic influences [36, 73]. At least two studies have been developed in Catalonia focusing on size structure as a bioassessment tool in Mediterranean streams [26, 74].

Murphy et al. [74] focused their assessments of population size structure responses to anthropogenic perturbation on chub (*Squalius laietanus*), one of the most widespread native stream fish in Mediterranean basin. They studied the anthropogenic perturbation on 311 sites across Catalonia, including local data on stream condition and landscape indicators of degradation, via principal component analysis. Anthropogenic perturbation in streams was collinear with altitudinal gradients and highlights the importance of appropriate statistical techniques. Of the population size structure metrics explored, average length was the most sensitive to anthropogenic perturbation and generally increased along the disturbance gradient. Changes in variance, kurtosis and skewness were weak. The unexpected increases of mean *S. laietanus* body size with anthropogenic perturbation, strong effects of river basin, collinearity with spatial gradients and the species-specific nature of responses preclude the direct application of size structure in freshwater bioassessments.

Also significant results on size structure were found in a study of ecological impacts of small hydropower plants on headwater stream fish [26]. They studied the effects of water diversion of 16 small hydropower plants on fish assemblages and habitat features in the upper Ter river basin, which has headwater reaches with good water quality and no large dams but many of such plants. In the control reaches they detected higher average fork length and total weight, higher fish abundance and better fish condition than in impacted reaches, although the results were species-specific. Accordingly, species composition was also affected, with lower relative abundance of brown trout (*Salmo trutta*) and Pyrenean minnow (*Phoxinus bigerri*) in the impacted reaches and higher presence of stone loach (*Barbatula quignardi*) and Mediterranean barbel (*Barbus meridionalis*). Brown trout was the only fish species that has its size-related variables changed significantly.

Although the application of size-related variables in fish-based freshwater bioassessments appears difficult, population size structure can provide insights into species-specific applications and management.

6 Assessing Longitudinal Connectivity and Fish Passes

Currently, most fish can no longer migrate to complete their life cycle in Catalonia, Europe and most of the world because their natural habitats were modified by human activity. River obstacles cause direct effects on population biology, such as local extinctions due to a lack of dispersion and recolonization, genetic isolation, non-accessibility to spawning or feeding areas, refuges from predators and shelter areas or sites for harmful environmental conditions – i.e. pollution, big floods, droughts or other human disturbances and natural disasters [75]. Migrating fish upstream of reservoirs and large rivers are also an important contribution of food for other species, such as otter [76]. Existence of rivers with poor connectivity is considered one of the major causes of declines in many continental fish species in Iberian Peninsula [32, 77], Europe [78–80] and worldwide [81].

Transverse obstacles in river beds cause serious ecological consequences because they block the natural flow of water, sediments and biota. In Mediterranean regions, water abstraction may change a perennial stream to an intermittent one, increasing the duration and magnitude of droughts and limiting the stream’s ability to support aquatic biota.

Restoration of fish migration should pay proper attention to dam and weir removal, which is the most environmental positive solution at medium and long term [81]; a total restoration of river longitudinal connectivity is only possible by demolishing obstacles [82]. If the obstacle cultural value or its current use (hydro-power, irrigation, etc.) does not allow their removal, the promotion of close-to-nature fish passes, such as lateral channels and fish ramps, which provide optimum conditions for a wider range of species, individuals and flows [83], should be carried out. Rehabilitation measures should ensure the re-establishment of at least a good ecological status of rivers according to the European Water Framework Directive (2000/60/EC). This rehabilitation should include effective fish passages, but also habitat recovery and connection with well-preserved source areas [82]. Similarly, implementation of environmental flow regimes is urgently needed because without this, other measures could be useless.

Reestablishment of river connectivity became a legal requirement under the Water Framework Directive (2000/60/EC) and the European Plan for Eel Recovery (Regulation 1100/2007). It also is extremely important for the conservation of endangered freshwater species included in the Habitats Directive (92/43/CEE). However, the capacity of native fish fauna to use fish passes and their natural patterns of movement are still poorly understood [83]. Moreover, fish pass assessments could provide important knowledge regarding fish movement patterns [75, 84].

The presence of 886 big obstacles (according to the Catalan Water Agency database), mostly small weirs and some dams, seriously affects migratory fish species into the Catalan rivers. Migration routes of fish, some of which Iberian endemisms, were damaged. Large migratory fish, as European eel (*Anguilla anguilla*), are not present upstream of the dams in Catalonia. Twaite shad (*Alosa fallax*), European sturgeon (*Acipenser sturio*) –which is locally extinct – and sea lamprey (*Petromizon marinus*) populations are similarly affected [32, 39], while other non-diadromous fish have also had their migration routes negatively impacted and are consequently now endangered. Moreover, transforming rivers into a series of ponds especially benefits foreign fish [85].

During the period 2006–2010, a study of fish pass facilities in Catalonia was carried out through direct inspection of 93 detected fish ways present in 10.6% of the total obstacles [86] (Fig. 2). Especially retro-fitted solutions using broad-spectrum technical structures, mainly pool fishway or pool pass facilities, were located. Most of them were mainly in the Pyrenees to improve trout fisheries.

The existing solutions in Catalonia to improve fish migration have been in some cases insufficient, and where they do exist, fish passes can be poorly maintained, or insufficient, for all of the native fish fauna from each water body. Less than one-half (36% of total) of fish passes are currently reliable for all native fish in Catalan rivers. With some exceptions, fish passage rates were quite low; only those species with great ability to overcome obstacles – such as salmonid – or larger individuals of other fish groups were able to migrate [86]. Currently, there are few examples in Catalonia of weir removal and close-to-nature fish passes (Table 4).

This situation was quite equivalent, for example, in Australia in 1985, when it only had 44 fish passage devices for the thousand obstacles present throughout the country, most of which were poorly maintained and generalized unable to practice all native fish species [89]. The same happened in other European countries, such as France [90], the UK [91] and the Netherlands [92] until the 1990s.

To compare the stream flow and the fish assemblage in different basins, a team of Girona University [93] selected gauging stations in middle reach, downstream of reservoirs; they also estimated the “naturalized flow” (i.e. the flow expected if there was no direct human influence on the watercourse, e.g. from water abstraction) using the Sacramento Soil Moisture Accounting (SAC-SMA) model, a flexible, well-known model initially developed by Burnash et al. [96] and widely used by the US National Weather Service and also the Catalan Water Agency. The SAC-SMA model is a concept-based rainfall-runoff model, with areal precipitation and potential evapotranspiration as inputs. The assessment of hydrological alterations,

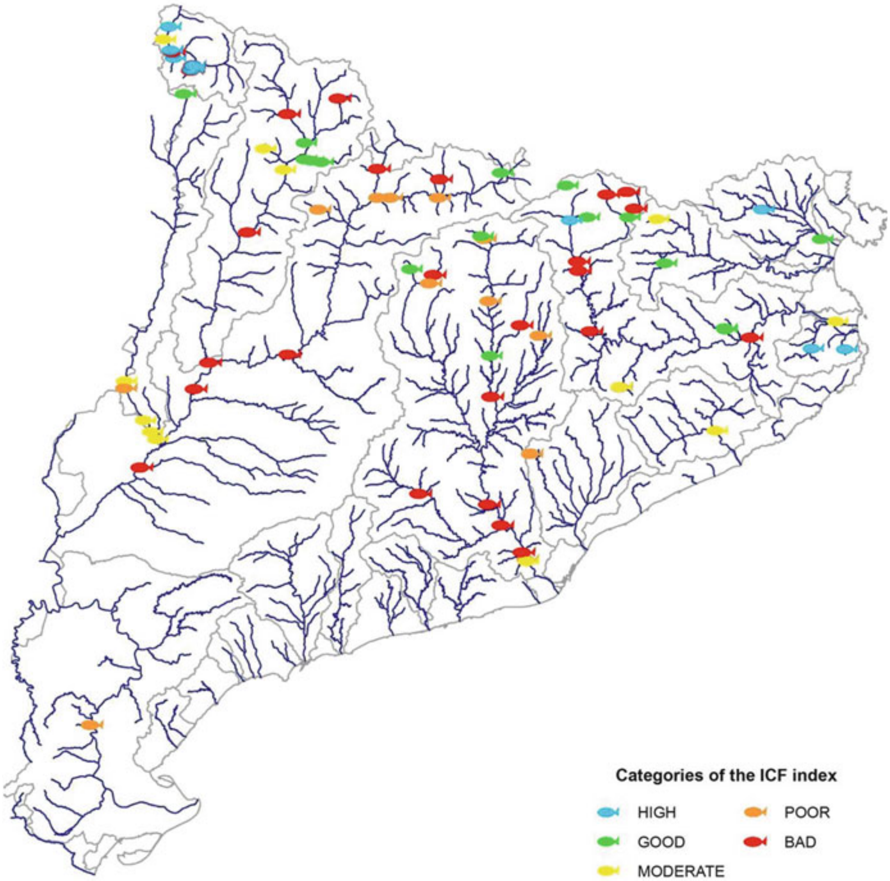

Fig. 2 Fish passes from Catalonia in 2010 [86] and results of the index of river connectivity (ICF index) [87] of each

following the Kappa index, among others, also has been done by members of the Lleida University [94].

Fish pass effectiveness was almost assessed in Catalonia following useful previous criteria for Mediterranean rivers [77, 86, 88]: (1) general data collection, using rapid assessment techniques, including the calculation of the ICF index (River Connectivity Index) [87], to evaluate the theoretical degree of impediment for fish passage; (2) indirect estimation techniques, using trapping fishing systems and/or electric fishing systems (CEN standard norm *UNE-EN 14011:2003*) to compare fish population structure between river sections [79, 84, 95]; mark-recapture methods and individual mark-recapture methods, using Passive Induction Transmitters (PIT tags) at many sites; and (3) direct estimation techniques, installing fish traps at the water intake of the fish pass to compare fish population structure and fish crossing rates with potentially migrating downstream fish

Table 4 Existing connectivity solutions and typologies of fish passes in the rivers of Catalonia in 2010

Solutions		Number
Restoration solutions	Total obstacle removal	1
	Partial obstacle removal	15
Close-to-nature solutions	Fish ramps	7
Broad-spectrum technical solutions	Pool fish passes	34
	Pool fish passes without drops	3
	Slot passes or vertical slot fishways	9
	Deflectors	8
	Denil or baffle fish passes	2
Mechanical or specific technical solutions	Eel ladders	6
	Siphons and fish pumps	2
Other solutions not considered effective	Smooth ramps	6

Adapted from [88]

population, obtained using electric fishing systems, complemented by daily collection of hydrological and environmental data, mainly using fish crossing rates and deviations of size frequencies [75, 84]. In some places, despite being limited by water turbidity and the presence of a large number of migrating fish, visual counts [83, 95] have been done as well.

The index of river connectivity (ICF, from the Catalan name *Índex de Connectivitat Fluvial*) [87], designed and improved by members of the Catalan Water Agency in collaboration with the Center for the Study of Mediterranean Rivers – Ter River Museum (CERM), evaluates the theoretical degree of impediment for fish passage and is based on comparison between physical characteristics of the obstacle, the fish pass (if any) and the swimming and/or jumping skills to overcome the obstacle of the potentially native fish fauna present in an evaluated river section. The ICF is divided into three blocks that encompass assessment of the obstacle and the fish pass as well as the estimation of certain modulators. Finally, the ICF classifies connectivity into five levels from very good to bad depending on the degree of permeability for different fish groups, discriminating among infrastructures based on the chance they can be crossed by all species, only by some species, or by no species.

The ICF was tested for 101 transverse obstacles in rivers of Catalonia, obtaining representation of the five expected quality levels (from very good to bad, Table 5), and it is considered coherent with the real permeability of the obstacles. Its ease of application compared to in situ measurements of fish movements and the detailed information recorded by the index make it a very useful tool for the diagnosis of the longitudinal connectivity of rivers and for guiding measures for hydromorphological quality improvement. In addition, due to the variety of species and hydrological regimes addressed and solutions used to date, it is essential to complement this quick assessment technique with the determination of the in situ fish pass effectiveness of any new solution implemented.

Table 5 Quality classification of connectivity for obstacles with and without fish pass solutions adapted from [87]

	With pass solution (%)	Without pass solution (%)	Total (%)
Very good	17 (21)	0 (0)	17 (17)
Good	12 (15)	6 (29)	18 (18)
Moderate	15 (19)	0 (0)	15 (15)
Poor	11 (14)	7 (33)	18 (18)
Bad	25 (31)	8 (38)	33 (32)
Total	80	21	101

Advancing the understanding of fish movement patterns will require regularly the monitoring of the efficiency of the principal fish migration solutions. For fish ways situated in key locations, for example, in the lower parts of rivers, because of their importance for amphidromous, anadromous and catadromous fish species, it would be appropriate to adapt fish pass structures to enable the installation of large permanent fish traps, as has been performed in many European countries, especially those that have important salmon or eel fisheries, or automatic fish counting devices (e.g. based on electric resistivity, infrared light and/or video camera system).

In many Catalan rivers, four fish metrics (catch per unit effort, number of benthic species, number of intolerant species and proportion of intolerant individuals) distinguished between sites impacted and unimpacted by water abstraction [93]. These four significant fish metrics, and probably others (number of insectivore species, number of native species, number of families), may be used to assess rivers suspected to have problems with abstraction. Some of these fish metrics are already used in existing European IBIs. In particular, low collective values of these fish metrics may warn of substantial hydrologic alteration [93].

Otherwise, the concordance between indexes of hydrological alteration and the IBICAT2010 index [64] which assess the ichthyofauna analysing the obtained results using the Kappa index in the rivers of Catalonia [94] is low. The indexes of hydrological alteration do not serve to assess hydrological impacts on fish community as they apply a much longer time scale and may not reflect specific changes in specific months or years. However, there is a slight relationship between these two indexes for dry years: dry years have major hydrologic alteration of the water bodies and a greater relationship with the number of present fish [94].

Regarding the existent fish passes in Catalonia until 2010 [86], all of them being broad-spectrum technical structures, their assessment indicates that brown trout (*Salmo trutta*), which exhibit a high capacity to overcome obstacles by swimming and/or jumping [90, 91], seem to be able to migrate upstream using the different types of fish passes present. However, these results show that if fish pass waterfalls are higher than 0.2 m and/or fish pass water velocity is higher than 2 m/s, only the largest individuals of species with a moderate capacity to overcome obstacles, including Mediterranean mullets (*Liza ramada*, *Mugil cephalus* and *Chelon labrosus*) and some cyprinid species, such as Ebro barbel (*Luciobarbus graellsii*; FL >55 mm), Western Mediterranean barbel (*Barbus meridionalis*; FL >0.13 m), Iberian redfin barbel (*Barbus haasi*) and Ebro chub (*Squalius laietanus*), are able to cross upstream. Moreover, if a fish pass waterfall is a maximum height of 0.1 m and/or a water velocity of less than 0.5 m/s, the results show that most species and individuals can use the fish pass, including small species with a low capacity to overcome obstacles, such as Pyrenean gudgeon (*Gobio lozanoi*), Pyrenean minnow (*Phoxinus bigerri*), European eel (*A. anguilla*) and youngs-of-the-year of other species including brown trout (*S. trutta*), Ebro barbel (*L. graellsii*) and Western Mediterranean barbel (*B. meridionalis*; FL<0.09 m). Finally, important movements of fish are mostly associated with particular spawning periods and/or periods just after high or moderate peak flows, as has been indicated in many other studies [75, 83, 90]. This finding also supports the idea that fish pass evaluation should be performed, at least, at times of maximum activity of different fish species, i.e. early spring for mullet species, spring for cyprinids and autumn for salmonids.

Close-to-nature fish passage assessment is almost pendent in Catalan rivers. However, information is already available, and positive, from two fish ramps. The fish ramp of the Teula's weir of the Ter River at Manlleu was evaluated in May 2012 and May 2014. With an ICF index [87] of 85 and the fish species size frequencies downstream and upstream being similar, it supposes a small barrier effect and a good fish pass effectiveness. The associated fish ramp at the gauging station of the Fluvià River at Olot (EA013) has been assessed between spring and autumn 2013. With a score of 95 of the ICF index, it allows the passage of all native fish species from this river. However, complementary actions at entire watershed scale are required to improve river connectivity in both cases, especially to recover European eel (*A. anguilla*) from sea to source, as happens in most Catalan river basins.

Acknowledgements We gratefully thank everybody who helped in the fieldwork. These studies were funded by the Catalan Water Agency. Additional financial support was provided by the Spanish Ministry of Economy and Competitiveness (projects CGL2009-12877-C02-01, CSD2009-00065), the Sant Celoni town council ("Observatori de la Tordera" project, led by Dr. M. Boada), the Obra social of UNNIM savings bank (2012) and the funds for conservation of the Spanish Fundación Biodiversidad ("Riberes del Ter" project, 2013).

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