Hydrobiologia **418:** 57–72, 2000.

117632

Development of a preliminary index of biotic integrity (IBI) based on fish assemblages to assess ecosystem condition in the lakes of central Mexico

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Received 2 February 1999; in revised form 29 July; accepted 19 August 1999

Key words: México, lake, fish, biotic integrity, IBI, ecosystem health

Abstract

The lakes of central Mexico have great cultural, economic, and biological value, but they are being degraded at an accelerating rate. We employed historical data on fish communities from 19 of these lakes and case studies of community responses to environmental degradation from four of the best-studied, Xochimilco, Cuitzeo, Chapala, and Pátzcuaro, to construct a preliminary index of biotic integrity (IBI). This IBI was designed to be an easily applied method for assessing lake ecosystem health and evaluating restoration efforts. The IBI had 10 metrics: number of total native species, number of common native species, number of native Goodeidae species, number of native *Chirostoma* species, number of native sensitive species, percent of biomass as tolerant species, percent of biomass as exotic species, percent of biomass as native carnivorous species, maximum standard length of native species, and percent of exotic invertebrate parasite species on or in native fishes. Initial applications of the index showed promise, accurately ranking the relative degradation of the four case-study lakes. Further tests of the index are warranted, and more data are needed to standardize sampling procedures, improve species classifications, and refine metric scoring criteria.

Introduction

Tropical highland lakes have played a key role in the development of the cultures and nation states of Latin America. Nowhere is this better illustrated than in central Mexico, where an extensive and diverse lake district occurs. The waters and biota of these lakes were instrumental in the rise of great pre-Columbian civilizations such as the Aztecs (Méxica) and Tarascans (P'uréhpecha) (Tamayo & West, 1964; Serra-Puche, 1980; Alcocer-Durand & Escobar-Briones, 1991). After the Spanish conquest in the 16th century, the lake district, stretching from just east of Mexico City to well to the west of Guadalajara, was the political, economic, and cultural center of what eventually became the nation of México. Today the lakes continue to play an important societal role as sources of water, fisheries, and recreation, and they are highly valued by the Mexican people (Chacón-Torres, 1993; De la Lanza-Espino & García-Calderón, 1995). They are also of great interest to aquatic scientists, having unique limnological and biotic characteristics and supporting numerous endemic species (DeBuen, 1944; Barbour, 1973a; Miller & Smith, 1986; Lyons et al., 1998).

Human modifications of central Mexican lakes began well before the Spanish conquest (e.g., O'Hara et al., 1993), but have been greatly amplified in the last 100 years (De la Lanza-Espino & García-Calderón, 1995). Since 1900, several lakes have been substantially reduced in size or even eliminated by hydrologic modifications and water extraction (Smith & Miller, 1980; Alcocer-Durand & Escobar-Briones, 1991; Chacón-Torres & Alvarado-Díaz, 1995). Others have suffered hyper-eutrophication and dramatically increased turbidity from watershed erosion and municipal, industrial, and agricultural pollution (Alvarado et al., 1985; Limón-Macias & Lind, 1990; Chacón-Torres, 1993). In nearly all of the lakes, overfishing and introduction of exotic species have fundamentally altered biological communities (Chacón-Torres & Rosas-Monge, 1995; Guzmán-Arroyo, 1995; Lyons et al., 1998; Soto-Galera et al., 1999).

A wide variety of restoration strategies have been proposed (e.g., Chacón-Torres, 1993; Ceballos-Corona et al., 1994; Chacón-Torres & Rosas-Monge, 1995; Guzmán-Arroyo, 1995), and, in at least one case, implemented (Stephan-Otto, 1995) in response to declines in the ecosystem quality and fisheries of Mexican lakes. However, restoration efforts are hampered by the lack of a holistic framework for assessing lake ecosystem quality. At present the degree of lake degradation and the goals of restoration can be quantified and expressed only in terms of single components of ecosystem condition such as hydrology, water quality, or fishery yields. There is as yet no integrated indicator of overall ecosystem health available for Mexican lakes.

Biological indices have shown great value as holistic indicators of ecosystem condition (Karr, 1987). The status and trends of biological communities reflect human effects on energy and nutrient inputs, hydrology, water quality, habitat quality, and biological processes of aquatic ecosystems, and integrate these effects across broad spatial and temporal scales (Karr, 1991). Fish communities are particulary effective as biological indicators (Karr, 1981; Fausch et al., 1990). They are usually the best studied and understood of the aquatic fauna, and perform a wide variety of ecological functions within the ecosystem. Equally important, fish have obvious direct value to people, and their status is of great interest to the public and their leaders. Documentation of declines in fish communities can help mobilize efforts toward ecosystem protection and rehabilitation.

Arguably the best, and certainly the most popular, family of biological indices based on fish communities is the index of biotic integrity or IBI (Karr, 1981; Fausch et al., 1990; Simon & Lyons, 1995). Indices within this family vary greatly in their specific make-up, but share two general attributes: 1) multiple components, usually termed "metrics", that encompass community structure (diversity), composition, and functional organization; 2) specific quantitative expectations for each metric that are largely empirically derived, with adjustments for inherent natural differences in communities among ecosystems. The IBI was originated in streams of the central United States nearly 20 years ago (Karr, 1981), and has since been applied to many different waters around the world (Hughes & Oberdorff, 1998). A version has been developed and applied succesfully to the streams and rivers of central México, but it needs modification for Mexican lakes, which have different fish communities (Lyons et al., 1995). Worldwide, the development of IBIs for lakes has lagged well behind development for streams and rivers, and only a few lake IBIs are extant, all designed for lakes and reservoirs of the temperate United States and Canada (Harig & Bain, 1998; Jennings et al., 1998).

In this paper, we develop a preliminary IBI for the lakes of central México. We then apply this IBI to four lakes with differing amounts and types of environmental degradation. Our purpose is to provide an easily applied index of overall ecosystem condition or "health" that can be used to document the extent and degree of lake degradation and to assess the relative success of restoration efforts.

Approach

We developed our IBI from a combination of historical data, which we used to characterize lake fish communities before they suffered dramatic human impacts, and more recent data, which we used to document the pattern of fish community change in response to environmental degradation. Historical fish community characteristics were estimated from literature citations and museum collections. We surveyed over 30 natural history museums for relevant specimens, but obtained most of our information from the Museum of Zoology, University of Michigan, Ann Arbor, and the Colección Nacional de Peces Dulceacuicolas Mexicanos, Escuela Nacional de Ciencias Biológicas, Instituto Politécnico Nacional, México, D.F. Fish communities were reconstructed as far back in time as possible, but lakes were only included if there was sufficient data from before major modern human impacts had occurred. For lakes near large cities such as Mexico City or Guadalajara, we only included those with data from before 1900, but for more distant lakes with lesser impacts, we considered data from as recently as the 1950s as representative of historical conditions.

We also estimated the historical surface area of all lakes, based on literature values and examination of maps. Many lakes in central México fluctuated greatly in size depending on climate conditions (Serra-Puche, 1990; Alocer-Durand & Escobar-Briones, 1991; Bernal-Brooks, 1998), and for these we approximated a median value.

For characterization of historical fish communities, fish species were categorized into discrete origin and abundance classes. The maximum standard length of each species in central México was also determined. Species origin was determined to be native or exotic (introduced from outside central Mexico) based on Miller & Smith (1986). Relative abundance of each native species was categorized as high, medium, or low. High-abundance species were those listed as "common" or "abundant" by early authors, the target of a long-term subsistence or commercial fishery, or regularly captured at a rate of more than 50 individuals per day in scientific surveys. Low abundance species were listed as "rare" or "uncommon" in early literature, rarely or never taken by fisheries, or caught at a rate of less than five individuals per day in scientific surveys. Moderate abundance species were intermediate between these extremes. Specimens that were of questionable identity or locality were excluded from analyses.

Fish species were classified into feeding and tolerance groups for IBI metric development following procedures outlined in Lyons et al. (1995). For feeding, we used our own unpublished stomach content and gut morphology data plus available literature to categorize species as carnivores (live animal material usually >75% of diet by volume), herbivores (live plant material >75% of diet), or omnivores (>25% animal and >25% plant material, or >50% detritus). Carnivores could usually be identified with reasonable certainty, but the distinction between omnivory and herbivory was often unclear, and several species were classified as "herb/omnivore". For tolerance, species were considered sensitive if they only occurred in areas with good habitat and water quality and rapidly declined as the environment became degraded. Tolerant species were common across a wide range of conditions, including sites with low dissolved oxygen, heavy organic pollution, high levels of sedimentation and turbidity, or severely modified habitat. Tolerant species typically remained common as lakes became increasingly degraded. Moderate species were intermediate in tolerance, and were not restricted to the best quality conditions but were absent from the worst.

We considered a variety of potential IBI metrics, including many from existing lake IBIs (Simon & Lyons, 1995; Harig & Bain, 1998; Jennings et. al., 1998; McDonough & Hickman, 1998; Thoma, 1998; Whittier, 1998) and others suggested by the unique fish fauna of central Mexican lakes. We selected preliminary metrics based on their broad applicability and stability across the study lakes and their consistent relation to environmental degradation. To assess responses to human impacts and develop scoring criteria for each metric, we examined the change in the fish community of four lakes from the historical period to the present. These four lakes, Xochimilco, Cuitzeo, Chapala, and Pátzcuaro, have the most data and encompass the range of degradation that affects central Mexican lakes. On a relative scale, degradation of Xochimilco and Cuitzeo was extreme, Chapala severe, and Pátzcuaro moderate. Note that all of the lakes for which we could find data had experienced at least moderate degradation in hydrology, water quality, habitat quality, or biotic communities over the last 100 years.

Historical fish communities

We obtained sufficient data to characterize the historical fish communities of 19 lakes (Table 1; Figure 1). These lakes differed greatly in environmental characteristics, ranging in surface area from 300 to 125,000 ha. Some, such as Zirahuén, were oligotrophic and relatively deep (maximum depth >43 m) with a small littoral zone (Bernal-Brooks, 1995; Gutiérrez-Hernández et al., in press), whereas others, such as Chapala, were eutrophic and shallow (maximum depth 7 m) with an extensive littoral zone (Guzmán-Arroyo, 1995).

A total of 49 native species were documented from the 19 lakes (Table 2). Two exotic species, *Carrasius auratus* and *Cyprinus carpio*, were common in lakes

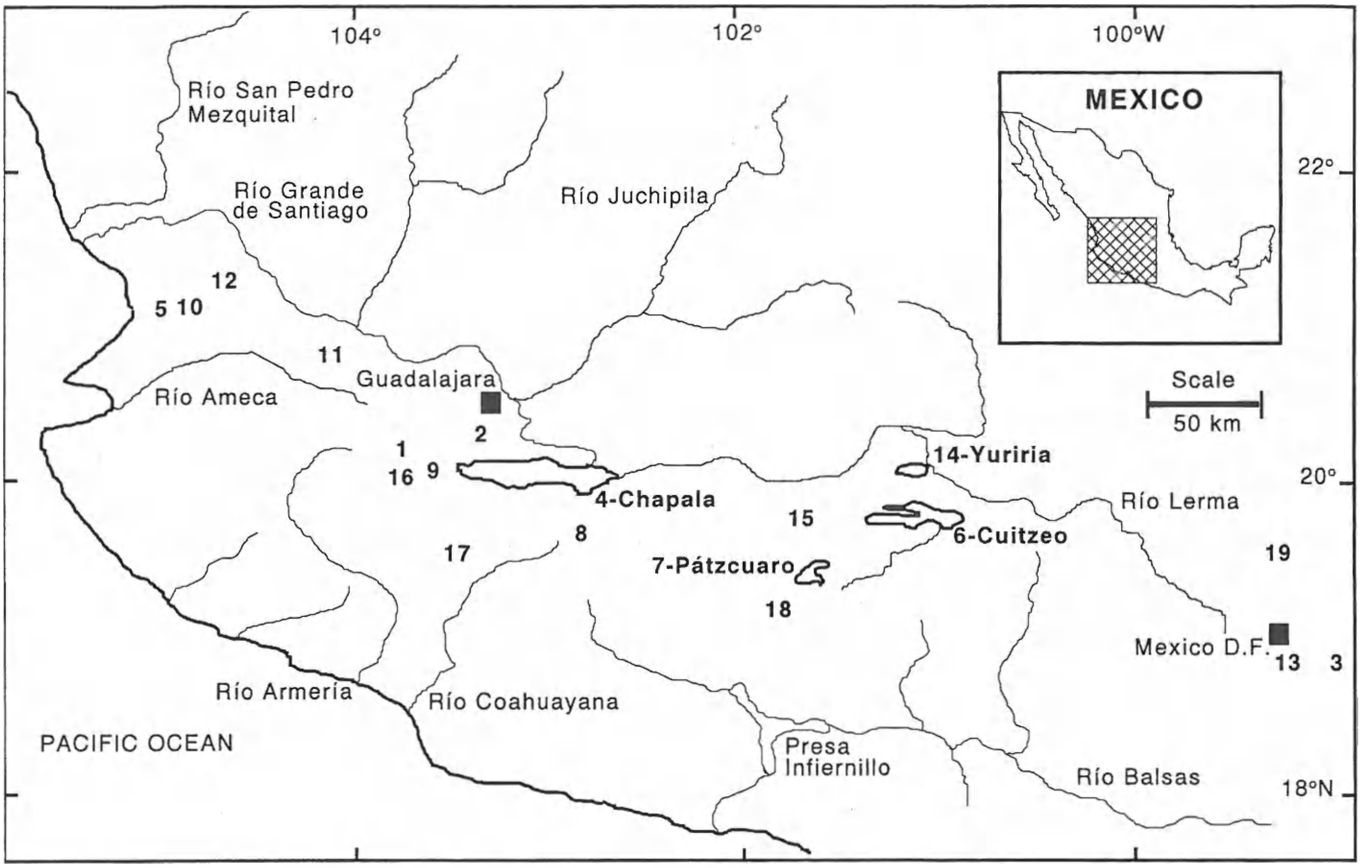

Figure 1. Map of central México, showing the 19 study lakes. Lakes are numbered as in Table 1.

near Mexico City before 1900 (Meek, 1904), and since 1900 at least another 10 exotics have been introduced into the study lakes. The number of native species per lake ranged from 3 to 26 (Table 3), and was significantly positiviely correlated with lake surface area (Pearson's $r = 0.91$, $P < 0.0001$; Figure 2a). The strength of this correlation was disproportionately affected by the two largest lakes, Chapala and Cuitzeo, and when these two were excluded the correlation, while still significant, was substantially weakened ($r = 0.56$, $P = 0.0207$; Figure 2b). The number of species with high abundance ("common") ranged from 3 to 9 and was also positively correlated with surface area ($r = 0.85$, $P < 0.0001$). This correlation was relatively little affected by exclusion of Chapala and Cuitzeo ($r = 0.73$, $P = 0.0008$).

The composition of the fish fauna varied greatly among the lakes, but several consistencies were evident. The most species-rich and widely distributed families in the lakes were Goodeidae (17 species; 19 lakes) and Atherinidae (17 *Chirostoma* species; 18 lakes), although Cyprinidae (10 native species; 14 lakes) and Poeciliidae (3 native species; 14 lakes) were also widely represented. The three remaining families had limited distributions: Petromyzontidae (1 species; 2 lakes), Catostomidae (1 species; 1 lake), and Ictaluridae (1 native species; 2 lakes). The number of goodeids per lake ranged from 1 to 9 species (Table 3) and was postively correlated with lake area when Chapala and Cuitzeo were included ($r = 0.65$, $P = 0.0028$) but not when they were excluded ($r = 0.22$, $P = 0.3929$). The number of *Chirostoma* species varied from 0 to 9 and was positively correlated with lake area ($r = 0.90$, $P = 0.0001$), but the correlation was weakened when Chapala and Cuitzeo were not included ($r = 0.59$, $P = 0.0125$).

All 19 lakes had species in at least two of the three feeding groups and 18 had all three tolerance groups. Omnivores were present in all lakes and dominated numbers and biomass in many, but carnivores also occurred in all lakes and were common in 14. The number of sensitive species per lake ranged from 1 to 11 species (Table 3), and was strongly correlated with lake area when Chapala and Cuitzeo were included ($r = 0.91$, $P < 0.0001$) but less so when they were not ($r = 0.67$, $P = 0.0034$). Tolerant species were com-

Table 1. Lakes included in this study (numbers refer to Figure 1). Surface area is estimated for the mid 1800s; if there has been a major permanent decline in size, the current area is also given in parentheses. For sources of data the codes refer to the References section, except for U1, which refers to our unpublished data, and U2, for specimens at the University of Michigan Museum of Zoology, Ann Arbor

	Lake	State	Surface Area (ha)	Sources of Data
1.	Atotonilco	Jalisco	3120	B1, M3, U2
2.	Cajititlan	Jalisco	1950	B1, P1, U2
3.	Chalco	México	6600 (dry)	A4, M3, U1
4.	Chapala	Jalisco/ Michoacán	125000 (90000)	B1, B2, C5, D3, G3, L3, L4, M3, M5, P1, S4, T1, U1, U2
5.	Colorado	Nayarit	350	B1, F1, U2
6.	Cuitzeo	Michoacán	42000	A3, B1, B2, B3, B6, C1, C3, D1, H1, L3, M3, M5, S6, T1, U1, U2
7.	Pátzcuaro	Michoacán	9000	A3, B1, B2, B4, B6, C2, C4, D2, D4, J1, M1, M3, M5, O1, S1, U1
8.	San Juanico	Michoacán	300	A2, B1, M5
9.	San Marcos	Jalisco	4060	B1, F1, U2
10.	San Pedro	Nayarit	400	B1, U2
11.	Sta Magdalena	Jalisco	14340 (100)	F1, G1, S2, T1
12.	Santa Maria	Nayarit	260	B1, F1, U2
13.	Xochimilco	México	4600 (canals)	A1, A4, B1, B2, L1, M3, M6, S7, T1, U1
14.	Yuriria	Guanajuato	5580	B1, B2, H1, M3, U2
15.	Zacapu	Michoacán	1500 (50)	M2, T1, U1, U2
16.	Zacoalco	Jalisco	1000	B1, B2, F1, U2
17.	Zapotlán	Jalisco	940	F1, H1, R1, U2
18.	Zirahuén	Michoacán	1050	A3, B1, B5, B6, D1, D4, G2, H1, M5, U1, U2
19.	Zumpango	México	1360	A4, B1, H1, M3

mon in all lakes, but rarely dominated total biomass. Every lake had a fishery, and the primary target species invariably included a relatively large-sized species (> 150 mm standard length), although in some lakes smaller-sized *Chirostoma* species were also important (e.g., Lyons et al., 1998). Obvious disease appeared to be uncommon, and parasite burdens were typically low, with only native parasite species present (Salgado & Osorio-Sarabia, 1987).

Patterns of degradation in four lakes

Many of the study lakes have experienced major changes in their fish faunas over the last 100 years. Case histories of four well-documented faunas illustrate the impacts of environmental degradation.

Xochimilco, located near Mexico City, is among the best-known but most degraded of all Mexican lakes (Stephan-Otto, 1995). It was a major source of fish, wildlife, and agricultural products for the great pre-Columbian civilizations of the Valley of México, including the Aztecs (Serra-Puche, 1990). The lake was shallow, and its surface area fluctuated dramatically in response to climatic variations. Long before the Spanish arrived, indigenous cultures had modified the hydrology of the lake to minimize flooding and to protect their highly developed "chinampa" or "floating garden" method of agriculture from incursions of saline water from nearby Lago de Texcoco (Alocer-Durand & Escobar-Briones, 1991). However, despite these modifications the fish community was relatively diverse and supported an important fishery (Alvarez & Navarro, 1957; Serra-Puche, 1990).

After the Spanish conquest, hydrologic modifications were increased, and by the early 1900s Xochimilco lake had been largely drained (Tamayo & West, 1964; Alocer-Duran & Escobar-Briones, 1991).

Table 2. Fish species found in study lakes, with origin, feeding, and tolerance classifications, maximum known standard length (SL) from central Mexico, and sources of information (codes refer to References section except U1, which refers to our unpublished data). Taxonomy follows Mayden et al. (1992), except for Goodeidae, which follows Webb (1998)

Species	Origin	Feeding	Tolerance	Maximum SL (mm)	Source
Petromyzontidae					
Lampetra spadicea Bean	Native	Carnivore (Parasite)	Sensitive	308	L3, L6, U1
Cyprinidae					
Algansea lacustris Steindachner	Native	Carnivore?	Moderate?	270	B2, D2
Algansea popoche (Jordan & Snyder)	Native	Herb/Omnivore	Sensitive	285	B2, L4, M3
Algansea tincella (Valenciennes)	Native	Omnivore	Moderate	175	B2, D4, L6
Aztecula sallei (Günther)	Native	Herbivore?	Moderate	83	A4, D4, L1
Carassius auratus (Linnaeus)	Exotic	Omnivore	Tolerant	212	G3, L2
Ctenopharyngodon idella (Valenciennes)	Exotic	Herbivore	Moderate	1000?	L2
Cyprinus carpio Linnaeus	Exotic	Omnivore	Tolerant	1000	G3, L6, U1
Evarra bustamantei Navarro	Native	Carnivore?	Sensitive	67	A4, M3
Evarra eigenmanni Woolman	Native	Carnivore?	Sensitive	80	A4, M3
Evarra tlahuacensis Meek	Native	Carnivore?	Sensitive	59	A4, M3
Hybopsis calientis (Jordan & Snyder)	Native	Carnivore	Moderate	75	L6, M2, U1
Yuriria alta (Jordan)	Native	Omnivore	Tolerant	177	D4, M2, S4, U1
Yuriria chapalae (Jordan & Snyder)	Native	Carnivore	Sensitive?	250	M3
Catostomidae					
Scartomyzon austrinus (Bean)	Native	Carnivore	Sensitive	350	M3, L5, L6, U1
Ictaluridae					
Ictalurus dugesi (Bean)	Native	Carnivore	Moderate	1050	D3, G3, L6
Ictalurus punctatus (Rafinesque)	Exotic	Carnivore	Moderate	600	L2, U1
Salmonidae					
Oncorhynchus mykiss (Walbaum)	Exotic	Carnivore	Sensitive	350	L2, U1
Atherinidae					
Chirostoma aculeatum Barbour	Native	Carnivore	Moderate?	140	B1, D4
Chirostoma arge (Jordan & Snyder)	Native	Carnivore	Moderate	65	B1, D4, M2
Chirostoma attenuatum Meek	Native	Carnivore	Moderate?	98	B1, D2, L4
Chirostoma chapalae Jordan & Snyder	Native	Carnivore	Tolerant?	87	B1, E1, L4, U1
Chirostoma charari (de Buen)	Native	Carnivore	Sensitive	65	B1, A3, S6
Chirostoma compressum de Buen	Native	Carnivore	Sensitive	101	B1, A3, S6
Chirostoma consocium Jordan & Hubbs	Native	Carnivore	Tolerant	125	B1, L4, U1
Chirostoma estor Jordan	Native	Carnivore	Moderate?	335	B1, C4, D2, S1
Chirostoma grandocule (Steindachner)	Native	Carnivore	Moderate?	170	B1, D2, L4
Chirostoma humboldtianum (Valenciennes)	Native	Carnivore	Sensitive?	233	B1, D4, L4, M2
Chirostoma jordani Woolman	Native	Carnivore	Tolerant	91	B1, D4, N1
Chirostoma labarcae Meek	Native	Carnivore	Moderate?	85	B1, D4, M2
Chirostoma lucius Boulenger	Native	Carnivore	Sensitive?	300	B1, L4
Chirostoma melanoccus Alvarez	Native	Carnivore	Sensitive?	63	A2, B1
Chirostoma patzcuaro Meek	Native	Carnivore	Moderate?	170	B1, D2, L4
Chirostoma promelas Jordan & Snyder	Native	Carnivore	Sensitive	165	B1, L6
Chirostoma sphyraena Boulenger	Native	Carnivore	Sensitive?	203	B1, L4

Continued on p. 63

Table 2. Continued

Species	Origin	Feeding	Tolerance	Maximum SL (mm)	Source
Poeciliidae					
Poecilia butleri Jordan	Native	Herbivore?	Tolerant	80	L5, L6, W2
Poecilia reticulata (Bloch & Schneider)	Exotic	Omnivore	Tolerant	50	L6, W1
Poeciliopsis infans (Woolman)	Native	Herb/Omnivore	Tolerant	50	L6, M2, W2
Poeciliopsis viriosa Miller	Native	Herb/Omnivore	Moderate?	35	M9
Goodeidae					
Alloophorus robustus (Bean)	Native	Carnivore	Moderate	200	H1, L6, S3
Allotoca diazi (Meek)	Native	Carnivore	Moderate	120	L4, M3, S6, W2
Allotoca dugesi (Bean)	Native	Carnivore	Sensitive	63	L4, S5, S6, U1
Allotoca maculata Smith & Miller	Native	Carnivore?	Moderate?	36	S2
Allotoca meeki (Alvarez)	Native	Carnivore?	Moderate?	90	S4, W1, W2
Chapalichthys encaustus (Jordan & Snyder)	Native	Herb/Omnivore	Tolerant?	80	D4, H1, W1, W2
Girardinichthys viviparus (Bustamante)	Native	Carnivore	Sensitive	67	A4, M3
Goodea atripinnis Jordan	Native	Omnivore	Tolerant	185	A2, A3, L6, W1
Hubbsina turneri de Buen	Native	Carnivore	Sensitive	65	B3, U1
Skiffia bilineata (Bean)	Native	Herb/Omnivore	Sensitive	50	L4, S4, S6, W1
Skiffia lermae Meek	Native	Herb/Omnivore	Sensitive	55	L4, D2, S4, W1
Skiffia multipunctata (Pellegrin)	Native	Herb/Omnivore	Sensitive	60	L6, W2
Xenotichthys eiseni (Rutter)	Native	Herb/Omnivore	Moderate	85	F1, U1, W1
Xenotichthys melanosoma (Fitzsimons)	Native	Carnivore	Sensitive?	75	F1, U1, W1
Xenotoca variata (Bean)	Native	Omnivore	Tolerant	83	F1, D4, M2, S4
Zoogonecticus quitzeoensis (Bean)	Native	Omnivore	Moderate?	50	L6, M2, U1
Centrarchidae					
Lepomis macrochirus Rafinesque	Exotic	Carnivore	Moderate	175	L2, L6, U1
Micropterus salmoides Lacèpede	Exotic	Carnivore	Moderate	500	L2, U1
Cichlidae					
Oreochromis aureus (Steindachner)	Exotic	Omnivore	Tolerant	350	G3, L5, L6, U1
Oreochromis mossambicus (Peters)	Exotic	Omnivore	Tolerant	300	D4, U1
Oreochromis niloticus (Linneaus)	Exotic	Omnivore	Tolerant	300	M2, U1
Tilapia rendalli (Boulenger)	Exotic	Omnivore	Moderate	250	B4, L5, L6, U1
Tilapia zilli (Gervais)	Exotic	Omnivore	Moderate	250	L5, L6, M5, U1

What remained was a system of canals with occasional wider pools. Large volumes of raw sewage and industrial wastes began to be discharged into these canals. Exotic species became established and achieved nuisance levels. Despite this, the lake remained an important recreational destination for boating among the canals, and the surviving chinampas continued to produce crops.

However, by the 1980s, Xochimilco had reached a crisis point (Stephan-Otto, 1995). Recreational use was declining because of the pollution. Chinampa agriculture had nearly disappeared because of increasingly saline water and encroaching urban development. In response, the Mexican government began a major restoration of the lake. Sewage and industrial discharges were diverted or treated, and the canals and associated chinampas were rehabilitated. Regular monitoring of lake conditions began. Consequently, water and habitat quality have improved, but they still are much worse than before 1900.

Changes in the fish community over the last 100 years parallel the environmental changes in the lake

Table 3. Expected values in the absence of major human degradation for selected metrics for each of the study lakes

Lake	Total native species	Common native species	Native Goodeidae species	Native *Chirostoma* species	Native sensitive species	Maximum standard length (mm)
Atotonilco	6	5	3	1	1	185
Cajititlan	9	3	6	1	3	200
Chalco	7	4	1	2	4	233
Chapala	26	9	9	9	11	1050
Colorado	6	3	3	1	1	185
Cuitzeo	15	5	9	2	6	308
Pátzcuaro	10	6	5	4	2	335
San Juanico	7	3	3	2	1	200
San Marcus	5	3	3	1	1	185
San Pedro	3	3	1	1	1	233
Sta Magdalena	7	5	3	2	2	233
Santa María	4	3	2	1	1	233
Xochimilco	6	3	1	2	4	233
Yuriria	12	5	6	2	3	700
Zacapu	9	3	6	1	3	233
Zacoalco	6	3	3	1	1	185
Zapotlán	4	3	2	0	1	185
Zirahuén	7	3	5	2	2	275
Zumpango	4	3	1	1	1	175

(Meek, 1904; Alvarez & Navarro, 1957; Stephan-Otto, 1995). Before 1900, Xochimilco had 6 native species, 4 of which were sensitive carnivores (Table 3). An important fishery existed. As the lake shrunk in size and became more polluted, 4 native species disappeared, 2 of which, *Evarra bustamantei* and *E. eigenmanni*, are now extinct (Miller et al., 1989). Of the 2 surviving species, *Chirostoma jordani*, a small, tolerant carnivore, declined from high to moderate abundance, and *Girardnichthys viviparus*, a small, sensitive carnivore, went from high to very low abundance. The fishery became dominated by a large, tolerant omnivorous exotic, *Cyprinus carpio*. However, soon this species was too contaminated for safe human consumption, and the fishery collapsed (Stephan-Otto, 1995). Despite recent restoration efforts, the fish fauna of Xochimilco continues to be dominated by *C. carpio*.

Cuitzeo, near the city of Morelia, is a large, shallow lake that, similar to Xochimilco, fluctuated greatly in surface area in response to climate variation (Bernal-Brooks, 1998). Like Xochimilco, Cuitzeo has also suffered extreme environmental degradation. Major hydrological modifications, including a large drainage canal, began in Cuitzeo in the late 1800s (Tamayo & West, 1964). These modifications mainly served to reduce the maximum extent of the lake during wet periods. However, a temporary diversion of the lake's major tributary, the Río Grande de Morelia, to fill a newly constructed reservoir during a particularly dry period led to the near complete desiccation of the lake during the winter of 1941 (De Buen, 1943). In more recent years, continued tributary diversions and groundwater pumping along with massive sedimenation from the lake's watershed appear to have permanently reduced the median size of the lake (Ceballos-Corona et al., 1994; Chacón-Torres & Alvarado-Díaz, 1995), although this conclusion has been questioned (Bernal-Brooks, 1998).

Without question, however, water quality in Cuitzeo has deteriorated dramatically (Alvarado et al., 1985;, Ceballos-Corona et al., 1994; Chacón-Torres & Alvarado-Díaz, 1995). As the city of Morelia has grown, increasing amounts of untreated municipal sewage and industrial pollutants have been discharged to the Río Grande de Morelia and hence to the lake. Coupled with major watershed soil erosion, these discharges have made the lake hypereutrophic, with ex-

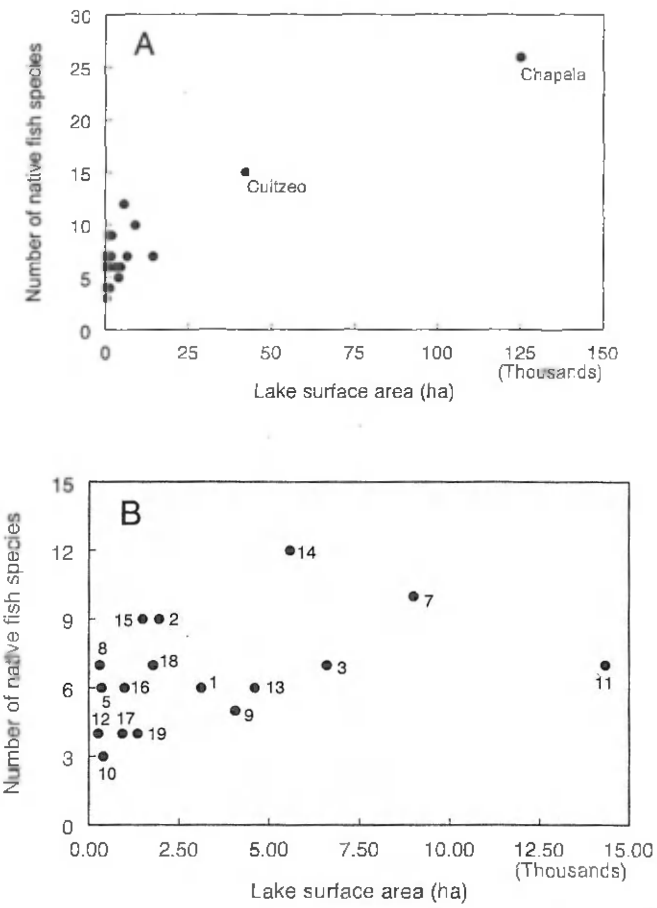

Figure 2. Relation between historical lake surface area and number of native fish species. (a) All 19 lakes. (b) Two largest lakes, Chapala and Cuitzeo, excluded; numbers refer to lake names from Table 1.

treme turbidity and phosphorus concentrations. Phytoplankton biomass has dramatically increased, and the community is now dominated by *Oscillatora*, a nuisance form. Major diel dissolved oxygen swings occur, with night levels sometimes below 1 mg l^{-1}.

The fish community of Cuitzeo has declined precipitously in response to water quality problems, particularly over the last 20 years (Chacón et al., 1995; Soto-Galera et al., 1999). Historically, 15 native species occurred in the lake, including 6 sensitive species and 6 carnivores (Table 3). There was a major fishery for many of these species. By about 1970, at least two sensitive species had disappeared, *Lampetra spadicea* (Lyons et al., 1994) and an endemic, *Chirostoma compressum* (Barbour, 1973b), and several other species had become uncommon (Chacón-Torres & Alvarado-Díaz, 1995). During the 1970s and 1980s the declines accelerated, and by the early 1990s only 4 native species persisted, 3 of which were tolerant (Soto-Galera et al., 1999). One small, sensitive herb/omnivore, *Skiffia bilineata*, remained, but it had gone from high to very low abundance, and it survived only in refugia where relatively high-quality spring systems discharged to the lake. Samples from the late 1990s suggest that this species may have now entirely disappeared from the lake, although it persisted in one small tributary stream (Omar Domínguez-Domínguez, Univeridad Michoacana de San Nícolas de Hidalgo, Morelia, unpublished data). Two exotic omnivores, *Cyprinus carpio* and *Oreochromis aureus* became established in the 1970s, and by 1989 comprised 79% of the biomass of the fishery (Ceballos-Corona et al., 1994). Exotic invertebrate parasites from these two species infested the remaining native fishes (Pineda-López, unpublished data). Major fish kills of both native and extoic fishes became common during periods of low dissolved oxygen concentrations.

Chapala is the largest natural lake in México. It too is shallow and subject to fluctuations in surface area with climate variation. It has been heavily impacted by human activities over the last 100 years, but not quite to the same degree as Cuitzeo and Xochimilco. Hydrological modifications in Chapala began in dramatic fashion in 1905, with the completion of a dike and water diversion/pumping system that permanently eliminated 35 000 ha of the marshy east end of the lake (Goldman, 1951). Subsequent construction of reservoirs and water diversions in the Río Lerma, the major tributary of the lake, exacerbated shrinkages in lake size during dry periods, to the extent that a drought in 1990 led to a 21% decline in surface area and 69% decline in volume compared to median values (Guzmán-Arroyo, 1995). Reduced water levels led to major sediment resuspension, increased turbidity, and changes in phytoplankton and zooplankton communities (Límon-Macías & Lind, 1990). Water quality in the lake was further compromised by increased pollutant inputs from the Río Lerma and nuisance-level outbreaks of the exotic floating plant *Eichornia crassipes* (Guzmán-Arroyo, 1995; Lyons et al., 1998).

The fish community of Chapala has also changed over the last 100 years. Historically, 26 species were know from the lake, including 11 sensitive species and 15 carnivores (Table 3). The Chapala fishery was one of the largest and most important in the country (Guzmán-Arroyo, 1995). No comprehensive survey of the fish fauna of the entire lake has been done in recent years, but the near elimination of two species, *Lampetra spadicea* and *Algansea popoche*, is well documented (Lyons et al., 1994, 1998). Sampling near the town of Chapala indicates that the near-shore assemblage, which historically yielded 12 or more native species, now typically produces 6 tolerant native species and 3 exotics. The fishery has overexploited 4 high-value species, *Ictalurus dugesi*, *Chirostoma lucius*, *C. promelas*, and *C. sphyraena*, and their abundance and size-structure has declined sharply (Lyons et al., 1998). The fishery formerly captured specimens of *I. dugesi* that exceeded 1000 mm standard length; now the maximum size rarely exceeds 500 mm (Guzmán-Arroyo, 1995). The fishery still produces large yields, but they are dominated by a small, tolerant, carnivorous, native species, *Chirostoma consocium*, and two large, tolerant, omnivorous exotics, *C. carpio* and *Oreochromis aureus* (Lyons et al., 1998). With the exotic fishes came exotic invertebrate parasties that infected the native species (Pineda-López, unpublished data).

Pátzcuaro differs from the other three lakes in being moderately deep, with a historical maximum of at least 15 m, and having a stable surface area (De Buen, 1944). The primary source of environmental degradation in this lake has been from watershed erosion and consequent increased turbidity, nutrient enrichment, and sedimentation (Chacón-Torres, 1993; Orbe-Mendoza & Acevedo-G., 1995). Erosion and sedimentation problems began more than 500 years ago (O'Hara et al., 1993), but have reached unprecedented levels in the last 50 years. Since the 1940's (De Buen, 1944) the depth of several subbasins within the lake have decreased by more than 2 m, bays that were once open water are now full of dense growths of rooted aquatic plants and are better characterized as marsh, and several former islands are now part of the shoreline (Orbe-Mendoza & Acevedo-G., 1995). The lake, once considered oligo-mesoptrophic, is now meso-eutrophic, with a strong south to north gradient of increasing productivity (Chacón-Torres, 1993). Secchi disk readings have declined from 3–4 m to 0.2–0.5 m (Orbe-Mendoza & Acevedo-G., 1995).

With these environmental stresses, the fish community of Pátzcuaro has changed. Historically, the lake supported 10 native species, including 2 sensitive species and 8 carnivores (Table 3). The fishery was large and nationally famous, focusing on the "pescado blanco" (whitefish) *Chirostoma estor* (Martin del Campo, 1940; De Buen, 1944). Since the 1930s, two sensitive species, the carnivore *Allotoca dugesi* and the herb/omnivore *Skiffia lermae*, have gone from moderate to low abundance (Berlanga-Robles et al., 1998; Shane Webb, Universidad Nacional Autónoma de México, México, D.F., personal communication). The declines in these two species have been attributed to an exotic predator, *Micropterus salmoides*, but evidence is circumstantial (De Buen, 1944; Berlanga-Robles et al., 1998). Pescado blanco have also declined in abundance and maximum size, from overfishing and possibly predation from *M. salmoides*, and the fishery is threatened with collapse (Salgado & Osorio-Sarabia, 1987; Chacón-Torres & Rosas-Monge, 1995; Orbe-Mendoza et al., 1995). The remaining native fishes remain common, but long-term trends in abundance are unclear (Jiménez-Badillo & Gracia-G., 1995; Berlanga-Robles et al., 1998). Two exotics, *C. carpio* and *Oreochromis niloticus*, have become important in the fishery, but do not dominate. One exotic invertebrate parasite has been reported from native fishes (Salgado & Osorio-Sarabia, 1987).

A preliminary index of biotic integrity

Based on our analyses and review of previously developed IBIs, we chose 10 metrics that we felt best represented historical fish community characteristics of the 19 study lakes and the patterns of decline in Xochimilco, Cuitzeo, Chapala, and Pátzcuaro. Preliminary scoring criteria are given in Table 4, and the metrics are described below.

(1) Number of Total Native Species – This metric is used in nearly all versions of the IBI, and reflects the general loss of species diversity with increasing environmental degradation (Fausch et al., 1990; Simon & Lyons, 1995). In our dataset species number was positively correlated with area, but the relationship was not particularly tight for lakes less than 15 000 ha, so lake-specific scoring criteria were established. We developed these expectations (Table 3) from a combination of scientific survey and fishery catch data.

(2) Number of Common Native Species – This metric is unique to our study, and reflects the decrease in abundance of many common species at low to moderate levels of degradation. The number of common species was a function of lake size, and we adopted lake-specific scoring criteria for this metric. We developed these expectations (Table 3) from a combination of scientific survey and fishery catch data.

(3) Number of Native Goodeidae Species – Goodeids were a ubiquitous and speciose component of the fish fauna in our lakes. They tended to occupy near-shore areas, and we believe that their species richness was an indicator of the quality of littoral-zone habitats. The number of goodeid species was weakly related to lake size, but we nonetheless es-

Table 4. Preliminary metrics and scoring criteria for an index of biotic integrity for lakes of central México. "EV" is the lake-specific "Expected Value" for that metric in the absence of major human degradation (see Table 3)

	Metric	Scoring criteria		
		Poor (0 points)	Fair (5 points)	Good (10 points)
1.	Number of total native species	< 50% of EV	50–74% of EV	> 74% of EV
2.	Number of common native species	< 66% of EV	66–79% of EV	> 79% of EV
3.	Number of native Goodeidae species	< 60% of EV	60–84% of EV	> 84% of EV
4.	Number of native *Chirostoma* species	< 60% of EV	60–84% of EV	> 84% of EV
5.	Number of native sensitive species	< 40% of EV	40–84% of EV	> 84% of EV
6.	Percent of biomass as tolerant species	> 90%	90–50%	< 50%
7.	Percent of biomass as exotic species	> 85%	85–50%	< 50%
8.	Percent of biomass as native carnivores	< 5%	5–20%	> 20%
9.	Maximum standard length of native species	< 50% of EV	50–74% of EV	> 74% of EV
10.	Percent exotic parasite species in/on native fishes	> 60%	60–25%	< 25%

tablished lake-specific scoring criteria for this metric. We developed these expectations (Table 3) primarily from scientific survey data, as goodeids were usually a minor component of the fishery in most lakes.

(4) Number of Native *Chirostoma* Species – *Chirostoma* species were also ubiquitous and speciose in our lakes. They were more likely to occupy offshore areas, and we used their species richness as an indicator of conditions in the pelagic zone. The number of *Chirostoma* species was also related to lake area, and we developed lake-specific criteria for this metric. We developed these expectations (Table 3) from a combination of scientific survey and fishery catch data.

(5) Number of Sensitive Species – This metric is nearly universal in existing IBIs (Simon & Lyons, 1995), and reflects the loss of those species most intolerant of human impacts at the early stages of environmental degradation. In our study, the number of sensitive species was positively correlated with lake area, so we developed lake-specific metric scoring criteria. We developed these expectations (Table 3) from a combination of scientific survey and fishery catch data.

(6) Percent of Biomass as Tolerant Species – Most IBIs use some measure of the relative dominance of tolerant species to assess moderate to high levels of degradation (Simon & Lyons, 1995). Percent by number has been more commonly used than biomass, but Minns et al. (1994) argued persuasively that biomass was a better indicator when there were large differences in the relative size of species, as was the case for our lakes. We established the same scoring criteria for all lakes for this metric, and developed these criteria from fishery data, which were always reported by biomass rather than number.

(7) Percent of Biomass as Exotic Species – Ecosystems with inherently low to moderate species richness, such as our lakes, appear to be especially vulnerable to impacts from exotics, and exotics tend to dominate these systems under highly degraded conditions (Karr, 1991; Simon & Lyons, 1995; Lyons et al., 1995). Again, we followed Minns et al. (1994) and used biomass rather than number. We established the

Table 5. Scores and values (in parentheses) for the 10 metrics from the four case-history lakes

Metric	Lake metric score and value			
	Xochimilco	Cuitzeo	Chapala	Pátzcuaro
Native species	0 (33%)	0 (20%)	5 (50%?)	10 (100%)
Common native species	0 (0%)	0 (60%)	0 (56%)	5 (67%)
Native Goodeidae species	10 (100%)	0 (22%)	0 (44%)	10 (100%)
Naitve *Chirostoma* species	0 (50%)	0 (50%)	5 (67%)	10 (100%)
Native sensitive species	0 (25%)	0 (0%)	0 (36%)	10 (100%)
Biomass as tolerant species	0 (99%)	0 (99%)	0 (95%)	10 (40%)
Biomass as exotic species	0 (99%)	5 (80%)	5 (60%)	10 (45%)
Biomass as native carnivores	5 (5%)	5 (20%)	10 (40%)	10 (50%)
Maximum standard length	0 (40%)	5 (50%)	5 (50%)	5 (72%)
Percent exotic parasites	0? (67%?)	0 (67%)	0 (67%)	10 (20%)
Total score	15	15	30	90

same scoring criteria for all lakes for this metric, and developed these criteria from fishery data.

(8) Percent of Biomass as Native Carnivores – A trophic group metric that focuses on carnivores is a common component of many IBIs (Simon & Lyons, 1995). In our study, carnivores declined at moderate to severe levels of degradation. We established the same scoring criteria for all lakes for this metric, and developed these criteria from fishery data.

(9) Maximum Standard Length of Native Species – This metric is unique to our study, but is similar to a size and age distribution metric suggested for lakes in the United States (Simon and Lyons, 1995). It reflects the combined effects of overfishing and environmental degradation on the longevity and maximum size of large-bodied species, and appears to be most responsive to low to moderate levels of human impact. Because the largest species differed among lakes, we developed lake-specific scoring criteria (Table 3) from fishery data.

(10) Percent of Exotic Invertebrate Parasite Species in or on Native Fish Species – Most versions of the IBI have a metric that deals with disease, deformities, or parasitism (Simon & Lyons, 1995). Fish parasites have been suggested as a particularly sensitive indicator of environmental stress in aquatic systems (Landsberg et al., 1998). Obvious disease and deformities were apparently rare even in our most degraded lakes, but internal and external invertebrate parasites were common. In highly degraded lakes most of the parasite species encountered were exotics, whereas native parasite species dominated in relatively undegraded lakes (Pineda-López, unpublished data). Exotic parasite incidence should be most sensitive to moderate levels of degradation. Our metric was the ratio of the mean number of exotic parasite species per individual native fish to the mean number of all parasite species (native plus exotic) per individual native fish, and was based on a sample of 15–30 parasitized individuals from at least two different native fishes. We established the same scoring criteria for all lakes for this metric, based on scientific survey data.

With the metrics and criteria from Table 4, it was possible to calculate an IBI score for Xochimilco, Cuitzeo, Chapala, and Pátzcuaro. Out of 100 possible points, Xochimilco and Cuitzeo had 15 each, Chapala had 30, and Pátzcuaro had 90 (Table 5). This ranking corresponds exactly with our a priori ranking of these lakes based on degree of environmental degradation.

Discussion

Our preliminary IBI for the lakes of central México is a benchmark against which to judge lake ecosystem condition. The IBI can be used to determine objectively the relative degree of ecosystem damage a lake has suffered and to evaluate the success of restoration efforts. In developing the IBI, we have established both a succinct summary of how the fish communities in these lakes should look in the absence of major human impacts and a model of how the communites will change when impacts occur.

The only other existing IBI for México, developed for streams and rivers in west-central México, has very different data collection procedures, metrics, and scoring criteria from the lake IBI presented here, reflecting the substantial differences between lentic and lotic fish communities in central México (Lyons et al., 1995). The two IBIs are not interchangeable. However, the final IBI score and "rating" (i.e, good, fair, poor) of each IBI have essential the same scale and are analagous measures of ecosystem condition. Scores from the two IBIs can be compared to assess relative levels of environmental degradation between rivers and lakes and to prioritize restoration efforts across different types of aquatic ecosystems.

The initial application of the lake IBI was successful. Rankings based on IBI scores for Xochimilco, Cuitzeo, Chapala, and Pátzcuaro matched rankings based on the type and degree of environmental degradation. However, this was not a definitive test of the index, as the same data from the four lakes were used in the development and in the application of the IBI. The next step in assessing the utility of the new IBI must be an independent test with data from lakes not included in this study (Lyons et al., 1995).

Undoubtedly, our IBI can be improved. The assignment of many species to tolerance and feeding groups was based on very limited data. With more information on the ecology and life history of these species, their designations may change. Additional diet information might also allow for establishment of more precise feeding categories and more sensitive metric criteria.

At present, our version of the IBI can only be applied to lakes that have sufficient historical data to characterize their fish community before major human impacts had taken place. This restricts use of the index to a limited number of well-studied lakes, which are generally large and easily accessible. A more broadly applicable IBI might be developed based on data from a series of representative "least-impacted" reference lakes with relatively little environmental degradation (Hughes, 1995). The larger lakes in this study, such as Chapala, Cutizeo, or Pátzcuaro, are unique in so many ways that no comparable reference lakes exist. However, among the more numerous smaller lakes of central México, it might be possible to find a sufficient number of least-impacted reference waters. Data from these lakes could be used to generate more generic metric expectations and scoring criteria. The development of such expectations would have to take into account inherent differences among fish faunas owing to such factors as lake size, water chemistry, habitat complexity, and isolation (Jennings et al., 1998; Whittier, 1998). A classification system that accounted for the major sources of variation among the fish faunas of Mexican lakes would be of great benefit to continued IBI development.

In some small Mexican lakes, the application of a solely fish-based IBI will be impractical because of the inherently low numbers of fish species present. Many isolated, high-altitude lakes in central México are naturally fishless or have only one or two native species. For these lakes, use of organisms other than fish is warranted to indicate lake ecosystem condition. Harig & Bain (1998) developed and applied successfully an IBI for small mountain lakes in the northeastern United States that had few fish species. Their index included metrics based on fish, benthic invertebrates, zooplankton, and phytoplankton.

The sampling protocol used to generate the present-day fish community data for IBI application is another area where additional work and refinement are needed. We used a combination of scientific survey and fishery assessment data, and tried to establish metric scoring criteria that were relatively insensitive to the way in which the data were gathered. In all other existing lake IBI applications, fish community data have been derived solely from a scientific survey, but there has been no consensus as to how the survey should be carried out (Simon & Lyons, 1995; Jennings et al, 1998; McDonough & Hickman, 1998; Thoma, 1998; Whittier, 1998). Relying solely on scientific surveys is impractical in many instances in México, given staff, funding, and equipment limitations (Lyons et al., 1998). For most Mexican lakes, fishery surveys provide a more efficient way to characterize many aspects of the fish community. Essentially every lake in central México has some sort of subsistence or commercial fishery, and in our experience the fishermen are usually willing to cooperate (e.g., Lyons, et al., 1994). In lakes with large fisheries, such as Chapala, Cuitzeo, and Pátzcuaro, data are already being collected by the Mexican government. Certainly, however, some scientific sampling is needed to supplement the fishery survey and to document the abundance of small species that are not targeted by fishermen. Development of a set of specific guidelines for how to conduct this sampling in a cost-effective and standardized manner would greatly improve the application of the IBI to Mexican lakes.

Our IBI is probably best suited to assessing and monitoring major long-term trends in ecosystem health rather than subtle or short-term changes. In streams and small lakes it is often possible to characterize the fish community in no more than a few days, allowing for the close tracking of biotic integrity. However, the large size and ecological complexity of many central Mexican lakes makes rapid assessment of the fish community unfeasible, and the quality of the fishery data used in metric calculation probably improves when integrated over periods of months or years. Our IBI is somewhat analagous to an IBI recently developed for central California, USA, which uses community attributes collected over multiple years and locations to assess the overall ecosystem quality of an entire watershed (Moyle & Randall, 1998).

Acknowledgements

We are especially grateful to Doug Nelson, Fish Collection Manager, for data on holdings in the Musuem of Zoology, University of Michigan, and to Maria de Lourdes Aguirre-Jones and other staff of the Parque Ecológico de Xochimilco, for literature and information on Lago de Xochimilco. We also thank Omar Domínguez-Domínguez, Univeridad Michoacana de San Nícolas de Hidalgo, Morelia, and Dr. Shane Webb Universidad Nacional Autónoma de México, México D.F., for providing helpful data on their recent fish collections from several lakes.

References

Alcocer-Durand, J. & E. G. Escobar-Briones, 1991. The aquatic biota of the now extinct lacustrine complex of the Mexico basin. Freshw. biol. Assoc. 2(3): 171–183.(A1)

Alvarado, D. J., T. Zubieta, R. Ortega, A. Chacón & R. Espinosa, 1985. Hipertroficación en un lago tropical somero (Lago de Cuitzeo, Michoacán, México). Bol. Dept Biol.. Esc. Biol., Univ. Michoacana de San Nícolas de Hidalgo, Morelia, México. 1: 19–33.

Alvarez, J., 1963. Ictiología michoacana. III. Los peces de San Juanico y de Tocumbo, Mich. Anal. Esc. nac. Cien. biol., Inst. nac. politécnico, México D.F. 12: 111–138.(A2)

Alvarez, J. & M. T. Cortes, 1962. Ictiología michoacana. I.–Claves y catálogo de las especies conocidas. Anal. Esc. nac. Cien. biol., Inst. nac. politécnico, México D.F. 11: 86–142.(A3)

Alvarez, J. & L. Navarro, 1957. Los Peces del Valle de México. Dir. Secreteriat Mar., Pesca e Indust. Conexas, México, D.F., 62 pp.(A4)

Barbour, C. D. 1973a. A biogeographical history of *Chirostoma* (Pisces: Atherinidae): a species flock from the Mexican plateau. Copeia 1973: 533–556.

Barbour, C. D.. 1973b. The systematics and evolution of the genus *Chirostoma* Swainson (Pisces, Atherinidae). Tulane Stud. Zool. Bot. 18: 93–141.(B1)

Barbour, C. D. & R. R. Miller, 1978. A revision of the Mexican cyprinid fish genus *Algansea*. Univ. Michigan Mus. Zool., Misc. Pub. 155: 1–72.(B2)

Barragán-Severo, J., 1993. Peces dulceacuícolas mexicanos VII. *Hubbsina turneri* (Cyprinodontiformes: Goodeidae). Zool. Informa (Esc. nac. Cien. biol., Inst. nac. politécnico, México D.F.) 25: 3–11.(B3)

Berlanga-Robles, C. A., A Ruiz-Luna, M. R. Nepta-Villanueva & J. Madrid-Vera, 1998. Estabilidad y diversidad de la composición de peces del lago de Pátzcuaro, Michoacán, México. Rev. Biol. trop. 45: 1553–1558.(B4)

Bernal-Brooks, F., 1995. El lago de Zirahuén. In De La Lanza-Espino, G. & J. L. García-Calderón (eds), Lagos y Presas de México. Cen. Ecol. Desarrollo, A.C., México D.F., 109–116.(B5)

Bernal-Brooks, F. W., 1998. The lakes of Michoacán (Mexico): a brief history and alternative points of view. Freshwat. biol. Assoc. 10: 20–34.(B6)

Ceballos-Corona, J. G. A., M. R. Ortega-Murillo, M. Medina-Nava, M. Martínez-Trujillo, L. Rodríguez-Jiménez & S. González-Santoyo, 1994. Analisis limnológico del lago de Cuitzeo, Michoacán, México. Secretaría Difusión cult., Edit. univ., Univ. Michoacana de San Nícolas de Hidalgo, Morelia, México. 45 pp.(C1)

Chacón-Torres, A., 1993. Lake Pátzcuaro, México: watershed and water quality deterioration in a tropical high-altitude Latin American lake. Lake reserv. Manage. 8(1): 37–47.(C2)

Chacón-Torres, A. & J. Alvarado-Díaz, 1995. El lago de Cuitzeo. In: De La Lanza-Espino, G. & J. L. García-Calderón (eds), Lagos y Presas de México. Cen. Ecol. Desarrollo, A.C., México D.F., 117–128.(C3)

Chacón-Torres, A. & C. Rosas-Monge, 1995. A restoration plan for pez blanco in Lake Pátzcuaro. Mexico. Am. fish. Soc. Symp. 15: 122–126.(C4)

Cuesta-Terrón, C., 1925. La fauna ictiológica y malacológica comestible del lago de Chapala, Jal., y su pesca. Mem. Rev. Soc. cient. "Antonio Alzate" 44(1–2): 39–67.(C5)

De La Lanza-Espino, G. & J. L. García-Calderón (eds), 1995. Lagos y Presas de México. Cen. Ecol. Desarrollo, A.C., México D.F. 320 pp.

De Buen, F. 1943. Los lagos Michoacanos. I. Caracteres generales. El Lago de Zirahúen. Rev. Soc. mex. His. nat. 4(3–4): 211–232.(D1)

De Buen, F., 1944. Limnobiología de Pátzcuaro. Anal. Inst. Biol., Univ. nac., México D.F. 15: 261–312.(D2)

De Buen, F., 1946. Investigaciones sobre ictiología mexicana III. La ictiofauna del Lago de Chapala con descripción de una nueva especie (*Haustor ochoterenai* De Buen). Anal. Inst. Biol., Univ. nac., México D.F. 17: 261–281.(D3)

Díaz-Pardo, E., M. A. Godínez-Rodríguez, E. L. López-López & E. Soto-Galera, 1993. Ecología de los peces de la cuenca río Lerma, México. Anal. Esc. nac. Ciencias biol., Inst. nac. politécnico, México D.F. 39: 103–127.(D4)

Enríquez, M. A. & J. Paulo-Maya, 1997. Peces dulceacuícolas mexicanas. XV. *Chirostoma chapalae* (Atheriniformes: Atherinidae). Zool. Informa (Esc. nac. Ciencias biol., Inst. nac. politécnico, México D.F.) 35: 13–24.(E1)

Fausch, K. D., J. Lyons, J. R. Karr & P. L. Angermeier, 1990. Fish communities as indicators of environmental degradation. Am. fish. Soc. Symp. 8: 123–144.

Fitzsimons, J. M., 1972. A revision of two genera of goodeid fishes (Cyprinodontiformes, Osteichthys). Copeia 1972: 728–756.(F1)

García-Calderón, J. L. & G. De la Lanza-Espino, 1995. La cuenca de México. In: De La Lanza-Espino, G. & J. L. García-Calderón (eds), Lagos y Presas de México. Cen. Ecol. Desarrollo, A.C., México D.F., 27–50.

Goldman, E. A., 1951. Biological investigations in Mexico. Smithsonian misc. Coll. (Washington D.C.) 115: 1–476.(G1)

Gutiérrez-Hernández, A., E. Díaz-Pardo & A. Chacón-Torres, In press. Patron hidrodinámico del lago de Zirahuen, Michoacán, México. Hidrobiológica.(G2)

Guzmán-Arroyo, M. (ed.), 1995. La Pesca en el Lago de Chapala: Hacia su Ordenamiento y Explotación Racional. Univ. Guadalajara, Com. nac. Agua., 302 pp.(G3)

Harig, A. L. & M. R. Bain, 1998. Defining and restoring biological integrity in wilderness lakes. Ecol. Applications 8: 71–87.

Hubbs, C. L. & C. L. Turner, 1939. Studies of the fishes of the order Cyprinodontes. XVI. A revision of the Goodeidae. Univ. Michigan Mus. Zool., Misc. Pub., 42: 1–80.(H1)

Hughes, R. M., 1995. Defining acceptable biological status by comparing with reference conditions. In Davis, W. S. & T. D. Simon (eds), Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publ., Chelsea, Michigan: 31–47.

Hughes, R. M. & T. Oberdorff, 1998. Applications of IBI concepts and metrics to waters outside the United States. In: Simon, T. D. (eds), Assessing the Sustainability and Biological Intgegrity of Water Resources Using Fish Communities. CRC Press, Boca Raton, Florida: 79–93.

Jennings, M. J., J. Lyons, E. Emmons, G. R. Hatzenbeler, M. Bozek, T. D. Simonson, T. D. Beard, Jr & D. Fago. 1998. Toward the development of an index of biotic integrity for inland lakes in Wisconsin. In: Simon, T. D. (eds), Assessing the Sustainability and Biological Intgegrity of Water Resources Using Fish Communities. CRC Press, Boca Raton, Florida: 541–562.

Jiménez-Badillo, M. de L. & A. Gracia-G., 1995. Evaluación de la pesquería multispecífica de charales (*Chirostoma* spp., Pisces, Atherinidae) del lago de Patzcuaro, Michoacán, México. Anal. Inst. Biol., Univ. nac. autónoma México, Ser. zool. 66: 205–231.(J1)

Karr, J. R., 1981. Assessment of biotic integrity using fish communities. Fisheries 6(6): 21–27.

Karr, J. R., 1987. Biological monitoring and environmental assessment: a conceptual framework. Environ. Manage. 11: 249–256.

Karr, J. R., 1991. Biological integrity: a long-neglected aspect of water resource management. Ecol. Applications 1: 66–84.

Landsburg, J. H., B. A. Blakesley, R. O. Reese, G. McRae & P. R. Forstchen, 1998. Parasites of fishes as indicators of environmental stress. Env. Mon. Assessment, 51: 211–232.

Limón-Macías, J. G. & O. T. Lind, 1990. The management of Lake Chapala (México): considerations after significant changes in the water regime. Lake reserv. Manage. 6: 61–70.

López-López, E. & P. Vallejo de Aquino. 1993. Peces dulceacuícolas mexicanos VIII. *Notropis sallei* (Cypriniformes: Cyprinidae). Zool. Informa (Esc. nac. Ciencias biol., Inst. nac. politécnico, México D.F.) 25: 12–24.(L1)

Lyons, J., 1992. Using the index of biotic integrity (IBI) to measure environmental quality in warmwater streams of Wisconsin. U.S. For. Serv., N. Cen. For. Exp. Stat., St. Paul, Minnesota, Gen. Tech. Rept NC-149. 51 pp.(L2)

Lyons, J., P. A. Cochran, O. J. Polaco & E. Merino-Nambo, 1994. Distribution and abundance of the Mexican lampreys (Petromyzontidae; *Lampetra*, subgenus *Tetrapleurodon*). Southwest. Nat. 39: 105–113.(L3)

Lyons, J., G. González-Hernández, E. Soto-Galera & M. Guzmán-Arroyo, 1998. Decline of fishes and fisheries in selected drainages of west-central Mexico. Fisheries 23(4): 10–18.(L4)

Lyons, J. & S. Navarro-Pérez. 1990. Fishes of the Sierra de Manantlán, west-central México. Southwest. Nat. 35: 32–46.(L5)

Lyons, J., S. Navarro-Pérez, P. A. Cochran, E. Santana C. & M. Guzmán-Arroyo, 1995. Index of biotic integrity based on fish assemblages for the conservation of streams and rivers in west-central Mexico. Cons. Biol. 9: 569–584.(L6)

Martín del Campo, R., 1940. Los vertebrados de Pátzcuaro. Anal. Inst. Biol., Univ. nac., México 11: 481–492.(M1)

Mayden, R. L., B. M. Burr, L. M. Page & R. R. Miller, 1992. The native freshwater fishes of North America. In: Mayden, R. L. (eds), Systematics, Historical Ecology, and North American Freshwater Fishes. Stanford Univ. Press, Palo Alto, California: 827–863.

McDonough, T. A., & G. D. Hickman, 1998. Reservoir fishery assessment index development: a tool for assessing ecological health in Tennessee Valley Authority impoundments. In: Simon, T. D. (eds), Assessing the Sustainability and Biological Intgegrity of Water Resources Using Fish Communities. CRC Press, Boca Raton, Florida: 523–540.

Medina-Nava, M., 1997. Ictiofauna de la subcuenca del río Angulo, cuenca del Lerma-Chapala, Michoacán. Zool. Informa (Esc. nac. Ciencias biol., Inst. nac. politécnico, México D.F.) 35: 25–52.(M2)

Meek, S. E., 1904. The fresh-water fishes of Mexico north of the Isthmus of Tehuantepec. Field Columbian Mus., Chicago, Zool. Ser. 5: 1–252.(M3)

Miller, R. R., 1975. Four new species of viviparous fishes, genus *Poeciliopsis*, from northwestern Mexico. Univ. Michigan Mus. Zool., Occ. Pap., 619: 1–11.(M4)

Miller, R. R. & M. L. Smith, 1986. Origin and geography of the fishes of central Mexico. In: Hocutt, C. H. & E. O. Wiley (eds), The zoogeography of North American freshwater fishes. John Wiley and Sons, New York: 487–518.(M5)

Miller, R. R., J. D. Williams & J. E. Williams. 1989. Extinctions of North American fishes during the past century. Fisheries 14(6): 22–38.(M6)

Minns, C. K., V. W. Cairns, R. G. Randall & J. E. Moore, 1994. An index of biotic integrity for fish assemblages in the littoral zone of Great Lakes' areas of concern. Can. J. Fish. Aquat. Sci. 51: 1804–1822.

Moyle, P. B. & P. J. Randall. 1998. Evaluating the biotic integrity of watersheds in the Sierra Nevada, California. Cons. Biol. 12: 1318–1326.

Navarrete, N. A., R. Sánchez & M. L. Rojas, 1996. Selección del zooplancton por el charal *Chirostoma jordani* (Atheriniformes: Atherinidae). Rev. Biol. trop. 44: 757–761.(N1)

O'Hara, S. L., F. A. Street-Perrott & T. P. Burt, 1993. Accelerated soil erosion around a Mexican highland lake caused by prehispanic agriculture. Nature 362: 48–51.

Orbe-Mendoza, A. & J. Acevedo-G., 1995. El lago de Pátzcuaro. In: De La Lanza-Espino, G. & J. L. García-Calderón (eds), Lagos y Presas de México. Cen. Ecol. Desarrollo, A.C., México D.F., 89–108.(O1)

Pellegrin, J., 1901. Poissons recueillis par M. L. Diquet, dans l'etat de Jalisco (Mexique). Bol. Mus. Hist. nat., Paris 7: 204–207.(P1)

Rosales-Figueroa, F., S. Navarro-Pérez & J. Téllez-López, 1994. Zoogeografía de peces de las cuencas endoreicas de Sayula y Zapotlán, Jalsico: estudio comparativo (abstract). In: IV Cong. nac. Ictiol., 22–26 Nov. 1994, Morelia, Michoacán, México. Soc. Ictiol. mex., A.C., 48.(R1)

Salgado, G. & D. Osorio-Sarabia, 1987. Helmintos de algunos peces del lago de Pátzcuaro. Cien. Desarollo 13: 41–57.(S1)

Serra Puche, M. C., 1980. Ecología y economía lacustres en el sur de la cuenca de México. Ciencia 31: 7–16.

Simon, T. D., and J. Lyons, 1995. Application of the index of biotic integrity to evaluate water resource integrity in fresh water ecosystems. In: Davis, W. S. & T. D. Simon (eds), Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publ., Chelsea, Michigan: 243–260.

Smith, M. L. & R. R. Miller, 1980. *Allotoca maculata*, a new species of goodeid fish from western México, with comments on *Allotoca dugesi*. Copeia 1980: 408–417.(S2)

Soto-Galera, E., E. Díaz-Pardo & C. Guerra-Magaña, 1990. Peces dulceacuícolas mexicanos VIII. *Alloophorus robustus* (Cyprinidontiformes: Goodeidae). Zool. Informa (Esc. nac. Ciencias biol., Inst. nac. politécnico, México D.F.) 19–20: 21–29.(S3)

Soto-Galera, E., E. Díaz-Pardo, E. López-López & J. Lyons, 1998. Fishes as indicators of environmental quality in the Río Lerma basin. Aquat. Ecosys. Health Manage. 1: 267–276.(S4)

Soto-Galera, E. & J. Paulo-Maya, 1995. Peces dulceacuícolas mexicanos. XI. *Allotoca dugesi* (Cyprinodontiformes: Goodeidae). Zool. Informa (Esc. nac. Cien. biol., Inst. nac. politécnico, México D.F.) 31: 5–15.(S5)

Soto-Galera, E., J. Paulo-Maya, E. López-López, J. A. Serna-Hernández & J. Lyons, 1999. Change in the fish fauna as an indication of aquatic ecosystem condition in the Río Grande de Morelia – Lago de Cuitzeo basin, México. Environ. Manage. 24: 133–140.(S6)

Stephan-Otto, P. E. (ed.), 1995. Memorias del segundo seminario internacional de investigaciones de Xochimilco, Vol. I, II. Asoc. internac. Invest. Xochimilco, A.C., México, D.F. 475 pp.(S7)

Tamayo, J. L. & R. C. West, 1964. The hydrography of Middle America. In: West, R. C. (eds), Handbook of Middle American Indians, Vol. I. Natural Environment and Early Cultures. Univ. Texas Press, Austin: 84–121.(T1)

Thoma, R. F., 1998. Biological monitoring and an index of biotic integrity for Lake Erie's nearshore waters. In: Simon, T. D. (ed.), Assessing the Sustainability and Biological Intgegrity of Water Resources Using Fish Communities. CRC Press, Boca Raton, Florida: 417–462.

Webb, S. A., 1998. A phylogenetic analysis of the Goodeidae (Teleostei: Cyprinodontiformes). Ph.D. Thesis, University of Michigan, Ann Arbor.(W1)

Whittier T, R., 1998. Development of IBI metrics for lakes in southern New England. In: Simon, T. D. (eds), Assessing the Sustainability and Biological Intgegrity of Water Resources Using Fish Communities. CRC Press, Boca Raton, Florida: 563–583.

Wischnath, L., 1993. Livebearers of the World. TFH Pub., Neptune City, New Jersey. 336 pp.(W2)