Vol.48, n. 1 : pp. 91-108, January 2005
ISSN 1516-8913 Printed in Brazil

BRAZILIAN ARCHIVES OF
BIOLOGY AND TECHNOLOGY

A N I N T E R N A T I O N A L J O U R N A L

Effects of Natural and Anthropogenic Environmental Changes on Riverine Fish Assemblages: a Framework for Ecological Assessment of Rivers

Francisco Leonardo Tejerina-Garro[1*], Mabel Maldonado[2], Carla Ibañez[2], Didier Pont[3], Nicolas Roset[3] and Thierry Oberdorff[4]

[1] Centro de Biologia Aquática; Campus II; Universidade Católica de Goiás; Av. Bela Vista km 2; Jardim Olímpico; 74605-010; Goiânia - GO - Brazil. [2] ULRA; Universidad Mayor de San Simon; Facultad de Ciencias y Tecnologia; Casilla de correo 992; Cochabamba - Bolivia. [3] Laboratoire d'Ecologie des Eaux Douces; ESA-CNRS 5023; Université Lyon I; 43 Bld du 11 Novembre 1918; 69622 Villeurbanne cedex; France. [4] Institut de Recherche pour le Développement; ULRA; Universidad Mayor de San Simon; Facultad de Ciencias y Tecnologia; Casilla de correo 992; Cochabamba - Bolivia

ABSTRACT

Freshwater is a basic need for the mankind. Effective biological tools (ecologically based, efficient, rapid and consistently applicable to different ecological regions) are needed to measure the "health" of rivers. Adapting such tools over a broad geographic area requires a detailed understanding of both the patterns of organisms assemblage composition and distribution within and among water bodies under natural conditions, and the nature of the major environmental gradients that cause or explain these patterns. A comprehensive review of the available litterature dealing with the identification of environmental factors structuring riverine fish assemblages under natural conditions permits to identify the most consistent ones.

Keywords: Biological indices, fish community, environmental parameters, habitat

INTRODUCTION

Rivers are among the most intensively human influenced ecosystems on the earth. They serve for transportation, water supply and power generation and also as source of food and sinks for waste products. As a result, in highly industrialized countries and in some developing countries, many rivers are now severely polluted. Most common impacts are channel and bank modifications (i.e., canalisation for navigation or agricultural purposes, bank protection), flow regulation and fragmentation (i.e. dams and weirs, reservoirs for water supply, diversion for irrigation and industrial purposes), chemical pollution (e.g. heavy metals, pesticides, fertilizers), and organic pollution (e.g. domestic and cattle-raising waste water). All these alterations have led to an extensive ecological degradation of these rivers making them no longer sustainable in providing goods and services (e.g. decline in water quality and availability, intense flooding, changes in the distribution and structure of aquatic biota) (Poff et al., 1997) (Fig. 1). Recognition of these adverse effects on river systems has driven initiatives for river restoration. Nevertheless, until recently river restoration protocols were contingent upon defined uses,

* Author for correspondence

which were typically human-oriented (drinking water, fishing, swimming) or extremely ill-defined (aquatic life, fish passage).
This kind of policy proved successful to solve problems related to point source pollution, but was poorly adapted to integrate management of river ecosystems. As a consequence, while the chemical water quality in running waters has been considerably improved, the biological and hydro-morphological qualities have continued to deteriorate.

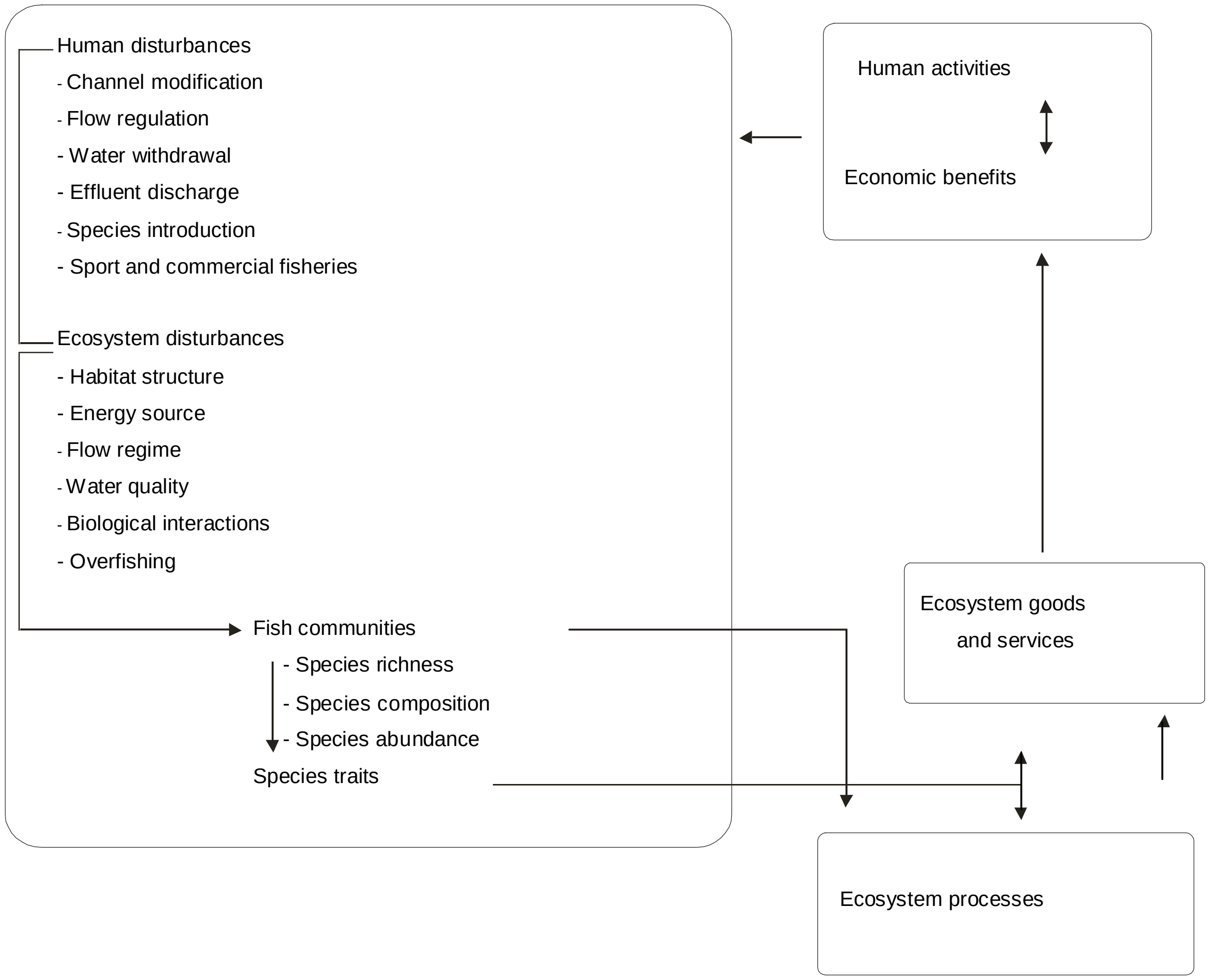

Figure 1 - Relationships between human activities and river ecosystem processes.

Developing countries, like those in South America, and highly industrialized countries, like those in Western Europe, have faced this situation differently. For example, water policy in Brazil continues to concentrate on water pollution even if major river environmental changes are observed due to deforestation, hydroelectric dams, waste water or gold mining (Pringle et al., 2000). In this case measures that attempt to anticipate or predict significant economic, social and ecological impacts rather than react to them, are increasingly necessary for avoiding extreme environmental degradation (Hocutt et al., 1994). The European Community has recently changed its water policy as emphasized by the new European Water Framework Directive (WFD), which requires the restoration and maintenance of "healthy" aquatic ecosystems by the assessment of their hydromorphological, chemical and biological characteristics. Thus, the goal is not only to preserve these ecosystems, but also to rehabilitate them in an attempt to restore their ecological structures, functions, and integrity. Consequently, in both highly industrialized and less developed countries, it is necessary to develop practical and effective ecological tools based on biological assemblage for monitoring water resource quality (Hughes and Oberdorff, 1999).

These tools need to be ecologically based, efficient, rapid and consistently applicable to different ecological regions. Nevertheless, effectively adapting such tools over a broad geographic area requires a detailed understanding of both patterns of organisms assemblage composition and distribution within and among water bodies under natural conditions, and the nature of the major environmental gradients that cause, or at least explain, these patterns (Smogor and Angermeier, 1999). This will permit to obtain a response of aquatic biota to human stressors that can be discriminated from natural variation. For aquatic ecosystems, biological indicators can be chosen from many assemblages (i.e. phytoplankton, macrophytes, benthic invertebrate or fish), but fish are of particular interest because 1) they are present in most water bodies, 2) their taxonomy, ecological requirements and life histories are generally better known than those of other assemblages, 3) they occupy a variety of trophic levels and habitats, and 4) they have both economic and aesthetic values and thus help raise awareness of the value of conserving aquatic systems.

This paper proposes to illustrate the elaboration process of such biological tools. To address this issue we will first review the most important findings on the role of environmental factors in influencing local fish assemblages' structure in natural condition. We will limit to particular sets of factors that have been identified as significant in multiple studies and focus on both temperate and tropical fish fauna. We will also describe and evaluate (advantages and disadvantages) the fish-based methods integrating information on assemblage species richness, composition and abundance, and currently available for the assessment of the ecological quality of streams and rivers. Finally, we will give some guidelines for the elaboration of a biological tool based on fish assemblages for better assessment of rivers health across large regions for long time periods.

FACTORS STRUCTURING RIVERINE FISH ASSEMBLAGES IN TEMPERATE AND TROPICAL REGIONS

Although for many years intrinsic and extrinsic local processes (e.g. competition, predation, disturbance) were the focus of studies seeking to explain local fish assemblage structure (Schlosser, 1995), emphasis on the role of regional processes has increased as some studies have demonstrated their pervasive role in shaping local assemblages (Hughes et al., 1987; Whittier et al., 1988; Hugheny and Paugy, 1995; Hugueny et al., 1997; Belkessam et al., 1997; Angermeier and Winston, 1998; Oberdorff et al., 1998). Consequently, complete answers for the explanation of local fish assemblage richness and structure must address the relative importance of large-scale processes, which determine the species available to occur locally and small-scale processes, which should limit the number of species that actually occur locally (Angermeier and Winston, 1998). The important ecological question to be answered before defining biological tools based on fish assemblages to assess anthropogenic perturbations becomes what is the relative importance of local (biotic and abiotic) and regional factors in determining local assemblages structure and richness? The answer to this question it is crucial for establishing, and possibly regionalizing, suitable biological tools for evaluating the biotic integrity of rivers.

ROLE OF ABIOTIC FACTORS

PROCESSES OCCURRING AT THE LOCAL LEVEL

Longitudinal changes in local assemblage richness and composition have usually been attributed to one of two processes: biotic zonation or continual addition of species downstream. Biotic zonation corresponds to discontinuities in river geomorphology or abiotic conditions promoting distinct assemblages along the longitudinal gradient (Huet, 1959; Schlosser, 1982; Balon et al., 1986; Rahel and Hubert, 1991; Oberdorff et al., 1993; Belliard et al., 1997). For example, species replacement may occur as a result of physiological specialization for temperature (Ferguson, 1958). However, additions of species are usually related to environmental gradients having smooth transitions of abiotic factors contributing to nested patterns of assemblage composition along the longitudinal gradient (Sheldon, 1968, Rahel and Hubert, 1991).

Whatever be the process (i.e. biotic zonation or species addition) the local species richness usually increases along the upstream-downstream gradient. The few studies conducted in tropical streams and rivers reveal patterns that generally agree with patterns from temperate regions (e.g. Ibarra and Stewart 1989, Tito de Morais and Lauzanne, 1994; Mazzoni and Lobon-Cervia, 2000). This gradual accumulation of species is often attributed to a downstream increase in habitat size, habitat diversity, or both (e.g. measured as a function of stream width, volume, discharge, order, drainage basin area, depth, current velocity, substrate composition) (Sheldon, 1968; Bussing and Lopez, 1977; Sydenham, 1977; Gorman and Karr, 1978; Schlosser, 1982; Angermeier and Karr, 1983; Winemiller, 1983; Perez, 1984; Angermeier and Schlosser, 1989; Hugueny, 1990; Winemiller and Leslie, 1992; Paller, 1994; Mérigoux et al., 1998; Tejerina-Garro, 2001) and in environmental stability (Horwitz, 1978; Matthews and Styron, 1981; Grossman et al., 1982; Schlosser, 1987; Poff and Ward, 1989; Schlosser and Ebel, 1989; Poff and Allan, 1995). Indeed, rivers are highly variable environments and are periodically subjected to extreme and often unpredictable fluctuations in their physical and chemical characteristics (e.g. flow, temperature, dissolved oxygen, pH, conductivity) and these fluctuations have been shown to affect the richness and structure of river fish assemblages (Horwitz, 1978; Grossman, 1982; Grossman et al., 1982, 1985, 1990, 1998; Schlosser, 1985; Merona, 1986; Schlosser and Ebel, 1989; Henderson and Walker, 1990; Poff and Allan, 1995; Landivar, 1995; Agostinho and Zalewski, 1995; Tito de Morais et al., 1995; Carrel and Rivier, 1996; Danehy et al., 1998; Lamouroux et al., 1999; Oberdorff et al., 2001b; Tejerina-Garro, 2001; Fialho 2002) by leading to local population extinctions, individual immigration and emigration in response to current conditions and through recruitment success (Freeman et al., 1988; Carrel and Rivier, 1996). Furthermore, the importance of intradrainage immigration in shaping assemblage richness and structure has been emphasized by Osborne and Wiley (1992). These authors observed that within a river basin, a higher local species richness occurred in sites belonging to tributary streams located lower in a drainage network and connected to a main channel system than from similarly sized streams located in the headwaters of a drainage network. The potential mechanism responsible for this observed pattern was related to the immigration-extinction hypothesis (i.e. there should be a higher immigration rate in sites connected to the main channel which is assumed to be the colonization source).

These results suggest that extinction and colonization at the local scale are important processes in shaping fish assemblages and that environmental factors leading to temporal variability in populations size (e.g. discharge variability) are key components in explaining local fish assemblage structure and richness. However, the majority of the above studies mainly focused on species richness patterns without addressing explicitly the potential role of environmental factors on the functional aspect of these assemblages. Major exceptions are the studies of Rahel and Hubert (1991), Oberdorff *et al.* (1993), Belliard *et al.* (1997), Mérigoux *et al.* (1998), Smogor and Angermeier (1999), Tejerina-Garro (2001) in lotic systems and Rodriguez and Lewis Jr. (1997) in lentic systems, which provided support for environmental factors effects on trophic and reproductive attributes of fish assemblages. Therefore, one can reasonably expect that functional attributes of fish assemblages would be related, as for species richness, to natural environmental gradients.

PROCESSES OCCURRING AT THE REGIONAL LEVEL

Patterns and processes observed in local fish assemblages are not only determined by local mechanisms acting within assemblages, but also result from processes operating at larger spatial scales (Hugueny and Paugy, 1995; Hugueny et al., 1997; Angermeier and Winston, 1998; Oberdorff et al., 1998, Jackson et al., 2001). The richness and structure of local fish assemblages has been linked to factors ranging from geomorphology and climate (Nelson et al., 1992; Hughes et al., 1987; Whittier et al., 1988; Matthews and Matthews, 2000; Tejerina-Garro, 2001), to richness of regional species pool (Hugueny and Paugy, 1995; Hugueny et al., 1997; Belkessam et al., 1997; Angermeier and Winston, 1998; Oberdorff et al., 1998; Gido and Brown, 1999). Concerning this last relationship (local/regional richness) the emerging pattern is that few fish assemblages are trully saturated (Hugueny and Paugy 1995, Hugueny et al., 1997; Belkessam et al., 1997; Oberdorff et al., 1998). For example, Oberdorff *et al.* (1998) working on local fish assemblages of coastal streams of North-Western France found that these assemblages were unsaturated with species and with individuals and that inter-annual changes in populations were not strongly affected by densities of co-occurring species. Obviously in this study competition was not the main force driving these assemblages. Gido and Brown (1999) analysing colonization patterns by introduced freshwater fishes in 125 drainages across temperate North America, suggested that North American fish communities were not saturated in species, but instead, were capable of supporting higher levels of diversity if the pool of potential colonists and the rate of colonization from that pool was increased by species introduction. Then, studying local species assemblages in isolation cannot discover the determinants of local assemblage structure and richness, and the principal direction of control for local assemblage structure and richness is from regional to local (Cornell and Lawton, 1992; Lawton, 2000).

ROLE OF BIOTIC FACTORS

COMPETITION AND PREDATION

An important question is to what extent predation and interspecific competition structure local riverine fish assemblages? The knowledge about it remains somewhat superficial even if some authors have suggested that these interactions may be strong enough to have pervasive effects (Werner, 1984, Jackson et al., 2001). However, there is little evidence that either predation or interspecific competition strongly affects local fish assemblages in rivers with the exception of few studies (Zaret and Rand, 1971; Schut et al., 1984; Wikramanayake and Moyle, 1989; Taylor, 1996; Resetarits, 1997, Jackson *et al*. 2001).

If we first consider interspecific competition, we can hypothesize that if this is really an important process, then it should set an upper limit to the number of species in an assemblage (another species could only be accommodated by the loss of a species). This hypothesis can be tested, for example, when introductions take place in a river. Relative to this point, results of different studies previously detailed above show that local and regional fish communities are usually not saturated with species and are capable of supporting greater number of species if the pool of potential colonists and the rate of colonization from that pool was increased by species introduction (Belkessam et al., 1997; Angermeier and Winston, 1998; Oberdorff et al., 1998; Gido and Brown, 1999). These results strongly suggest that competition does not set the species saturation level in the assemblages studied and thus that competition is not a major force structuring these fish assemblages.

If we now consider predation, different studies have shown that this process can affect the choice of habitat by prey species within a river (Gorman, 1988; Schlosser and Angermeier, 1990). In tropical regions, mainly floodplain lakes, results suggest that predation is the mechanism responsible for fish structure in response to water transparency changes (Rodriguez and Lewis Jr., 1994, 1997). In other words, in some cases, fish assemblages' structure could be due to prey species' common avoidance of predators. Nevertheless, studies concerning competition or predation have noticed effects only on limited range of species combinations and thus are unable to provide real evidence that one of them is a major factor in organizing species assemblages.

SYNTHESIS

Table 1, even if obviously non-exhaustive, shows the significant relationships between local riverine fish assemblages and different environmental factors. Of the factors examined, we found the most consistent patterns of local assemblage structure and richness related to measures of river size (e.g. distance from sources, basin area, stream order, river width), elevation, river gradient, water velocity, depth, temperature, conductivity, habitat diversity, flow regimes, ecoregions and/or regional richness (i.e. pool of potential colonists). Relationships with competition and/or predation (biotic factors) were more equivocal. However, in this case it is necessary to point out the influence of the spatial scale used in each study considered in this paper. That is, small-scale studies usually indicate a greater importance of competition is structuring fish assemblages while large-scale

studies usually emphasize abiotic controls (Jackson et al., 2001).
Another possible explanation for the noticed weak effect of predation and competition in structuring local assemblages could come from the predominance of studies carried out in temperate zones (compared to tropical ones) where fish fauna (e.g. Europe, North America) is reduced in richness due to historical processes (Mahon, 1984; Oberdorff et al., 1997) and where few congeneric species co-exist. If we assume that congeneric species have similar ecological niches (closely related species) then they should be strong competitors and competitive exclusion or density adjustments should occur more often among congeneric species than in more distantly related ones. Then we can suppose that competition is more common in tropical zones compared to temperate ones (Ricklefs, 1993). Nevertheless, more studies are needed to quantify this effect and its possible impact on assemblage structure in tropical rivers. Thus, apparently development of accurate biological indicators will have to integrate the relevant environmental factors to obtain a response of fish assemblages to human stressors that can be discriminated from natural variation.

FISH-BASED METHODS CURRENTLY AVAILABLE

There are relatively few ecological tools based on fish assemblages that uses structural and functional components of fish assemblages for assessment of river condition in temperate and tropical rivers. Two major approaches (tools) can be distinguished. Both use the “reference condition approach” (Bailey et al., 1998), which involves testing an ecosystem exposed to a potential stress against a reference condition that is unexposed to such a stress. Most common way is to select the reference sites that are “minimally disturbed” because pristine conditions no longer exist in most industrialized countries and coming back to prehistoric conditions first, will deny the place of humans in the landscape (Norris and Thoms, 1999) and second, will make restoration goals obsolete because obviously not attainable.

Table 1 - Results of empirical studies that describe the effect of environmental factors or phenomenon on local fish assemblage structure at different spatial scales.

Scale *Factor*	**Effect**	**No effect**
Local (site) *Altitude*	Beecher et al., 1988; Lauzanne et al., 1991*; Rahel and Hubert, 1991; Mastrorillo et al., 1998; Angermeier and Winston, 1998; Oberdorff et al., 2001a	Maret et al., 1997; Waite and Carpenter, 2000
River size *Basin area* *Distance from sources* *River width* *Stream order*	Huet, 1959; Sheldon, 1968; Bussing and Lopez, 1977*; Sydenham, 1977*; Horwitz, 1978; Lauzanne and Loubens, 1988*; Angermeier and Karr, 1983*; Winemiller, 1983*; Mahon, 1984; Balon et al., 1986; Hugues and Gammon, 1987; Beecher et al., 1988; Matthews and Robinson, 1988; Paugy et al., 1988*; Ibarra and Stewart, 1989; Hugueny, 1990*; Lyons and Schneider, 1990*; Osborne and Wiley, 1992; Winemiller and Leslie, 1992*; Oberdorff et al., 1993; Lyons, 1996; Belliard et al., 1997; Maret et al., 1997; Mastrorillo et al., 1998; Kamdem-Toham and Teugels, 1997*; Mérigoux et al., 1998*; Angermeier and Winston, 1998; Matthews and Matthews, 2000; Tejerina Garro, 2001*	Mérona, 1981*
River gradient	Huet, 1959; Lyons, 1996; Maret et al., 1997; Mastrorillo et al., 1998; Waite and Carpenter, 2000; Oberdorff et al., 2001[a]	
Water velocity	Hugueny, 1990*; Angermeier and Schlosser, 1989*; Lamouroux et al., 1999; Matthews and Matthews, 2000; Oberdorff et al., 2001[a]	

Cont. Table 1

Cont. Table 1

Habitat diversity **$**	Gorman and Karr, 1978*; Schlosser, 1982; Perez, 1984*; Angermeier and Schlosser, 1989*; Kamdem-Toham and Teugels, 1997*; Mérigoux et al., 1998*; Tejerina-Garro, 2001*	Grossman et al., 1998
Depth	Sheldon, 1968; Evans and Noble, 1979; Schlosser, 1982; Gorman, 1988; Hugueny, 1990*; Winemiller and Leslie, 1992*; Taylor et al., 1993; Matthews and Matthews, 2000; Oberdorff et al., 2001a	
Conductivity	Taylor et al., 1993; Kamdem-Toham and Teugels, 1997*; Mérigoux et al., 1998*; Tejerina-Garro, 2001*	
Temperature	Verneaux, 1977; Baltz et al., 1982; Schlosser, 1987; Rathert et al., 1999; Waite and Carpenter, 2000	
Flow variability	Horwitz, 1978; Meffe, 1984; Schlosser, 1985; Poff and Allan, 1995; Grossman et al., 1998; Oberdorff et al., 2001b	
Competition and/or Predation	Zaret and Rand, 1971*; Fausch and White, 1981; Baltz et al., 1982; Schut et al., 1984*; Gorman, 1988; Wikramanayake and Moyle, 1989*; Taylor, 1996; Resetarits, 1997	Schlosser, 1982; Oberdorff et al., 1998; Grossman et al., 1998; Gido and Brown, 1999; Oberdorff et al., 2001a
Regional (basin) *Ecoregion/Physiography Hydrological units*	Hughes et al., 1987; Hughes et al., 1998; Matthews and Robinson, 1988; Whittier et al., 1988; Nelson et al., 1992; Belliard et al., 1997; Oberdorff et al., 2001a	
Basin richness	Beecher et al., 1988; Hugueny and Paugy, 1995*; Belkessam et al., 1997; Hugueny et al., 1997*; Angermeier and Winston, 1998; Matthews and Robinson, 1988; Oberdorff et al., 1998	Matthews and Matthews, 2000

$ usually measured in three dimensions: depth, water velocity and substrate; * tropical studies

THE INDEX OF BIOTIC INTEGRITY (IBI)

The first approach to quantify the impact of human activities on the aquatic ecosystem is a multimetric index, the Index of Biotic Integrity (IBI), first formulated by Karr (1981) and latter refined by Karr *et al.* (1986) for use in Midwestern USA streams. The IBI is based on the hypothesis that there are predictable relationships between fish assemblage structure and the physical, chemical and biological condition of stream systems. The IBI employs a series of metrics based on assemblage structure that give reliable signals of river condition to calculate an index score at a site, which is then compared to the score expected at an unimpaired comparable site. Classes of metrics in the IBI include species richness, species composition, trophic structure, total fish abundance, and individual fish condition (Table 2). Each metric reflects the quality of a different aspect of the fish assemblage that responds in a different manner to aquatic ecosystem stressors (Hughes and Noss, 1992). The combination of metrics reflects insights from individual, population, assemblage, ecosystem and zoogeographic perspectives.

The IBI methodology is outlined in Table 3. The primary underlying assumptions of the IBI concept are presented in Table 4. Since its introduction, the IBI has been modified for use in other regions and types of ecosystems throughout North America (Karr and Chu, 1999). It has also been modified for use outside North America (Hughes and Oberdorff, 1999) on six continents: Europe

(Oberdorff and Hughes, 1992; Oberdorff and Porcher, 1994; Berrebi dit Thomas et al., 1998; and Belliard et al., 1999 in France; Kestemont et al., 2000 and Belpaire et al., 2000 in Belgium, Kesminas and Virbickas, 2000 in Lithuania), Africa (Hugueny et al., 1996 in Guinea, Hocutt et al., 1994 on the Namibia-Angola border, Hay et al., 1996 in Namibia, Kamdem-Toham and Teugels, 1999 in Gabon), Asia (Ganasan and Hughes, 1998 in India), Australia (Harris, 1995), Central America (Lyons et al., 1995 in Mexico) and South America (Gutierrez, 1994 in Venezuela; Araújo, 1998 in Brazil; Tejerina-Garro, 2001 in French Guiana). In South America, the index adaptations made by Gutierrez (1994) and Araújo (1998) have conserved the same metrics as used in temperate regions. However, a new approach was used in French Guiana (South America), which selected the metrics to be used based on an empirical study of the interaction fish fauna-habitat using taxonomical and functional descriptors (Tejerina-Garro, 2001).

Table 2 - IBI metrics for Midwestern USA streams (from Karr et al., 1986; Miller et al., 1988). [a]Value approximates (5), deviates somewhat (3), or deviates strongly (1) from the reference condition; [b]Expected value varies with stream size, region, and basin; [c]Adult diets typically include $\geq$25 % plant and $\geq$25 % animal material; [d]Adult diets usually composed largely of aquatic vertebrates or crayfish; [e]Disease, eroded fins, lesions, tumors, discoloration, excessive mucous, skeletal abnormalities, missing organs, and other external symptoms.

Category *Metric*	Scoring Criteria[a]		
	5	3	1
Species Richness			
1. *Total number of fish species*	**b**	**b**	**b**
2. *Number of darter species*	**b**	**b**	**b**
3. *Number of sunfish species*	**b**	**b**	**b**
4. *Number of sucker species*	**b**	**b**	**b**
Habitat guilds			
5. *Number of intolerant species*	**b**	**b**	**b**
6. *% individuals as green sunfish*	<5	5-20	>20
Trophic guilds			
7. *% individuals as omnivores*[c]	<20	20-45	>45
8. *% individuals as insectivorous cyprinids*	>45	20-45	<20
9. *% individuals as piscivores*[d]	>5	1-5	<1
Abundance			
10. *Number of individuals*	**b**	**b**	**b**
Reproduction and Condition			
11. *% individuals as hybrids*	0	>0-1	>1
12. *% individuals with anomalies*[e]	0-2	>2-5	>5

Even if these applications attest to the utility of the concept (Karr and Chu, 1999), it should be noticed anyway that none of these studies (except Belliard et al., 1999 and Tejerina-Garro, 2001) truly validated the methodology with independent datasets of both disturbed and reference sites. Properly developed IBI's usually incorporate region-specific metrics and adjust metric criteria (usually only for taxonomic metrics) by river size (e.g. stream order or catchment's area) to isolate natural versus anthropogenic influences on local fish assemblage structure. Region-specific criteria are set using broad regional land classification (e.g. ecoregions). The basis of this approach is the understanding that the character of a river (e.g. its water quality, flow regime, habitat structure, energy base) is in large part a function of the climate, topography, geology, soil, vegetation, and land use of its geographic region. Such an approach is efficient in grouping similar rivers (at least at some level of resolution), allowing the reduction of the natural regional variability.

THE FISH-BASED INDEX (FBI)

The second approach originates from a research program (1996-2000) initiated by the French Water Agencies and the Ministry of the Environment to develop a fish-based index that could be applicable nationwide (Oberdorff et al., 2001a; Oberdorff et al., 2002).

Such an index had to encompass the relative importance of potential regional and local processes influencing the distribution of riverine fish. Convinced that the IBI's concept was ecologically sound effective for assessment of the status, trends, and ecological integrity of a water body Oberdorff *et al.* (2001a, 2002) tried to improve the accuracy of such an index while maintaining its theoretical foundations. They did it by using the recent findings in aquatic ecology to distinguish, as far as possible, effects of anthropogenic disturbances from natural variation in assemblage structure and richness. The rational for the development of the FBI is summarized in Table 5 and detailed in Oberdorff *et al.* (2002).

Three independent data sets were used: 1) two sets of reference sites, fairly evenly distributed across French rivers; 2) a third set of exposed (disturbed) sites. A variety of metrics based on occurrence and abundance data and reflecting different aspects of the fish assemblage structure and function were selected from available litterature and for their potential to indicate degradation. For metrics based on species occurrences, logistic multiple regression procedures were applied, using the first data set of reference sites and defined by the main regional and local factors known to influence local fish assemblages (see Table 1) (i.e. drainage area, distance from sources, altitude, river gradient, water velocity, depth, temperature, and hydrological units), to elaborate the simplest possible response model that adequately explains the observed patterns of occurrence for each species of a fish assemblage for a given site of any given river.

For a given occurrence metric, a theoritical assemblage for each site is obtained by summing the predicted probability of each species included in the considered metric. For metrics based on abundance data, stepwise multiple regression procedures were applied to elaborate the simplest possible response model that adequately explains the observed value of each metric (i.e. the sum of log-transformed density of individuals belonging to species considered in the metric) for a given site of any given river. All models retained a majority of environmental factors underlying their importance in structuring local fish assemblages as discussed earlier. After eliminating metrics for which residuals distribution values statistically differed from a normal distribution using the initial data set of reference sites, and after converting residual values of the n metric models into probabilities, models obtained for each metric were validated using the two independent data sets of reference and disturbed sites. These procedures allowed to select the most effective metrics in discriminating between reference and disturbed sites (Table 6). Overall, the FBI performed well in discriminating beween reference and disturbed sites and in distributing sites along the gradient of perturbations (Fig. 2). It is thus a useful indicator of running-water ecosystems, which could be used to monitor change and provide a baseline for measuring the full biotic response to restoration of these rivers. Moreover, it can be applied in the different regions and river types of France using a consistent set of metrics despite the complex and heterogeneous geology and climate of that country.

The final index score was obtained by computing the combined probabilities corresponding to the remaining effective metrics. To avoid logical circularity, the optimal cut-off level for a local assemblage "impairment" was obtained by analysing distributions of index scores for the two independent data sets of reference and disturbed sites.

Table 3 - Principles of fish assemblage assessment with the IBI (Modified after Hughes and Oberdorff, 1999).

1. Select a relatively homogeneous region. A region may be an ecoregion, basin, or fish faunal region that is homogeneous with respect to a combination of environmental characteristics (e.g., climate, physiography, soil, vegetation) and potential fish species.
2. Determine the reference condition(s). References may be a set of minimally disturbed reference streams, a disturbance gradient, historical data, paleoecological information, and professional judgement.
3. List candidate metrics and assign species to trophic, tolerance, and habitat guilds. Regional fish texts usually provide this information, at least in developed countries.
4. Sample fish assemblages. This is best done (a) when they are least variable yet most limited by anthropogenic stressors and (b) in a manner yielding a representative collection of species and proportionate abundances, but that (c) is cost-effective.
5. Tabulate numbers of individuals collected by species at each reach.
6. Calculate values for each candidate IBI metric. Typically these are proportions or percents of individuals, or numbers of species in particular categories.
7. Develop scoring criteria. These are based on previously available information from step 2 or from fish data collected at minimally disturbed sites in step 4. Scoring criteria may be continuous (0-1 or 0-10) or based on classes (1, 3, 5 or 0, 5, 10). An IBI score represents comparisons between metric value at a sample site and those expected under reference conditions. Metric criteria are usually adjusted by river size.
8. Calculate metric scores and add these to obtain an IBI score.
9. Evaluate metric and index scores. Consider, differences between expected and obtained scores, compare variance results from repeated samples, assess responsiveness to environmental stressors. Modify or reject metrics that are highly variable or unresponsive, and recalculate if necessary.
10. Interpret IBI score as indicating an acceptable, marginally impaired, or highly impaired fish assemblage; or as excellent, good, fair, poor, very poor.

Table 4 - Assumed effects of environmental degradation on fish assemblages (from Fausch et al., 1990 and Hughes and Noss, 1992). [a]In some waters, especially oligotrophic cold water systems, increased nutrients and temperatures often result in additional species and individuals.

Number of native species and of those in specialized taxa or guilds declines[a]
Number of sensitive species declines
% of trophic and habitat specialists declines
Total number of individuals declines[a]
% of large individuals and the number of size classes decrease
% of tolerant individuals increases
% of trophic and habitat generalists increases
% individuals with anomalies increases

Table 5 - General principles of fish assemblage assessment with the FBI (Oberdorff et al., 2002).

1. Determine the reference condition(s)

2. List candidate metrics and assign species to trophic, tolerance, and habitat guilds based on literature review

3. Model metrics in relation to regional and local environmental factors. The method is designed to predict a metric value at a particular reference site, independent of natural environmental factors. Eliminate metrics not adequately modelised

4. Validate the models using independent data sets of reference and disturbed sites in order to select the most effective metrics in discriminating between reference and disturbed sites (reject metrics that are highly variable or unresponsive)

5. Add metrics values to obtain an index score

6. Develop scoring criteria

7. Interpret index score as excellent, good, fair, poor, very poor

Table 6 - Fish assemblage metrics used to calculate the FBI for French rivers (after Oberdorff et al., 2002).

Category	**Metrics**
Taxonomic richness	1. Total number of species
Habitat composition	2. Number of reophilic species 3. Number of lithophilic species
Assemblage sensitivity	4. Tolerant species individuals
Trophic composition	5. Invertivorous species individuals 6. Omnivorous species individuals
Fish abundance	7. Total density of individuals

ADVANTAGES AND DISADVANTAGES OF BOTH INDEX

Both index have several advantages in common. They are broadly based ecological indexes that assess both assemblage structure and function at several trophic levels; they are flexible and widely adaptable and combine several types of metrics (*e.g.* taxonomic, reproductive, trophic and tolerance metrics) that individually provide different responses to perturbations. Consequently, they are responsive to general types of degradation, and should then be able to quantify the biological effects of human activities on aquatic ecosystems.

The main difference between the FBI and the IBI methodologies lies on the way metric (fish assemblage attributes) criteria are adjusted (*i.e.* the expected value of a metric for a given site under conditions least affected by anthropogenic disturbance). As previously mentioned, the IBI approach consists in adjusting species richness-metric (*e.g.* total species richness, number of tolerant species, number of benthic species) criteria exclusively on the basis of empirical relations between river size (i.e. position of a given site along the upstream-downstream gradient) and taxa richness. Nevertheless, stratifying intra-regional criteria by using only a single factor like river size is clearly inadequate as previoulsly discussed in this paper (see Table 1). Moreover, most of the time, abundance related metrics (i.e functional metrics such as total number of individuals, proportional abundance of omnivores, proportional abundance of lithophilic individuals) are not adjusted at all suggesting that these metrics are invariant across river sizes or other environmental factors. Ignoring potential relations between environmental factors and these last metrics seems contrary to evidence that such relations exist (see Table 1). For example, the River Continuum concept (Vannote et al., 1980) explicitly predicts changes in fish trophic structure along a longitudinal gradient. This concept attempts to relate the gradient in physical factors that occurs along river systems, to change in assemblage structure and function. According to this concept, available food resources should change along this gradient and thus should be reflected by the trophic composition of the assemblages. These predictions have been confirmed for fish assemblages in French river by Oberdorff *et al.* (1993) (*i.e.* a decrease in invertivorous species and an increase in omnivorous species from upstream to downstream). Moreover, Oberdorff *et al.* (2002), provided empirical support that other functional metrics varied with river size and other environmental factors. Oberdorff *et al.* (2002) used predictive models to assess the response of local assemblage attributes (metrics) to natural environmental gradients. The environmental variables selected correspond to five categories of environmental attributes of sites (i.e. river size (measured by a combination of drainage area and distances from sources), altitude, water velocity (measured by a combination of river width, river depth and river gradient) temperature, and hydrological units). All five attributes appeared critical in predicting metrics value for a given site. Although the predictor factors for each of the metric models were slightly different, all models included factors that incorporate information on each of these five attributes (Table 7).

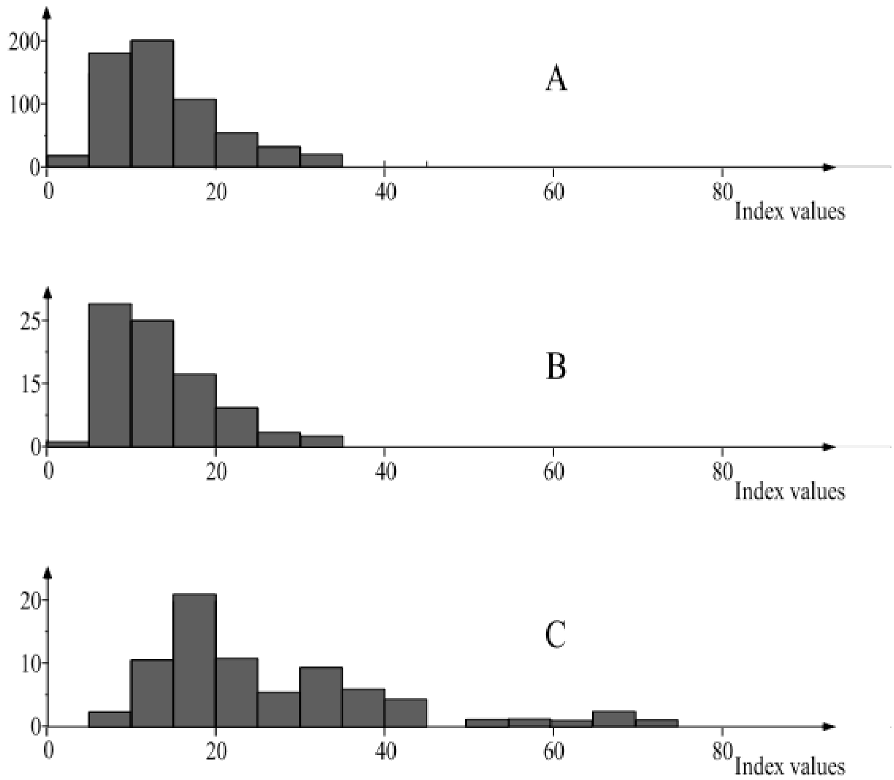

Figure 2 - Distribution of the index scores for the three independent data sets. (A) and (B) reference sites, (C) disturbed sites. From Oberdorff *et al.* (2002).

Thus, it is clear that to set appropriate metric criteria, one should compare how metrics vary with river size relative to how they differ across regions and/or drainages, and relevant local environmental gradients within each. This type of approach appears to be of importance for elaboration of an accurate biological indicator. This strategy was adopted for the EC research programme (FAME, 2001-2004; http://www.fame.boku.ac.at) to develop a fish-based assessment method for the ecological status of European rivers.

Table 7 - Commonly used predictor factors for FBI models. *Total number of predictive models tested=38.

Scale *Factor*	Number of models*integrating factor as a predictor
Local	
Altitude	24
River size	36
Basin area	
Distance from sources	
Water velocity	27
River width	
River gradient	
Depth	
Temperature	33
Regional	
Hydrological units	26

CONCLUSIONS

The ability to protect biological resources relies on the ability to identify and predict the effects of human activities on biological systems. This depends first on the capacity in distinguishing between natural and human-induced variation in biological condition. To achieve this goal, it is important for researchers to continue to develop and improve multimetric fish-based indexes by accounting for the many possible sources of inter and intraregional variation in assemblages structure in natural conditions. A special attention should be given to analyse natural environmental effects on functional metrics, which has been until now too often neglected. Accounting for these natural variations will greatly enhance index's intented function, *i.e.*, to solely reflect anthropogenic disturbance effects (Smogor and Angermeier, 1999).

ACKNOWLEDGMENTS

We thank grants from the Institut de Recherche pour le Développement (IRD), France, the EU FAME project (Contract n° EVK1-CT-2001-00094); the Universidade Católica de Goiás, Brazil (Project n° 84-VPG/UCG) and the Universidad Mayor de San Simón (Bolivia).

RESUMO

A água dos rios constituem um recurso básico para a humanidade. Instrumentos biológicos eficaces (com fundamento ecológico, eficientes, rápidos e aplicáveis à regiões ecologicamente diferentes) são necessários para medir a "saúde" destes. Adaptar tais instrumentos a uma grande área geográfica requer uma compreensão detalhada dos padrões da composição da assembléia de organismos e da sua distribuição dentro e entre os corpos da água em condições naturais, e da natureza dos principais gradientes ambientais que causam ou explicam estes padrões. Uma revisão da literatura disponível pode ajudar a identificar os fatores ambientais mais consistentes que estruturam a assembléia de peixes de ambientes lóticos em condições naturais.

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Received: July 15, 2003;
Revised: December 02, 2003;
Accepted: May 25, 2004.