Ana Laura Ibáñez *Editor*

Mexican Aquatic Environments

A General View from Hydrobiology to Fisheries

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Editor
Ana Laura Ibáñez
Hydrobiology Department
Universidad Autónoma Metropolitana
Ciudad de Mexico, Distrito Federal, Mexico

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To the public universities and research centers of Mexico.

Preface

Mexico is a country of huge contrasts, with deserts at the North and at the South with rain forests and big marsh at the peninsula of Yucatan. Mexico has 11,122 km of mainland coastline bathed by two great oceans, the Pacific and the Atlantic (with the Gulf of Mexico and the Caribbean Sea). According to CONABIO, Mexico has large marine richness. The Gulf of California, with 1200 km long by 150 km wide and up to 4000 m deep, is one of the most diverse seas in the world where its high productivity is due to currents of upwelling where nutrients circulate from the bottom to the surface. In the Gulf of California, 875 species of fish, 580 of seabirds and 32 of marine mammals (including the vaquita marina) have been registered. The world's second largest coral reef is located in the Caribbean: the Mesoamerican Reef that extends from Mexico (Yucatan and Quintana Roo) to Honduras with an area of around 1000 km where about 60 species of coral, 350 species of mollusk, and 500 species of fish live. Its peculiar geography gives it a great biodiversity. Mexico is one of the 12 mega-diverse countries (Mexico, Colombia, Ecuador, Peru, Brazil, Congo, Madagascar, China, India, Malaysia, Indonesia, and Australia). In addition to the biological richness, there is also a great cultural richness; 10% of the population in Mexico are indigenous belonging to nearly 60 ethnic groups, most using a different language. In the country, around 68 indigenous languages are spoken; among the most important are the Nahuatl, Chol, Totonac, Mazateco, Mixteco, Zapoteco, Otomí, Tzotzil, Tzeltal, and Mayan, what confers a wide regional complexity. However, we have serious difficulties: 2600 species at risk of extinction with strong environmental problems, such as air and land pollution, deforestation, pollution of waters by chemical spills and drainage, pests, overfishing, and, among others, the global problem of climate change. In general, these issues have an important social component, and unfortunately, these difficulties advance under the complacency of the authorities which usually provide little to solutions and that barely even recognize the studies of the scientific community. Facing this panorama, it is necessary to have greater collaboration to perform constant monitoring of our environments that help us to care for and restore disturbed or altered habitats and provide greater assistance to our natural resources and cultural and biological wealth.

In this sense, this book highlights current challenges and potential solutions with a multidisciplinary approach for environmental water management. It includes a significant review of current literature and state of the art, providing a one-stop resource for researchers, graduate students, and environmental water managers. This book links science to practice for living organisms and their environment and the anthropogenic effect on our water ecosystems. It is the result of cooperation between 35 researchers from 7 Mexican academic institutions, 2 federal commissions, and 1 international organization. Particularly, the book addresses the following subjects: biodiversity in inland waters, physical and chemical characterization of inland waters, physicochemical characterization of Mexican coastal lagoons, microbiota in brackish ecosystems, diversity associated to southern Mexican pacific coral reefs, fry fish stockings in aquatic epicontinental systems, a review of tuna fisheries in Mexico, fishery resource management challenges facing climate changes, aquatic invasive alien species, harmful algal blooms and aquatic-protected areas, their ecological and social problems, and the importance in fisheries yield. This book presents a practical approach of the challenges on Mexican aquatic environment and will provide a much-needed synthesis of recent problematic of different disciplines in Mexican water environments. The different themes of each chapter are written by specialist. Five main disciplines are addressed in this book: estuarine ecology, aquatic resources, fish biology, toxicology, and public health problems.

We dedicate this book to all the public universities and research centers of Mexico which are important study points, and some of them appear in the main classifications of top universities. In addition, these universities and research centers provide a strong encouragement to new generations of scientists who certainly will make important discoveries and will produce a great culture impact and help to our country development.

Ciudad de Mexico, Mexico — Ana Laura Ibáñez

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Abbreviations

AEP	(Anuario Estadístico Pesquero) - Fisheries statistical yearbook
ANP	(Áreas Naturales Protegidas) - Natural Protected Areas
ASP	Amnesic shellfish poisoning
AMO	Atlantic Multidecadal Oscillation
ARMS	Autonomous Reef Monitoring Structures
BID	(Banco Interamericano de Desarrollo) - Inter-American Development Bank
BOD_5	(Demanda Bioquímica de Oxígeno a los cinco días) - Biochemical Oxygen Demand at five days
CCPR	(Código de Conducta PARA LA Pesca Responsible) - Code of Conduct for Responsible Fisheries
CDB	(Convenio sobre la Diversidad Biológica) – Convention on Biological Diversity
COD	Chemical Oxygen Demand
COFAA	(Comisión de Operación y Fomento de Actividades Académicas) Committee on Operation and Promotion of Academic Activities
COFEPRIS	(Comisión Federal para la Protección contra Riesgos Sanitarios) Federal Commission for the Protection Against Sanitary Risks
CONCIYTEY	(Consejo de Ciencia, Innovación y Tecnología del Estado de Yucatán) Council of Science, Innovation and Technology of the State of Yucatán
CONABIO	(Comisión Nacional para el Conocimiento y Uso de la Biodiversidad) - National Commission for the Knowledge and Use of Biodiversity
CONACYT	(Consejo Nacional de Ciencia y Tecnología) - National Council of Science and Technology
CONAGUA	(Comisión Nacional del Agua) - National Water Commission
CONANP	(Comisión Nacional de Áreas Naturales Protegidas) - National Commission for Natural Protected Areas
CONAPESCA	(Comisión Nacional de Acuacultura y Pesca) -National Commission on Aquaculture and Fisheries

COP	(Conferencia de las Partes) – Conference of the parties
COPESCAALC	(Comisión de Pesca Continental y Acuicultura para América Latina) - Commission for Inland Fisheries and Aquaculture of Latin America
CORECOS-UJAT	(Red de Cooperación de Recursos Costeros-Universidad Juárez Autónoma de Tabasco) Cooperation Network of Coastal Resources-University Juárez Autónoma de Tabasco
CRCC	Costa Rica Coastal Current
DA	Domoic acid
DEPESCA	(Departamento de Pesca) - Fisheries Department
DMSP	Dimethylsulfoniopropionate
DMS	Dimethylsulfide
DOF	(Diario Oficial de la Federación) - Official Journal of the Federation
ECOSUR	(El Colegio de la Frontera Sur) The College of the Southern Border
EEB	(Estrategias Estatales sobre Biodiversidad) - State Biodiversity Strategies
ENBM	(Estrategia Nacional de Biodiversidad de México) - National Strategy on Biodiversity of Mexico
EDI	(Programa de Estímulo al Desempeño de Investigación) – The Performance of Research Stimulus Program
EEB	(Estrategias Estatales sobre Biodiversidad) - State Biodiversity Strategies
EEZ	Exclusive Economic Zone
ENSO	El Niño-Southern Oscillation
EPO	Eastern Pacific
EPOMEX	(Instituto de Ecología, Pesquerías y Oceanografía del Golfo de México) Institute of ecology, fisheries and Oceanography of the Gulf of Mexico
ESSA	(Exportadora de Sal) – Salt Exporter
FAO	Food and Agriculture Organization
FADs	Flotsam and aggregate devices
FGRA	(Fundación Gonzalo Río Arronte) – Gonzalo Rio Arronte I.A.P. Foundation
FOMIX	(Fondos Mixtos del Conacyt) Mixed Founds from CONACyT
FR	(Refugios Pesqueros) - Fisheries Refuges
GAP Analysis	(Análisis de Vacíos y Omisiones en Conservación de la Biodiversidad Acuática Epicontinental) - Gaps and Omissions Analysis in Conservation of Epicontinental Aquatic Biodiversity
GEMStats	Global Environmental Monitoring System and Statistics
GEOHAB	Global Ecology and Oceanography of Harmful Algal Blooms
GFFF	Government Funded Freshwater Fish Farms

GIS	Geographical Information Systems
GNP	Gross national product
GoM	Gulf of Mexico
GW	(Calentamiento global) - Global warming
HABS	Harmful algal bloom
HR	Hydrological regions
IATTC	Inter-American Tropical Tuna Commission
ICCAT	The International Commission for the Conservation of Atlantic Tunas
ICES	International Council for the Exploration of the Sea
IEO	(Instituto Español de Oceanografía) Spanish Institute of Oceanography
INAPESCA	(Instituto Nacional de la Pesca) - National Fisheries Institute
INEGI	(Instituto Nacional de Estadística y Geografía) - National Institute of Statistics and Geography
INH	(Inventario Nacional de Humedales) - The National Wetland Inventory
IOC	Intergovernmental Oceanographic Commission
IOC SCC	The IOC Science and Communication Center on Harmful Algae
IOTC	The Indian Ocean Tuna Commission
IPHAB	Intergovernmental Panel on Harmful Algal Blooms
LC	Loop current
LGEEPA	(Ley General del Equilibrio Ecológico y la Protección al Ambiente) -General Law of Ecological Equilibrium and Environmental Protection
LTRS	Lobos-Tuxpan Reef System
MPA	(Áreas Nacionales Protegidas) - Marine Protected Areas
NABCI	North American Bird Conservation Initiative
NAO	North Atlantic Oscillation
NOAA	National Oceanic and Atmospheric Administration
NOM	(Norma Oficial Mexicana) - Mexican Official Norms
OECD	(Organización para la Cooperación y el Desarrollo Económicos) – The Organisation for Economic Co-operation and Development
OTUs	Operational taxonomic units
PIAS	(Programa Institucional de Año Sabático) Institutional Program of Sabbatical year
PNH	(Política Nacional de Humedales) - National Wetland Policy
PNRA	(Programa Nacional de Reservas de Agua) - National Water Reserves Program
PROMEP	(Programa de Mejoramiento del Profesorado) – Program for the Improvement of the Professorship

RED-CORECOS-UJAT	(Red para el Conocimiento de los Recursos Costeros del Suereste de la Universidad Juárez Autónoma de Tabasco) - Network for the Knowledge of the Coastal Resources of the Southeast of the University Juárez Autónoma of Tabasco
REDFAN	(Red de Investigación sobre Florecimientos Algales Nocivos) – Harmful Algal Blooms Research Net
RHP	(Regiones Hidrológicas Prioritarias) - Priority Hydrological Regions
RAPPAM	Rapid Assessment and Prioritization of Protected Area Management methodology
SAGARPA	(Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación) - Secretary of Agriculture, Livestock, Rural Development, Fishing, and Food
SCBD	Secretariat of the Convention on Biological Diversity
SCUBA	Self-contained underwater breathing apparatus
SEDESOL	(Secretaría de Desarrollo Social) - Secretariat of Social Development
SEMAR	(Secretaría de Marina) – Secretariat of Marine
SEMARNAP	(Secretaría de Medio Ambiente, Recursos Naturales y Pesca) Secretariat of the Environment, Natural Resources and Fisheries
SEMARNAT	(Secretaría de Medio Ambiente y Recursos Naturales) - Ministry of Environment and Natural Resources
SEPESCA	(Secretaría de Pesca) - Fisheries Ministry
SIAP	(Servicio de Información Agroalimentaria y Pesquera) - Processed Food and Fisheries Information Service
SIC	(Secretaría de Industria y Comercio) - Secretary of Industry and Commerce
SINA	(Sistema Nacional de Información del Agua) - National Water Information System
SOMEFAN	(Sociedad Mexicana para el estudio de los Florecimientos Algales Nocivos) – The Mexican Society of Harmful Algal Blooms
SRH	(Secretaría de Recursos Hidráulicos) - Secretariat for Water Resources
SST	The Eastern Pacific warm pool
TB	Tehuantepec Bowl
TDS	Total dissolved solids
TSS	Total suspended solids
UAC	(Universidad Autónoma de Campeche) – Autonomous University of Campeche
UAMI	(Universidad Autónoma Metropolitana Campus Iztapalapa) – Autonomous Metropolitan University at Iztapalapa Campus

USGS	United States Geological Survey
UNAM	(Universidad Nacional Autónoma de México) – Autonomous National University of Mexico
VRS	Veracruz Reef System
WGHABD	Working Group on Harmful Algal Bloom Dynamics
WMC	West Mexican Current
WWF México	(Fondo Mundial para la Vida Silvestre - México) – World Wildlife Fund Mexico
WPO	Western Pacific
WWF	World Wide Fund for Nature

Contents

Contributors

Verónica Aguilar-Sierra Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), Tlalpan, Mexico

Mirtha O. Albañez-Lucero Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz, Mexico

Javier Alcocer Grupo de Investigación en Limnología Tropical, FES Iztacala, Universidad Nacional Autónoma de México, Tlalnepantla, Estado de México, Mexico

Sergio H. Alvarez-Hernández Laboratory of Applied Phycology, Departamento de Hidrobiología, Universidad Autónoma Metropolitana, Mexico City, Mexico

Cuauhtémoc Aparicio-Cid Programa de Posgrado. Centro Interdisciplinario de Ciencias Marinas. Instituto Politécnico Nacional, La Paz, B.C.S., Mexico

Marine and Coastal Ecosystems A.C., Huatulco, Oaxaca, Mexico

Francisco Arreguín-Sánchez Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz, Mexico

Enrique Ayala-Duval Universidad Autónoma Metropolitana-Iztapalapa, Departamento de Hidrobiología, México City, Mexico

Norma A. Barrientos-Luján Instituto de Recursos, Universidad del Mar. Campus Puerto Ángel, Puerto Ángel, Oaxaca, Mexico

Francisco Benítez-Villalobos Instituto de Recursos, Universidad del Mar. Campus Puerto Ángel, Puerto Ángel, Oaxaca, Mexico

Fernando W. Bernal-Brooks Instituto de Investigaciones sobre los Recursos Naturales, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, Mexico

Juan E. Bezaury-Creel The Nature Conservancy Mexico (TNC), Mexico City, Mexico

Mónica Bonilla-Salinas Departamento de Hidrobiología, Universidad Autónoma Metropolitana-Iztapalapa, México City, DF, Mexico

Laura G. Calva-Benítez Departamento de Hidrobiología, Universidad Autónoma Metropolitana-Iztapalapa, México City, DF, Mexico

Guadalupe de la Lanza Espino The National Autonomous University of Mexico (UNAM), Mexico City, Mexico

María del Carmen Maldonado-Monroy Universidad Autónoma Metropolitana-Iztapalapa, Departamento de Hidrobiología, México City, Mexico

Pablo Del Monte-Luna Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz, Mexico

Gabriela Galindo-Cortes Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

Roberto González-Gómez Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

Posgrado en Ecología y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

Rebeca Granja-Fernández Doctorado en Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana-Iztapalapa, Ciudad de México, Mexico

David Gutierrez-Carbonell National Commission of Protected Areas, Mexico City, Mexico

Francisco José Gutiérrez-Mendieta The Metropolitan Autonomous University (UAM), Mexico City, Mexico

Luis Hernández Departamento Académico de Biología Marina, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., Mexico

Ana Laura Ibáñez Universidad Autónoma Metropolitana-Iztapalapa, Departamento de Hidrobiología, Mexico City, Mexico

Lourdes Jiménez-Badillo Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

Andrés López-Pérez Departamento de Hidrobiología, Universidad Autónoma Metropolitana-Iztapalapa, Ciudad de México, Mexico

Cruz Lozano-Ramírez Laboratory of Applied Phycology, Departamento de Hidrobiología, Universidad Autónoma Metropolitana, Mexico City, Mexico

César Meiners-Mandujano Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

Piedad S. Morillo-Velarde Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

CONACyT – Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Benito Juárez, Mexico City, Mexico

Florina Ramírez Vives Departamento de Biotecnología, Universidad Autónoma Metropolitana-Iztapalapa, México City, DF, Mexico

Mónica Rodríguez-Palacio Laboratory of Applied Phycology, Departamento de Hidrobiología, Universidad Autónoma Metropolitana, Mexico City, Mexico

Eduardo J. Tlalpan Universidad Autónoma Metropolitana-Iztapalapa, Departamento de Hidrobiología, Mexico City, Mexico

María del Rocío Torres-Alvarado Departamento de Hidrobiología, Universidad Autónoma Metropolitana-Iztapalapa, México City, DF, Mexico

Ana M. Torres-Huerta Instituto de Recursos, Universidad del Mar. Campus Puerto Ángel, Puerto Ángel, Oaxaca, Mexico

Omar Valencia-Méndez Doctorado en Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana-Iztapalapa, Ciudad de México, Mexico

Marine and Coastal Ecosystems A.C., Huatulco, Oaxaca, Mexico

Manuel J. Zetina-Rejón Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz, Mexico

Chapter 1
Physical and Chemical Characterization of Inland Waters

Javier Alcocer and Fernando W. Bernal-Brooks

1.1 Introduction

The water quantity and quality in Mexico vary at a given point in relationship to the geographical position (latitude, altitude, and altitude) and the seasonal cycles that alternate drought and rain, the typical seasonality in tropical-subtropical latitudes. The country, with a geographical position around the Cancer tropic (14.32°N–32.32°N), converges with strong direct solar radiation comparable to other desert regions of the world, like the Sahara. Moreover, the mountainous elevations on both sides of the oceans – the Pacific and the Gulf of Mexico – along with the highest altitudes at the East-West Volcanic Axis and Mesa Central thwart the appearance of cool atmospheric precipitations toward the inner land, especially for the vast northern territories.

Therefore, approximately two thirds of the Mexican terrain remains dry and arid, except for the refreshing episodes of rain occurring with more intensity during August and September. In contrast, the spatial environmental scenario changes radically at the wet southern region in which strongly humid conditions prevail, abundant rivers and rain forests, including the highest terrestrial and aquatic biodiversity (SEDESOL 1993; Toledo et al. 1989).

This chapter highlights the importance of rainfall as the main water supply for Mexico, since liquefying ice and consequent cold runoff at the vicinity of higher peak mountains such as Popocatepetl, Iztaccíhuatl, Citlaltepetl, or the Xinantécatl barely supply the crater lakes at such high altitude such as El Sol and La Luna (see

J. Alcocer (✉)
Grupo de Investigación en Limnología Tropical, FES Iztacala, Universidad Nacional Autónoma de México, Tlalnepantla, Estado de México, Mexico
e-mail: jalcocer@unam.mx

F. W. Bernal-Brooks
Instituto de Investigaciones sobre los Recursos Naturales, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, Mexico

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exceptional lakes). This circumstance makes a huge contrast with the other countries located in America's northern hemisphere, the United States and Canada, where water source of melting glaciers (nival regime) becomes more relevant.

After the rain falls on the ground, the water runs free over the land if no vegetation cover impedes the turbulent flow downhill; otherwise it follows a subsequent path to a rather stationary phase in lakes/dams or percolates into the deep soil for a long-term storage. The following text deals with a brief introduction to Mexico's geography, geology, and climate, as the basis to further review and explain specific physical and chemical characteristics of lake/reservoirs located in diverse regions, from the perspective of fragmentary studies available.

1.2 The Mexican Territory

1.2.1 Geography

Mexico includes seven mountainous ridges (SRH 1976): Sierra Madre Oriental, Sierra Madre Occidental, Trans-Mexican Volcanic Belt, Sierra Madre de Oaxaca, Sierra Madre del Sur, Sierra Madre de Chiapas, and Baja California Sierra (Fig. 1.1).

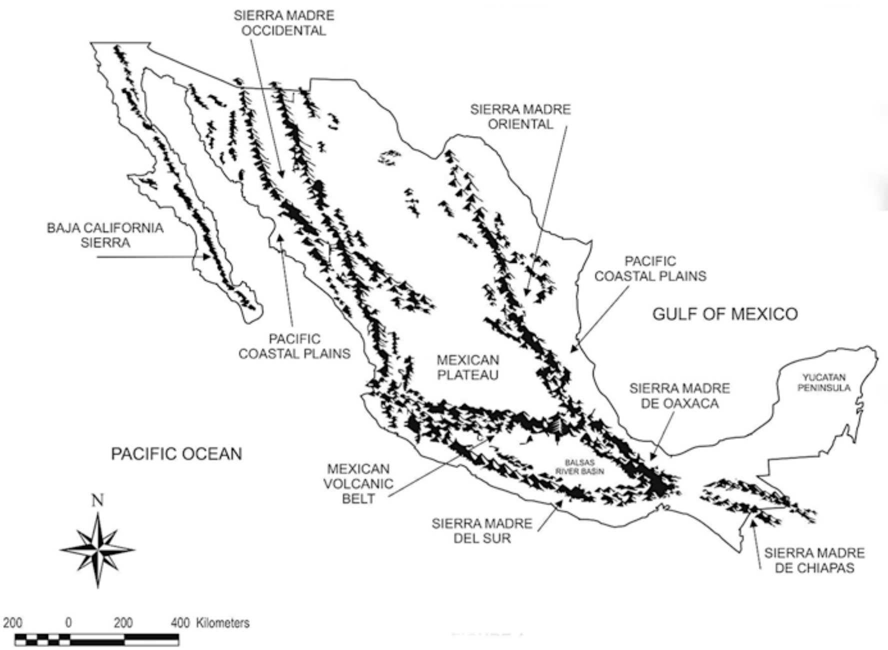

Fig. 1.1 Main mountainous ridges of Mexico. (Modified from Alcocer and Bernal-Brooks 2010)

1.2.2 Climate

Four climatic zones cover the Mexican countryside (Fig. 1.2): (1) arid (1,027,051 km^2 or 52.47% of territory), typical of the northern part of Mexico; (2) dry tropical (254,927 km^2 or 13.01% of territory) including the Pacific watershed with water deficits relative to a mean annual precipitation of 500–600 mm; (3) temperate (390,241 km^2 or 19.92% of territory) at the Sierra Madre Oriental, Sierra Madre Occidental, the Trans-Mexican Volcanic Belt, and the Sierra Madre del Sur; and (4) humid tropical zone (285,983 km^2 or 14.6% of territory), from the Gulf of Mexico coastal plains to the south and southwest.

1.3 Water Administration by the Government

The National Water Commission (CONAGUA), in-charge of managing the inland waters of Mexico as a natural resource, acknowledges 13 administrative hydrologic regions since 1997 (García-Calderón and De-la-Lanza-Espino 2002) based on the water drainage over the land topography, basin frontiers, and the interrelationship of basin groups (Fig. 1.3, Table 1.1), including 37 hydrologic regions and 731 basins (Fig. 1.4, Table 1.1). Alternative regionalizations based on geological and

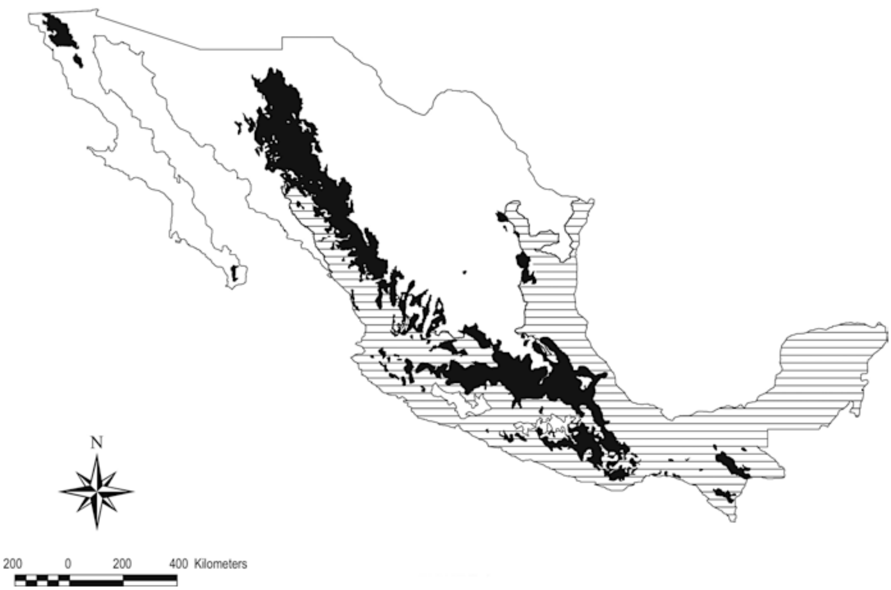

Fig. 1.2 Climatic regions of Mexico. (Modified from Alcocer and Bernal-Brooks 2010). [Arid and dry tropical (white), temperate (black), and humid tropical (horizontal lines)]

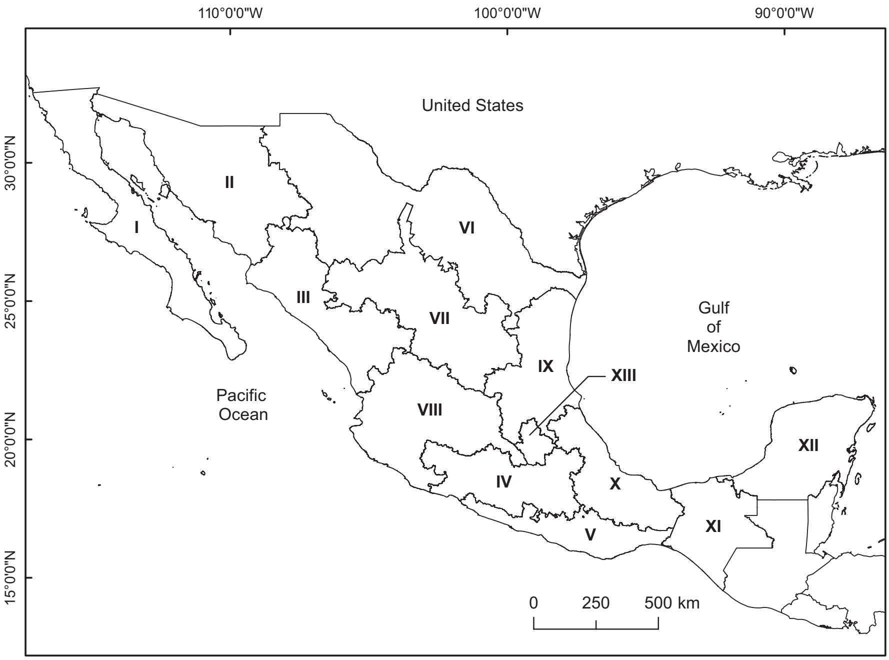

Fig. 1.3 Administrative regionalization of the Mexican territory by Mexico's National Water Commission (CONAGUA 2016). I Baja California Peninsula, II Northwest, III North Pacific, IV Balsas, V South Pacific, VI Grande/Bravo river, VII North-Central Basins, VIII Lerma Santiago Pacific, IX North Gulf, X Central Gulf, XI Southern Border, XII Yucatan Peninsula, XIII Mexico Valley Waters. See also Table 1.1

hydrological criteria do exist (e.g., Velázquez and Ordaz 1992; Ferrusquía-Villafranca 1993); however, the present document follows the government framework as the administrative authority in the matter.

1.4 Background Studies

Based on research made at the Estación Limnológica de Pátzcuaro (1939–1944), Deevey Jr (1957) considered Lake Pátzcuaro as "the only lake in Middle America that has been studied at all comprehensively" and "one of the best-known lakes on the continent." In the mid-1970s though, after almost four decades in dormancy, the studies on lakes and rivers acquired a new impulse re-taking the pioneer research of the early 1940s.

Later, Limón et al. (1989) stated: "we know very little about the limnology of the waters in Central America and Mexico. Only two pages in Lakes of the Warm Belt by Serruya and Pollinger (1983) were given to Mexico." Moreover, Dávalos-Lind and Lind (1993) claimed: "Mexican Limnology has consisted of the monitoring of

Table 1.1 Mexico's administrative and hydrologic regions (CONAGUA 2016)

Hydrological administrative region		Surface (km²)	Renewable water (hm³/y) 2015	Population at the mid-2014 (millions hab.)	Population density (hab./km²)	Per-capita renewable water (m³/hab./y)	Gross national internal product 2014 (%)
I	Baja California peninsula	154,279	4958	4.45	28.8	1115	3.61
II	Northwest	196,326	8273	2.84	14.5	2912	2.86
III	North Pacific	152,007	25,596	4.51	29.7	5676	2.88
IV	Balsas	116,439	21,678	11.81	101.4	836	6.14
V	South Pacific	82,775	30,565	5.06	61.1	6041	2.29
VI	Grande/Bravo river	390,440	12,352	12.3	31.5	1004	14.29
VII	North-Central Basins	187,621	7905	4.56	24.3	1733	4.19
VIII	Lerma Santiago Pacific	192,722	35,080	24.17	125.4	1451	19.08
IX	North Gulf	127,064	28,124	5.28	41.6	5326	2.24
X	Central Gulf	102,354	95,022	10.57	103.2	8993	5.62
XI	Southern border	99,094	144,459	7.66	77.3	18,852	4.93
XII	Yucatán peninsula	139,897	29,324	4.6	32.9	6373	7.38
XIII	México Valley waters	18,229	3442	23.19	1272.2	148	24.49
	National	1,959,248	446,777	121.01	61.8	3692	100

Hydrologic region			Territory (km²)	Yearly precipitation 1981–2010	Internal runoff (hm³/y)	Import/export from other countries (hm³/y)	Average surface runoff (hm³/y)	Number of hydrological basins
I	1	Northwest B.C.	28,492	209	337		337	16
I	2	Center-west B.C.	44,314	116	251		251	16
I	3	Southwest B.C.	29,722	200	362		362	15
I	4	Northeast B.C.	14,416	151	122		122	8

(continued)

Table 1.1 (continued)

Hydrologic region			Territory (km²)	Yearly precipitation 1981–2010	Internal runoff (hm³/y)	Import/ export from other countries (hm³/y)	Average surface runoff (hm³/y)	Number of hydrological basins
I	5	Center-east B.C.	13,626	132	101		101	15
I	6	Southeast B.C.	11,558	291	200		200	14
I	7	Colorado river	6911	98	78	1850	1928	4
II	8	North Sonora	61,429	297	132		132	5
II	9	South Sonora	139,370	483	4934		4934	16
III	10	Sinaloa	103,483	747	14,319		14,319	23
III	11	Presidio	51,717	819	8201		8201	23
VIII	12	Lerma-Santiago	132,918	717	13,180		13,180	58
VIII	13	Huicicila river	5225	1400	1279		1279	6
VIII	14	Ameca river	12,255	1063	2205		2205	9
VIII	15	Jalisco coast	12,967	1144	3606		3606	11
VIII	16	Armería-Coahuayana	17,628	866	3537		3537	10
VIII	17	Michoacán coast	9205	944	1617		1617	6
IV	18	Balsas	118,268	947	16,805		16,805	15
V	19	Big coast of Guerrero	12,132	1215	5113		5113	28
V	20	Small coast of Guerrero	39,936	1282	18,170		18,170	32
V	21	Oaxaca coast	10,514	951	2892		2892	19
V	22	Tehuantepec	16,363	884	2453		2453	15
XI	23	Chiapas coast	12,293	2220	12,617	1586	14,203	25
VI	24	Bravo-Conchos	229,740	399	5588	−432	5156	37
IX	25	San Fernando-Soto la Marina	54,961	703	4864		4864	45
IX	26	Pánuco	96,989	855	19,673		19,673	77
IX	27	North of Veracruz (Tuxpan-Nautla)	26,592	1422	14,155		14,155	12
X	28	Papaloapan	57,355	1440	48,181		48,181	18
X	29	Coatzacoalcos	30,217	2211	34,700		34,700	15

(continued)

Table 1.1 (continued)

Hydrologic region			Territory (km^2)	Yearly precipitation 1981–2010	Internal runoff (hm^3/y)	Import/ export from other countries (hm^3/y)	Average surface runoff (hm^3/y)	Number of hydrological basins
X	30	Grijalva-Usumacinta	102,465	1703	59,297	44,080	103,378	83
XII	31	West Yucatán	25,443	1175	707		707	2
XII	32	North Yucatán	58,135	1143	0		0	0
XII	33	East Yucatán	38,308	1210	576	864	1441	1
VII	34	Northern closed basins	90,829	298	1261		1261	22
VII	35	Mapimí	62,639	292	568		568	6
VII	36	Nazas-Aguanaval	93,032	393	2085		2085	16
VII	37	El Salado	87,801	393	2876		2876	8
Total			1,959,248	740	307,042	47,948	354,992	731

physical and chemical components – a descriptive limnology." Bernal-Brooks (2002) review on available papers for Lake Pátzcuaro found, despite Deevey Jr (1957) comments, "snapshot" studies at specific times, lack of continuity, fragmentary databases, and diverse methodologies among documents. A further scrutiny of limnological knowledge for the whole Mexican territory contains even more incomplete information.

Alcocer and Bernal-Brooks (2009) emphasized the importance of long-term series of data for the study of water ecosystems in the country, with two examples: lakes Alchichica and Pátzcuaro, the latter actually with less continuous data than the former. A third case study, Valle de Bravo reservoir, includes data for 10 years on the community metabolism (Guimarais-Bermejo et al. 2018). In agreement, the indicator becomes an integrated reference of ecosystem functioning as relates to organic matter production and consumption.

Alternative approaches prefer living organisms as indicators of water conditions, such as phytoplankton (Komárková and Tavera 2003; Hernández-Morales et al. 2008; Saldana-Fabela et al. 2014), zooplankton (Cervantes-Martínez and Gutiérrez-Aguirre 2015), benthic macroinvertebrates (Rico-Sánchez et al. 2014; García-Rodríguez et al. 2015; Padilla-González et al. 2016), or experiments with test organisms (López-López and Dávalos-Lind 1998; Bernal-Brooks et al. 2002a, 2003; Ramos-Higuera et al. 2008; Ramírez-Olvera et al. 2009).

In this chapter, we put forth the information obtained at national/regional scale by the Mexican government (CONAGUA). As well, the sect. 1.4.6 emphasizes the physical and chemical characteristics of the hydric resource before humans change the original water composition with wastes; certainly the impacts of mismanagement appear everywhere in the country with evident consequences. Exceptional

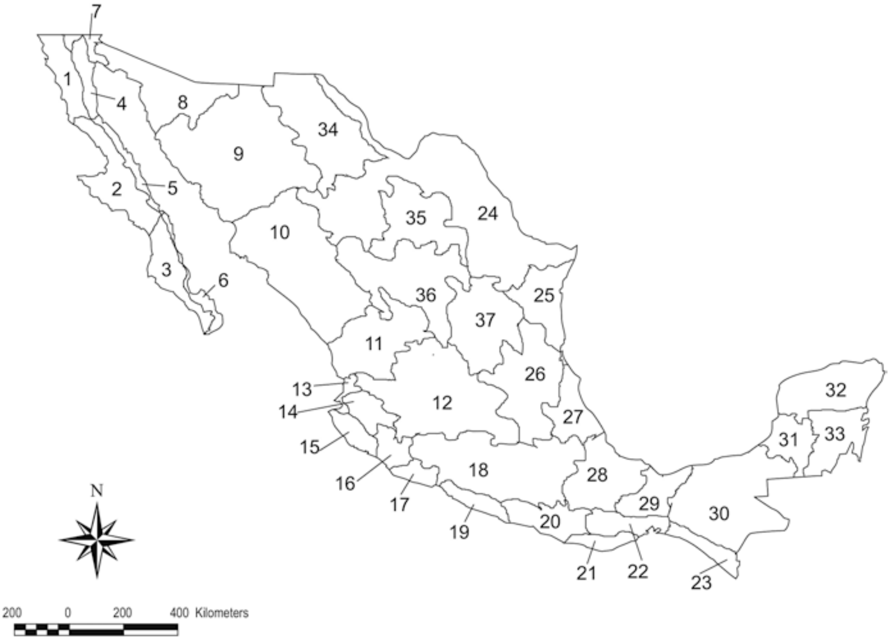

Fig. 1.4 Hydrological Regions (HRs) of Mexico (CONAGUA 2016). See also Table 1.1. (1 Northwest B.C., 2 Center-West B.C., 3 Southwest B.C., 4 Northeast B.C., 5 Center-East B.C., 6 Southeast B.C., 7 Colorado river, 8 North Sonora, 9 South Sonora, 10 Sinaloa, 11 Presidio, 12 Lerma-Santiago, 13 Huicicila river, 14 Ameca river, 15 Jalisco Coast, 16 Armería-Coahuayana, 17 Michoacán Coast, 18 Balsas, 19 Big Coast of Guerrero, 20 Small Coast of Guerrero, 21 Oaxaca Coast, 22 Tehuantepec, 23 Chiapas Coast, 24 Bravo-Conchos, 25 San Fernando-Soto la Marina, 26 Pánuco, 27 North of Veracruz (Tuxpan-Nautla), 28 Papaloapan, 29 Coatzacoalcos, 30 Grijalva-Usumacinta, 31 West Yucatán, 32 North Yucatán, 33 East Yucatán, 34 Northern Closed Basins, 35 Mapimí, 36 Nazas-Aguanaval, 37 El Salado)

lakes (sect. 1.4.7) also exist, an interesting subject to consider. Certainly, a majority of research titles related to water bodies refers to the Central part of Mexico where most important urban developments and universities and their staff are located; therefore, the financial support for water investigations comes mainly from CONACYT (National Council of Science and Technology) to two active sources, government (CONAGUA) or universities.

1.4.1 National/Regional Scale

Actually, Mexico contains few lakes today (Fig. 1.5); woodcutting, influent deviation for agriculture, groundwater over-extraction, water pollution, and eutrophication in combination with natural processes (geologic and climatic) promote a progressive disappearance of surface waters. The central part of Mexico to the west

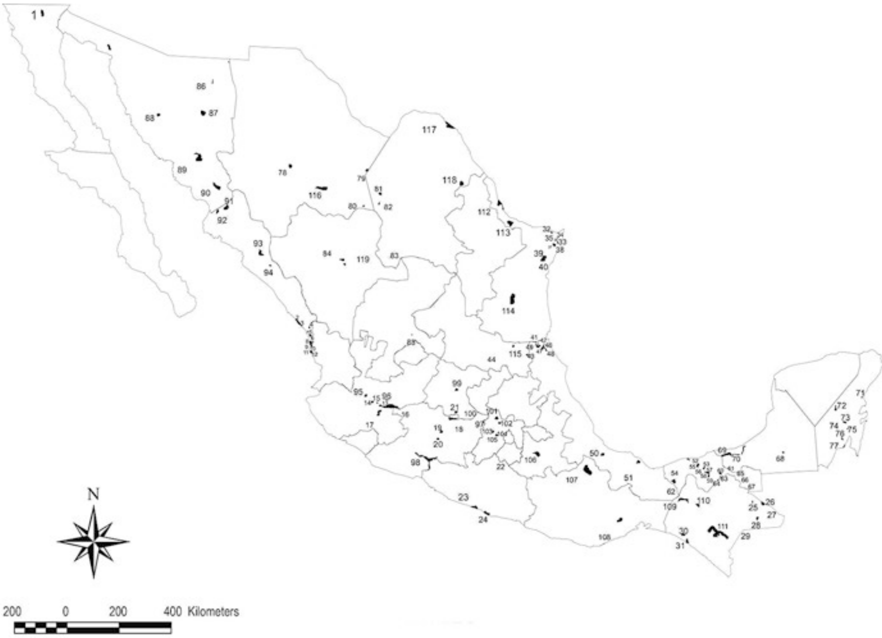

Fig. 1.5 Largest Mexican lakes and reservoirs detected. (Modified from Alcocer and Bernal-Brooks 2010). (*Lakes*: 1 Laguna Salada; 2 Del Caimanero, 3 Los Cerritos, 4 Pozo Puerco, 5 El Fuerte, 6 Chaquin, 7 Grande, 8 El Caimanero, 9 La Puente, 10 Los Vergeles, 11 Los Pericos, 12 Cabeza de Canoa, 13 Cajititlán, 14 Atotonilco, 15 San Marcos, 16 Chapala, 17 Sayula, 18 Cuitzeo, 19 Pátzcuaro, 20 Zirahuén, 21 Yuriria, 22 Tequesquitengo, 23 Coyuca, 24 Tres Palos, 25 Guineo, 26 Santa Clara, 27 Lacanja Chansayab, 28 Miramar, 29 Bosque Azul, 30 La Jova, 31 El Mosquito, 32. V. Palito Blanco, 33 El Barril, 34 Santa María, 35 Tres Mezquites, 36 Tío Castillo, 37 Jasso, 38 El Rabón, 39 Anda la Piedra, 40 La Nacha, 41 La Salada, 42 Champayán, 43 Chajil, 44 Grande, 45 La Vega Escondida, 46 El Chairel, 47 Chila, 48 Pueblo Viejo, 49 Cerro Pez, 50 Coralillo, 51 Catemaco, 52 Cantemual, 53 El Viento, 54 La Palma, 55 La Ramada, 56 El Maluco, 57 Laguacte, 58 Sabana Nueva, 59 Ismate y Chilapilla, 60 Pitahaya, 61 Acostadero, 62 El Rosario, 63 La Sombra, 64 Guerrero, 65 Chashchoc, 66 San José del Río, 67 Canitzán, 68 Noh, 69 Colorada, 70 El Vapor, 71 Chunyaxché, 72 Chinchancanab, 73 X-Paytoro, 74 Petén Tulix, 75 Nohbec, 76 La Virtud, 77 San Felipe, 78 Bustillos, 79 Jaco, 80 Palomas, 81 El Coyote, 82 Del Rey, 83 Desierto de Mayrán, 84 Santiaguillo, 85 El Tule. *Reservoirs*: 86 Angostura, 87 Plutarco E. Calles, 88 Abelardo L. Rodríguez, 89 Álvaro Obregón, 90 Adolfo R. Cortines, 91 Miguel Hidalgo, 92 Josefa Ortíz de Domínguez, 93 Adolfo López Mateos, 94 Sanalona, 95 De la Vega, 96 El Ahogado, 97 Tepuxtepec, 98 Infiernillo, 99 I. Allende, 100 Solís, 101 Huapango, 102 Danxhó, 103 Villa Victoria, 104 Antonio Alzate, 105 Ignacio Ramírez, 106 Ávila Camacho, 107 Miguel Alemán, 108 Benito Juárez, 109 Nezahualcóyotl, 110 Chicoasén, 111 La Angostura, 112 Falcón, 113 Marte R. Gómez, 114 Vicente Guerrero, 115 Las Lajillas, 116 La Boquilla, 117 La Amistad, 118 V. Carranza, 119 Francisco Zarco)

reaches the highest number of reservoirs (Fig. 1.5). On the contrary, Mexico contains numerous rivers (Fig. 1.6); the most important rivers – Usumacinta and Grijalva – contribute with more than 50% of the total watershed discharge (Alcocer and Bernal-Brooks 2010).

Most aquifers under exploitation correspond to the Lerma-Santiago River, Bravo/Grande River, Baja California Peninsula, Northern Central Basins, Northeast, and Mexico Valley Waters, all of them classified as over-exploited in some degree (Table 1.2). Unfortunately, the marine intrusion into the groundwater permeates the Northwest region (e.g., Sonora) and the Baja California Peninsula, while the soil/water salinization advances over the latter and the North-Central Basins. CONAGUA provides a list of 862 sample sites at national level for total dissolved solids (TDS) that integrates the database.

CONAGUA (http://sina.conagua.gob.mx/sina/) synthesize the effect of biodegradable organic matter, industrial organic matter, as well as wastewater/soil erosion, over the Mexican territory, on the basis of three key variables: BOD_5 (biochemical oxygen demand at 5 days, Table 1.3), COD (chemical oxygen demand, Table 1.4), and TSS (total suspended solids, Table 1.5). For each one, respectively,

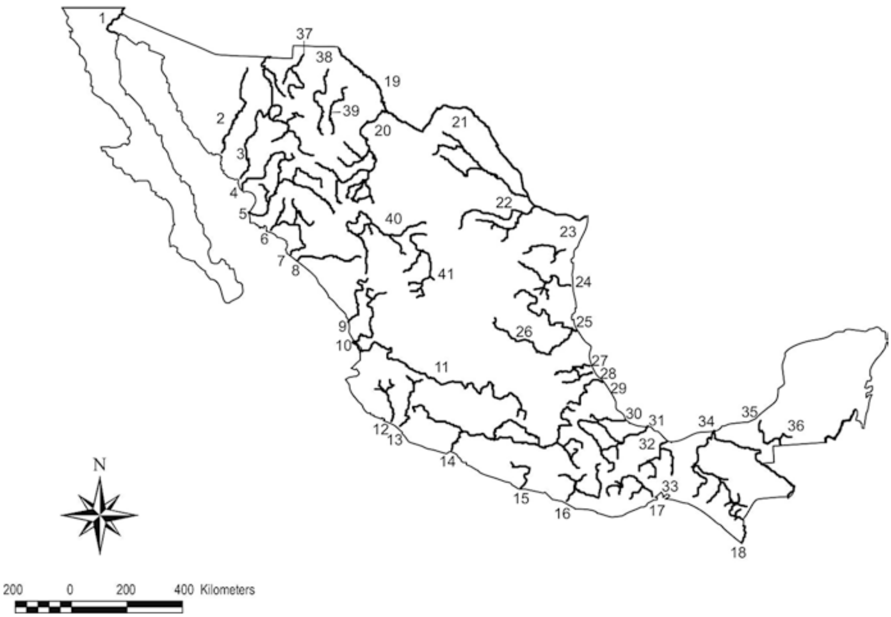

Fig. 1.6 Mexico's main rivers. (Modified from Alcocer and Bernal-Brooks 2010). (1 Colorado, 2 Sonora, 3 Yaqui, 4 Mayo, 5 Fuerte, 6 Sinaloa, 7 Culiacán, 8 San Lorenzo, 9 Acaponeta, 10 San Pedro, 11 Lerma-Santiago, 12 Armería, 13 Coahuayana, 14 Balsas, 15. Papagayo, 16 Verde, 17 Tehuantepec, 18 Suchiate, 19 Bravo or Grande, 20 Conchos, 21 Salado, 22 Pesquería, 23 San Fernando, 24 Soto La Marina, 25 Tamesí, 26 Pánuco, 27 Tuxpan, 28 Cazones, 29 Tecolutla, 30 Jamapa, 31 Papaloapan, 32 Coatzacoalcos, 33 Uxpanapa, 34 Grijalva, 35 Usumacinta, 36 Candelaria, 37 Casas Grandes, 38 Santa María, 39 Del Carmen, 40 Nazas, 41 Aguanaval)

Table 1.2 Mexico's aquifers (CONAGUA 2016)

Administrative region	Aquifers	Overexploited	With marine intrusion	Soil/water salinization	Average renewal (hm^3)	Freshwater	Slightly salty	Salty	Total
I Baja California peninsula	88	14	11	5	1658.1	42	27	21	90
II Northwest	62	10	5	0	3206.6	82	11	5	98
III North Pacific	24	2	0	0	3076.4	61	2	2	65
IV Balsas	45	1	0	0	4873.1	59	2	0	61
V South Pacific	36	0	0	0	1935.9	10	1	0	11
VI Grande/Bravo river	102	18	0	8	5935.4	77	20	12	109
VII North-Central Basins	65	23	0	18	2375.6	181	29	16	226
VIII Lerma Santiago Pacífico	128	32	0	0	9656.3	190	7	4	201
IX North Gulf	40	1	0	0	4108.1	44	7	8	59
X Central Gulf	22	0	0	0	4598.5	18	4	2	24
XI southern border	23	0	0	0	22,717.7	25	1	0	26
XII Yucatán peninsula	4	0	2	1	25,315.7	36	26	7	69
XIII México Valley waters	14	4	0	0	2330.2	26	7	0	33
National	653	105	18	32	91,787.6	851	144	77	1072

Table 1.3 BOD_5 indicator for the Mexican territory (CONAGUA 2016)

Water quality assessment on BOD as indicator (% sampling sites)					
	Excellent	Good quality	Acceptable	Polluted	Strongly polluted
I Baja California peninsula	46.4	18.6	27.8	6.2	1
II Northwest	71.5	15.8	9.5	1.1	2.1
III North Pacific	83.2	9.9	4.3	1.7	0.9
IV Balsas	32.7	19.1	21.9	18.2	8.1
V South Pacific	79.9	6.7	6	3.4	4
VI Grande/Bravo river	58	20.8	16.8	4.4	0
VII North-Central Basins	83.2	11.1	1.9	1.9	1.9
VIII Lerma Santiago Pacífico	41.6	10.5	35.9	7.1	4.9
IX North Gulf	77.4	6.3	10.3	2.4	3.6
X Central Gulf	59.4	18	13.2	6.4	3
XI southern border	73.3	19	6.5	8	4
XII Yucatán peninsula	85.1	4.3	10.6	0	0
XIII México Valley waters	2.9	14.5	39.1	27.5	16
National	57.5	13.9	18.6	6.4	3.6

Table 1.4 COD indicator for the Mexican territory (CONAGUA 2016)

Water quality assessment on COD as indicator (% sampling sites)					
	Excellent	Good quality	Acceptable	Polluted	Strongly polluted
I Baja California peninsula	23.7	14.4	17.5	39.2	5.2
II Northwest	39.9	23.2	15.8	17.9	3.2
III North Pacific	43.5	25	20.3	9.5	1.7
IV Balsas	11.4	12.3	29	31.5	15.8
V South Pacific	2	17.4	57.7	17.4	5.5
VI Grande/Bravo river	37.5	27.4	15.7	19	0.4
VII North-Central Basins	27.8	37	25.9	7.4	1.9
VIII Lerma Santiago Pacífico	13.4	13.2	24.1	40.1	9.2
IX North Gulf	58.1	12.6	11.5	14.2	3.6
X Central Gulf	16	12.4	36.7	28.5	6.4
XI southern border	23.9	42.6	24	7.6	1.9
XII Yucatán peninsula	25.5	31.9	27.7	14.9	0
XIII México Valley waters	0	4.1	17.8	43.8	34.3
National	24.2	19.3	24.8	24.9	6.8

Table 1.5 TSS indicator for the Mexican territory (CONAGUA 2016)

Water quality assessment on TSS as indicator (% sampling sites)					
	Excellent	Good quality	Acceptable	Polluted	Strongly polluted
I Baja California peninsula	71.4	19.8	6.6	2.2	0
II Northwest	51.9	29.2	9.1	9.1	0.7
III North Pacific	48.2	39.8	7.5	3.9	0.6
IV Balsas	46	28.2	10.6	12.9	2.3
V South Pacific	26.9	45	17.9	6.6	3.6
VI Grande/Bravo river	59.9	25.3	10.9	3.5	0.4
VII North-Central Basins	65.4	25.5	5.5	1.8	1.8
VIII Lerma Santiago Pacífico	48	31.2	15.1	4.6	1.1
IX North Gulf	60.4	30.7	7.3	1	0.6
X Central Gulf	55.1	37.3	5.4	2.1	0.1
XI southern border	40.9	39.3	16.1	3.7	0
XII Yucatán peninsula	68.8	27.6	3.1	0.5	0
XIII México Valley waters	24.7	43.8	16.4	13.7	1.4
National	50	33.1	11.1	4.8	1

71%, 43%, and 83% of the sampled sites showed excellent and acceptable conditions (see the meaning of such qualitative terms at Table 1.6) in 2016.

BOD_5 (Table 1.3) reach the range of pollution and strong pollution at Balsas (26.3%) and Mexico Valley Waters (43.5%); COD (Table 1.4) attain maximum values at Baja California Peninsula (44.4%), Balsas (47.3%), Lerma-Santiago Pacific (49.3%), and Mexico Valley Waters (78.1%); while TSS (Table 1.5) include highest concentrations at Balsas (15.1%) and Mexico Valley Waters (15.1%).

1.4.2 Rivers

The Global Environmental Monitoring System and Statistics (GEMStats 1979–1996, Fig. 1.6, Table 1.7) analyzed chemical variables for 11 rivers in Mexico (http://portal.gemstat.org) obtained from government sources. Extreme values appear for the following variables and rivers, respectively: conductivity (>1 mS cm^{-1}) at Colorado, Conchos, Bravo, Coatzacolacos, Atoyac, and Lerma Rivers; alkalinity (>100 mg l^{-1}) at Colorado, Conchos, Pánuco, Balsas, Atoyac, Lerma, and Usumacinta Rivers; hard waters (Ca and Mg) in all the study cases, except the Lerma River; total and fecal coliform bacteria at Colorado, Atoyac, and Lerma Rivers; COD at all the rivers under study; and extreme concentrations of nutrients, N and P, at Atoyac and Lerma Rivers.

Table 1.6 Qualitative terms for water classification (CONAGUA 2016)

Range	Classification	Description
$0 < BOD_5 \leq 3$	Excellent	Without pollution
$3 < BOD_5 \leq 6$	Good	Surface waters with low biodegradable organic content
$6 < BOD_5 \leq 30$	Acceptable	With some contamination. Surface waters with self-depuration capacity or biologically treated wastewaters
$30 < BOD_5 \leq 120$	Polluted	Surface waters with raw wastewaters of municipal origin
$120 < BOD_5$	Strongly polluted	Surface waters with strong impact by raw wastewaters both municipal and nonmunicipal in origin
$0 < COD \leq 10$	Excellent	Without pollution
$10 < COD \leq 20$	Good	Surface waters with low biodegradable and non-biodegradable organic content
$20 < COD \leq 40$	Acceptable	With some contamination. Surface waters with self-depuration capacity or biologically treated wastewaters
$40 < COD \leq 200$	Polluted	Surface waters with raw wastewaters of municipal origin
$200 < COD$	Strongly polluted	Surface waters with strong impact by raw wastewaters both municipal and nonmunicipal in origin
$0 < TSS \leq 25$	Excellent	Very good quality (exceptional)
$25 < TSS \leq 75$	Good	Surface waters with low biodegradable and non-biodegradable organic content
$75 < TSS \leq 150$	Acceptable	Surface waters with some pollution. Raw wastewaters. Regular condition for fish. Restricted irrigation
$150 < TSS \leq 400$	Polluted	Surface waters with bad quality with raw wastewaters. Water with high content of suspended matter
$400 < TSS$	Strongly polluted	Surface waters with strong impact caused by a heavy pollution load of raw municipal and nonmunicipal wastewaters. Bad condition for fish

1.4.3 Trans-Mexican Volcanic Belt

Sigala et al. (2017) studied 30 water bodies along an altitudinal gradient from 737 to 4283 m a.s.l. across Central Mexico (excerpts at Table 1.8 along with results obtained by other references, Michoacán not included as part of the next section in this document). These authors put forth three different origins for each study case: (a) tectonic (4), (b) volcanic (18, including 11 craters and maars and 7 volcanic damming), and (c) reservoirs (8). Most cases include fresh, alkaline ($pH > 7.5$), with Ca-Na-HCO_3 water type.

1.4.4 Michoacán

Israde (2005) divided the water bodies of Michoacán also on the basis of their origin: tectonic lakes, volcanic-tectonic lakes, crater lakes, rivers, and reservoirs. In the area, 1746 water bodies detected by GIS (Bernal-Brooks and Israde-Alcántara 2012)

Table 1.7 GEMStats: 11 Mexican rivers database (1979–1996)

		T	O_2	K_{25}	SS	BOD	COD	pH	T ALK	Tot col	Feac col
		°C	Mg l^{-1}	mS cm^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	No/100 ml	No/100 ml
Colorado	1979–1981	23.0	7.9	1380	59	7	59	8	156		674
Latitude 32° 42′ 00″	1982–1983	19.3	8.1	1699	37	5	44	7.8	164		344
Longitude 114° 43′ 00″	1985–1987	19.3	8.1	1699	37	5	44	7.8	161	17	224
Altitude	1989–1990	22.8	8.7	1445	20	2	17	7.7	193		237
Depth 4 m	1991–1993	24.1	8.1	1168	188	3	28	8	229	7.30E+06	9.30E+05
I.D.	1994–1996	22.1	8.4	1289	30	2	19	7.9	191	1484	190
	X	21.8	8.2	1447	62	4	35	7.9	182	2,433,834	155,278
	DE	2.0	0.3	216	63	2	17	0.1	28	4,214,224	379,535
	MAX	24.1	8.7	1699	188	7	59	8.0	229	7,300,000	930,000
	MIN	19.3	7.9	1168	20	2	17	7.7	156	17	190
Conchos	1980–1981	20.1	7.7	1001	167	2	16	7.9	245		1.40E+04
Latitude 29° 34′ 00″	1982–1984	20.7	7.7	1168	45	3	25	7.7	254		14,500
Longitude 104° 26′ 00″	1985–1987	21.4	7.2	1033	64		44	7.9	254	1969	
Altitude 1210 m a.s.l.	1988–1990	21.1	7	1063	47	6	5	7	251	298	
Depth 1.1 m	1991–1993	20.9	7.2	1280	204	5	15	7.8	220	1.10E+06	3.80E+05
I.D.	1994–1996	23.5	8.3	1820	105	5	17	7.2	265	4.90E+04	7.30E+03
	X	21.3	7.5	1228	105	4	20	7.6	248	287,817	103,950
	DE	1.2	0.5	308	67	2	13	0.4	15	541,926	184,063
	MAX	23.5	8.3	1820	204	6	44	7.9	265	1,100,000	380,000
	MIN	20.1	7.0	1001	45	2	5	7.0	220	298	7300
Bravo	1979–1981	23	8.6	1126	160	3	62	7.4	153		
Latitude 25° 53′ 00″	1982–1984	24.7	8.7	823	131	3	25	8.1	152		
Longitude 97° 30′ 30″	1985–1987	25.3	8.3	1561	26	3	39	8.2	192	1598	230
Altitude 1.5 m a.s.l.	1988–1990	24.7	7.8	1380	58	4	44	7.7	171	2465	2400

(continued)

Table 1.7 (continued)

		T	O_2	K_{25}	SS	BOD	COD	pH	T ALK	Tot col	Feac col
		°C	Mg l^{-1}	mS cm^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	No/100 ml	No/100 ml
Depth 3 m	1991–1993	24.5	7.4	1292	109	29	42	7.7	182		3.70E+05
I.D. 80 m^3 s^{-1}	1994–1996	24.4	7.7	1511	80	4	34	8.1	164		234
	X	24.4	8.1	1282	94	8	41	7.9	169	2032	93,216
	DE	0.8	0.5	274	49	10	12	0.3	16	613	184,525
	MAX	25.3	8.7	1561	160	29	62	8.2	192	2465	370,000
	MIN	23.0	7.4	823	26	3	25	7.4	152	1598	230
Panuco	1979–1981	25.9	7.5	772	337	1	19	8.1	171		1138
Latitude 23° 03′ 00″	1982–1984	26.9	8.5	852	5	2	16	7.9	174		161
Longitude 98° 18′ 30″	1985–1987	25.9	8.4	849	217	3	23	8.4	183	3461	1224
Altitude 12 m a.s.l.	1988–1990	28	8.1	883	69	2	10	8.3	184		349
Depth 10 m	1991–1993	26.7	8.7	639	94	2	15	8.2	186	6.00E+05	1.50E+05
I.D. 540 m^3 s^{-1}	1994–1996	27.7	7.6	745	133	1	27	7.9	165	2460	203
	X	26.9	8.1	790	143	2	18	8	177	201,974	25,513
	DE	0.9	0.5	91	118	1	6	0	8	344,701	60,988
	MAX	28.0	8.7	883	337	3	27	8	186	600,000	150,000
	MIN	25.9	7.5	639	5	1	10	8	165	2460	161
Coatzacoalcos	1979–1981	26.2	6.5	600	74	3	64	7.4	87		2073
Latitude 18° 06′ 30″	1982–1983	26.7	8.3	10,176	64	2	135	6.7	97		110
Longitude 94° 25′ 00″	1985–1987	25.8	5.7	3983		13	330	7.5	119	4.5 + E04	1.10E+04
Altitude 1.1 m a.s.l.	1988–1990	24.4	5.3	4382	25	30	308	6.4	83	21,023	1.40E+05
Depth 10 m	1991–1993	27.2	6.4	3702	89	3	188	7.1	68	2.00E+05	4.90E+04
I.D.	1994–1996	26.1	6.1	4167	42	2	59	7	69	6.30E+04	2.30E+04
	X	26.1	6.4	4502	59	9	181	7	87	94,674	37,531
	DE	1.0	1.0	3113	25	11	118	0	19	93,598	53,299

	MAX	27.2	8.3	10,176	89	30	330	8	119	200,000	140,000
	MIN	24.4	5.3	600	25	2	59	6	68	21,023	110
Balsas	1979–1981	29.3	6.9	287	4641	2	176	8.1	302		1.40E+04
Latitude 17° 56′ 30″	1982–1983	29.1	7.3	1160	3221	1	214	8	150		4.00E+04
Longitude 99° 35′ 30″	1985–1987	28	6.4		2133		130	8.1	149	1.1 + E05	9.70E+04
Altitude 499.1 m a.s.l.	1988–1990	27.9	6.3	923	2562	15	307	7.8	148	4.20E+04	8.70E+04
Depth 0.9 m	1991–1993	27.9	6.6	918	442	8	111	7.8	216		3.50E+06
	1994–1996	28.1	6.4	1110	1334	38	76	7.4	144	1.70E+05	1.10E+05
	X	28.4	6.7	880	2389	13	169	8	185	106,000	641,333
	DE	0.6	0.4	349	1467	15	83	0	64	90,510	1,400,930
	MAX	29.3	7.3	1160	4641	38	307	8	302	170,000	3,500,000
	MIN	27.9	6.3	287	442	1	76	7	144	42,000	14,000
Atoyac	1979–1981	19.7	3.4		411	47	111	7.2			3.10E+05
Latitude 18° 55′ 30″	1982–1983	19	4		1175	55	183	7.7			1.90E+05
Longitude 98° 16′ 30″	1985–1987	20.3	1.7	1323	328	53	126	7.5	386	1.80E+05	3.70E+05
Altitude 2100 m a.s.l.	1988–1990	19.7	1.1	987	961	33	154	7.6	356	1.00E+06	1.00E+06
Depth 12 m	1991–1993	19.7	3.2	1022	429	57	164	7.6	384	1.40E+07	9.60E+06
I.D. 2260 m^3 s^{-1}	1994–1996	19.7	2.5	1102	564	53	183	7.5	328	6.00E+06	3.40E+06
	X	19.7	2.7	1109	645	50	154	7.5	364	5,295,000	2,478,333
	DE	0.4	1.1	151	343	9	30	0.2	27	6,347,816	3,691,511
	MAX	20.3	4.0	1323	1175	57	183	7.7	386	14,000,000	9,600,000
	MIN	19.0	1.1	987	328	33	111	7.2	328	180,000	190,000
Blanco	1979–1981	23.5	5	449	74	22	59	7.5	250		4.10E+04
Latitude 18° 44′ 30″	1982–1983	22.4	4.4	520	156	13	46	7.7	203		4.00E+04
Longitude 96° 26′ 00″	1985–1987	22.7	3.6	437	106	11	69	7.4	215	5.10E+04	1.10E+05
Altitude 91 m a.s.l.	1988–1990	22.3	3.7	473	26	11	69	6.6	205	6.70E+04	3.80E+04
Depth 1.1 m	1991–1993	22.4	5.4	449	129	20	196	7.6	248	1.70E+06	7.30E+05

(continued)

Table 1.7 (continued)

		T	O_2	K_{25}	SS	BOD	COD	pH	T ALK	Tot col	Feac col
		°C	Mg l^{-1}	mS cm^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	No/100 ml	No/100 ml
I.D. 25.5 m^3 s^{-1}	1994–1996	25.3	4.1	429	85	14	98	7.3	192	1.10E+05	3.60E+04
	X	23.1	4.4	460	96	15	90	7.4	219	482,000	165,833
	DE	1.2	0.7	33	45	5	55	0.4	24	812,382	277,855
	MAX	25.3	5.4	520	156	22	196	7.7	250	1,700,000	730,000
	MIN	22.3	3.6	429	26	11	46	6.6	192	51,000	36,000
Lerma	1979–1981	24.1	0.7	1634	273	75	208	8.5	321		3.00E+05
Latitude 20° 34′ 00″	1982–1984	27.1	0.6	1736	214	68	279	8.2	348		3.00E+05
Longitude 101° 12′ 00″	1985–1987	23.1	1	699	107	21	407	7.6	258	1.70E+05	1.40E+05
Altitude	1988–1990	24.4	1.1	1700		101	203	7.5		6.70E+05	6.80E+05
Depth	1991–1993	24.1	1.4	946	156	11	58	7.6	289	1.70E+07	1.70E+07
I.D. 1788 m^3 s^{-1}	1994–1996	23.7	1.3	1144	90	23	107	7	274	1.30E+06	1.10E+06
	X	24.4	1.0	1310	168	50	210	7.7	298	4,785,000	3,253,333
	DE	1.4	0.3	441	76	36	124	0.5	36	8,156,447	6,743,396
	MAX	27.1	1.4	1736	273	101	407	8.5	348	17,000,000	17,000,000
	MIN	23.1	0.6	699	90	11	58	7.0	258	170,000	140,000
Usumacinta	1985–1987	28.2	7.2	548		2	22	7.8	152	3679	7410
Latitude 17° 51′ 40″	1988–1990	27.8	7.5	283	83	2	16	7.5	132	1.20E+04	5.20E+03
Longitude 92° 47′ 10″	1991–1993	27.6	7.5	519	61	3	23	8	136	1.10E+06	2.40E+05
Altitude	1994–1996	28.1	7.6	527	77	3	16	8.2	138	4224	5960
Depth 24 m	X	27.9	7.5	469	74	3	19	8	140	279,976	64,643
I.D. 1.0 m^3 s^{-1}	DE	0.3	0.2	125	11	1	4	0	9	546,696	116,909
	MAX	28.2	7.6	548	83	3	23	8	152	1,100,000	240,000
	MIN	27.6	7.2	283	61	2	16	8	132	3679	5200
Grijalva	1985–1987	29.4	5.1	436		6	22	7.4	139	5.60E+04	3.90E+04
Latitude 17° 59′ 20″	1988–1990	27.1	5.3	236	89	3	23	7.2	116	2.50E+04	2.50E+04

Longitude 92° 34′ 50″	1991–1993	28.4	5.6	1577	31	4	27	7.8	121	2.60E+06	1.30E+06
Altitude	1994–1996	28.1	5.5	391	45	4	18	7.9	110	4.50E+04	3.30E+04
Depth 3 m	X	28.3	5.4	660	55	4	23	8	122	681,500	349,250
I.D. 1.0 $m^3 s^{-1}$	DE	0.9	0.2	617	30	1	4	0	13	1,279,064	633,859
	MAX	29.4	5.6	1577	89	6	27	8	139	2,600,000	1,300,000
	MIN	27.1	5.1	236	31	3	18	7	110	25,000	25,000

		SO_4	Cl	Ca	Mg	Na	K	N (Kjel)	NO_2+ NO_3	NH_3	P-PO_4 (sol)	P-PO_4 (total)
		Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}
Colorado	1979–1981	260	164	90				1.4		0.22	0.063	0.207
Latitude 32° 42′ 00″	1982–1983		195	171	158			1		0.22	0.049	0.211
Longitude 114° 43′ 00″	1985–1987	188	99	157	154			0.5	0.3	0.47	0.072	0.147
Altitude	1989–1990	208	161	203	143			0.8		0.15	0.016	0.453
Depth 4 m	1991–1993	237	205	101	141			1	0.01	2.09	0.366	0.036
I.D.	1994–1996	278	170	90				0.4		0.1	0.067	0.016
	X	234	166	135	149	ND	ND	0.9	0.16	0.54	0.106	0.178
	DE	37	37	48	8			0.4	0.21	0.77	0.129	0.158
	MAX	278	205	203	158			1.4	0.30	2.09	0.366	0.453
	MIN	188	99	90	141			0.4	0.01	0.10	0.016	0.016
Conchos	1980–1981	179	38	106				0.7		0.11	0.278	0.45
Latitude 29° 34′ 00″	1982–1984	154	36	95	105			0.3		0.05	0.098	0.148
Longitude 104° 26′ 00″	1985–1987	225	34	174	109	7			1.59		0.093	0.259
Altitude 1210 m a.s.l.	1988–1990	219	37	236	96	52	2.9		1.03	0.53	0.167	0.462
Depth 1.1 m	1991–1993	274	27	81	53				1.77		0.533	0.414
I.D.	1994–1996	510	70	119		90	4.9		3.11		0.254	
	X	260	40	135	91	50	3.9	0.5	1.88	0.23	0.237	0.347
	DE	129	15	59	26	42	1.4	0.3	0.88	0.26	0.164	0.138

(continued)

Table 1.7 (continued)

		SO_4	Cl	Ca	Mg	Na	K	N (Kjel)	NO_2+ NO_3	NH_3	P-PO_4 (sol)	P-PO_4 (total)
		Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}
	MAX	510	70	236	109	90	4.9	0.7	3.11	0.53	0.533	0.462
	MIN	154	27	81	53	7	2.9	0.3	1.03	0.05	0.093	0.148
Bravo	1979–1981	292	286	91				0.8		0.18	52,000	
Latitude 25° 53′ 00″	1982–1984	321	216									1847
Longitude 97° 30′ 30″	1985–1987	321	217	308	170				0.39		0.95	1450
Altitude 1.5 m a.s.l.	1988–1990	286	209						0.12	0.42		
Depth 3 m	1991–1993	260	194	98		138	3.6		0.24	1.11	0.162	0.02
I.D. 80 m^3 s^{-1}	1994–1996	312	207	94		125	6.4		0.19	0.31	0.111	0.16
	X	299	222	148	170	132	5.0	0.8	0.24	0.51	13000.306	824.30
	DE	24	33	107		9	2.0		0.11	0.42	25999.796	965.41
	MAX	321	286	308		138	6.4		0.39	1.11	52000.000	1847.00
	MIN	260	194	91		125	3.6		0.12	0.18	0.111	0.02
Panuco	1979–1981	200	34	98	27	33	5.5	0.4	2.84	0.1	0.062	0.077
Latitude 23° 03′ 00″	1982–1984	225	29	114	10	14	3.3	0.3	0.32	0.08	0.024	0.029
Longitude 98° 18′ 30″	1985–1987	204	29	105	27	27	3.9	0.8	0.46	0.16	0.043	0.049
Altitude 12 m a.s.l.	1988–1990	226	30	94	40	30	4.1		0.63	1.26	0.024	0.058
Depth 10 m	1991–1993	148	26	72	36	26	4.6	0.5	0.5	0.05	0.09	0.097
I.D. 540 m^3 s^{-1}	1994–1996	217	13	104		22	2.1		0.26	0.04	0.066	0.042
	X	203	27	98	28	25	3.9	0.5	0.84	0.28	0.052	0.059
	DE	29	7	14	12	7	1.2	0.2	0.99	0.48	0.026	0.025
	MAX	226	34	114	40	33	5.5	0.8	2.84	1.26	0.090	0.097
	MIN	148	13	72	10	14	2.1	0.3	0.26	0.04	0.024	0.029
Coatzacoalcos	1979–1981	1107	872	39				0.6		0.27	0.079	0.477
Latitude 18° 06′ 30″	1982–1983	63	732					0.5	0.06	0.35	0.14	0.304
Longitude 94° 25′ 00″	1985–1987	184	2124						0.36	0.81	0.069	0.235

Altitude 1.1 m a.s.l.	1988–1990	481	2125		1024				0.58		0.216	0.502
Depth 10 m	1991–1993	85	1265	62					0.29	0.17	0.274	0.321
I.D.	1994–1996	184	1805	76					0.42	0.32	0.11	
	X	351	1487	59	1024	ND	ND	0.6	0.34	0.38	0.148	0.368
	DE	399	618	19				0.1	0.19	0.25	0.081	0.116
	MAX	1107	2125	76				0.6	0.58	0.81	0.274	0.502
	MIN	63	732	39				0.5	0.06	0.17	0.069	0.235
Balsas	1979–1981	505	25	215				1.7		0.84	0.836	1226
Latitude 17° 56′ 30″	1982–1983	40	79							0.59	0.07	0.697
Longitude 99° 35′ 30″	1985–1987	554	121							0.55	0.356	0.729
Altitude 499.1 m a.s.l.	1988–1990	322	162								0.111	0.595
Depth 0.9 m	1991–1993	329	33	75	2			1.7		0.06	0.101	0.423
	1994–1996	318	22	148					0.09		0.219	
	X	345	74	146	2	ND	ND	1.7	0.09	0.51	0.282	245.689
	DE	181	58	70				0.0		0.33	0.291	548.011
	MAX	554	162	215				1.7		0.84	0.836	1226.000
	MIN	40	22	75				1.7		0.06	0.070	0.423
Atoyac	1979–1981							3.4		2.77	6130	12,092
Latitude 18° 55′ 30″	1982–1983							4.9	0.54	5.13	3236	6542
Longitude 98° 16′ 30″	1985–1987	63	27	46	19	33	7.6	4.4	0.18	8.04	4794	5934
Altitude 2100 m a.s.l.	1988–1990		45		10	13	3.5	5.9	0.98	9.56	1578	2578
Depth 12 m	1991–1993	111	58	73	14	41	10.5	12	0.79	10.6	2579	4062
I.D. 2260 $m^3 s^{-1}$	1994–1996	129	60	91	40	41	18.7	5.1	0.75	10.07	3590	
	X	101	48	70	21	32	10.1	6.0	0.65	7.70	3651	6242
	DE	34	15	23	13	13	6.4	3.1	0.30	3.11	1617	3626
	MAX	129	60	91	40	41	18.7	12.0	0.98	10.60	6130	12,092
	MIN	63	27	46	10	13	3.5	3.4	0.18	2.77	1578	2578

(continued)

Table 1.7 (continued)

		SO_4	Cl	Ca	Mg	Na	K	N (Kjel)	NO_2+ NO_3	NH_3	P-PO_4 (sol)	P-PO_4 (total)
		Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}	Mg l^{-1}
Blanco	1979–1981	26	17		75			3		0.38	0.229	0.545
Latitude 18° 44′ 30″	1982–1983	32	16	125	18			2.3	1.1	3.04	0.188	0.452
Longitude 96° 26′ 00″	1985–1987	30	23	121	45				2.13	2.78	0.154	0.374
Altitude 91 m a.s.l.	1988–1990	29	20	234	67				1.28	0	0.426	1211
Depth 1.1 m	1991–1993	18	13	69					0.88		0.588	0.377
I.D. 25.5 $m^3 s^{-1}$	1994–1996	34	15	58					1.74	2.75	0.432	
	X	28	17	121	51	ND	ND	2.7	1.43	1.79	0.336	242.550
	DE	6	4	70	26			0.5	0.50	1.47	0.172	541.380
	MAX	34	23	234	75			3.0	2.13	3.04	0.588	1211.000
	MIN	18	13	58	18			2.3	0.88	0.00	0.154	0.374
Lerma	1979–1981	274	32	37				9.1	1.07	42.71	1552	3424
Latitude 20° 34′ 00″	1982–1984	672	126	1	1	3		12	3.37	78.38	0.793	23,811
Longitude 101° 12′ 00″	1985–1987		139	20.2	11	93		8.3	2.07	25.68	1610	2224
Altitude	1988–1990			45	27	306					0.925	4740
Depth	1991–1993	410	102	42	10	63	19.1	1.3	1.91	6.79	0.365	0.834
I.D. 1788 $m^3 s^{-1}$	1994–1996	244	62	32		165		3.2	0.98	15.9	49,780	
	X	400	92	30	12	126	19.1	6.8	1.88	33.89	8824.014	6839.967
	DE	195	45	16	11	116		4.4	0.96	28.21	20079.193	9645.926
	MAX	672	139	45	27	306		12.0	3.37	78.38	49780.000	23811.000
	MIN	244	32	1	1	3		1.3	0.98	6.79	0.365	0.834
Usumacinta	1985–1987	109	11						0.86	0.04	0.205	0.241
Latitude 17° 51′ 40″	1988–1990	100	9						0.38	0.09	0.155	0.234
Longitude 92° 47′ 10″	1991–1993	131	9	101				1	0.18	0	0.066	0.042
Altitude	1994–1996	153	11	117					0.07	0	0.063	

Depth 24 m	X	123	10	109	ND	ND	ND	1	0.37	0.03	0.122	0.172
I.D. 1.0 $m^3 s^{-1}$	DE	24	1	11					0.35	0.04	0.070	0.113
	MAX	153	11	117					0.86	0.09	0.205	0.241
	MIN	100	9	101					0.07	0.00	0.063	0.042
Grijalva	1985–1987	48	30						0.89	0.15	0.305	0.27
Latitude 17° 59′ 20″	1988–1990	47	23	159					0.6	0.08	0.175	0.332
Longitude 92° 34′ 50″	1991–1993	142	571	110				1	0.17	0	0.067	0.082
Altitude	1994–1996	39	27	60					0.07	0	0.104	
Depth 3 m	X	69	163	110	ND	ND	ND	1	0.43	0.06	0.163	0.228
I.D. 1.0 $m^3 s^{-1}$	DE	49	272	50					0.38	0.07	0.105	0.130
	MAX	142	571	159					0.89	0.15	0.305	0.332
	MIN	39	23	60					0.07	0.00	0.067	0.082

Table 1.8 Physical and chemical characteristics of Mexican water bodies (References included for each case at the right last column)

Region	Lake	Mixing type[a]	Z_{SD} (m)	Temp. (°C)	pH	DO (mg l^{-1})	Conductivity (µS cm^{-1})	Main anion	Main cation	Salinity g l^{-1}	References
III North Pacific											
	San Pedro Lagunillas, nay.				8.2			HCO_3	Na^+		Sigala et al. (2017)
	Santa María del Oro; nay.				8.6			HCO_3,cl^-	Na^+		Sigala et al. (2017)
	Tepetiltic, nay.				8.3			HCO_3	Ca^{2+}		Sigala et al. (2017)
IV Balsas											
	Zempoala, Mor.	WM	180–420	18.2–19.0	6.6–7.7	1.0–10.7	83–96	HCO_3	Ca^{2+}		Quiroz-Castelan et al. (2007)
	Tonatiahua, Mor.	WM	220–520	16.6–18.0	6.0–7.2	1.0–7.2	111–142	HCO_4	Ca^{2+}		Quiroz-Castelan et al. (2007)
	Atlangatepec,Tlax.	WP	8–20	19.3–21.3	7.7	5.4–7.5		HCO_3	Na^+		Rodríguez Maldonado and Ritter (2007); Sigala et al. 2017
VI Grande/Bravo river											
	Cuatro Ciénegas, Coah.	MM		25–38	7.0–9.7	>100%		SO_4	Ca^{2+}		Alcocer and Kato (2002); Alcocer (2017)
VIII Lerma Santiago Pacífic											
	El sol, Edo. Mex.	WP	300–740	5–11	5.5–7.0	5.6–6.8	15–18	HCO_3	Ca^{2+}		Alcocer et al. (2004)
	La Luna, Edo. Mex.	WP	400–900	5.5–11.5	4.5–5.6	6.3–9.5	13–15	HCO_3	Ca^{2+}		Alcocer et al. (2004)
	Rincón de Parangueo, Gto.[b]	WP	60	19–23	9.8		70,000–80,000	HCO_3	Na^+	>120	Alcocer et al. (2002), Escolero-Fuentes and Alcocer (2004)
	La Alberca, Gto.[b]	WP	100	19	9.5		5000–6000	HCO_3	Na^+		Alcocer et al. (2002); Escolero-Fuentes and Alcocer (2004)

	Yuriria, Gto.				8			HCO_3	Na^+		Sigala et al. (2017)
	Atotonilco, Jal.				9.6			HCO_3	Na^+		Sigala et al. (2017)
	Sayula, Jal.				9.3			HCO_3,cl-	Na^+		Sigala et al. (2017)
	Colorada, Jal.				7.8			HCO_3	Ca^{2+}		Sigala et al. (2017)
	Juanacatlán, Jal.				9.2			HCO_3	Ca^{2+}		Sigala et al. (2017)
	La Vega, Jal.				8.5			HCO_3	Na^+		Sigala et al. (2017)
	Ojo de Agua, Jal.				8.5			HCO_3	Ca^{2+}		Sigala et al. (2017)
	Santa Gertrudis, Jal.				8			HCO_3	Ca^{2+}, Mg^{2+}, Na^+		Sigala et al. (2017)
	Santa Rosa, Jal.				9			HCO_3	Mg^{2+}		Sigala et al. (2017)
	Chapala, Mich.-Jal.	WP	30–110	17.2–28.8	8.4–8.9	6–7.9	238–1053	HCO_3			Limón et al. (1989); Guzmán-Arroyo and Orbe-Mendoza (2002)
IX North Gulf											
	Sistema Zacatón, tamps.										Gary and Sharp (2006)
	El Zacatón			29–30	6.7–7.0	0–0.5	732–778	HCO_3	Ca^{2+}		
	Caracol			30–31	6.7–6.9	0.1–0.5	857–934	HCO_3	Ca^{2+}		
	Poza Verde			23–26.5	7.4–7.6	2.1–7.4	703–767	HCO_3	Ca^{2+}		
	La Pilita			31.5–32	6.9–7.1	0.1–0.9	884–957	HCO_3	Ca^{2+}		
	La Azufrosa			30–34	6.5–6.8	0.1–0.7	893–915	HCO_3	Ca^{2+}		

(continued)

Table 1.8 (continued)

Region	Lake	Mixing type[a]	Z_{SD} (m)	Temp. (°C)	pH	DO (mg l^{-1})	Conductivity (μS cm^{-1})	Main anion	Main cation	Salinity g l^{-1}	References
	La Cristalina			28	6.8–7.0	1.1–1.4	725–745	HCO_3	Ca^{2+}		
	Cav. Travers.			25	6.9	1.1	632	HCO_3	Ca^{2+}		
	Poza Seca			32	6.8	3.2	913	HCO_3	Ca^{2+}		
	Tule			25.27	8.7–8-9	8.4–8.8	3407–3457	HCO_3	Ca^{2+}		
	La alameda			23–24.5	5.9	5.9–6.3	763–837	HCO_3	Ca^{2+}		
	Los Jagueyes, tamps.	PM		26.3	6.8	2.9	149	HCO_3	Ca^{2+}		Hoz-Zavala and De-la-Lanza-Espino (2002)
	Media Luna lake, SLP.	WP	2205	30	7.7	2.4	1870	HCO_3	Ca^{2+}		Chacón-Torres et al. (2007)
X Central Gulf											
	Totolcingo, Pue-Tlax. (lake)			14–26	9.4–10.1	0.7–20	7130–46,000	HCO_3	Na^+		Alcocer et al. (2007a)
	Alchichica, Pue.	WM	500	14.5–20	8.6–9.2	0–7	17,800	Cl^-	Na^+	8.5	Alcocer et al. (2000); Vilaclara et al. (1993)
	SL Atexcac	WM		15–20	8.2	0–10	11,000	HCO_3	Mg^{2+}	6.8	Vilaclara et al. (1993)
										6	Macek et al. (1994)
	Quechulac, Pue.	WM		15.5–19.5	8.7	4.1–7.7	750			1	Vilaclara et al. (1990)
	Tecuitlapa, Pue.	WP		21.9–26.3	9.7	6.5–12.1	1650	CO_3^{2-}	Na^+	16.3	Vilaclara et al. (1993)
	Aljojuca, Pue.	WM		19.4–23.4	8.9	3.7–9.1	1225	HCO_3	Na^+	Subsaline	Vilaclara et al. (1993); Sigala et al. (2017)

	La Preciosa, Pue.	WM		17.4–24.5	8.7	5.5–12.8	2150	HCO_3	Mg^{2+}	Subsaline	Vilaclara et al. (1990, 1993); Sigala et al. (2017)
	Colorada, Ver.	WM	55	22–32	7.4–9.1	0.7–11.0	146–192	HCO_3, cl	Na^+		Vázquez and Caballero (2013)
	Majahual, Ver.	WM	377	21–30	6.6–7.0	0.7–6.3	161–201	HCO_3	Mg^{2+}		Vázquez and Caballero (2013)
	Manantiales, Ver.	WM	211	21–29	6.2–7.4	0.6–11.4	171–215	HCO_3	Na^+		Vázquez and Caballero (2013)
	Chalchoapan, Ver.	WM	85	21–26.5	6.6–7.4	0.3–7.3	149–168	HCO_3	Mg^{2+}		Vázquez and Caballero (2013)
	Verde, Ver.	WP	33	29–33	8.5–8.9	5.5–13.9	239–243	HCO_3	Na^+		Vázquez and Caballero (2013)
	Mogo, Ver.	WP	55	29–30	>8	7.3–8.4	253–259	HCO_3	Ca^{2+}		Vázquez and Caballero (2013)
	Catemaco	WP	30	21–31	8.2–9.2	0–10.3	140–180	HCO_3			Torres-Orozco and Pérez-Rojas (2002); Torres-Orozco et al. (1994)
	Atezca, Hgo.	WM	100–120	16–27	6.5–9.1	0–7		HCO_3	Ca^{2+}		Vázquez and Favila (1998); Sigala et al. (2017)
	Tecocomulco, Hgo.				8.8			HCO_3	Na^+		Sigala et al. (2017)
	Metztitlán, Hgo.	WP	20–30	16–27	7.0–8.7	3–7		HCO_3	Ca^{2+}		Ibañez-Aguirre et al. (2002)

(continued)

Table 1.8 (continued)

Region	Lake	Mixing type[a]	Z_{SD} (m)	Temp. (°C)	pH	DO (mg l^{-1})	Conductivity (μS cm^{-1})	Main anion	Main cation	Salinity g l^{-1}	References
XI southern border											
	Dos Lagos, chis.	Mm?									Alcocer (2017)
	Upper stratum			18–23	6.9–8.1	6–8	662				
	Lower stratum			19	7.1–7.5	0	1143				
XII Yucatan peninsula											
	Nohoch Hol, Quintana Roo										Torres-Talamante et al. (2011)
	Mixolimnion (0–9 m)			25–26	7.0–7.5	1–7.3	5000				Alcocer (2017)
	Chemolimnion (9–15.5 m)			26.1–26.7	6.7–7.4	0	5000–54,600				
	Monimolimnion (>15 m)			26	7	0	55,100				

[a] *WP* warm polymictic, *WM* warm monomictic, *MM* meromictic
[b] extinct

uphold, in turn, diverse links with the physiography, hydrology, and climate. In such way, any attempt to establish general patterns between aquatic ecosystems becomes very complicated, especially for those small reservoirs of multiple uses in the rural environment, where the organic contamination reflects the intensity of productive activities in the neighborhood. Cultural eutrophication, industrial pollution, silting, or combinations meet the characteristics of “forced ecosystem” (Margalef 1983), in contrast to those “pristine ecosystems” of touristic and recreational use at the highest altitudes (e.g., Pucuato, Sabaneta, and Mata de Pinos reservoirs).

Thus, Bernal-Brooks and Israde-Alcántara (2012) analyzed physical and chemical variables for 30 water bodies in the area of Michoacán during 2005 and put forth 3 generalizations for lakes in the area:

- The dominance of the bicarbonate-carbonate system in the ionic content with three levels of dissolved content: Low (<300 μS cm^{-1}), intermediate (300–1000 μS cm^{-1}), and high (>1000 μS cm^{-1}). The first group includes reservoirs higher than 2300 m a.s.l. (Pucuato, Sabaneta, and Mata de Pinos) and 1700 m a.s.l. (Zirahuén, la Alberca de Tacámbaro, Cointzio, Tarecuato, Aristeo Mercado Wilson, El Fresno, Malpaís, Chincua, Urepetiro, and Santa Teresa), respectively; the second group encompasses water bodies from 0 to 2100 m a.s.l. (Lago de Camécuaro, La Alberca de Teremendo, and the reservoirs of El Pejo, san Juanico, Los Olivos, Tepuxtepec, Zicuirán, Infiernillo, and La Villita); while the third group comprises the endorheic basins of Pátzcuaro, Cuitzeo, and Los Negritos.
- The low/intermediate groups follow an inverse relationship with altitude: At higher elevations, the water in lakes/reservoirs maintains a low conductivity close to that of pluvial precipitation, while the variable increases progressively downhill to a maximum value near the sea level. The reservoirs of Melchor Ocampo and Tepuxtepec appear as outliers of extreme organic/industrial contamination.
- The temporal variations induced by the absence or presence of rainfall. During 8 months of drought approximately, the water loss by evapotranspiration leads to an increase of substances by volume unit, and then the conductivity rises in general; otherwise, when the atmospheric precipitation appears over lakes and reservoir surfaces, the dilution process of the ionic content undergoes to such degree that may even cause a slight increase in transparency at the regularly turbid shallow waters (e.g., Alcocer and Bernal-Brooks 2002).

Eighteen years ago, Bernal-Brooks and MacCrimmon (2000) re-took the argument of climatic sensitivity put forth by Hutchinson et al. (1956) for lakes Zirahuén, Pátzcuaro, Cuitzeo, and Chapala. Based on Lake Pátzcuaro evidence (Bernal-Brooks et al. 2002b, 2003; Alcocer and Bernal-Brooks 2002), a dilution effect of the lake water occurs in response to rainwater inputs and seasonal lake level increase. Not only a long-term level oscillation in parallel between the abovementioned water bodies follows the scale of decades, without recovery since 1978. The application of Geographical Information Systems (GIS) to aerial and satellite images includes the analysis of the historic relationship between levels, area, and surface changes for several sectors within the water body of Lake Pátzcuaro for 1969, 1974, 1986, 1991, 1995, and 2000 (Gomez-Tagle-Chávez 2001; Gomez-Tagle-Chávez et al. 2002) as a counterpart that corroborates the lake level database.

1.4.5 Yucatan Peninsula

The Yucatán Peninsula, with absence of rivers in the northern portion, includes a karstic topography in which rainfall infiltration through the calcareous soil structure fills sinkholes or "cenotes" – a word derived from Maya language *dtzonoot* (literally, hole with water). Wilson (1980) identified 14 physiographic districts around the Peninsula, 8 of them located in the northern zone. Because of dissolution of calcareous rocks and, in some areas, the incursion of marine water flow, the conductivity tends to exceed 600 μS cm^{-1} with sodium, bicarbonates, chloride, and sulfates as dominant ions (Alcocer and Escobar 1996).

The salinity of the underground water in the Peninsula varies between 0.4 and 2.9 g l^{-1}; the alkalinity reaches 696 mg l^{-1}, and the total dissolved solids keep a uniform concentration < 3 mg l^{-1}, except for those cases with marine influence. In "open flow or lotic cenotes" (with underwater flows), the temperature tends to be very stable relative to underground water exchange below 10 meters (24–29 °C); the pH maintains less than 7. In turn, for the "restricted flow or lentic cenotes," a chemical stratification appears with a vertical gradient of salinity, fresh to brackish water at the top mixolimnion and marine water at the deep monimolimnion (Schmitter-Soto et al. 2002a, b). An example of a meromictic sinkhole, Nohoch Hol (Alcocer 2017) unveils the relevance of the chemolimnion in the aquatic ecosystem dynamics (Torres-Talamante et al. 2011). The halocline fluctuates in position and also depends on the distance relative to the seashore.

Pérez et al. (2011) built up a table with main physical and chemical variables and water chemistry for 63 lake surface sample sites, 34 sites at Mexican territory including 16 points at lowlands, 10 at the so-called cenotes or sinkholes, 2 coastal water sites, 3 rivers, and 3 wetland ponds (Table 1.9). The broad conductivity range, from 168 to 55,300 μS cm^{-1} 25 °C, reflects saline intrusion over the coastal aquatic environments, and the effect of a NW–S precipitation gradient, from 450 to 3200 mm $year^{-1}$.

1.4.6 Water Bodies of Other Areas

The aquifers, in general, bear the trace of the geologic substrate as the rocks add some salinity into the water. As soon as the liquid comes out at the surface, it undergoes dramatic chemical changes achieved by an immediate human management in a situation of limited resource availability.

Alcocer and Hammer (1998) described extensively the saline ecosystems of Mexico, commonly found in endorheic basins of semi-arid regions within wide

Table 1.9 Yucatán Peninsula water bodies

	Temp.	Diss. Oxygen	pH	Cond.	SO_4	Cl	HCO_3	Ca	K	Mg	Na
	(°C)	(mg l^{-1})		(µS cm^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})
Mexican lowlands											
Milagros	27.9	12.4	8.1	2720	1296	125	120	404	17	101	110
Bacalar	27	7.9	7.8	1220	1374	83	190	452	1	84	64
Nohbec	29.2	9.4	8.5	1230	553	550	73	161	6	42	244
Ocom	27.9	7.2	8	774	657	143	141	150	3	45	127
Chichancanab	28.5	7.7	8	2060	2410	235	120	595	20	156	158
Punta Laguna	26.8	7.2	8	754	337	156	280	96	6	31	130
San José Aguilar	–	4.8	8	488	–	–	244	47	–	7	55
Sabanita	27.5	8.1	8	139	–	–	73	19	–	4	7
Chacan-Bata	26.3	2.2	7	146	–	–	85	23	–	3	12
Chacan-Lara	28.1	6	7.5	174	–	–	104	20	–	4	20
Jobal	31.7	10.9	8.3	241	–	–	171	42	–	4	2
San Francisco Mateos	24.8	0.9	7.3	474	–	–	189	93	–	6	12
La Misteriosa	26.7	7.7	8	1410	–	–	104	351	–	15	23
Cayucón	25.3	3.3	7.4	127	–	–	85	28	–	4	4
Yalahau	28.8	8.7	8.9	2350	340	189	617	23	17	99	213
Cobá	28.9	8.7	8.5	1210	31	281	256	100	–	5	127

(continued)

Table 1.9 (continued)

	Temp. (°C)	Diss. Oxygen (mg l^{-1})	pH	Cond. (µS cm^{-1})	SO_4 (mg l^{-1})	Cl (mg l^{-1})	HCO_3 (mg l^{-1})	Ca (mg l^{-1})	K (mg l^{-1})	Mg (mg l^{-1})	Na (mg l^{-1})
Cenotes											
Xlacah	27.9	4	7	1450	–	–	482	115	–	40	169
Petén de Monos	26.6	1.4	6.9	3670	–	–	482	23	–	115	781
San Ignacio Chochola	27.4	2.7	6.9	2110	147	370	500	169	–	35	326
Chenhá	28.3	10.4	7.6	2520	–	–	476	217	–	59	382
Timul	30.4	11.4	9.1	1470	–	–	604	116	–	81	209
Yokdzonot	25.2	5.3	7.4	949	–	–	421	80	–	28	78
Juárez	27.9	8.7	8.1	643	–	–	293	68	–	23	53
Yaa'x ec	26.4	10.6	8	793	–	–	287	71	–	19	61
San Francisco kana	30.7	9.7	8.2	1750	–	–	311	192	–	17	244
Tekom	25.5	6.7	7.3	958	–	–	415	121	–	17	55
Coastal water bodies											
Rosada	28.1	10.5	8.7	55,300	–	–	244	–	–	–	–
Celestún	24.9	5.2	7.8	38,200	262	657	348	150	12	73	375
Rivers											
Cuba	24.9	7.3	7.8	2040	–	–	250	575	–	19	32
Candelaria	26.9	1.9	7.7	1560	–	–	384	359	–	44	17
Guerrero	26.2	3.6	7.7	2700	–	–	421	330	–	117	303
Jamolún	25.7	2.9	7.3	2520	–	–	189	45	–	7	13
Wetland ponds											
Loche	32	14.4	9.4	4340	–	–	482	99	–	109	908
Silvituc	30.2	7.7	8.2	183	–	–	122	27	–	3	11

belts between latitudes 20° and 40°. Although most studies on crater lakes, "dolinas" or "cienegas," reveal the characteristics of the waters coming from the deep soil and exposed at the land surface, not all the water becomes saline. Following, we put forth some examples of the two counterparts (details at Table 1.8).

Cuatro Ciénegas, Coahuila, include a group of water bodies located within an endorheic calcareous basin. The lentic shallow ponds as deep as 5 m and in the order of 20 hectares' maximum contain water hardness at extreme values (1100–1700 mg l^{-1}) and SO_4 as main anion (Alcocer and Kato 2002; Alcocer 2017). The exceptional case of Laguna Salada attains 62,000 mg l^{-1} hardness, unique in the Mexican territory. This type of shallow, meromictic pond collects the inflows of other water bodies in the area as density currents moving to the bottom, less saline.

The "*dolinas*" or "*cenotes*" of Sistema Zacatón, in Aldama, Tamaulipas, represents one of the unique actively forming karst systems in the world (Gary and Sharp 2006).

La Media Luna Lake ranges as one of the most crystalline waters of Mexico with 22 m of Secchi disk transparency; however, a remarkable hardness, alkalinity, and conductivity reach 1184 mg l^{-1}, 213 mg l^{-1}, and 1870 µS cm^{-1}, respectively (Chacón-Torres et al. 2007).

Dos Lagos, Chiapas, included in the national park "*Lagunas de Montebello*" along with more than 50 lakes (sinkholes), becomes one of the possible meromictic lakes (Alcocer 2017) with 42 m of maximum depth.

Crater lakes – maar – called "axalapascos," Puebla, contain some degree of salinity that qualify Alchichica, Atexcac, and Tecuitlapa as hyposaline (Vilaclara et al. 1993; Macek et al. 1994) or subsaline in cases of Quechulac, Aljojuca, and La Preciosa (Sigala et al. 2017).

Crater lakes of Rincón de Parangueo, San Nicolás de Parangueo, La Alberca, and Cíntora, in Guanajuato, nowadays an extinct group of four crater lakes (maars) at the top of some of Las Siete Luminarias, remain empty as the result of an abusive extraction of underground water for agriculture in the neighborhood (Alcocer et al. 2000; Escolero-Fuentes and Alcocer 2004; Kienel et al. 2009).

Certainly, almost 65% of Mexico's surface water qualify as saline, and a selection of typical freshwater include:

Zempoala and Toniahua lakes, Morelos (in the order of 1 hectare and 53 m^2, respectively, both less than 10 m deep), collect predominantly rainfall and runoff within their respective endorheic basins; therefore a high water transparency (as high as 4–5 m) and fairly low conductivity (in the order of 100 µS cm^{-1}) prevails, slightly higher at the latter relative to the former (>100 µS cm^{-1}) (Table 1.8; Quiroz-Castelan et al. 2007).

Lake Zirahuén (see also National/Regional studies), Michoacán, at 2080 meters above the sea level, supports touristic and recreation activities as a well-known water body of high transparency. The lake waters with 110–120 µS cm^{-1} receive waters from the Arroyo de la Palma with slightly higher conductivity (110–140 µS cm^{-1}) than the rest of the water body (Bernal-Brooks et al. 2002a). The fact suggests an underwater exchange of water that avoids any accumulation of salt, as in fact occurred in the nearby Lake Pátzcuaro with a close basin (a counterpart about ten times higher in conductivity at some points). Despite the condition of a “blue water lake,” this natural beauty underwent dramatic changes during the last two decades in terms of eutrophication.

Los Jagüeyes in the neighborhood of Altamira, Tamaulipas, include some 20 small water bodies fed from rainfall filtered through the rocks of Sierra Madre Oriental, with suggested values in average of conductivity (149 μS cm^{-1}) and pH (6.8) (Hoz-Zavala and De-la-Lanza-Espino 2002).

Large, shallow, and turbid lakes such as Chapala, Cuitzeo, Pátzcuaro, and Catemaco (Limón et al. 1989; Martínez-Pantoja et al. 2002; Alcocer and Bernal-Brooks 2002; Torres-Orozco et al. 1996) with daily mix (polymictic regime; Lewis 1983) differ from deeper (<10 m) Atexcac, Alchichica, and Zirahuén lakes (even the small crater lake of Teremendo with 9 m of maximum depth or Zempoala with only 5 m of maximum depth) and usually stratify thermally from March to October (warm monomictic regime; Lewis 1983) (Macek et al. 2007, 2009; Bernal-Brooks et al. 2002a, 2016).

The addition of poorly mineralized atmospheric precipitation into the hydrologic basins induces lower values of alkalinity, hardness, and conductivity in the water; therefore, if no addition of underground waters occurs, a dilution effect appears during the rainy season at the surface waters already present (Hernández-Avilés et al. 2001; Alcocer and Bernal-Brooks 2002) (Table 1.8). Some shallow “playa lakes” appear or disappear depending on the rainfall availability:

Tecocomulco (Rico-Sánchez et al. 2014), Hidalgo, becomes a relic of ancient lakes at the Anahuac, 2 m deep in average and 17.7 km^2. During the drought, the water reach 401–1237 μS cm^{-1}, 31–246 mg l^{-1} suspended solids, 50–435 mg l^{-1} alkalinity, and 50–100 mg l^{-1} hardness, while the conditions change in January to 291–752 μS cm^{-1} conductivity and 22–178 mg l^{-1} suspended solids.

Coatetelco, Morelos, a very shallow lake (<2 m) with wide fluctuations of area and volume, maintains well-oxygenated waters of low transparency (9–36 cm Secchi disc) at 660–1150 μS cm^{-1} conductivity, total dissolved solids content (330–1328 mg l^{-1}), 130–325 mg l^{-1} hardness, and 850 μg l^{-1} total P (Gómez-Marquez et al. 2007).

Totolcingo (also called El Carmen or Oriental), an episodically filled lake, includes a very shallow inundation zone in the limits of Puebla and Tlaxcala. The waters reach 7130–46,000 μS cm^{-1} conductivity, pH 9.3–9.8, equivalent to 0.7 to 0.8 g l^{-1} salinity (Alcocer et al. 2007a).

Metztitlán, Hidalgo, represents a polymictic water body with 20–28 cm Secchi disk transparency and wide level fluctuations to such degree that in some years (1988, 1998) dried up completely (Ibañez-Aguirre et al. 2002).

Atezca, Hidalgo, a warm monomictic lake with an average depth of 6.4 m, receives inflows from three permanent streams and surrounding runoff, with a constant level regulated by an outflow. The calcium hardness reaches 28–42 mg l^{-1} (Díaz-Pardo et al. 2002).

The Atlangatepec reservoir, Tlaxcala, maintains low Secchi disk transparency (8–20 cm) and high content of suspended solids (300–900 mg l^{-1} in January, while less than 300 mg l^{-1} for the rest of the year) (Rodríguez-Maldonado and Ritter 2007).

Majahual, Manantiales, and Chalchoapan lakes, Veracruz, with a warm monomictic regime (Vázquez et al. 2007; Vázquez and Caballero 2013) differ from warm polymictic *Mogo and Verde lakes* in the same area. In contrast, *Majahual* and *Manantiales* transparency (230, 120 cm), nitrates (0.6, 0.8 mg l^{-1}), ammonia (0.2, 0.3 mg l^{-1}), and total phosphorus (4.4, 3.2 mg l^{-1}) differ from Chalchoapan, Mogo, and Verde, with low transparency (<50 cm) as eutrophic systems with high content of nitrates (1.6, 1.1, and 1.4 mg l^{-1}), ammonia (2.1, 0.5, and 0.8 mg l^{-1}), and total phosphorus (3.2, 4.4, 4.8 mg l^{-1}).

1.4.7 Exceptional Lakes

Crater lakes of El Sol and La Luna at the top of the Nevado de Toluca volcano, Estado de México, both represent unusual cases at high altitude (4200 m a.s.l.) filled up, at least in part, with melted ice. El Sol ranged 3–7.4 m of Secchi disk water transparency, while La Luna lake 4–9 m, the temperature 7.1 °C and 6.5 °C, respectively; mean pH of 5.5 and 4.7; and an exceptional low conductivity of 16 μS cm^{-1} and 14 μS cm^{-1}, respectively (Alcocer et al. 2004).

Crater lakes of El Chichón, Chiapas, and *Popocatepetl*, Mexico City-Puebla, become two more outstanding singularities since both lakes are in the crater of active volcanoes. In the former, the water temperature "varied from 56°C in 1983 to 35.4°C in 1997," while in the latter "increased from 26°C in 1986 to 65°C in 1994." The highest registered conductivity of 124 mS cm^{-1} corresponds to Popocatepetl (Armienta et al. 2000).

Lake Isabella in the island with the same name located in front of Nayarit, at the Pacific Ocean, represents a rare case of meromictic water body of Mexico with low water transparency (10 cm approx.) of abiogenic and biogenic origin combined (Alcocer and Hammer 1998; Alcocer et al. 2007b), surface temperature around 26–33 °C, and dissolved oxygen at oversaturation. Three well-defined strata by haloclines include the following conductivity ranges: 70–80 mS cm^{-1} (0–3 m of depth), 80–100 mS cm^{-1} (4–12 m of depth), and 100–113 mS cm^{-1} approx. (14–18 m of depth), with permanent anoxia at the third layer. Salinity exceeds values characteristic of seawater (68–112 g l^{-1} vs. 35 g l^{-1}), and calcium and magnesium hardness reaches 140–180 mg l^{-1} and 840–1070 mg l^{-1}, with total P and soluble N at the deep waters in extreme values as high as 97 mg l^{-1} and 16 mg l^{-1}, respectively. In contrast, Kienel et al. (2013) obtained four temperature profiles to conclude that Lake Isabela chemically stratifies on an annual basis. Also, the dissolved oxygen data suggest that the water column mixes annually to the bottom.

1.5 Water Management

According to data provided by CONAGUA (Atlas del Agua 2016), the impact in Mexico of productive activities and human settlements involves an interesting paradox between (1) renewal water, (2) human population, and (3) gross national product (GNP): the southeast contains two thirds of 1 but 20% of 2 and 3, while the north, center, and northeast include one third of 1 but 80% of 2 and 3. Moreover, 80% of freshwater lies in impoundments below 500 m a.s.l., and only 5% above 2000 m a.s.l.; conversely, 76% of Mexicans dwell at the Mexican highlands (e.g., the Mexican Plateau) (Athié 1987; INEGI 1995), as well as two thirds of the manufacturing industry and agricultural land.

A careless use of the hydric reserves in Mexico derives from government plans centered on the economic progress in detriment of the ecosystems stability (Alcocer and Bernal-Brooks 2010). In this way, the increasing demands for clean water by human settlements as well as agricultural and industrial sectors entail a struggle to obtain most of the hydric resource available no matter the social consequences at the long term for future generations. To meet such immediate needs, the Mexican government strategy includes water impounding at the land surface or extraction from underground sources.

Hoz-Zavala and De-la-Lanza-Espino (2002) consider that in Mexico “the high evapotranspiration, aquifers overexploitation, eutrophication of epicontinental water bodies by a constant supply of nutrients and organic/toxic inorganic loadings, including wastewaters without treatment with final deposition into lakes and rivers, produce deterioration of the hydric resource availability”.

On the basis of information provided by CONAGUA, Mexico City becomes the origin of huge contamination for the surrounding areas, especially Balsas, Lerma-Santiago Pacific, and Pánuco basins. As a mortgage for all kinds of life in peripheral areas of human development, the temporary benefits of short- and middle-term projects based on water demands, especially those depending on water at deep soil – stored by long-term geologic processes – turn out to be a bill kept in advance for future generations. Of course, after use, the original water characteristics change by aggregation of wastewaters into neighboring rivers and the sea as final deposition. In sum, all the running waters in the list appear with anthropic impact because of the proximity with human settlements and agricultural/industrial areas (see Tables 1.3, 1.4, and 1.5).

Besides, the water quantity and quality decreases with human consumption, even a tendency to a more desert climate has been postulated for lakes located at the Mesa Central (Bernal-Brooks and MacCrimmon 2000; Bernal-Brooks 2002; Bernal-Brooks et al. 2002b; Gomez-Tagle-Chávez 2001; Gomez-Tagle-Chávez et al. 2002) in order to explain a generalized situation of low water levels during the last 40 years. Lakes and rivers disappear, especially in desert areas at the Mesa Central, as well as all the local flora and fauna associated. The drop of groundwater levels in Valle de Santiago, Guanajuato, was followed by decrease in lake levels, desiccation of springs, and salinization of the natural waters in the area

(Alcocer et al. 2000; Escolero-Fuentes and Alcocer 2004; Kienel et al. 2009; Alcocer and Bernal-Brooks 2010), a scenario forecasting the fatal destination of other crater lakes and ciénegas in Mexico.

Recent findings about the nutrient that limits the aquatic productivity differ from what is usual in the northern countries (P, Elser et al. 1990), as in Mexico which might be either phosphorus (P) or nitrogen (N); temporal and spatial differences may appear lake-to-lake and sometimes within one single water body (Bernal-Brooks et al. 2016; Ramírez-Olvera et al. 2009). This information becomes crucial to cope with pollution for water treatment strategies, and this part is still missing in most cases.

Mexico progressive desertification causes impacts in areas with strong deficit of this invaluable natural resource, able to provide the continuity of life in human settlements as well as the development of agriculture/industry, a cornerstone for societies based on consumption. Thus, a little availability of the liquid in a predominantly desert country demands, certainly, a wise management – a balance between use (including recycling) and conservation. An economic development without ecological restriction becomes a threat for the human society viability as such. The exchange of the natural resources for money already took its toll at the arid frontier of Central Mexico; this is a clear example to consider new ways of relationship with nature.

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Chapter 2
Biodiversity in Inland Waters

Javier Alcocer and Verónica Aguilar-Sierra

2.1 History

The diversity of ecosystems and habitats in Mexico has played a very important role in the development of epicontinental aquatic communities, many of which occupy important surfaces, mainly in (a) the Gulf of Mexico region, in the States of Tamaulipas and Veracruz; (b) the southeastern region, in the States of Tabasco, Campeche, and Chiapas; (c) the tropical Pacific region, in the State of Nayarit; and (d) the central region, in the States of Jalisco and Michoacán (Arriaga Cabrera et al. 2000).

In order to establish epicontinental aquatic biodiversity conservation and rehabilitation priorities, several exercises were carried out consisting in regionalizations and inventories at different scales to identify those areas or sites in which important ecological and evolutionary phenomena occur, as well as to maintain viable populations, natural habitats, and processes that allow for a response toward large-scale disruptions and long-term changes. Thus, the time and space analysis scales have been varied and dependent on the established objectives. The following is a listing of the major epicontinental aquatic ecosystem regionalization and inventory exercises that include Mexico.

J. Alcocer (✉)
Grupo de Investigación en Limnología Tropical, FES Iztacala,
Universidad Nacional Autónoma de México, Tlalnepantla, Mexico
e-mail: jalcocer@unam.mx

V. Aguilar-Sierra
Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO),
Tlalpan, Mexico
e-mail: vaguilar@conabio.gob.mx

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2.1.1 Freshwater Ecoregions of the World

This map represents a biogeographical regionalization of the epicontinental aquatic systems of the world. It is mainly based on the distribution and composition of fish species of epicontinental waters, as well as information on their main ecological and evolutionary patterns, the types of habitats, and associated information (Abell et al. 2008).

A total of 19 ecoregions have been identified in Mexico only, as well as 8 border ecoregions: 6 at the border with the United States (Southern California Coastal-Baja California, Guzmán-Samalayuca, Colorado, Gila, Upper Rio Grande-Bravo, and Lower Rio Grande-Bravo); one at the border with Guatemala, Belize, and Honduras (Quintana Roo-Motagua); and one at the border with Guatemala, El Salvador, Honduras, and Nicaragua (Chiapas-Fonseca). The ecoregions selected based on the important number of endemisms were the Pánuco River, belonging to the Neotropical zone, with tropical and subtropical coastal habitats, and the Mayran-Viesca region, located in the Nearctic zone, characterized by its endorheic basins and desert habitats.

The Freshwater Ecoregions of the World map is a useful tool at the global and regional levels to carry out efforts regarding planning and conservation of aquatic biodiversity since it serves as a reference framework for establishing large-scale conservation strategies, as well as providing the base for one of the existing approximations toward practical knowledge on the biogeography of ichthyofauna.

2.1.2 Priority Hydrological Regions

In light of the need to assess the state of information regarding epicontinental aquatic diversity and the biological value of Mexican hydrological basins, in addition to assessing direct and indirect threats to resources and the potential for their conservation and appropriate use, the National Commission for the Knowledge and Use of Biodiversity (CONABIO) started Mexico's Priority Hydrological Regions (RHP, in Spanish) program (Arriaga Cabrera et al. 2000) with the purpose of developing a reference framework to contribute to the conservation and sustainable use of the country's limnetic environments.

As part of that program, a diagnostic was made of the epicontinental water environments to select those areas which would be singled out based on their biological richness, level of general knowledge or lack of information, current and potential use activities, current and potential negative impacts on their biodiversity, environmental services, and conservation efforts and use. The analysis unit used in this study was the hydrological basin, defined as "the minimal area of natural delimitation to implement an ecosystem approximation into the analysis, planning, management and sustainable use of epicontinental hydrological resources" (Arriaga Cabrera et al. 2000).

One hundred and ten RHPs were identified for their aquatic biodiversity, of which 75 (68.2%) corresponded to areas of high biological richness with potential

Table 2.1 Number of priority hydrological regions of Mexico (RHPs in Spanish) by large hydrological regions (GRH in Spanish) and their statuses

GRH	RHP No. (%)	AAB No. (%)	AU No. (%)	AA No. (%)	ADC No. (%)
Northwest region	22 (20)	15 (68)	16 (73)	11 (50)	6 (27)
Tropical Pacific region	10 (9)	8 (80)	8 (80)	8 (80)	1 (10)
Northern plateau region	22 (20)	15 (68)	20 (91)	20 (91)	7 (32)
Central region	16 (15)	9 (56)	12 (75)	10 (63)	2 (13)
Gulf of Mexico region	13 (12)	11 (85)	9 (69)	10 (77)	2 (15)
Southeast region	27 (24)	17 (63)	17 (63)	16 (59)	11 (41)
Total	110 (100)	75 (68)	82 (75)	75 (68)	29 (26)

AAB = high-biodiversity areas, AU = areas of use, AA = threatened areas, ADC = areas which lack scientific knowledge

for conservation, 82 (74.6%) corresponded to use areas, and 75 (68.2%) were facing some king of threat. Furthermore, 29 (26.4%) areas were identified as biologically important but lacking sufficient scientific information regarding their biodiversity. Table 2.1 shows RHPs sorted into large hydrological regions and status.

Of the 110 RHPs, 68% corresponded to high biodiversity areas. The largest group (17) is located in the southeast region, followed by the northwest and northern plateau regions with 15. It is necessary to mention that the large hydrological regions with the highest percentages of diversity are the Gulf of Mexico (85%) and the tropical Pacific (80%) regions (Annex 1).

High biodiversity RHPs are a mosaic of aquatic environments that are kept in a good state of ecological conservation that, altogether, represent resources that need to be preserved due to their current and potential economic importance, their ecological roles, and the value that nature itself represents.

As such and given the accelerated loss of aquatic environments, it is necessary to protect an area large enough to ensure the conservation of these ecosystems and water resources per se. Therefore, an important strategy for the conservation of biodiversity is the creation of adequate incentives for users of the resources within and outside the protected natural areas, not only at a regional level but at a national and international one as well. This requires well-designed innovative management programs in carefully selected sites where local community participation is effective and participatory (UNEP 1995).

2.1.3 Gaps and Omissions Analysis in Conservation of Epicontinental Aquatic Biodiversity of Mexico

Mexico participated in the Seventh Conference of the parties (COP-7) of the Convention on Biological Diversity (CBD) in 2004 during which it was agreed to strengthen the protected area systems through a Program of Work on Protected Areas (SCBD 2004). One of the commitments of this program consisted in determining the gaps and omissions in biodiversity conservation with the purpose of having an effective network of protected areas that adequately represent biodiversity, as well as strengthening management plans and financing mechanisms (CONABIO-CONANP 2010).

For this purpose and after two expert workshops, biodiversity elements and conservation goals were chosen (3536 conservation objects), and costs were determined due to (39) pressure factors. The criteria and values of the goals and costs were defined for the seven hydrographical regions into which the Mexican territory was divided: Plateau, Central, Gulf of Mexico, North-west, Tropical Pacific, Yucatan Peninsula, and Baja California Peninsula, as well as by functional altimetric zone—high, medium, and low basin (Garrido et al. 2008).

The analyses were made with the 1.8 version of the Marxan program using a grid of 83,091 hexagons of 25 km^2 each that allowed for having homogeneous sampling units. The grid resolution was determined based on analysis feasibility and pertinence of the variables used at that scale. 10,000 runs were executed with 1000,000 iterations each. A border factor of 0.5 was used, as well as a penalty factor of 10, to guarantee the achievement of the goals in all of the selected conservation objects. The advantage of this program is that it provides good solutions to complex problems, allows for the identification of irreplaceable sites to reach the conservation goals, and incorporates a large number of pressure factors (Lira-Noriega et al. 2015).

In this case, the best solution of the program was selected with a representation of 24,775 hexagons covering 30% of the country's surface. It accomplishes over 94% of the conservation goals. The Plateau was the region with the largest area with a 28% of the total national territory, followed by the Northwest region (19%) and the Central region (17%). The smallest region was that of the Yucatan Peninsula with 6%. However, the largest percentage of hexagons of the best solution and irreplaceable corresponded to the Tropical Pacific and the Gulf of Mexico regions, followed by the Central region (Table 2.2).

Regarding the conservation objects, the Gulf of Mexico was the region with the most (25%), followed by the Central region with 19%. The region with the fewest conservation objects was the Baja California Peninsula. Furthermore, the number of threats remained similar throughout all regions, though the Northwest, followed by the Central region, presented the most threats with a total of 33 and 32, respectively (Table 2.2).

The sites were sorted into three priority levels (extreme, high, and medium) for each of the seven regions. At a national level, the extreme priority sites added up to 5201 hexagons that corresponded to 6.4% of the total number of hexagons, 6154 high priority sites that represented 7.6%, and 12,600 medium-priority sites representing 15.5% (Table 2.3).

The Central region was the one that presented the highest number of extreme priority sites (20.9%), followed by the Gulf of Mexico region (18.5%); with high priority sites, the Central region (25.5%) and the Plateau region (22.2%); and with medium priority, the Gulf of Mexico region (23%) and the Plateau region (22%) (Table 2.3).

Table 2.2 Total area, number, and percentage of total hexagons (sampling units) of the best solution and irreplaceable and number of conservation objects and threats of the gaps and omissions analysis in epicontinental aquatic biodiversity conservation

Region	Total area, km² (%)	Total no. of hexagons	Total no. (%) of hexagons of the best solution	No. (%) of irreplaceable hexagons	No. of conservation objects	No. of threats
Plateau	560,316 (28%)	22,967	4897 (21.3%)	188 (0.82%)	779 (10%)	29
Central	348,026 (17%)	13,915	4943 (35.5%)	437 (3.14%)	1476 (19%)	32
Gulf of Mexico	271,156 (14%)	11,720	4725 (40.3%)	430 (3.67%)	1889 (25%)	31
Northwest	375,147 (19%)	15,871	4406 (27.8%)	206 (1.3%)	1029 (13%)	33
Tropical Pacific	129,871 (7%)	5880	2380 (40.5%)	214 (3.64%)	1028 (13%)	31
Yucatan Peninsula	115,006 (6%)	5227	1077 (20.6%)	168 (3.21%)	1092 (14%)	28
Baja California Peninsula	137,103 (9%)	7511	1527 (20.3%)	101 (1.34%)	484 (6%)	31

Table 2.3 Total number of sites (hexagons) by priority and for each region of the gaps and omissions analysis in epicontinental aquatic biodiversity conservation

Priority	Plateau	Central	Gulf of Mexico	Northwest	Tropical Pacific	Yucatan Peninsula	Baja California Peninsula	Total
	Hexagon number							
Extreme	749	1087	960	784	616	364	641	5201
High	1367	1567	861	966	767	215	411	6154
Medium	2781	2289	2904	2656	997	498	475	12,600
Void	17,865	8967	6728	11,069	3246	3989	5300	57,164
Total	22,762	13,910	11,453	15,475	5626	5066	6827	81,119

The gaps and omissions analysis in conservation showed that, at a national scale, the priority sites cover an area of 598,875 km², but only 15.8% of the surface of these sites is considered for some kind of protection (i.e., federal, state, municipal, or certified protected areas). Furthermore, only 32.2% of the protected areas' surface coincides with the priority sites for epicontinental aquatic biodiversity conservation, which indicates large gaps in inland water biodiversity conservation, as well as a lack of representation of these ecosystems within the Natural Protected Areas (ANP in Spanish) system of the country (CONABIO-CONANP 2010). This low representativeness is due to the fact that the selection of these areas has focused on the conservation of land ecosystems, casting aside inland water ecosystems, especially wetlands, many of which are under high use pressure and very altered.

It is important to mention that the analysis of gaps and omissions in epicontinental aquatic biodiversity conservation is based on the best scientific information readily available and is a reference framework to ensure the viability of the ecological processes in the long term and in situ conservation of aquatic biodiversity. Furthermore, it is a tool that provides technical information for decision-making in matters of management, research, planning, and formulation of public policies that may contribute to reducing threats and reversing deterioration processes of water environments (CONABIO-CONANP 2010).

2.1.4 The National Wetland Inventory

The interest in knowing the value of wetlands and the need to preserve them counter the transformation trends, generating conflicts that, in order to be solved, call for the creation and implementation of conservation policies based on updated inventories that support putting programs in place for their management, with reliable information, at a local, regional, and national level (https://www.gob.mx/conagua/acciones-y-programas/inventario-nacional-de-humedales-inh).

It is CONAGUA's responsibility to keep and maintain the National Wetland Inventory (INH in Spanish), as well as to determine their areas; sort them; suggest regulations for their protection, restoration, and use; promote and undertake actions and establish the needed measures to rehabilitate or restore them; and establish a natural surrounding or protection perimeter of the wet areas to preserve their hydrological conditions and ecosystems. All of the above have the general purpose of having cartographic, environmental, and statistical information to lead decision-making and support management in terms of their sustainable use, conservation, and relationship with climate change (https://www.gob.mx/conagua/acciones-y-programas/inventario-nacional-de-humedales-inh).

The multi-scale approach of the INH, along with its assessment and monitoring components, will enable obtaining hierarchically organized information based on the level of detail with which wetlands and their conditions are characterized. In this case, the scale at the national level is of 1:1000,000, by hydrological basin 1:250,000, by wetland complex 1:50,000, and by wetland 1:20,000 (http://sigagis.conagua.gob.mx/Humedales/).

Currently, the INH has an interinstitutional and multipurpose information system via a wetland visualizer that offers users an analysis and information platform through geospatial consulting tools pertaining to wetland administration in Mexico. It also offers normative, technical, and legal information such as the guidelines for hydrological delimitation and establishment of protection perimeters for wetlands, the guidelines for wetland classification, the methodologies for the drawing of maps at a national level, for the evaluation of wetlands at a basin and site level, and the catalogue and illustrated guide of plants indicative of wetlands, among others. Furthermore, it contains information on case studies at a national level and a priority basin selection strategy for wetland care (https://www.gob.mx/conagua/acciones-y-programas/visualizador-de-humedales-de-la-republica-mexicana-inventario-nacional-de-humedales).

There is also information generated by other institutions that collaborate with the INH on topics of fauna and flora inventories, invasive species, species in some kind of protection category, a national mangrove and forest inventory, protected natural areas, mapping related to physical characteristics, types of vegetation, and some elements of human activity, among others. In its second phase, the INH will provide information regarding the types of wetlands and their uses, as well as their state of conservation and their associated natural resources (https://www.gob.mx/conagua/acciones-y-programas/instituciones-que-colaboran-en-el-inh).

In Mexico, in terms of the law, authorities and society both have access to a broad range of environmental policy instruments aimed at better planning and management regarding the sustainable use and protection of aquatic biodiversity and its environmental services. The following are among these.

2.1.5 The Ramsar Convention on Wetlands: Mexico

The Ramsar Convention is the intergovernmental treaty that offers a framework for the conservation and rational use of wetlands and their resources. Mexico has been a part of the Ramsar Convention since 1986 and the government body in charge of leading the application of The National Commission of Natural Protected Areas (CONANP, in Spanish) as part of the Federal Government. Mexico has 142 Ramsar sites, accounting for a total surface of 8,657,057 hectares. Fifty-two of these sites correspond to continental wetlands such as swamps, lakes, rivers, high mountain wetlands, oases, karstic systems, and sites with threatened species (https://www.ramsar.org/es/humedal/mexico).

2.1.6 National Wetland Policy

The National Wetland Policy (PNH in Spanish) tackles the urgent need to create a governing instrument to establish holistic objectives and goals, define priorities, coordinate actions, and allow for compliance of the commitments adopted in the Convention on Wetlands (Ramsar, Iran, 1971).

The PNH includes all national territory wetlands: those protected through a natural protected area decree at a federal level and listed in the Ramsar Convention, as well as those lacking a protection figure (SEMARNAT 2014).

Finally, the PNH not only aligns the actions of different federal public administration bodies but will also promote their dissemination with state and municipal authorities, civil society, and the academic sector in order to promote active participation in their implementation, which will generate synergy between other government and social actions and this policy.

2.1.7 State Biodiversity Studies and Strategies

Planning for conservation and sustainable use of biodiversity is a continuous and dynamic process that must reflect the changes within the socioenvironmental setting. The generated strategies and action plans represent important instruments for establishing basic goals and objectives (in the short, medium, and long term) and courses of action and allocating the necessary resources to reach the set goals (http://www.biodiversidad.gob.mx/region/EEB/estudios.html).

In order to reach the objectives established in the United Nations Convention on Biological Diversity (CBD) and execute the actions established in the National Strategy on Biodiversity of Mexico (ENBM in Spanish) from a national perspective, the CONABIO, in collaboration with state governments and representatives of different sectors of society, has begun working on the creation of the State Biodiversity Strategies (EEB in Spanish), a process that takes the cultural, geographical, social, and biological diversity of Mexico into account.

2.1.8 Environmental Flow and Water Reserves (WWF-FGRA-CONAGUA)

One of the management instruments that establishes the quality, quantity, and water flow regime required to maintain the components, functions, processes, and resilience of water ecosystems that provide goods and services to society is the environmental flow. As such, the environmental flow seeks to reproduce, to some extent, the natural hydrological regime by preserving the stationary patterns of minimal and maximum flows, that is, drought and rain periods, respectively, its flooding regime and rate of ecological exchange, which are of special interest regarding management of hydraulic or hydroelectric infrastructure.

To balance environmental and socioeconomic demands regarding water, the environmental flow's determination is based on the definition of the management objectives for each section of river, subbasin or basin, depending on their ecological state and the amount of use pressure. This enables the definition of the hydrological regime to maintain ecological processes such as reproduction, migration, diet, species succession, etc., as well as connectivity throughout the entire basin and long-term hydrological balance which determines water availability for all (WWF 2010).

The WWF (World Wildlife Fund) Mexico-Gonzalo Río Arronte Foundation, I.A.P. (FGRA) Alliance, in collaboration with CONAGUA (The National Water Commission) and other government bodies, academic institutions, organizations, water users, and rural communities, made very different environmental flow proposals with contexts of conservation, pressure, and management in 33 sites in three basins: Conchos in Chihuahua, Copalita-Zimatán-Huatulco in Oaxaca, and San Pedro Mezquital in Durango, Nayarit, and Zacatecas (WWF 2011).

Based on these experiences, CONAGUA, as an authority in matters of administration, management, and conservation of water resources, summoned and led a working group for the creation of the Mexican Environmental Flow Regulation, in which the WWF-FGRA was invited to participate as technical secretary given their experience on the matter.

The objective of the group was to establish a procedure and its technical specifications in order to define the environmental flow regime in national currents and bodies of water in a hydrological basin, the application and results of which would direct the yearly average availability agreements, concessions and allocations of water, as well as the development of an infrastructure and other projects that would imply water transfers between basins (WWF 2011).

Two key adopted concepts were the Natural River Paradigm (Poff et al. 1997) and The Biological Condition Gradient (Davies and Jackson 2006). This way, the natural hydrological regime is acknowledged as the main driver of change in a variable physical environment to which the ecosystems and species that inhabit them have adapted, and therefore, the alteration of which leads to the degradation of ecosystems and biological integrity.

Methodologies that are hydrological, hydrobiological, or of habitat and holistic simulation are all of them acceptable for the implementation of the environmental flow regulation as long as they put into practice the key scientific foundations:

- They must allow for an ecological understanding of each component of the natural hydrological regime and generate functional proposals for its conservation or restoration.
- Proposals will have to consider the natural range of hydrological variability in regular conditions and in a flooding regime as well.
- It must be acknowledged that an aquatic ecosystem modifies its attributes as a response to the increase of stress levels. This therefore allows for an adjustment of the environmental flow proposals to the river's environmental or conservation objectives.

Based on the above, the Environmental Flow Norm NMX-AA-159-SCFI-2012 was created, a norm that promotes a holistic management of water resources and a regulation of water demands by managing its supply. It favors the strategic conservation of biodiversity through the protection of the components of the hydrological regime and promotes the resilience of society and the ecosystems faced with the impacts of climate change (drought and flood management).

Upon the need to incorporate the "environmental dimension" into water resource management processes with the objective of reducing the ecologic fragility of aquatic ecosystems and achieving a better adaptation to climate change, the WWF-FGRA Alliance and CONAGUA proceeded to carry out a study to identify the country's hydrological basins with water availability that, due to their biological richness, ecological importance, and low water pressure, presented favorable conditions to establish water reserves that would guarantee flows for ecologic protection (https://www.gob.mx/conagua/acciones-y-programas/programa-nacional-de-reservas-de-agua-pnra-para-el-medio-ambiente).

This analysis identified 189 feasible basins for establishing water reserves, which enabled the establishment of the National Water Reserves Program (PNRA) with three main objectives: (i) establishing a national water reserve system; (ii) proving the benefits of water reserves as an instrument to guarantee the functionality of the hydrological cycle and its environmental services; and (iii) strengthening the capacity for applying the environmental flow norm throughout the country (CONAGUA-WWF-FGRA 2011).

The water reserve is a legal instrument created by the National Water Law to care for a basin's water in the present and the future. It consists in allocating part of the yearly volume that flows naturally for the conservation of ecosystems. This volume must remain in the river or body of water and therefore cannot be extracted for any purpose, except in situations that may put the population's supply at risk. This permanence of water in the environment represents the continuity of the hydrological cycle and its functionality. The interaction that the cycle has with the basin is a very important and diverse source of environmental or ecosystem services which are seldom acknowledged or appreciated (WWF-FGRA-CONAGUA-BID 2012).

Some of the program benefits are (i) hydrological connectivity in basins and wetlands (300 basins, 74% of the total); (ii) conservation of wetlands and activities carried out within them; (iii) better resilience conditions (adaptation to climate change) and carbon capture in wetlands; (iv) legal guarantee of water (decree); (v) creation of capacity and water culture in terms of its conservation and protection; (vi) complementing the biodiversity conservation strategy and its environmental services in 97 protected natural areas (54% of the total), 55 Ramsar sites (39% of the total), and 78,500 km^2 of additional basins; (vii) joint management of ground and superficial waters; and (vii) support for several environmental services such as storage, piping, and supply and improvement of water quality and protection against extreme events (WWF 2012).

2.2 Biodiversity

Mexico is one of the world's most biologically diverse countries, which represents an important contribution to national heritage. Its location between tropical and temperate regions and its uneven topography favor the development of a large variety of aquatic environments, as well as a biota that is diverse and rich in native species (Alcocer et al. 1993; SEDESOL 1993; INEGI 1995).

According to CONAGUA (2014), two thirds of the territory are considered to be arid or semi-arid land with precipitations under 500 mm, while the southeast is humid with average precipitations above 2000 mm per year. Additionally, between 1950 and 2000, the country's population quadrupled and went from being mostly rural to predominantly urban, a situation that does not correspond to the availability of water resources (National Institute for Statistics and Geography INEGI 2014). This has caused an imbalance of supply and demand of resources (López-Portillo and Ramos 1982) that has led to the overexploitation of the aquifers and to transfers of water between basins.

Water disparity is not only latitudinal but also seasonal and altitudinal. Ninety percent of rainwater is discharged during rainy season (from May to October), which translates into a lack of rainwater for the remaining 6 months of the year. Furthermore, 80% of the vital liquid's altitudinal distribution is located below an altitude of 500 m and only 5% above one of 2000 m. Also, according to the General Population and Housing Census 2010 (INEGI 2014), 53.2% of the country's population lives at altitudes over 1500 m above sea level.

This latitudinal, altitudinal, heterogeneous distribution makes it very difficult to develop programs for management and appropriate use of water, as well as to preserve its quality and volume (Athié-Lambarri 1987), something that has had a direct impact on the biodiversity of Mexican inland waters.

In Mexico, there are close to 731 hydrological basins, which represent and average yearly volume of 471.5 billion cubic meters of renewable freshwater (CONAGUA 2014). On the basis of the conducted volume, 50 basins stand out through which 87% of the surface runoff travels and the basins of which cover 65% of the country's continental territory surface. Seventeen of these flush out into the Gulf of Mexico and the Caribbean Sea and 32 into the Pacific Ocean and the Sea of Cortez. Moreover, the yearly precipitation average in the country is 1489 billion m^3, 71.6% of which is evaporated/transpired and returns to the atmosphere, 22.2% trickles down into rivers and streams, and the remaining 6.2% infiltrates the soil naturally and refills the aquifers (CONAGUA 2014).

Regarding groundwater, there are over 653 registered aquifers in the country, of which 106 are currently overexploited. The approximate volume of water that was extracted from them in 2013 was of a little over 30 km^3/year (CONAGUA 2014). 55.2% of all groundwater is extracted from overexploited aquifers for all types of uses: mainly agricultural, followed by public supply and industry. Aquifer overexploitation has caused the exhaustion of natural springs, the disappearance of lakes and wetlands, the reduction of rivers' baseflows, the elimination of native vegetation, and the loss of ecosystems, as well as a deterioration of many aquifers' water quality, mainly due to saline intrusion and migration of low-quality fossil water (CONAGUA 2014).

Inland or epicontinental waters are divided into lotic and lentic bodies. Among lotic environments (i.e., rivers and streams), in the Pacific watershed, the rivers Colorado, Yaqui, Fuerte, Sinaloa, Culiacán, San Lorenzo, Piaxtla, Presidio, Baluarte, Acaponeta, San Pedro, Lerma-Santiago, Armería, Coahuayana, Balsas, Papagayo, Ometepec, Verde, Tehuantepec, and Suchiate can be highlighted. These rivers are usually small, with rapid flows, steep slopes, low discharge volume, non-navigable, and with a long summer period, with the exception of the Lerma-Santiago and the Balsas.

In the Gulf of Mexico watershed, the rivers Bravo, Pánuco, Nautla, Tuxpan, Cazones, La Antigua, Tecolutla, Jamapa, Papaloapan, Coatzacoalcos, Grijalva-Usumacinta, and Candelaria are characterized by their extensiveness, slow flow, soft inclines, large discharge volumes, navigability, and a short summer period. Lastly, from the inland basins, the rivers Nazas, Santa María, Casas Grandes, Carmen, Aguanaval, and De la Cadena can be highlighted. These rivers are of great local importance because, in spite of their reduced discharge volume, they constitute an important element in the regional economy.

Furthermore, it is worth mentioning poor superficial currents characterize the peninsulas of Baja California and Yucatán (Bassols-Batalla 1977; Toledo et al. 1989). Regarding cross-border basins, Mexico shares eight basins with neighboring countries: three with the United States (Bravo, Colorado and Tijuana), four with Guatemala (Grijalva-Usumacinta, Suchiate, Coatán, and Candelaria), and one with Belize and Guatemala (Rio Hondo) (CONAGUA 2014).

With respect to lentic environments (i.e., lakes, ponds, and dams), it is estimated that there are over 70 lakes in the country, the extensions of which vary between 1000 and 10,000 ha, which in turn jointly cover an area of 370,891 ha. The disparity between lakes and reservoirs is very significant as the major reservoirs of 10,000 ha cover 66% of the flooded surface (De la Lanza Espino and García Calderón 2002). Chapala, Jalisco, is the largest Mexican lake, followed, in order of importance, by lakes Cuitzeo and Pátzcuaro (Michoacán), Catazajá (Chiapas), Del Corte (Campeche), Bavícora and Bustillos (Chihuahua), and Catemaco (Veracruz), among others (Alcocer and Escobar 1996).

Through time, the surface covered by bodies of water has been transformed, going from mostly natural to predominantly artificial due to the large reservoirs built to supply large irrigation areas and hydroelectric projects. There are over 5163 dams and weirs (incomplete record) with a storage capacity of 150 trillion m^3. The most important dams include La Amistad, Falcón, Vicente Guerrero, Álvaro Obregón, Infiernillo, Aguamilpa, Cerro de Oro, Temascal, Caracol, Requena, and Venustiano Carranza (CONAGUA 2014). Chiapas, with only three large reservoirs (Chicoasén, La Angostura, and Malpaso), is the federative entity with the largest water storage capacity (28% of the total at a national level). Jalisco has the highest number of dams, which store 14% of the total volume nationally (SEMARNAP 1995; Alcocer and Escobar 1996; Alcocer et al. 2000a; De la Lanza Espino and García Calderón 2002; Alcocer and Bernal-Brooks 2010; Calderón-Aguilera et al. 2012).

2.2.1 Main Aquatic Ecosystems

The enormous diversity of aquatic ecosystems in Mexico has played a very important role in the development of aquatic communities, which are not able to survive without water, matter, and energy. Therefore, the physiochemical and ecological attributes of a body of water are mainly derived from the environment that surrounds it, from human settlements, and from activities that take place within the basin. The following is a description of the main systems and their characteristics.

2.2.1.1 Lotic – Rivers and Streams Systems

River systems house a great diversity of fish, crustacean, mollusk, and insect species, which are key resources in food webs. They are also notable for their biological diversity since many sustain exclusive ichthyofauna. Some examples are the

Table 2.4 Percentage of endemic fish for different basins in Mexico

Basin	Total species	% of endemisms
Lerma-Santiago	57	58
Usumacinta-Grijalva	NA[a]	36
Pánuco	75	30
Balsas	20	35
Ameca	NA[a]	32
Papaloapan	47	21
Coatzacoalcos	53	13
Conchos	34	21
Tunal	13	62

Miller (1986)
[a]*NA* not available information

Lerma-Santiago basin, characterized by its high degree of endemism in the Goodeidae and Atherinidae families; the Grijalva-Usumacinta system and the Pánuco River with endemic species of the Poeciliidae and Cichlidae families; and the Tunal River, with endemisms mainly of the Cyprinidae family (Espinosa-Pérez et al. 1998; Miller 1986). Table 2.4 shows the percentages of endemic fish species in different basins.

Maintaining the integrity of these communities requires special management and, in some cases, protection against desiccation, piping, pollution, deforestation, road construction, intensive recreational use, and other types of exploitation. Their scarce protection has caused them to become very degraded due to their use.

2.2.1.2 Lentic – Lakes and Ponds Systems

Location and uneven topography favor the development of a large diversity of bodies of water, as well as a diversified biota that is rich in native species. In terms of geochemical flows of organic and inorganic matter, lakes are independent from land systems. Therefore, the physiochemical and ecological attributes of a lake mainly stem from the natural environments that surround them—the drainage or hydrographic basin—of human settlements and the activities that take place within the basin (Arriaga Cabrera et al. 2000).

Among these ecosystems, a series of lakes are worth mentioning of tectonic-volcanic origin and with particular characteristics: the crater and the alpine-tropical lakes, as well as oases and sinkholes. There are also lakes located in the arid basins of northern Mexico called playa lakes, which are of the endorheic type and that, due to their evolution and climate conditions, are in an advanced state of desiccation (De la Lanza Espino and García Calderón 2002).

Located in the northern and central regions of the country are saline lakes. This type of ecosystem is favored by the association of endorheic basins and semi-arid climate (Alcocer and Hammer 1998); however, they are very threatened by anthropogenic activities and climate change, mostly because the trend in these regions is moving toward a change in aridity and a reduction of precipitation.

The magnitude and persistence of these stress factors, both natural and human, on saline lakes are leading, in many cases, to the loss of resilience of these ecosystems or their extinction. An example of this situation is the desiccation of the Valle de Santiago lakes, Guanajuato (Alcocer et al. 2000b); Lake Texcoco, Mexico (Alcocer and Williams 1996); as well as the existing threat on Lake Alchichica, Puebla (Alcocer et al. 1996; Alcocer and Escobar-Briones 2007).

Among the most important lake systems given their diversity and the high number of known endemisms, it is important to highlight Lake Chapala, the crater lakes of the Cuenca Oriental, particularly Alchichica, Lake Catemaco, and the "pozas" of Cuatro Ciénegas. The ones formed by recent volcanism are also present and located on the Neovolcanic Belt, as is the case of the Lakes Zacoalco-Sayula, in Jalisco, and Lakes Pátzcuaro, Zirahuén, Cuitzeo, and Zacapu in Michoacán, all of which are under threat by human activities (De la Lanza Espino and García Calderón 2002). Espinosa-Pérez et al. (1998) and Miller (1986) also include Lagunas Chichancanab in Quintana Roo and La Media Luna in San Luis Potosí and warn of the need to preserve biodiversity in these bodies of water.

2.2.1.3 Wetlands

Wetlands are complex, dynamic, and highly productive ecosystems. They take place in continuously and intermittently flooded sites, whether by drainage toward a depression, by ground currents, or by excess in the precipitation rate with respect to evapotranspiration (Brooks et al. 1997). There are different biota communities in continental wetlands among which gallery vegetation, the low floodable jungle, the floodable palm grove, the savannah, the mangrove, the floodable thorn scrubland, the floodable thorn scrub, the thornless scrub, the popal, the tular, the reed bed, and floating vegetation can be highlighted (Lot 2004; Lot et al. 2015).

Due to their diverse shapes and sizes depending on their geographic location, physical structure, and chemical composition, wetlands provide habitat, food, shelter, and rearing and reproduction areas for a large number of fish, bird, amphibian, reptile, mammal, and invertebrate species (Sánchez 2007). Their high level of endemisms, particularly of fishes and invertebrates, recognizes them by its highly specialized fauna and by their representing a refuge for a great diversity of migratory bird species. Some examples are the Pantanos de Centla in Tabasco, Cuatro Ciénegas in Coahuila, Ría Lagartos in Yucatan, the Marismas Nacionales in Nayarit, and Xochimilco and Tláhuac in Mexico City.

Wetlands also play a very important ecological role when it comes to the control of erosion, sedimentation and flooding, water supply and purification, and maintenance of fisheries. Currently, these systems have lost considerably due to the drainage and refilling of their areas for different uses (Arriaga Cabrera et al. 2000).

2.2.2 Biological Richness

The importance of hydrophilic vegetation in aquatic ecosystems consists in the infinity of interactions that plants have between them and especially with aquatic fauna, as well as in the environmental services that they provide. Among the most important aquatic vegetation communities that can be highlighted are the popals of the *Calathea* and *Thalia* genders that cover large swamp extensions and shallow waters in southwest Campeche, Tabasco, northern Chiapas, and southern Veracruz. Tules and reed beds that grow in lake and swamp environments, or in the banks of rivers with muddy beds and calm waters, are made of cattails *Typha* spp., common reeds *Phragmites communis*, sedges *Scirpus californicus,* and *Cyperus giganteus*. The gallery forest or riparian vegetation contains a group of trees that grow on riverbanks under favorable humidity conditions: such is the case of the Montezuma cypress *Taxodium mucronatum* (Arriaga Cabrera et al. 2000).

According to Miranda and Hernández-X (1963), another group is comprised of palm groves represented by the corozo palm *Scheelea liebmannii*, manaca palm *Scheelea preusii*, royal palm *Roystonea dunlapiana,* and the cocos guacuyule palm *Orbignya guacoyule*. The first are distributed in deep alluvial soils, very often floodable, of the banks of large rivers of the Gulf of Mexico; the second group can be found in identical situations but on the plains of the Pacific in the Soconusco region of Chiapas. The royal palm is often mixed with the evergreen jungle of frequently floodable areas from the central parts of Veracruz to Tabasco and in the coastal region of the northeast Yucatan Peninsula.

The cocos guacuyule palm is distributed in the Pacific slopes and plains, between Sinaloa and Oaxaca, in floodable areas or has a superficial phreatic layer. The palm trees comprised of the *Sabal* species are distributed along the shores of lakes or lagoons in south Quintana Roo (*Sabal morrisiana*) and in sandy terrains along the Pacific and Gulf coasts (*Sabal mexicana*). The paurotis palm (*Acoelorrhaphe wrightii*) can be found mainly along the flooded shores of popals or lagoons, on the shores of swamps, or within floodable savannahs in southeast Veracruz, while the sombrero palms or soyates (*Brahea dulcis*) are distributed throughout rocky limestone soils in areas of transition toward oak groves in the central area of Chiapas, in the high basin of the Papaloapan River and the Balsas River basin.

The diversity of aquatic flora corresponds to 86 families, 262 genders, and 763 species and includes ferns, gymnosperms, and angiosperms (Lot and Ramírez-García 1998). Furthermore, Mora-Olivo et al. (2013) register 240 strict aquatic plant species distributed into 106 genders and 62 families, including 227 native ones and 13 introduced. Of the total, only 8.3% are endemic to Mexico (20 species). The states that record the highest number of species are Veracruz (145), Jalisco (123), Michoacán (115), and Tamaulipas (113).

There is also a multitude of invertebrates and microorganisms that use bodies of water temporarily and permanently and that have not been studied enough regarding their biological diversity (Arriaga Cabrera et al. 2000).

At a national level, the epicontinental ichthyofauna ascends to 509 species. Approximately 300 of these are endemic to Mexico and another 48 are shared with other countries in binational basins (Hernández-Betancourt et al. 2013). Thus, one of the remarkable characteristics of Mexican epicontinental ichthyofauna is its high level of endemism.

The fish orders with the largest number of endemic species are Petromyzontiform, Cypriniform, Siluriform, Atheriniform, Cyprinodontiform, and Perciform (Miller et al. 2005; Froese and Pauly 2015). At the hydrological basin level, the largest proportion of endemic species can be found in the basins of Lerma-Santiago (70%), Usumacinta-Grijalva (36%), Balsas (35%), Ameca (38%), Pánuco (30%), and Papaloapan (21%) (Díaz-Pardo et al. 2016a, b). Among the species with a distribution limited to a region or particular site, there are several species of the *Cyprinodon* genus and of the Goodeidae and Atherinidae families (Espinosa-Pérez et al. 1998; Miller 1986).

There are also relict taxonomic and biogeographical species that appeared during the Paleozoic and that, at a global level, are currently represented by a few of them. This is the case of the lampreys *Lampetra spadicea* and *L. geminis* that inhabit the lakes and rivers of Michoacán and Jalisco and that are mainly characterized by the absence of jaws. Other examples are the sturgeons *Acipenser oxyrinchus* and *Scaphirhynchus platorynchus* from the Bravo River basin and rivers that flow into the Gulf of Mexico. Other ancestral representatives are the gars *Lepisosteus oculatus*, *L. osseus*, *Atractosteus spatula,* and *A. tropicus*. The first three are distributed throughout the water bodies of the Tamaulipas and Veracruz coastal plains, while the last one inhabits Tabasco and Chiapas (Díaz-Pardo et al. 2016a).

Fish are the most diverse group among vertebrates, yet one of the most threatened as well. This is mainly due to the fact that they live in aquatic environments that are used by humans for different purposes, a situation that has caused irreversible transformations in these ecosystems at an unprecedented scale (Díaz-Pardo et al. 2016b). Some of the most serious threats are desiccation and habitat modification, the alteration of water quality due to pollution, the introduction of exotic species, and overexploitation.

As a result, a high percentage of freshwater fish species are included in the Official Mexican Norm regarding species at risk (NOM-ECOL-059-SEMARNAT 2010). This norm includes 195 species of fish in risk categories, 11 of which are now extinct. At an international level, according to the International Union for Conservation of Nature, 167 Mexican species are catalogued in risk categories, 14 of which are considered extinct (IUCN 2015).

Regarding aquatic herpetofauna, Flores-Villela (1998) points out a richness of 285 species of amphibians and 41 reptiles mainly belonging to Testudines and Crocodylia. The amphibian families with greater endemism are Hylidae, Plethodontidae, Leptodactylidae, Ranidae, and Ambystomatidae.

The data shows a high percentage of endemisms due to uneven topography, environmental variability, and low vagility of amphibians, which has contributed to the differentiation and the specific diffusion of these isolated populations, making Mexico an exceptionally diverse country when it comes to amphibians (Table 2.5).

Table 2.5 Percentage of endemic amphibians in different natural regions

Natural regions	Endemic species	% of endemisms
Central tropical highlands	123	80
Pacific tropical lowlands	29	48
Gulf of Mexico and Caribbean	20	65

Flores-Villela (1998)

The central tropical highlands are comprised of the Central Plateau, part of the eastern Sierra Madre, and the southern Sierra and Plateau. They include southeast Nayarit; the southernmost part of Zacatecas; northern, central, and eastern Jalisco; southern Aguascalientes; Guanajuato; northern Michoacán; Querétaro (except for its northernmost region); Hidalgo (excluding the northeast); the State of Mexico (except for its southernmost region); Mexico City; Tlaxcala; Puebla (except for its north and southwest regions); the westernmost region of Veracruz; the northern part of Morelos; and the southern Sierra Madre in Oaxaca, Guerrero, and Michoacán.

The Pacific tropical lowlands cover the entire coast, the Balsas basin, and the Chiapas Valley. It includes central and southern Sinaloa, the southernmost part of Baja California, western Nayarit, the western and southernmost regions of Jalisco, Colima, central and western Michoacán (except for the Coalcoman Mountain Range), northern and southern Guerrero, central and southern Morelos; southwestern Puebla; southern Oaxaca; and southern Chiapas.

The Gulf of Mexico and Caribbean region includes small parts of the following states: the southernmost region of Tamaulipas, eastern San Luis Potosí, northeastern Hidalgo, northern Puebla, north and northeastern Oaxaca, Veracruz (except for the western central region), central, north, and northeastern Chiapas, Tabasco, Campeche, Yucatán, and Quintana Roo.

The avifauna of aquatic environments has a total of 201 species that inhabit lakes, ponds, rivers, streams, swamps, lagoons, and mangroves (NABCI/CONABIO 2009). They are resident, migratory in winter or summer, in transit, and accidental. Based on information from the CONABIO, the number of bird species, aquatic or linked to wetlands and bodies of water, is shown by guilds in Table 2.6.

It is obvious that biodiversity in aquatic environments is not homogeneous throughout national territory. The specific richness, abundance, and composition of species vary between regions, basins, and types of ecosystems. The following are some examples of the most relevant ecosystems in Mexico when it comes to biological diversity.

2.2.2.1 Lake Chapala, Jalisco

Chapala is the largest lake in Mexico. This natural body of water of tectonic origins (a graben) is located in western Mexico and has a total capacity of approximately 8000 cubic hectometers and a total surface of 114,659 hectares, 86% of which are in Jalisco and the remaining 14% in Michoacán, at an altitude of 1524 m above sea level. Lake Chapala is part of a large system of Pleistocene lake basins associated

Table 2.6 Number of bird species, aquatic or linked to wetlands and water bodies, by guild

Guilds	R	R, MW	R, MV	MW	MW, R	T	MW, T	(a) MW,MS,R (b) MW,MS,T	T, MW	A	Total
Water birds and similar	27	13		33	19					8	100
Pipits and wagtails				2						2	4
Orioles and larks	1	1		1							3
Woodpeckers, toucans, and similar	4			1							5
Jays, crows, and magpies	1										1
Warblers and similar	3			4	1			1a,b			9
Cinclodes	1										1
Cuckoos and roadrunners	1										1
Flamingos	1										1
Swallows	1							1b			2
Wrens		1			1						2
Knots, plovers, and similar	3	4		27	1	6	2	1a	3	12	59
Towhees and similar		1		1	1						3
Vireos	2										2
Birds of prey	4		1		3						8
Total	49	20	1	69	26	6	2	3	3	22	201

NABCI/CONABIO (2009)
R resident, *MW* migratory in winter, *MS* migratory in summer, *T* in transit, *A* accidental

with the Neovolcanic Belt, which is confirmed by the regional distribution pattern of silverside fishes from the Atherinidae family, silversides, locally known as "charales" (Guzmán 1989).

Thirty-nine fish species have been identified in Lake Chapala; eight species are endemic: the silversides *Chirostoma labarcae, C. chapalae*, *C. sphyraena*, *C. consocium,* and *C. promelas,* the Lerma catfish *Ictalurus dugesii,* the popoche *Algansea popoche,* and the barred splitfin *Chapalichthys encaustus*. Other native species economically relevant are the silversides *Chirostoma aculeatum, C. arge, C. estor, C. lucius*, the Chapala lamprey *Lampetra spadicea*, the tiros *Goodea atripinnis,* and *Allotoca dugesii*, the Lerma livebearer *Poeciliopsis infans*, the Montezuma swordtail *Xiphophorus montezumae,* and the picote splitfin *Zoogoneticus quitzeoensis*.

Other economically important fish species in Lake Chapala are the Amur carp *Cyprinus rubrofuscus*, the goldfish *Carassius auratus*, the catfish *Ictalurus punctatus* and *I. ochoterenai,* the Mesa silverside *Chirostoma jordani*, the introduced common carp *Cyprinus carpio*, the black bass *Micropterus salmoides*, the grass carp *Ctenopharyngodon idella,* and two tilapia species: *Oreochromis aureus* and *Oreochromis mossambicus*.

The silverside (*Chirostoma*) and the catfish *Ictalurus dugesii* and *I. ochoterenai* fisheries that were traditionally important are collapsed since 1990 due to three main factors: (a) habitat degradation associated with eutrophication and pollution, (b) overfishing and nonselective use of fishing nets, and (c) introduction of invasive exotic species that have damaged the food web and precipitated the collapse of the ecosystem (Díaz-Pardo et al. 2016b; Gutiérrez-Nájera et al. 2008). These are the reasons of the disappearance of the native cyprinid *Algansea popoche* (Lyons et al. 1998).

There are also two species of bivalve mollusks: *Anodonta chapalensis* and *A. astarte*. Among the crustaceans, there are the crayfish *Cambarellus (Cambarellus) chapalanus, C. prolixus,* and *C. montezumae*, as well as the semi-terrestrial crabs *Pseudothelphusa mexicana* (Álvarez et al. 2012).

The lake also constitutes a resting and feeding area for a large number of different species of migratory birds such as ducks and the Atlantic gull (Arriaga Cabrera et al. 2000). Other species found in the lake are the white pelican *Pelecanus erythrorhynchos*, the Mexican duck *Anas platyrhynchos diazi*, the northern pintail *Anas acuta*, the blue-winged teal *Anas discors*, the cattle egret *Bubulcus ibis*, the great (white) egret *Casmerodius albus*, the American coot *Fulica americana*, the snowy egret *Egretta thula*, the common moorhen *Gallinula chloropus*, the olivaceous cormorant *Phalacrocorax olivaceus*, the black-crowned night heron *Nycticorax nycticorax*, and the white-faced ibis *Plegadis chihi*.

2.2.2.2 Cuatro Ciénegas, Coahuila

Cuatro Ciénegas, in the states of Coahuila, is a region located in the westernmost part of the eastern Sierra Madre, in northern Mexico, with a surface of approximately 1200 km^2, an altitude of 735 m above sea level, and that is surrounded by a mountain system that reaches up to 3000 m. It is characterized by a great diversity of aquatic ecosystems, which includes wetlands such as marshes, swamps, ponds, marginal wetlands, and playa lakes. Underground currents, springs, canals, rivers, artesian aquifers, and seasonal pools are also present.

The broad diversity of habitats and the geographical isolation has allowed the aquatic fauna that inhabits these environments to develop an explosive adaptive radiation and speciation, the result of which is a high number of endemisms (McCoy 1984; Alcocer and Kato 2002).

According to Alcocer and Kato (2002), there is a rich aquatic and semi-aquatic fauna integrated by endemic species, relicts, and common broad distribution species. Of its 12 crustacean species, 6 are endemic: the isopods *Speocirolana thermydronys, Sphaerolana affinis, S. interstitialis,* and *Mexistenasellus coahuila*, and the amphipods *Paramexiweckelia particeps* and *Mexiweckelia colei* (Cole 1984). Furthermore, Hershler (1984) determined 9 mollusk genders, 5 of which are endemic, *Coahuilix, Paludiscala, Mexithauma, Mexipyrgus,* and *Nymphophilus*, and 13 species, 9 of which are endemic: *Coahuilix hubbsi, Coahuilix* n. sp., *Paludiscala caramba, Mexithauma quadripaludium, Cochiliopina milleri, Durangonella coahuilae, Mexipyrgus churinceanus, Nymphophilus minckleyi,* and *Nymphophilus* n. sp.

There are 8 fish families with 16 species, 8 of which are endemic and endangered (Minckley 1984; Contreras-Balderas 1990). Some examples of these endemic fish are the Bolson pupfish *Cyprinodon atrorus*, the Cuatro Ciénegas pupfish *C. bifasciatus*, the Cuatro Ciénegas killifish *Lucania interioris*, the Cuatro Ciénegas gambusia *Gambusia longispinis*, the Cuatro Ciénegas platyfish *Xiphophorus gordoni*, the Cuatro Ciénegas cichlid *Cichlasoma minckleyi,* and the Cuatro Ciénegas darter *Etheostoma lugoi* (Minckley 1984; Williams et al. 1985).

A total of 70 amphibian and reptile species have been recorded in Cuatro Ciénegas, 6 of which are endemic, the frog *Rana pipiens*; the turtles *Trionyx spiniferus, T. ater,* and *Pseudemys scripta;* and the water snakes *Nerodia erythrogaster* and *N. rhombifera* (McCoy 1984), and 6 are introduced or exotic. Based on the data from McCoy (1984), only 18% of its herpetofauna is aquatic or semi-aquatic, of Tamaulipas affinity, as opposed to a riparian one (20%). The remaining 62% of organisms are of the desert type, with Chihuahua affinity or similarity. In the Tamaulipas group, 44% of organisms are characteristic of the plains and desert region, 31% of the Gulf of Mexico coastal region, and the rest (25%) are endemic to the area.

Sixty-one bird species have been recorded, some of which are linked to water bodies. Some of them are the pied-billed grebe *Podilymbus podiceps*, the mallard *Anas platyrhynchos*, the northern shoveler *Spatula clypeata*, the kingfisher *Megaceryle alcyon*, the western pipit *Anthus spinoletta pacificus,* and the great blue heron *Ardea herodias* (Contreras-Balderas 1984).

The types of vegetation found there are the following: pastureland, aquatic and semi-aquatic vegetation, desert scrubland, chaparral, oak-pine and oak forest, and the high-elevation conifer forest. The flora is represented by 49 taxa, making it one of the richest of the Chihuahua desert, 23 of which are endemic (Pinkava 1981, 1984). Seventy-five species in 33 families have been recorded as belonging to aquatic or semi-aquatic environments, of which the following are some examples: the water lily *Nymphaea ampla*; the water hyacinth *Eichhornia crassipes*; the rushes and reeds *Scirpus americanus, S. maritimus paludosus, Phragmites australis,* and *Typha domingensis*; the widgeon grasses *Ruppia maritima* and *Spartina spartina*; and the salt grasses *Distichlis stricta* and *D. spicata* (Contreras-Balderas 1990; Alcocer and Kato 2002).

The high number of endemic plant and animal species makes Cuatro Ciénegas a unique place, making its conservation and protection an urgent priority in the face of the dangers that threaten it due to anthropogenic activities related to water demand for urban and agricultural use, reservoir piping with the resulting desiccation of swamp and pond areas, road construction, garbage accumulation and pasture burning for farming purposes, the grazing of goats and beef cattle, dune gypsum exploitation, immoderate mountain forest logging, and unregulated tourism (Alcocer and Kato 2002).

2.2.2.3 Cenotes of the Yucatán Peninsula

The Yucatan Peninsula has different geohydrological characteristics from other regions of the country. The soil is composed of high permeability limestone and dolomite, as well as highly soluble gypsums and anhydrites, which present dissolution faults, fractures, and cavities that generate a complex network of interconnected underground currents. These subterranean currents occasionally dissolve the superficial limestone, which, in turn, upon breaking down, form water deposits regionally known as "cenotes" or sinkholes (Hall 1936). Two types of cenotes have been classified (Schmitter-Soto et al. 2002a, b): lotic and lentic. In the younger (lotic) cenotes, the water is well interconnected with the groundwater through fractures and dissolution features, and its residence time is short. Older cenotes have a lentic condition with slow flow and turnover through sedimentation and blocking of the water source and the siphon.

Many of the organisms that live in cenotes are endemic. This is due to their isolation, geological history, and geographical characteristics. Cenotes and caves located near coastlines contain brackish and marine waters (anchialine environments) that fluctuate with the tides, while those located inward contain mainly freshwater.

The sinkholes or cenotes of the Yucatán Peninsula are complex and dynamic systems comprised of a natural interaction between the sea, interstitial water, and the rain, as well as human activity. The term refers to any underground space containing water, with the sole condition that is open to the exterior to some degree (Gaona-Vizcayno et al. 1980). The Yucatan Peninsula, considered one of Mexico's five physiographical regions, is a platform of Cenozoic limestone and evaporites. The region is flat and, on average, does not surpass 10 m above sea level (Escobar-Nava 1986).

Given the fact that the landscape is of karstic topography, it features sinkholes, such as cenotes and caves, and minor hollows due to cracked soil, all of which are the result of the passing or seeping of water rich in carbon dioxide (CO_2) through soluble rocks such as limestone (Alcocer and Escobar 1996).

The cenotes of the Yucatan Peninsula are home to a large variety of biological groups, from microorganisms to vertebrates. Among them are bacteria, fungi, algae, and protozoa, in the first trophic levels. Furthermore, very little is known about most of their invertebrates as studies carried out until now have focused mainly on macrocrustaceans and zooplankton.

The phytoplankton fauna includes records of approximately 150 species of which Chlorophyceae, Cyanophyceae, and diatoms can be mentioned as dominant (López-Adrián and Herrera-Silveira 1994; Díaz-Arce 1999; Sánchez et al. 2002). Of the green algae, *Monoraphidium caribeum* and *M. tortile* are the most common species; among the Cyanophyceae, the species *Aphanocapsa pulchra, Chroococcus dispersus,* and *Microcystis aeruginosa*; and among the diatoms, *Achnanthes gibberula, Amphora ventricosa, Cocconeis placentula,* and *Gomphonema lanceolatum* species are the most common ones (Schmitter-Soto et al. 2002a, b).

According to the invertebrate inventory, cenotes are home to a large diversity of faunistic groups. Knowledge regarding groups such as the protozoans, hydrozoans, gastrotrichs, tardigrades, annelids, and free-living nematodes is scarce

(Suárez-Morales and Rivera-Arriaga 1998). The microcrustacean group includes the rotifers with 102 species in only 12 sampled sites (Sarma and Elías-Gutiérrez 1999) (50% of all Mexican rotifers described); cladocerans (28% of the national total); ostracods with 4 species, 2 of which are endemic, *Spelaeoecia mayan* and *Danielopolina mexicana* (Furtos 1936; Kornicker and Iliffe 1989; Álvarez and Iliffe 2008); and 35 species of copepods (Suárez-Morales and Reid 1998) (45% of the country's total). *Balinella yucatanensis, Exumella tsonot, Diacyclops chakan, D. puuc, Mesocyclops chaci, M. yutsii, Prehendocyclops abbreviatus,* and *P. monchenkoi* are endemic copepods (Álvarez and Iliffe 2008).

Regarding amphipods, isopods, mysidaceans, and decapod crustaceans in the Peninsula, these were derived, in their majority, from marine forms that became trapped in these anchialine environments. Anchialine organisms lack eyes or pigmentation. Examples of these are the *Mayaweckelia cenoticola, Tuluweckelia cernua, Bahadzia bozanici*, and *B. setodactylus* (Holsinger 1977; Álvarez and Iliffe 2008; Álvarez et al. 2015)*;* the restricted distribution *Bahalana mayana* (Bowman 1987; Iliffe 1992), *Creaseriella anops*, *Cirolana (A.) yucatana*, *Haptolana bowmani*, *H. yunca, Metacirolana mayana,* and *Yucatalana robustispina* (Kensley and Schotte 1989; Álvarez and Iliffe 2008; Álvarez et al. 2015); the *Antromysis cenotensis* and *Stygiomysis cokei* (Iliffe 1992; Álvarez and Iliffe 2008; Álvarez et al. 2015); and the *Typhlatya campechae* (Reddell 1977; Álvarez and Iliffe 2008)*, Creaseria morleyi* (Iliffe 1992; Pérez-Aranda 1983; Álvarez and Iliffe 2008; Álvarez et al. 2015)*, Typhlatya dzilamensis, T. mitchelli, T. pearsei, Calliasmata nohochi* (Álvarez and Iliffe 2008; Álvarez et al. 2015), *Somersiella sterreri* (Iliffe et al. 1983)*, Agostocaris bozanici, Yagerocaris cozumel, Janicea antiguensis,* and *Parahippolyte sterreri* (Iliffe 1992; Álvarez and Iliffe 2008), the last five of which were collected only in Cozumel (Escobar-Briones et al. 1997). Among the more primitive crustaceans are the *Speleonectes tulumensis* remipede, which is endemic to several sites in the region (Yager 1987), and the *Tulumella unidens* (Bowman and Iliffe 1988) found in three cenotes near Tulum, Quintana Roo.

The ichtyofauna is characterized by the catfish *Rhamdia guatemalensis*; the guppy *Gambusia yucatana;* the cichlids *Archocentrus octofasciatus, Cichlasoma synspilum, C. urophthalmus, Petenia splendida,* and *Thorichthys meeki*; and the poeciliidae *Belonesox belizanus* and *Poecilia orri*. Some of these species have populations that are relatively differentiated, several of which have been suggested as subspecies. Troglobite fish such as the *Ogilbia pearsei* and *Ophisternon infernale*, as well as the endemic *Astyanax altior* and *Poecilia velifera,* are considered vulnerable or endangered (Schmitter-Soto 1998a,b). Cenotes are also home to the crocodile *Crocodylus moreletii*; the turtles *Chrysemys scripta, Dermatemys mawii, Kinosternon creaseri, K. leucostomum, K. scorpioides, Rhinoclemmys areolata*, and the *Leptodactylus labialis;* and the anura *Bufo marinus* (Navarro-Mendoza 1988; Pozo de la TC et al. 1991; Prezas 1996).

The aquatic vegetation of cenotes that are farthest from the sea is usually associated with *Ficus cotinifolia* (Reddell 1981), while more coastal cenotes are often inhabited by mangroves with a predominance of *Rhizophora mangle*; other cenotes located more inland can be surrounded by *Conocarpus erectus,* *Cladium jamaicense,* and *Phragmites australis*, with a frequent presence of *Typha domingensis, Acrostichum danaefolium, Nymphaea ampla, Sagittaria lancifolia, Cabomba palaeformis, Sesbania emerus, Rhabdadenia biflora, Thrinax radiata,* and *Bravaisia tubiflora*. Some cenotes are associated with the paurotis palm *Acoelorrhaphe wrightii*. In flooded banks and shallow cenotes, it is common to find the algae *Chara* (Esquivel 1991; Sánchez et al. 1991; Cabrera-Cano and Sánchez-Vázquez 1994).

2.2.2.4 Oases of the Baja California Peninsula

Small "green patches" called oases characterize the Baja California Peninsula, immersed in an arid landscape characterized by thistle and mesquites. Oases are fertile depressions, usually saturated with water and surrounded by desert (Budiko 1974). They are refuges of biological interest since they are considered relicts of biogeographical and evolutionary important habitats in which mesic-type plants and animals live (Arriaga 1997). Oases also function as layover sites for migratory birds where they feed, reproduce, rest, and obtain protection from their predators. Some of the most famous oases are San Ignacio, Santiago, La Purísima, Mulegé, San José del Cabo, and Boca de la Sierra, all located in the Baja California Peninsula.

In most cases and despite their being highly modified environments, the oases of the Baja California Peninsula shelter a large number of native species exclusive to these sites and some introduced species. For this type of habitat, there are records of 67 families, 170 genders, and 238 species that correspond to the vegetation of the wetlands as well as the xeric scrublands that surround them. Among these, 25 species were found to be strictly associated with the body of water or the riparian zones. Given its physiognomy and structure, the palms *Washingtonia robusta* and *Phoenix dactylifera* are those of greatest importance, followed by ground and scrub vegetation composed of *Phragmites communis, Cryptostegia grandiflora, Panicum purpurascens, Typha domingensis,* and *Baccharis glutinosa* (Arriaga et al. 1997).

This type of environment's ichthyofauna is characterized by a narrow diversity of native and endemic species such as the Baja California killifish *Fundulus lima* and the peninsular clingfish *Gobiesox juniperoserrai,* both endangered (Miller et al. 2005), as well as species of marine descent represented by *Awaous tajasica, Eleotris picta, Gobiomorus maculatus, Dormitator latifrons,* and *Agonostomus montícola* (Follet 1960; Ruíz-Campos et al. 2000).

However, the continental ichthyofauna and its habitats in these oases have been affected, mainly in the last few years, by anthropic activities derived from the construction of hydraulic works, changes in soil use, and the introduction of exotic species such as *Tilapia* cf. *zilli, Cyprinus carpio, Xiphophorus helleri, X. maculatus,* and *Poecilia reticulata*, some of which were introduced as part of rural fish farming programs, causing a reduction in native species populations and, in some cases, the extirpation of populations in certain oases, as was the case of the *Fundulus lima* (Ruíz-Campos 2000; Ruíz-Campos et al. 2006; Ruíz-Campos et al. 2012; Ruíz-Campos et al. 2014).

In the case of amphibians and reptiles, 32 species have been recorded, nine of which are endemic and ten have adapted to the mesic environments. The amphibians *Bufo punctatus* and *Hyla regilla*, reptiles such as the turtle *Trachemys scripta*, and the water snakes *Thamnophis hammondii* and *T. valida* are among the mesophilic species, as well as the endemic species of lizards *Elgaria paucicarinata, Phyllodactylus unctus, Ctenosaura hemilopha, Petrosaurus thalassinus, Sceloporus licki, S. hunsakeri,* and *Urosaurus nigricaudus* and the snakes *Bogertophis rosaliae, Eridiphas slevini, Crotalus enyo, Chilomeniscus stramineus,* and *Masticophis aurigulus* (Álvarez et al. 1997).

Ninety-four species of birds have been recorded, 39.4% of these correspond to winter migratory birds. Some of the more abundant resident species are *Icterus cucullatus, Melanerpes uropygialis, Auriparus flaviceps, Carpodacus mexicanus, Archilochus alexandri, Calypte costae,* and *Zenaida asiatica*, and, among the wintering species, *Dendroica coronata, Troglodytes aedon, Wilsonia pusilla, Cistothorus palustris, Vermivora celata,* and *Zonotrichia leucophrys* can be highlighted (Rodríguez-Estrella et al. 1997).

The oases of the Baja California Peninsula represent patches containing mesic vegetation that is immerse in a relatively homogeneous xeric scrubland and where yearly precipitations are sometimes under 200 mm (Turner and Brown 1994; Minckley and Brown 1994). These patches play the role of a habitat for resident species and of a layover site for migratory birds that use them to recover from their migration and stock up on food for their return to their reproduction sites. Nevertheless, due to the impacts caused by human activity, several species have seen their populations reduced or have disappeared from certain oases. Other species such as *Geothlypis beldingi, Melospiza melodia, Cistotorus palustris, Icteria virens, Icterus cucullatus,* and *I. parisorum* are being currently affected by the loss and modification of these oases (Rodríguez-Estrella et al. 1997).

An example of the latter is the case of the Belding's yellowthroat *Geothlypis beldingi*, and endemic bird species with a patch distribution, relatively small and isolated populations, and with specific habitat requirements as it is completely associated with oases and depends on the vegetation associated with the body of water. It is currently endangered due to the strong anthropogenic pressure on its habitat (Rodríguez-Estrella et al. 1997).

2.2.2.5 Lake Alchichica, Puebla

Lake Alchichica is a small (2.3 km^2) and deep (62 m maximum and 40.9 m mean depth) mar – volcanic, phreatomagmatic explosion – lake (Filonov et al. 2006). It is on the easternmost portion of the Trans-Volcanic Belt in the endorheic Oriental basin. The lake is saline (8.5 g L^{-1}) and alkaline (pH 9.5), with the following ionic abundance: $Na^+ > Cl^- > Mg^{+2} > SO_4^{-2} > K^+ > Ca^+$ (Armienta et al. 2008). Among Alchichica's unique and quite relevant characteristics regarding aquatic biodiversity are (1) low species richness and (2) a strikingly high degree of endemism.

The phytoplankton assemblage includes 19 species. Small chlorophytes (e.g., *Monoraphidium minutum*) dominate numerically, but large diatoms (e.g., *Cyclotella alchichicana*, *C. choctawhatcheeana*) are overwhelming in biomass (Oliva et al. 2001). Only three species are found in the pelagic zooplankton, a calanoid copepod and two rotifers. The copepod is *Leptodiaptomus garciai* and the rotifers are *Brachionus* sp. Mexico (*B. plicatilis* group) and *Hexarthra jenkinae* (Alcántara-Rodríguez et al. 2012; Ciros-Pérez et al. 2015; Mills et al. 2017).

Up to 21 taxa are found in the littoral benthos (Alcocer et al. 2016). Though dominated by oligochaetes (*Limnodrilus hoffmeisteri*) and amphipods (*Hyalella azteca*), the deep benthos is composed of just two species (*Candona alchichica* and *Chironomus alchichica*), the ostracod being the dominant one (Hernández et al. 2014). The vertebrate fauna is represented by only two species: the atherinid fish *Poblana alchichica* (Álvarez 1950) and the ambystomatid salamander *Ambystoma taylori* (Taylor 1943; Brandon et al. 1982).

As mentioned, despite its reduced dimensions, Alchichica displays a high number of endemisms, or "microendemism" more specifically, because their distributions are "very restricted" (less than 5% of the national territory), meaning that it is limited to the lake itself. So far, there are ten microendemic species described for Alchichica including a cyanobacterium, an alga, four crustaceans, two insects, a fish, and an amphibian.

The copepod *Leptodiatomus garciai* was the first endemic species described in Alchichica (Osorio-Tafall 1942; Montiel-Martínez et al. 2008). The Alchichica silverside (*Poblana alchichica)* was the second endemic species described for the lake (Álvarez 1950), and it is listed in the NOM-059-SEMARNAT-2010 under the "threatened species" category. The amphibian *Ambystoma taylori*, or Alchichica axolotl, is also listed in NOM-059-SEMARNAT-2010 under the "species subject to special protection" category. It is the third endemic species described for the lake (Taylor 1943; Brandon et al. 1982). The fourth endemic species for this lake is a "boatman" insect (Hemiptera, Corixidae), *Krizousacorixa tolteca* (Jansson 1979).

The isopod *Caecidotea williamsi,* an aquatic "cochineal," was the fifth endemic species described for Alchichica (Escobar-Briones and Alcocer 2002). The ecology of *C. williamsi* was further discussed (Alcocer and Escobar 2007). The golden algae or diatom *Cyclotella alchichicana* is the sixth endemic species described for the lake (Oliva et al. 2006). The seventh described species (2013) is the harpacticoid copepod *Cletocamptus gomezi*, also endemic to Alchichica (Suárez-Morales et al. 2013).

Recently, three more species were described in Alchichica bringing the number up to ten new and endemic species: the clam shrimp *Candona alchichica* (Ostracoda, Candoniadae) by Cohuo et al. (2017), the nonbiting midge *Chironomus alchichica* (Diptera, Chironomidae) by Acosta et al. (2017), and the cyanobacteria *Gloeomargarita lithophora* by Moreira et al. (2017). However, it is known that there are other species that are new to science and also most likely microendemic to Alchichica that have yet to be described as another cyanobacteria provisionally identified as *Nodularia aff. spumigena*.

Just as striking as its endemicity, is the unique characteristic of the lake regarding the presence of structures or carbonate deposits known as microbialites, in this particular case, stromatolites. They form an almost continuous ring that runs parallel to the shoreline. These structures were formed underwater long ago through a combined chemical-biological effect. When the groundwater, which is rich in calcium, reaches surface water, which is rich in carbonates, calcium carbonate is precipitated to build these structures. Microorganisms, especially cyanobacteria, create layers or biofilms, which in turn precipitate the dissolved calcium and magnesium carbonates to form layers that create stromatolites. In fact, it seems that the chemical process is not as effective without the microorganism communities.

Stromatolites are among the most ancient examples of life in the world. Although common in the Precambrian fossil record, now they can be considered living relicts because of their scarcity. These "living fossils," from the same lineage as those that appeared approximately 3.5 billion years ago, are a true scientific treasure that can take us back in time to the origin of life on this planet. In Mexican inland waters, there is only one other place with modern stromatolites, Cuatro Ciénegas, Coahuila. Alchichica's stromatolites show three different forms, sponge, pillar, and crusts, and contribute to the patrimony of Mexico as a megadiverse country.

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Chapter 3
Physicochemical Characterization of Mexican Coastal Lagoons, Current Status, and Future Environmental Scenarios

Francisco José Gutiérrez-Mendieta and Guadalupe de la Lanza Espino

3.1 Introduction

Mexico has a long coastal area (>10,000 km) characterized by the presence of 144 coastal lagoons and estuaries (Contreras 2010; de la Lanza-Espino et al. 2013a). The diversity of origin, geology, climatology, and environmental conditions that cause the physicochemical characteristics of each one of these coastal systems present a wide variation at local, spatial, diurnal, and seasonal levels. This variation is determined by the magnitude of the exchanges with the adjacent system among other aspects. Additionally, each of these systems is located within a regional context with its own climatic differences (semiarid, subtropical, and tropical) and human activities (human settlements, agriculture, aquaculture) which impact and modify their conditions even more, generating wide gradients on their physicochemical variables.

These ecosystems are highly relevant in terms of their fishery production and the high economic value that these environments generate. Likewise, they present a great biodiversity which is highly linked to their productivity.

The study of the physicochemical characterization of coastal lagoons in Mexico began only in the middle of the last century with the study of Villalobos et al. (1975) in Alvarado lagoon. Since then, the study of coastal lagoons and estuaries presented a constant increase. This has generated several reviews that have summarized

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F. J. Gutiérrez-Mendieta (✉)
The Metropolitan Autonomous University (UAM), Mexico City, Mexico
e-mail: fgm@xanum.uam.mx

G. de la Lanza Espino
The National Autonomous University of Mexico (UNAM), Mexico City, Mexico

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and integrated information regarding these ecosystems (Ayala-Castañares and Phleger (1969) Contreras 2010, de la Lanza-Espino 1994; de la Lanza-Espino et al. 2013a, b).

However, despite these efforts, the knowledge we have of these environments is still limited and has especially focused on very specific ecosystems such as the Terminos, Alvarado, and Madre lagoons, among others.

Due to the above reasons, the present review will provide elements to better understand the reasons behind the wide range of spatiotemporal variation of the physicochemical and biological parameters (chlorophyll a) that are routinely measured in Mexican coastal systems which could be used to discriminate a natural or normal condition from a condition with human influence.

In order to fulfill this objective, a wide (but not exhaustive) search of information was performed for the ranges of variation for salinity, temperature, pH, oxygen, nutrients (nitrogen and phosphorus), and phytoplankton biomass (chlorophyll *a*) of 75 coastal environments of Mexico based on published studies dating from 1975 to 2017. In some cases, data for the same system for different years are provided to illustrate the year-to-year variability of each estuarine system.

The information will be explained in the context of local and regional environmental characteristics for each system. We aim that this information will be helpful in the analysis or diagnosis of these valuable ecosystems in future environmental studies and scenarios and will help in the development and implementation of a Mexican methodology that helps in the elaboration of an environmental index based on the natural variability present in Mexican coastal ecosystems (Fig. 3.1).

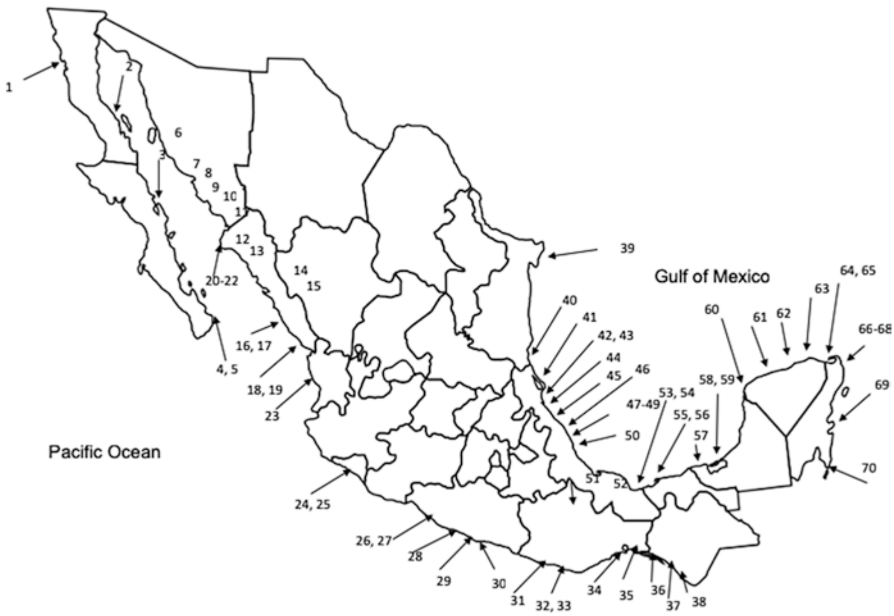

Fig. 3.1 Location of the coastal systems included in this review. Numbers correspond to system number included in Table 3.1

Table 3.1 Location, size, depth, number of connections with the sea, tidal range, origin, and geological classification according to Lankford (1977) and the geomorphological types according to Kjerfve (1986, 1994)

							Type	Type	
	System	Surface (ha)	Average depth	Number of inlets	Tidal regime	Precip/ evap	Lankford	Kjerfve	Reference
	Pacific coast								
1	Bahía San Quintín	41,600	1.8	1	Semidiurnal	15/140	V-B	Choked	Alvarez-Borrego (2004)
2	Bahia de los Ángeles	10,750	41.3			250/1900	I-E	Leaky	Gilmartin and Revelante (1978)
3	Bahía Concepción	27,985	15.4	1	Mixed	185/1900	V-A	Leaky	Gilmartin and Revelante (1978)
4	Ensenada de la Paz		1.9	1	Mixed	185/1900	III-A-B	Leaky	Gilmartin and Revelante (1978)
5	Bahía de La Paz	8200		1	Mixed	185/1900	I-B	–	Cervantes-Duarte and Guerrero-Godínez (1988)
6	Laguna de la Cruz		1.4		Mixed	234/2550		Leaky	Gilmartin and Revelante (1978)
7	Bahía de Guaymas	3750 (5803)	2.3	1	Mixed	259/2550		–	Gilmartin and Revelante (1978)
8	Bahía de Lobos	11,907	1.6	2	Mixed	259/2550	II-A	Restricted	Gilmartin and Revelante (1978)
9	Estero de Huivuilay		1.5		Mixed		II-A	–	Gilmartin and Revelante (1978)
10	Bahía Yavaros	6505	1.1	1	Mixed	259/2550	II-A	Restricted	Gilmartin and Revelante (1978)
11	Estero de Agiabampo	18,633	2.5	1	Mixed	259/2550	II-A	Restricted	Gilmartin and Revelante (1978)
12	Estero de Lechuguilla	54	0.9		Mixed	259/2550		Choked	Gilmartin and Revelante (1978)
13	Bahía Ohuira	9900	1.0	1	Mixed	259/2550	III-A and III-C	–	Gilmartin and Revelante (1978)
14	Bahía de Santa María	4500	3.0	1	Mixed	259/2550	III-A and III-C	–	Gilmartin and Revelante (1978)
15	Canal de Salíaca		1.4	1	Mixed			–	Gilmartin and Revelante (1978)
16	Estero de Quevedo		3.8	1	Mixed			–	Gilmartin and Revelante (1978)
17	El Verde	47		1	Mixed	812/1500	III-A	Choked	Flores-Verdugo et al. (1998)
18	Huizache-Caimanero	17,100	1.2	1	Semidiurnal	812/1500	III-A	Choked	Contreras et al. (1996)

(continued)

Table 3.1 (continued)

	System	Surface (ha)	Average depth	Number of inlets	Tidal regime	Precip/evap	Type Lankford	Type Kjerfve	Reference
19	Estero de Urías	9900	0.3	1	Mixed	812/1500	III-A and III-B	–	Gilmartin and Revelante (1978)
20	El Verde	47		1	Mixed	812/1500	III-A	Choked	Flores-Verdugo et al. (1998)
21	Santa María	45,000	3.0	1	Mixed			Restricted	
22	Topolobampo-Ohuira-Sta. María	6300		1	Mixed		I-C and II-A	Restricted	Escobedo-Urías (2010)
23	San Ignacio-Navachiste-Macapule	27,400	2.5	2	Mixed		I-D and I	Restricted	Escobedo-Urías (2010)
24	Mexcaltitlán	7392			Mixed			Choked	de la Lanza-Espino and Flores-Verdugo (1998)
25	Cuyutlán	7232	1		Mixed	1012/1900	III-A	Choked	Contreras et al. (1996)
26	Juluapan	176	1	1	Mixed	1012/1900			Contreras et al. (1996)
27	Nuxco	835	2.5	1	Mixed	1360/1900	III-A	Choked	Contreras et al. (1996)
28	Mitla	3600	3		Mixed	1360/1900	III-A	Choked	Contreras et al. (1996)
29	San Marcos	3200		1	Mixed		III-A	–	Contreras et al. (1996)
30	Chautengo	3400	1	1	Mixed	1360/1900	III-A	Choked	Contreras et al. (1996)
31	Coyuca	4200	2.5	1	Mixed	1360/1900	III-A	Choked	Contreras et al. (1996)
32	Corralero	3158		1	Mixed	1515/2100	III-A	Choked	Contreras et al. (1996)
33	Chacahua-Pastoría	3200		2	Mixed	1515/2100	III-A	Choked	Contreras et al. (1996)
34	Manialtepec	1640	5.4	1	Mixed	1515/2100	III-A-B	Choked	Contreras et al. (1996)
35	Superior e Inferior	78,500		1	Mixed	1095/2100	III-A	Restricted	Contreras et al. (1996)
36	Mar Muerto	28,505		1	Mixed	1095/2100	III-A	Restricted	Contreras et al. (1996)
37	Joya-Buenavista	4750		2	Mixed	3039/1700	III-A	Restricted	Contreras et al. (1996)
38	Carretas-Pereyra	3696	1.15	1	Mixed	3039/1700	III-A	Choked	Contreras et al. (1996)

39	Chantuto-Panzacola	3160	1	1	Mixed	3039/1700	III-A	Choked	Contreras et al. (1996)
	Gulf of México and Caribbean								
40	Madre	200,000	0.7	3 (13)	Diurnal	756/1700	III-A	Restricted	Contreras et al. (1996)
41	Pueblo Viejo	9300	1.3	1	Diurnal	1735/1300	III-B	Choked	Contreras et al. (1996)
42	Tamiahua	88,000	2.2	2	Diurnal	1735/1300		Restricted	Contreras et al. (1996)
43	Rio Tuxpan	88,000			Diurnal	1735/1300		–	Contreras et al. (1996)
44	Tampamachoco	1500	1	1	Diurnal	1735/1300	II-B	Choked	Contreras et al. (1996)
45	Casitas								
46	Grande-Chica	2250	0.7	1	Diurnal	1735/1300	III-C	Choked	
47	La Mancha	130	1	1	Diurnal	1676/1500	III-C	Restricted	Contreras et al. (1996)
48	Farallón								
49	El Llano								
50	Laguna Verde								
51	Mandinga	3250	2.5	1	Diurnal	1676/1500	III-C	Choked	Contreras et al. (1996)
52	Alvarado	11,800	2.5	1	Diurnal	2780/1500	I-D	Choked	Contreras et al. (1996)
53	Sontecomapan	891	2.7	1	Diurnal	2780/1500	V	Choked	Contreras et al. (1996)
54	Ostión	1270		1	Semidiurnal	2780/1500	I-D	Choked	Contreras et al. (1996)
55	Río Calzadas			1	Semidiurnal	2780/1500	II-A and V-A	–	Contreras et al. (1996)
56	Carmen-Machona	8800	1	1	Semidiurnal	1800/1300	II-A	Choked	Contreras et al. (1996)
57	Mecoacán	5168	1.2		Semidiurnal		II-A	Choked	Contreras et al. (1996)
58	Pom-Atasta	8800	2.7	1	Semidiurnal	1540/1500		Choked	Barreiro-Güemes and Aguirre-León (1999)
59	Términos	196,000	3.5	2	Semidiurnal	1540/1500	II-A	Restricted	Contreras et al. (1996)
60	Estero Sabancuy	3200			Semidiurnal	1540/1500		Choked	González-Solís and Torruco (2013)
61	Celestún	3100	1.5	1	Diurnal	726/2100	III-A	Choked	Contreras et al. (1996)
62	Chelem	1360	1		Semidiurnal	726/2100		Choked	Herrera-Silveira and Morales-Ojeda (2009)

(continued)

Table 3.1 (continued)

	System	Surface (ha)	Average depth	Number of inlets	Tidal regime	Precip/evap	Type Lankford	Type Kjerfve	Reference
63	Dzilam	1000	°	1	Semidiurnal	550/2100	III-A	Choked	Herrera-Silveira and Morales-Ojeda (2009)
64	Ría Lagartos	9467		1	Semidiurnal	550/2100	III-A	Choked	Herrera-Silveira and Morales-Ojeda (2009)
65	Holbox	27,500		1	Mixed			Restricted	Herrera-Silveira and Morales-Ojeda (2009)
66	Yalahau								
67	Chacmochuk	12,200		1	Mixed			–	Herrera-Silveira and Morales-Ojeda (2009)
68	Nichupte	2300			Mixed	1106/1500	III-B and IV-B	Choked	Herrera-Silveira and Morales-Ojeda (2009)
69	Bojorquez	300		2	Mixed	1106/1500		Choked	Herrera-Silveira and Morales-Ojeda (2009)
70	Bahía Ascención	74,000		1	Mixed		I-F	Leaky	Herrera-Silveira and Morales-Ojeda (2009)
71	Bahía Chetumal	109,800		1	Mixed	1230/1500	I-F	Leaky	Herrera-Silveira and Morales-Ojeda (2009)

3.2 Information Analysis

Relevant information regarding the size, depth, number of connections with the sea, tidal range, origin, and geological classification according to Lankford (1977) as well as the geomorphological types according to Kjerfve (1986, 1994) is presented in Table 3.1. For each system, Supplementary Data Table 3.1 presents the average, minimum, and maximum values of the physicochemical variables divided by the Pacific coast and the Gulf of Mexico and Caribbean coast.

In this revision, mainly estuarine environments were included; these are environments subject to the exchange of both freshwater and marine water and that present at least a permanent or ephemeral communication with the sea. However, some of them are bays, but they were included by Lankford (1977) in his classification of coastal environments. The surface of each system (without considering surrounding environments such as wetlands and marshes) fluctuates between 47 and 200,000 ha. Most have 1 mouth to communicate with the sea; however, some have more than 1, such as Laguna Madre that has 3 permanent inlets and 13 ephemeral ones (Contreras 2010).

In this paper we will use the definition of Potter et al. (2010) of an "estuary": "..... a coastal body of water that is either permanently or temporarily opened with the sea and that receives at least periodically discharge from a river (s), and therefore, while its salinity is typically less than that of seawater and varies temporally along its length, it can become hypersaline in regions where the evaporative loss of water is high and tidal and freshwater inputs are negligible." Unlike the definitions of Pritchard (1967) and Lankford (1977), this definition takes into account environments that may be hypersaline, such as several of the systems included in this review.

The information collected covers a period of time of more than 40 years, and in several cases, information is provided for the same system generated by different authors in different years. This allows us to appreciate the variability that occurs in these systems throughout time.

3.2.1 Temperature

Given that Mexico is located in the tropical–subtropical region, the water temperature rarely decreases below 15 °C. Exceptions can be found in two regions, in the northwest of the country as a result of the decrease in environmental temperature in the months of November to February (13 °C, Estero Punta Banda, Pritchard et al. 1978) and in the Gulf of Mexico as a consequence of the incoming masses of cold air from the north during the months of November to February in the phenomenon known as "Nortes."

3.2.2 Salinity

Using the criteria of Contreras-Espinosa and Warner (2004), based on the salinity of each system, the lagoons were grouped into four types: oligohaline (0–10), estuarine (10–30), euhaline (30–40), and hypersaline (>40). This resulted in 5 systems presenting oligohaline conditions, 18 estuarine, 24 euhaline, and 11 hyperhaline. The oligohaline lagoons are located on the coast of the Gulf of Mexico, in areas of discharges of main rivers which determines their low salinity. The euhaline lagoons are mostly found on the Mexican Pacific coast, while the hyperhaline systems are located both in the Yucatan Peninsula and in the northeast of Mexico and the Gulf of Tehuantepec, where high temperatures and low rainfall favor the increase in salinity.

3.2.3 pH

The range of values goes from 6.37 to 9.4 reflecting the influence of freshwater inputs as well as marine lagoons, with 8 being the average for all systems. These values reflect a strong seasonality due to the dry and rainy seasons present in most of the Mexican coasts. Although there are areas where the decomposition of organic matter has decreased the concentration of dissolved oxygen to suboxic and, in some cases, anoxic conditions, this does not significantly modify the pH, since there are no records of values below 6, which, if present, would indicate an external effect of anthropogenic origin (discharges of urban or industrial wastewater).

3.2.4 Oxygen

The content of dissolved oxygen ranges from anoxia–hypoxia conditions (0 to <2 mL/L) to well oxygenated conditions (from 4 to >5 ml/L) and even to supersaturation levels (>100%). For example, the Tampamachoco lagoon is worth noting, which has been sampled several times between 1979 and 2013. During this period, the oxygen contents have presented an average of 4.3–5.5 mL/L, and the intervals have fluctuated between anoxia–hypoxia (0.3–1.8 mL/L) and high oxygen content (8–9 mL/L), between the years 1980 and 2013. These oxygenation conditions are similar despite the population increase that the area has experienced as well as the various anthropogenic activities that are carried out on its margins. Also interesting are the cases of anoxia–hypoxia quantified in the lagoons of Celestún, Dzilam, Nuxco, Mitla, Chantuto-Panzacola, and La Joya Buenavista (Supplementary Data Table 3.1), just to mention a few, between 1970 and 2010. These oxygen fluctuations can be considered as "normal" for Mexican coastal lagoons. Low oxygen concentrations will occur in isolated sites during the first hours of the day after a period of nighttime respiration, and high concentrations will occur in hours with high photosynthetic activity such as midday. It is expected that the inlets, which are characterized by high water dynamic and water exchange, will have high concentrations of oxygen. As an example of this situation, we can mention the lagoons of Celestún and Dzilam in the Mexican Caribbean coast and the La Joya Buenavista lagoon, with oxygen intervals of 0.3–9.7 mL/L, and also the Chantuto-Panzacola system where intervals of 0.1–5.9 mL/L have been recorded.

It is also important to note that in general in the lagoons located in the Gulf of Mexico, there are a greater number of lagoons with anoxic–hypoxic conditions, while in the Pacific coast, this situation is less evident (Supplementary Data Table 3.1). However, Coyuca lagoon presented a similar situation in 1999 with reported values that range from anoxia to supersaturation (>100%), with levels that exceeded 8 mL/L. Another case is the Chelem lagoon, which, in 1998, showed fluctuations between anoxia (0.2 mL/L) and supersaturation (10.9 mL/L). The Mexican coasts are experimenting a population increase in their margins, therefore, of sewage discharges rich in organic matter which require oxygen to decompose or remineralize, accelerating the conditions of hypoxia; however, oxygen increments can also occur due to the enhancement in photosynthesis as a response of the primary producers to high nutrient concentrations.

3.2.5 Nutrients

Among the nitrogenous forms, ammonium is the predominant form with respect to oxidized forms (nitrates and nitrites) in most systems (Supplementary Data Table 3.1). Exceptions to this situation are the lagoons of Bojorquez, Dzilam, and Celestún located in the Yucatan Peninsula and the lagoons of Chacahua-Pastoría and Chantuto-Panzacola lagoons on the Pacific coast. In the case of nitrates, their range intervals have increased not only by the discharges of urban sewage but also by the increase in the constant and intensive use of fertilizers that drain from the agricultural fields surrounding these drainage systems, and these nutrients eventually flow into the coastal ecosystems. Riley and Chester (1971) propose maximum concentrations of 35 μM as "normal" levels for the marine environment; however, in coastal systems, such as the lagoons analyzed here, these concentrations can be increased up to 50 μM, without considering that these lagoons are eutrophicated. In the case of ammonium, it can normally present a temporal space variation depending, among several factors, on the geomorphology of lagoons with isolation conditions and, therefore, low circulation where the decomposition processes are intense and increase their concentration. Similar maximum concentrations have also been recorded in various environments of the Gulf of Mexico and the Caribbean coast (Supplementary Data Table 3.1).

In the case of orthophosphates, the concentration range is low, and high concentrations were found only in specific areas. The concentration ranges from undetectable to 5 μM in 80% of cases and up to 10 μM in 11% of cases. This high concentration can be considered as "normal," exemplified by the values recorded in the lagoons of La Joya Buenavista, Ohuira, Santa María, Huizache-Caimanero, and Manialtepec (Supplementary Data Table 3.1).

Concentrations higher to these values are considered as a condition of eutrophy. An example of the situation is the Calzadas River (which discharges into the Ostion lagoon located in the state of Veracruz), which has maximum concentrations of up to 104 μM (Supplementary Data Table 3.1). Concentrations higher than 10 μM will be a response not only to discharges of anthropogenic origin but as a consequence of the particular geomorphology of each system and the geochemistry of this nutrient, where the sedimentary phase plays an important role due to the shallowness of these lagoons. Other factors impacting the concentration of orthophosphate are hydrodynamic and desiccation conditions, sedimentation rates, removal due to wind and tide, and oxide reduction chemicals that increase or decrease the concentration of phosphorus.

3.2.6 N:P Ratio

In most of the lagoons reported here, the ratio is less than 16:1, which suggests that the element that is a limiting primary producers is N more than P (Supplementary Data Table 3.1). This limitation of nitrogen to the phytoplankton community was demonstrated experimentally by Varona-Cordero et al. (2014) in the lagoon of La Mancha. In the Pacific, this limitation is even more severe given that in several systems the ratio is less than 10:1. On the other hand, in lagoons of the Mexican Caribbean, the limitation is apparently due to P, since the values of this ratio are greater than 20 and even higher (Bojorquez, Nichupté, Dzilam, Supplementary Data Table 3.1), similar to those found in freshwater environments. In other cases, the ratios reported suggest that both elements can be a limiting factor: P in 1 year and N in the next (Laguna de Alvarado, Supplementary Data Table 3.1).

3.2.7 Chlorophyll a

The chlorophyll *a* content in coastal ecosystems provides an idea of the natural or human-altered trophic conditions (Vázquez-Botello et al. 2006). It is characterized by its wide temporal (diurnal) and spatial variation (distribution in patches). Under conditions with no impact from anthropogenic activities, the recorded values can range from <1 mg/m^3 to over 143 mg/m^3, as in Chantuto-Panzacola in 1991 (considered an extreme case). However, 25 years later (2015), contents of 43 mg/m^3 were determined, a decrease that could be the result of the distribution in patches of phytoplankton. Based on the information collected, the ranges of concentrations of this pigment can range from <4 to 20 mg/m^3, which represent between 27% and 50% of the cases, respectively. These wide intervals also vary locally; for example, Laguna La Cruz (Sonora) recorded a chlorophyll *a* level of 3.89 in summer and 4.79 mg/m^3 in winter (Morales-Soto et al. 2000).

3.2.8 Trophic Status and Eutrophication

In order to establish the trophic status and the degree of eutrophication in the Mexican coastal lagoons, several indexes have been used. Among these are those of Karydis (Karydis et al. 1983), Ignatiades (Ignatiades et al. 1992), OECD (OECD 1982), Carlson (Contreras-Espinosa et al. 1994), TRIX (Vollenweider et al. 1998), AZCI (Mendoza-Salgado et al. 2005), and ASSETS (Bricker et al. 2003; Arreola-Lizárraga et al. 2018). However, the application of indexes with different requirements (nutrients, chlorophyll, nutrients + chlorophyll) results in the same system obtaining completely different categories, ranging from oligotrophic to eutrophic (e.g., Bahía Concepción, Arreola-Lizárraga et al. 2018). The above is most likely due to the fact that these indexes were established for different latitudes and do not consider the particular characteristics of Mexican coastal environments. de la Lanza-Espino and Gutiérrez-Mendieta (2017) established that the wide ranges of concentration of the different physicochemical and chlorophyll parameters present wide ranges of variation at spatial and seasonal levels, which are the result of both local factors and conditions, often with unique characteristics for each ecosystem and as a result of typical conditions of tropical latitudes in addition to the interaction with adjacent environments. Therefore, this variability must be considered if we want to generate an index to classify coastal environments and identify those that have received an anthropogenic impact.

The above calls attention to the need to expand, intensify, and perform long-term monitoring to better understand the variability of the physicochemical conditions of Mexican coastal environments. This will eventually allow the implementation of an index that, taking into consideration these conditions, will allow an adequate classification for any given environment, as mentioned by Contreras-Espinosa and Warner (2014), de la Lanza-Espino and Gutiérrez-Mendieta (2017), and Arreola-Lizárraga et al. (2018).

3.3 Future Environmental Scenarios

The Mexican coasts are undergoing a wide transformation as a result of the increase in several factors. Among these are the increase in agricultural activity and the expansion of agriculture and livestock at the expense of important coastal environments (mangroves, wetlands). Also, the different industrial and transportation activities that are carried out on coastal areas and a change in the location of the population in general, going from being mainly in the mainland to a greater proportion located on the coasts, especially in centers of high tourist activity.

The activities that generate the greatest impact from coastal discharges are agriculture, followed by fishing and port activities, tourism, aquaculture, diverse industries, and urban planning. Azuz-Adeath and Rivera-Arriaga (2009) found that in 1990, approximately, 43% of the total population was found in 17 coastal states, and the coastal municipalities themselves contained 23% of the total population (19.2 million), while in 2010, the percentage of the population in the coastal states increased to 46%.

3.4 Final Considerations

Coastal lagoons located in tropical latitudes, as is the case of the coasts of Mexico, should be considered in a delicate balance due to its location between the sea–land transition, with wide ranges on their physicochemical characteristics that make them vulnerable to anthropogenic activities. Adequate measures to their protection should be implemented, taking into consideration their natural spatiotemporal variation. Therefore, it is imperative to have a strong database that can discriminate their "natural" vs impacted conditions before making incorrect environmental diagnostics based on norms or standards generated in different latitudes with an anthropogenic point of view rather than with an ecological perspective. Consequently, it is recommendable to continue collecting and integrating the available scientific information regarding these ecosystems, in order to asses and differentiate the natural variability from the effects of the different anthropogenic activities that take place in these valuable ecosystems.

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Chapter 4
Microbiota in Brackish Ecosystems: From Water Quality to Ecological Processes

María del Rocío Torres-Alvarado, Mónica Bonilla-Salinas, Laura G. Calva-Benítez, and Florina Ramírez Vives

4.1 Introduction

Coastal ecosystems extend inland from seashore up to 100 km and below sea level up to 50 m (Dayton et al. 2005). Several ecosystems with the highest productivity of the biosphere, coral reefs, seagrass beds, wetlands (marshes and mangroves), estuaries, and coastal lagoons, are included in this extension.

Estuaries and coastal lagoons are the most complex environments, representing an important interface between terrestrial and marine environments. They are formed by the mixture of freshwater of continental origin with seawater. The estuaries are morphologically funnel shaped, having their main axis perpendicular to the coastline, with an open connection with the sea. The river that flows into the ocean represents an effective limit of tidal influence; this is the reason why seawater is diluted, forming a longitudinal salinity gradient (Perillo 1995). Coastal lagoons are defined as shallow bodies of water (generally less than 5 m deep), characterized by the presence of a sandy barrier known as the littoral cord that separates the lagoon from the open sea. These ecosystems, unlike estuaries, are characterized by a restricted flow to the sea, where the marine connection is maintained through the mouth or tidal channels. Most of the lagoons are related to a freshwater continental basin, enhanced with variable fluvial discharges (de Wit et al. 2001).

The input of marine water and freshwater to estuaries and coastal lagoons results in unique ecological characteristics such as the presence of intricate biogeochemical cycles, a high habitat diversity, and the presence of intricate trophic webs. In these

M. R. Torres-Alvarado (✉) · M. Bonilla-Salinas · L. G. Calva-Benítez
Departamento de Hidrobiología, Universidad Autónoma Metropolitana-Iztapalapa, México City, DF, Mexico
e-mail: rta@xanum.uam.mx

F. Ramírez Vives
Departamento de Biotecnología, Universidad Autónoma Metropolitana-Iztapalapa, México City, DF, Mexico

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ecosystems, a complex biotic community is developed, and it includes organisms of commercial importance. The estuarine–coastal lagoon ecosystem plays an important ecological role in protection, reproduction, and feeding zones for different marine organisms such as fishes and crustaceans (for this reason, coastal fisheries depend on the presence of coastal lagoons and mangroves).

Estuarine–coastal lagoon ecosystems are fundamental zones for the establishment of human settlements and the development of cities, which in many cases have high population densities that negatively impact the coastal zone. Coastal ecosystems experience severe environmental alterations by changes in land use, dredging and pollution by extensive fishing, agricultural, touristic and industrial activities that take place in these ecosystems, being lagoons more susceptible to anthropogenic pollution because their limited water exchange capacity.

Mexico has approximately 11,592.77 km of coastline, divided as the Pacific Ocean coast (8,475.06 km), the coast of the Gulf of Mexico, and the Caribbean Sea (3,117.71 km) (INEGI 2017). The estuarine ecosystems represent 30–35% of the total coastal area, covering 1,567,300 ha, including 125 coastal lagoons (Morán-Silva et al. 2005). The Mexican coastal lagoons can be classified into regions on the basis of climatic characteristics, which may influence their properties (Contreras 2010):

1. North of Mexican Pacific (peninsula of Baja California, Sonora, and Sinaloa). The coastal lagoons of this region are located in arid zones, where runoff is low and evaporation is higher than precipitation, with the resulting predominance of hypersaline systems.
2. Central and South Pacific of Mexico, from Sinaloa to the Guatemala–Mexico border. Coastal lagoons occur in a variety of climates, from semi-arid to subhumid and very humid in the south; precipitations are more abundant in summer. Coastal lagoons are associated with small basins with numerous rivers of short length.
3. Gulf of Mexico, including the coastal lagoons and estuaries from the border with the United States to Yucatan. In this area, there are three climatic seasons: rainy, dry, and "nortes." The rainy season (July–October) is characterized by high precipitation values (400–700 mm) and high air temperatures (30–35 °C). The "nortes" season (November–February) is characterized by the influence of cold fronts accompanied by strong winds (80 km/h), low air temperatures (20–23 °C), and scarce rainfall (<50 mm). In the dry season (March–June), the high air temperatures (36–40 °C) promote high rates of evaporation (Tapia-González et al. 2008). The largest rivers Papaloapan and Grijalva-Usumacinta are located in the southern portion of the Gulf of Mexico (Veracruz and Tabasco states).
4. Mexican Caribbean, which is the coastal zone in Quintana Roo. The coastal plain is very extensive. There is no surface runoff because of their carbonated surface composition. Groundwater is the principal freshwater supply for these coastal lagoons. In the area there are three different climatic seasons, as in the case of the Gulf of Mexico region.

Estuarine–lagoon ecosystems in tropical regions possess a high biodiversity in comparison with temperate and boreal regions; however, the major part of biodiversity research in estuaries and coastal lagoons in Mexico is centered on their macroorganisms, leaving a gap of information about other taxonomic levels, including the hyper-diverse groups such as microorganisms, despite their enormous recognized importance in the functioning of the ecosystem. This chapter provides an overview of the microbiology of estuary–coastal lagoon ecosystems in Mexico. This is a compilation of useful information regarding human health and the ecological role of microorganisms, mainly bacteria and archaea, in the coasts of the Pacific and Mexican Caribbean, as well as in the Gulf of Mexico. The information presented here includes only articles published in book chapters and indexed journals, several of these in Spanish; gray literature was not included as project or congress reports.

4.2 Microbial Ecology

The microbiota in coastal areas includes natural (autochthonous) populations and those introduced from different sources (alloctone) including microorganisms associated with feces having sanitary importance.

The natural microbiota is composed of members of Bacteria, Archaea, and Eukarya domains as well as the virus group. Microbial communities are important components in the estuarine–lagoon ecosystem and performing many functions; particularly, bacteria and archaea play a key role in the transformation of inorganic and organic constituents including pollutants. The microbial utilization of dissolved and particulate biogenic matter, as well as several pollutants, depends on their size, nature, and reactivity and age. Microorganisms have important key roles in different biogeochemical cycles such as nitrogen, phosphorus, and sulfur, contributing to the recycling of nutrients and the detoxification of the environment (Cabello et al. 2004; Barbier et al. 2011). Microbial communities are important members of the microbial food web, being primary producers, degraders, and consumers; they produce cellular biomass, a potential source of energy for several detritivores organisms (Moran and Hodson 2000; Sun et al. 2014).

The growth and survival of microorganisms are due to their availability of energy uptake sources such as organic or inorganic compounds as well as to their adaptations in different environmental conditions. All these factors shape the structure and composition of microbial communities (Centeno et al. 2012, 2016; Hanson et al. 2012). The few reports available for tropical systems have shown that changes in temperature, nutrient load, dissolved oxygen, pH, and principally salinity are associated with changes in structure and function of microbial communities (Sun et al. 2011; Zhang et al. 2014).

Tropical estuarine–coastal lagoons are characterized by a high degree of enclosure and resident times of water. These ecosystems present important spatio and temporal salinity variations because of drastic seasonal changing volumes of river influents. The marine and freshwater influences in the coastal lagoons generate salinity gradients. Salinity is an important stress factor, which has a direct or indirect effect on the establishment, composition, and distribution of different taxa in microbial communities. Salinity gradients are also related to the distribution of nutrients and organic matter, whose concentration is highest at the mouths of rivers and lowest near to the sea. All these factors determine characteristics of microbial communities in the estuarine–lagoon ecosystem.

4.2.1 Microbial Diversity

Research performed in estuaries located in tempered zones has demonstrated a link between salinity gradient and microbial composition. The predominant microbial communities in the marine zone are α-proteobacteria, in the freshwater zone are β-proteobacteria, and in the middle of the estuary are *Cytophaga–Flavobacterium* (Bouvier and del Giorgio 2002). In other studies, ecological changes have been detected such as the decrease in biodiversity and the dominance of some microorganisms (Rodríguez-Valera 1988, 1993; Benlloch et al. 2002). The constant presence of some bacterial groups such as Actinobacteriales and γ-proteobacteria including purple sulfur bacteria has also been observed. The presence of these microorganisms is related to their tolerance to salinity fluctuations (Methé et al. 1998).

Biodiversity in coastal areas located in tropical climates has been less studied than that in coastal areas located in temperate zones. Brazil and Australia provide a bigger range of information about the microbial composition of their coastal lagoons than other tropical countries.

In Brazil, the predominant bacterial groups identified in the estuarine–lagoon ecosystem of Mundaú-Manguaba were β-, ε-, and γ-proteobacteria; these microorganisms were found in the freshwater zone, and their presence was associated with high nutrient and organic matter concentrations (from sugarcane plantations), whereas in the middle of this ecosystem and close to the ocean, the main microbial groups identified were γ-proteobacteria (*Acinetobacter*), *Cyanobacteria* (*Synechococcus* spp.), *Bacteroidetes*, and *Actinobacteria* (Wolf et al. 2010). The archaea plankton present in Guanabara Bay is higher in the freshwater zone where great inputs of wastewater effluents and anoxic conditions exist. The microorganisms detected were closely related to hydrocarbon degraders, reported in oil, industrial wastes, and sewage. This fact shows a correlation between water pollution and the archaea composition communities in this ecosystem (Vieira et al. 2007).

In the Darwin Harbor in Australia, the main microbial group identified in the water column during the dry season was the family *Chromatiaceae* (purple sulfur bacteria), while in the rainy season, the microorganisms detected were cyanobacteria such as *Phormidiaceae*, the family of blue–green algae containing the genus *Planktothrix*, as well as members of *Burkholderiales*, *Phormidiaceae*, *Verrucomicrobia*, and *Planctomycetes*. In the anaerobic sediment, the main microorganisms identified were sulfate-reducing bacteria (*Desulfobacteraceae*), nitrifying *Nitrosomonadales*, *Chloroflexi* bacteria (green nonsulfur bacteria), and *Clostridiales* (Kaestli et al. 2017).

Research on microbial biodiversity in the coastal lagoons of Mexico is still scarce. Most studies on microbial composition have been conducted in one of the few hypersaline environments in Mexico, the coastal lagoon of Guerrero Negro, located on the occidental coast of the state of Baja California Sur, in the Biosphere Reserve of Vizcaino (CONABIO 2000). Guerrero Negro is part of the lagoon system Ojo de Liebre, an oligotrophic environment, having a surface of 300 km^2. Water inputs for this ecosystem come from the ocean, through the mouth of a lagoon of 1.7 km. The flow of shallow channels forms chemical gradients due to the annual evaporation rates. The main economic activity in this area is related to the biggest worldwide salt export company "Exportadora de Sal" (ESSA-Salt Exporter); in the second place, other economic activities are developed, such as artisanal fishing, oyster cultivation, and grey whale watching tourism; this ecosystem is used by the grey whale (*Eschrichtius robustus*) for reproduction and nurturing (Javor 1983; Morales-Zárate et al. 2016).

In hypersaline environments, worldwide research has shown the presence of microorganisms from three domains, including phototrophs and anaerobic heterotrophs (Javor 1989; Benlloch et al. 2001; Baati et al. 2008). In these environments, the diversity of the Bacteria domain decreases in higher salinity levels, while the presence of Archaea domain members increases (Maturrano et al. 2006; Oh et al. 2010).

Guerrero Negro lagoon possesses a complex microbial community in the water column, as well as in the benthonic mats and evaporites due to the presence of longitudinal and vertical physicochemical gradients (Feazel et al. 2008; Dillon et al. 2009). Dillon et al. (2013) studied the planktonic microbial communities in the water column of three ponds along a gradient salinity (180–370 g/l). The sequences of these organisms were identified for γ-proteobacteria (*Spiribacter salinus*, photoheterotropic), *Bacteroidetes* (*Psychroflexus*, *Sediminibacterium*, *Owenweeksia*, and *Salinibacter*), *Firmicutes*, *Verrucomicrobia* (*Puniceicoccus*-like), and algae plastids (*Dunaliella*). In ponds with higher salinity, the presence of members of δ-proteobacteria (*Desulfobacca acetoxidans*) was prevalent. In contrast with other studies, bacterial diversity in Guerrero Negro was higher in the ponds with major salinity, probably due to major halite precipitations. It was also found that Archaea diversity increased in the ponds with the highest salinity, being the sequences detected close to *Halorubrum*, *Halorhabdus utahense* and *Haloquadratum*-like, this one with 99% of similarity with *H. walsbyi*. The dominance of *Haloquadratum* is related to their tolerance of extreme salinity (Oh et al. 2010). These sequences were similar to those of the genera reported in hypersaline environments from Australia, Spain, California, Chile, Turkey, Tunisia, and Israel.

Microbial mats are benthic communities that grow on a solid substrate; they are conformed with different microorganisms embedded in an organic matrix that could contain some minerals such as silicates and carbonates (Stal 2012; Bolhuis et al. 2014). The growth of microbial mats is complex; it requires the coordination, interaction, and communication between multiple bacterial species. The assemblages of microorganisms act as a cooperative coordinated consortium. These microbial ecosystems have importance in the atmosphere composition for the production of oxygen, hydrogen, and methane (Hoehler et al. 2001). In the microbial mats, there are physicochemical gradients changing during day and night, depending on the availability of light, temperature, salinity, oxygen, pH, and Eh; these gradients promote the presence of microniches, favoring several microbial metabolic activities in a three-dimensional stratified structure. In their surface, where light has access, a photosynthetic metabolism is registered, which decreases when the depth of the mat increases; on the contrary, in the intermediate and deep layers, there are processes of degradation of the organic matter generated by the primary producers, and this degradation is carried out by means of two fundamental processes: fermentation and sulfate reduction (DesMarais 2003; Lee et al. 2014).

Ley et al. (2006) determined that microbial mats in Guerrero Negro lagoon could be divided into three different habitats organized vertically: a superficial layer characterized by fluctuations in oxygen concentrations during the day, the medium layer with variations in H_2S along the day/night, and the deep layer with elevated H_2S amounts. The principal phyla identified were *Cyanobacteria*, *Chloroflexi* (green nonsulfur bacteria), *Proteobacteria*, *Bacteroidetes*, *Spirochaetes*, *Verrucomicrobiota*, and several novel candidate phyla. *Cyanobacteria* represented 10% of the total microorganisms, and they were detected only in the surface layer of mats. *Chloroflexi* was the dominant species in the superficial layer, representing 24% of the microorganisms detected; these sequences were closely related to those of *Chloroflexus* and *Chlorothrix* spp. (photosynthetic microorganisms). *Chloroflexus* members are principally chemoorganoheterotrophic, and some of them can grow in chemolithoautotrophic conditions, using hydrogen or H_2S (Canfield et al. 2005). *Chloroflexi* was found in an exopolysaccharide coat produced by *Microcoleus chthonoplastes*, a microfilamentous cyanobacterium. In the case of *Proteobacteria* members, the γ-group (*Desulfobacteraceae*, a sulfate-reducing bacterium) was more abundant, but α-proteobacteria (diazotrophic bacteria and purple nonsulfur bacteria) and γ-proteobacteria (sulfur-oxidizing bacteria) were also detected. The phylum *Bacteroidetes* includes anaerobic microorganisms capable of degrading polysaccharides. In the three layers of the microbial mats, “novel candidate phyla” were detected, and 9 of the 15 were found in the middle layer; these microorganisms are anaerobes with resistance to H_2S daily variations (Ley et al. 2006).

Another important aspect observed in the microbial mats in Guerrero Negro is the trophic relationships related to the hydrogen cycle, particularly in submerged and intertidal mats. *Microcoleus chthonoplastes* dominates in the submerged mats, while in intertidal mats, *Lyngbya* spp. is dominant. These cyanobacteria are present during the desiccation periods of low tide. In these microbial mats, there is a complex relationship between cyanobacteria, filamentous anoxygenic phototrophs, and sulfate-reducing bacteria. The cyanobacteria group produces organic carbon by photosynthesis, which will be used in a fermentation reaction in anoxic conditions at night, producing volatile fatty acids (acetate, formate, propionate, and hydrogen). Hydrogen corresponds to 16% of the carbon fixation during the day, forming bubbles in the mat surfaces. The products formed could be subsequently used by sulfate-reducing bacteria (considered the principal consumer of hydrogen and organic acids in mats) or by *Chloroflexi* in heterotrophic reactions (Lee et al. 2014).

Spear et al. (2003) studied the endoevaporites in a pond with gypsum, and the observation was similar to that in microbial mats along with the presence of a vertical zonation of microbial communities. In the surface layer, cyanobacteria (*Euhalothece* sp.), belonging to the group of *Cytophaga–Flexibacter–Bacteroides* and α-proteobacteria (*Planctomyces* spp. and *Rhodobacter* spp.), were identified. Cyanobacteria decreases with depth by light diminution. In deeper layers, the main microorganisms detected were δ-proteobacteria (sulfate-reducing bacteria), ε-proteobacteria (*Clostridium* spp.), and γ-proteobacteria (*Alcalilimnicola halodurans*). Extremely halophilic microorganisms performing diverse metabolic reactions (anaerobic processes or oxygenic photosynthesis) were also detected in microbial mats.

In coastal lagoons of Yucatan (Bacalar and Sian Ka´an), vertical stratification of microbial communities related to organo-sedimentary structures (microbialites) was also documented. In superficial layers, *Cyanobacteria* are highly present with photoautotrophic and diazotrophic metabolisms, while in intermediate and deeper layers, *Bacteroidetes*, *Planctomycetes*, *Verrucomicrobia*, and *Proteobacteria* are the main heterotrophic microorganisms forming cell groups (Centeno et al. 2016).

4.2.2 Biogeochemical Cycles

A biogeochemical cycle involves the movement of chemical compounds between the earth components: atmosphere, geosphere, hydrosphere, and biosphere. Nitrogen and carbon are the most important cycles linked to the mineralization of organic matter carried out mainly by bacteria and archaea in estuaries and coastal lagoons.

Aspects of Nitrogen Cycle The nitrogen cycle is one of the more complex cycles due to the different oxidation states of their components. Metabolic transformations take place in aerobic and anaerobic conditions, with nitrification being the principal process in the presence of oxygen. Nitrification, the microbial oxidation of ammonia (NH_3) to nitrate (NO_3^-) via nitrite (NO_2^-), plays a critical role in the nitrogen cycle, and this process is carried out by ammonia-oxidizing bacteria (AOB) phylogenetically restricted to the β- and γ-proteobacteria and members of the domain Archaea (*Crenarchaeota*).

The diversity of the nitrifying microbial community was studied in Tóbari harbor, an estuary located in Sonora State in the northwest coast in the Gulf of California. This ecosystem is situated in an arid zone with scarce precipitation, near the Yaqui Valley, a region of intensive wheat-based agriculture where the fertilizer application rates are exceptionally high; as a result, Tóbari receives substantial amounts of N in runoff. This ecosystem is a mixed estuary with negative and positive characteristics, depending on the seasons. *Nitrosomonas*-like sequences were detected along the salinity gradient, showing the adaptation of this microorganism to different environmental conditions. In the case of archaea, the sequences were closely related to that of *Nitrosopumilus maritimus*; this species was present throughout the estuary (Beman and Francis 2006). Research performed in the macrotidal estuary of the Australian wet–dry tropics showed that salinity was the principal factor responsible for the temporal variations of nitrogen cycle in sediments (Abell et al. 2009).

Aspects of Carbon Cycle Sediments are crucial for the functioning of coastal lagoons, and they are anoxic with high concentrations of organic matter and nutrients. The microorganisms present in these ecosystems are diverse and are related to mineralization of organic matter, since they are responsible for the oxidation of organic carbon by aerobic and anaerobic processes (Urakawa et al. 1999; Hansen et al. 2000; Zhang et al. 2008 a, b). The carbon cycle reactions correspond principally to anaerobic processes, depending on the oxidation–reduction potential values (Eh) and the concentration on electron acceptors (O_2, NO_3^-, SO_4^{-2}, and CO_2), to perform metabolic reactions such as fermentation, denitrification, sulfate reduction, and methanogenesis. Sulfate-reducing bacteria (SRB) and the methanogenic archaea (MA) share niches with similar characteristics, and these groups have a key role in the consumption of metabolic products previously generated by fermentation, and they improve the conservation of energy of fermentative bacteria, keeping the thermodynamic conditions required for the catabolism of volatile fatty acids.

Sulfate reduction and methanogenesis are processes well studied principally in temperate estuaries; these environments present a salinity gradient from freshwater to marine zones. SRB are responsible of the degradation of organic matter in marine zones with high sulfate content, while methanogenic archaea are mainly responsible for mineralization in freshwater portion with low sulfate content (Takii and Fukui 1991; Purdy et al. 2001).

There is scarce research related to the sulfate reduction processes and methanogenesis in tropical zones where the precipitation is considered one of the responsible factors of hydrologic and biological changes. MA are the main microbial components in coastal lagoon sediments associated with mangroves, and these archaea can use methanol and methylamines as the substrate (Mohanraju and Natarajan 1992; Mohanraju et al. 1997). The aquatic macrophytes in Cabiúnas lagoon in Brazil are related to methane dynamics, which is the source of organic matter to the methanogenic processes (dos Santos Fonseca et al. 2004).

Research carried out in coastal lagoons in the Mexican Pacific and Gulf of Mexico showed that dry and wet seasons had the greatest impact on sulfate reducers and methanogenic microbial communities; their distribution and abundance are related to the discharged volumes from the runoff of freshwater depending on the precipitation and climatic conditions. The coastal lagoons of the southern portion of the Mexican Pacific are characterized by their association with rivers with short longitude; they produce a great accumulation of sediments and organic matter, particularly in those lagoons associated with mangroves and intertidal mudflats such as estuarine–lagoon ecosystems Carretas-Pereyra y Chantuto-Panzacola (Chiapas

State). In these ecosystems, the high rate of freshwater inflow with organic debris from the land as well as from adjacent mangroves is a key factor related to the anaerobic mineralization of organic matter.

Carretas-Pereyra and Chantuto-Panzacola are part of a dynamic ecosystem that is significantly influenced by large hydrological changes as a result of freshwater discharge and precipitation patterns throughout the year; changes in precipitation and its influence on fluvial inputs significantly impacted salinity and sulfate content. This hydrological variability is reflected on the spatial distribution and density of SRB and MA, although both microbial groups are capable of adapting to these seasonal changes. During months of high precipitation, the increasing river discharges cause a reduction in salinity, low sulfate concentrations, sediment resuspension, and decreasing reducing redox potentials; these physicochemical conditions promote the abundance of MA (10^6–10^7 cells/g), which use hydrogen, acetate, and methanol as their preferential substrates. The peak of methanogenic activity in the rainy season suggests that these ecosystems may be an important source of atmospheric CH_4 and CO_2. The presence of SRB (10^6–10^7 cells/g), which use lactate, hydrogen, acetate, and propionate as substrates in this season was also determined. In contrast, during the dry season, methanogens are less abundant (10^4–10^6 cells/g), which use methanol, hydrogen, and acetate as substrates, and the number of SRB increases (10^8–10^9 cells/g), which use lactate, acetate, propionate, and hydrogen as substrates. Temperature increment and river discharge reduction increase the water salinity, contributing to the higher amount of sulfate concentrations in the sediment and negative redox conditions (Torres-Alvarado et al. 2013, 2015).

This cyclic pattern was also determined in two coastal lagoons located in Veracruz state in the Gulf of Mexico, La Mancha, and Alvarado-Camaronera; the dry and rainy seasons had major influence on sulfate reduction and methanogenesis, while the “nortes” was considered as an intermediate stage (Fig. 4.1) (Torres-Alvarado et al. 2016). The Alvarado-Camaronera coastal lagoon possesses a permanent communication with the ocean, and with the Papaloapan River, in this ecosystem, a vertical distribution of SRB and MA was also observed, with SRB being the dominant group present in the uppermost layer of the sediment (0–3 cm depth); in contrast MA abound at depths of 6 cm. This distribution is related to the pH and Eh, which is predominantly more negative below the sediment surface, and a lower concentration of sulfates (Torres Alvarado 2007; Torres Alvarado et al. 2012).

4.2.3 Microbiota and Contaminants

In the coastal lagoon of Terminos in Campeche State (Gulf of Mexico), with a great oil activity, a bacterial community was observed to be metabolically active in the water column that is capable of degrading the polycyclic aromatic hydrocarbons (PAHs). This community is being impacted by several environmental variables, and among them, the concentration of nutrients was contributed mainly by the Palizada

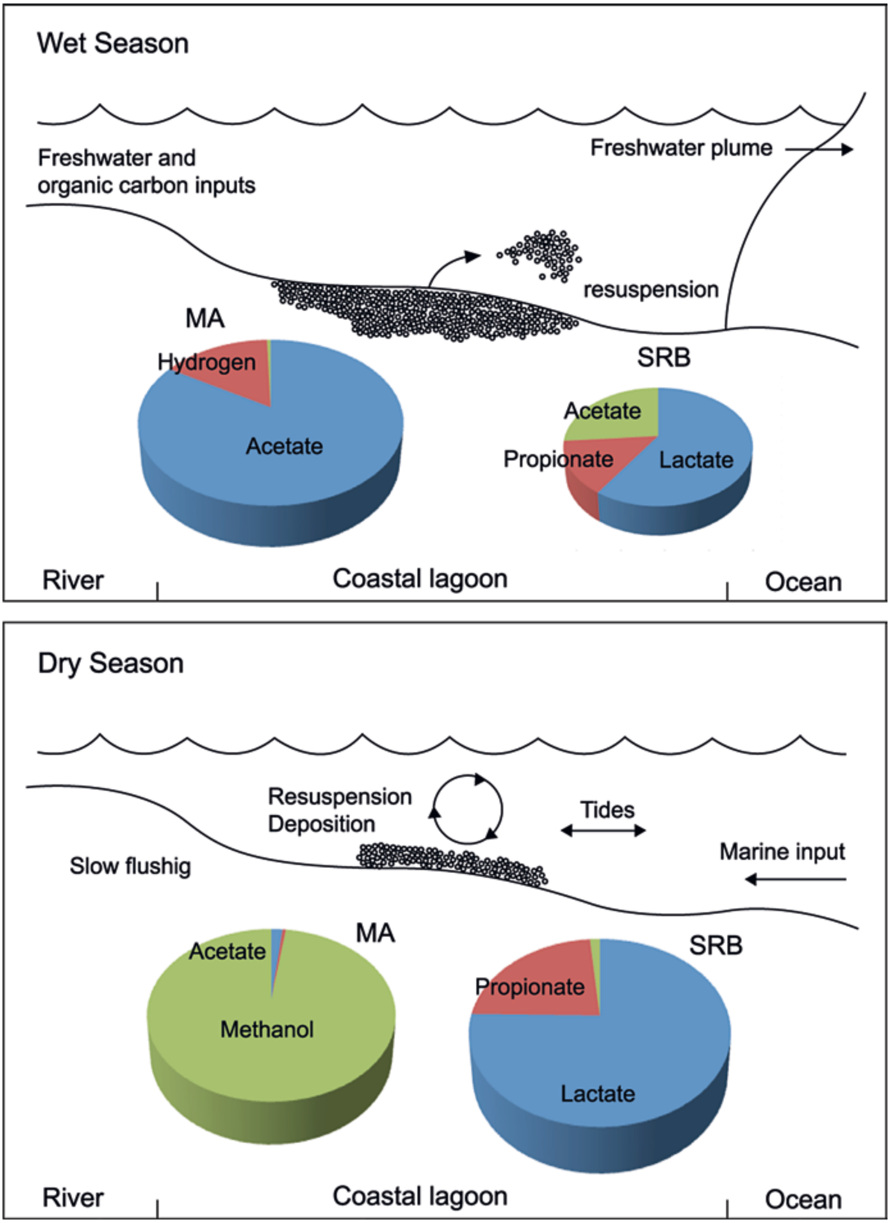

Fig. 4.1 Proposed model of the dynamics of sulfate-reduction and methanogenic communities in coastal lagoons of the state of Veracruz

River (Conan et al. 2017). Additional information related to bacteria that use polluting substances as a substrate does not exist for the coastal lagoons of Mexico.

It is a fact that the information available about the ecology of Bacteria and Archaea in estuarine–lagoon ecosystems in Mexico is limited. This is the reason why it will be necessary to perform more research including the role of microorganisms in the functioning, adaptation, resilience, conservation, and global health contribution of coastal systems, over the time, facing natural and anthropogenic disturbances. Better knowledge of the biogeochemical, biological, and ecological dynamics is highly valuable to preserve these ecosystems and to prevent their loss.

4.3 Sanitary Microbiology

Around 50% of the world's population currently lives in towns and coastal cities; in Mexico, the coastal population represents 40% of the total country population. In coastal areas, the economy is based on agricultural, livestock, mining, industrial, and tourist activities, as well as fishing and aquaculture. Specifically, fishing and aquaculture are the dominant activities in the Pacific, while in the Gulf of Mexico, the oil industry prevails within several offshore oil platforms in Campeche, and in the Caribbean, there are mainly tourist activities. In the Mexican Pacific, Ensenada, Guaymas, Topolobampo, Mazatlán, Puerto Vallarta, Manzanillo, Lázaro Cárdenas, Zihuatanejo, Acapulco, and Huatulco are the principal coastal cities; while in the Gulf of Mexico, the most important cities are Tampico, Veracruz, Coatzacoalcos, Tuxpan, El Carmen, and Campeche. In the Caribbean, there is a continuous population increment in Cancún, Tulum, Cozumel, and the Costa Maya.

The growth of human settlements is associated with changes in the use of land and generation of pollutants that are discharged through wastewater. Communities located in coastal areas have several alternatives in disposing their wastewater: by direct discharge into the sea through submarine outfalls and discharging in the watercourses and tributaries feeding the estuaries and coastal lagoons or directly in the estuarine waters. The increment in wastewater discharges to estuarine–coastal lagoon ecosystems contributes to large amounts of organic matter, several pollutants, and toxic substances, as well as pathogenic microorganisms (viruses, bacteria, fungi, and protozoa) associated with urine and fecal matter. These microorganisms can also be introduced into coastal systems through runoff and soil leaching, wild and domestic animal excreta, and other poorly understood environmental reservoirs such as soils and sands; these are nonpoint sources of pollution (Viau et al. 2011).

Once the microorganisms are in the water, they are transmitted into the environment by two pathways such as pelagic (water) and benthic (sediment). The pelagic pathway consists in the ingestion of suspended pathogenic bacteria or organic particulates containing these pathogens by zooplankton and small fishes, which are in turn ingested by larger fishes upward the food chain. The benthic pathway consists in the ingestion of the contaminated organic particulates from sediments dispersed at the bottom or located over the mangrove roots by meiofauna, mollusks, crustaceans, demersal fishes, and potentially by humans.

The presence of pathogenic microorganisms in coastal lagoons and estuaries deteriorates the sanitary quality of water, sediment, and the organisms from these ecosystems, causing alterations in the ecological balance. The presence of these microorganisms determines the quality of coastal waters, being in some cases no longer optimal for fishing, aquaculture, and recreation; their presence is a risk to human health because it is linked to the spread of infectious diseases.

Direct detection of pathogenic bacteria is not always feasible for time and economic resources, so microbiological quality can be analyzed through the quantification of the so-called microbiological indicators: total coliforms, fecal coliforms (*Escherichia coli*), and fecal streptococci. The coliform group has often been used as an indicator of water suitability, partly because these microorganisms originate exclusively from feces. *E. coli*, a commensal bacterium from the intestinal tracts of humans and vertebrate animals, has been used as a bacterial indicator of recent fecal contamination. The fecal streptococci are used as a complementary indicator of fecal contamination due to its greater capacity than coliforms to tolerate environmental changes and survive in natural environments. Fecal streptococci indicate fecal contamination of animal origin; their presence is associated with runoff from ranches and paddocks (APHA American Public Health Association, 1992).

4.3.1 Microbiological Indicators in Coastal Lagoons of Mexico

In Mexico, the maximum permissible limits of microbial contaminants in wastewater discharges to aquatic systems are established in the Official Mexican Standards based on the General Law of Ecological Equilibrium and Environmental Protection (LGEEPA). The ecological criteria of water quality (NOM-001-SEMARNAT-1996, NOM-242-SSAI-2009, CONAGUA 2008) establish that for Protection of Aquatic Life, the maximum permissible limit of total coliform must be less than 240 MPN/100 ml and less than 70 MPN/100 ml of fecal coliforms. For recreational use with primary contact, the level of fecal coliforms should not exceed 200 MPN/100 ml, and no more than 10% of samples per month should have a maximum of 400 MPN/100 ml.

In the studies of sanitary microbiology performed in coastal systems, the coliforms have been detected in all sampled lagoons, and in most of them, the concentrations were higher than the permitted levels either for cultivation of bivalve mollusks or for the protection of aquatic life in coastal waters and recreational use with primary contact. Most of these studies have been carried out in the coastal zone of the Gulf of Mexico, in comparison with the Mexican Pacific and Caribbean (Tables 4.1 and 4.2); however, in all cases, important seasonal fluctuations were observed in the bacteriological quality of the coastal lagoons.

In the North Pacific, characterized by an arid climate, in the estuarine–lagoon ecosystem of San Ignacio, Navachiste, and Macapule (220 km^2), the number of coliforms decreased in the spring when the amount of nutrients and dissolved oxygen decreased (7–8 mg/). On the contrary, an increase in microbiological indicators was quantified during the winter months (January–March), associating their presence with low temperatures, high concentrations of nutrients, dissolved oxygen (>8.5 mg/l), and total suspended solids; the solids, which are the result of the

Table 4.1 Abundance of total coliform bacteria in several coastal lagoons of Mexico

Coastal zone	Coastal lagoon (or system)	Environmental matrix	Minimum	Maximum	Reference
North Pacific (Sinaloa)	San Ignacio-Navachiste	Water	30	1500	Escobedo-Urías et al. (1999)
South Pacific (Chiapas)	Pozuelos-Murillo	Water		240,000	Hernández-Romero et al. (2004)
South Pacific (Chiapas)	Chantuto-Panzacola	Water	ND	24,000	Becerra and Botello (1995)
Gulf of Mexico (Veracruz)	Estuary of the Coatzacoalcos River	Water	ND	24,000	Rodríguez-Santiago and Botello (1987)
Gulf of Mexico (Veracruz)	Ostión	Water	120	2,400	Rodríguez-Santiago and Botello (1987)
		Sediment	150	24,000	
Gulf of Mexico (Veracruz)	Tamiahua	Water	4	2,400	Barrera Escorcia et al. (1999)
		Sediment	300	46,000	
Gulf of Mexico (Veracruz)	Tampamachoco	Flat clam	0	1,100	López Ortega et al. (2014)
		Isognomon alatus			
Gulf of Mexico (Veracruz)	Pueblo Viejo	Water	4	2,400	Barrera Escorcia et al. (1998)
		Sediment	300	240,000	
		Oyster	400	2,300	
Caribbean (Yucatán)	Dzilam, Nahochin, Celestún	Pink flamingo	10	2,300	Ferrer Sánchez et al. (2017)
Caribbean (Quintana Roo)	Yal Kú estuary	Water	ND	460	Barrera Escorcia and Namihira-Santillán (2004)

resuspension of the sediments due to the wind, represented an adequate microhabitat for bacterial growth, increasing its viability. Also, in winter, the stress of ultraviolet radiation on bacteria decreased (Escobedo-Urías et al. 1999). The microbiological indicators, mainly *E. coli* cells, are more sensitive to inactivation by sunlight, and the reason for this is that turbid water could provide protection to microbiological indicators from sunlight inactivation (Chandran and Hatha 2003). The microbiological quality can negatively impact the fishery resources of this system since this area is important for breeding, feeding, and capturing economically important species (Escobedo-Urías et al. 1999).

Table 4.2 Abundance of fecal coliform bacteria in several coastal lagoons of Mexico

Coastal zone	Coastal lagoon (or system)	Matrix	Minimum	Maximum	Reference
North Pacific (Sinaloa)	San Ignacio-Navachiste	Water	30	1,500	Escobedo-Urías et al. (1999)
South Pacific (Chiapas)	Chantuto-Panzacola	Water	ND	24,000	Becerra and Botello (1995)
Gulf of Mexico (Veracruz)	Tampamachoco	Flat clam	0	93	Becerra and Botello (1995)
		Isognomon alatus			
Gulf of Mexico (Veracruz)	Pueblo Viejo	Water	4	600	Barrera-Escorcia et al. (1998)
		Sediment	300	46,000	
		Oyster	ND	400	
Gulf of Mexico (Veracruz)	Laguna Tamiahua	Water	3	2,400	Barrera Escorcia et al. (1999)
		Sediment	230	46,000	
		Oyster		15,000	
Gulf of Mexico (Veracruz)	Ostión	Water	150	2,400	Rodríguez-Santiago and Botello (1987)
		Sediment	120	3,800	
Caribbean (Quintana Roo)	Yal Kú estuary	Water	ND	2,750	López-Ortega et al. (2012)
Caribbean (Quintana Roo)	Lagartos	Water	ND	3,500	
Caribbean (Quintana Roo)	Yal Kú estuary	Water	ND	240	Barrera-Escorcia and Namihira-Santillán (2004)
		Sediment	ND	230	

The presence of high levels of microbiological indicators has been detected in two estuarine–lagoon ecosystems (Pozuelos-Murillo and Chantuto-Panzacola), both located in the South Pacific (Chiapas) (Tables 4.1 and 4.2). In Pozuelos-Murillo, microbiological contaminants have a higher level of potential health risk, since these sites possess the highest fishing activity (Hernández-Romero et al. 2004). In Chantuto-Panzacola, the abundance of microbiological indicators in water and sediment has been evaluated in two different periods, obtaining contradictory results. Becerra and Botello (1995) documented in the rainy season a decrease in microbiological indicators, attributable to a process of self-purification in the system. In contrast, Calva-Benítez et al. (2014) reported maximum levels of microbiological indicators in the rainy months, which correlated to turbidity, solid content, lower salinity, and oxygen concentration.

The abundance of microbiological indicators is related to wastewater discharges, for example, the estuarine–lagoon ecosystem of San Ignacio receives approximately 709,660 m^3 per year of wastewater discharges from the city of Guasave in Sinaloa state, in addition with the discharges coming from the adjacent areas with intensive agriculture activities. Pozuelos-Murillo, a coastal lagoon in the Soconusco region (Chiapas), is sited in an agricultural area; this system receives wastewater discharges from Tapachula city and from other villages sited along the Cahoacán River. Touron et al. (2007) mentioned that indicator bacteria levels in coastal waters were greatly influenced by point source pollutants. The coastal zone of the Pacific is an area very sensitive to chemical and bacteriological contamination due to the long residence time of the substances, which causes high retention of incorporated contaminants.

In the Gulf of Mexico, several coastal lagoons have reported high levels of microbiological contamination, which fluctuates throughout the year, depending on the climatic season (Wong-Chang and Barrera-Escorcia 1996). In general terms in months associated with the rainy season, microbiological contamination increases due to high concentrations of nutrients (favoring the development of opportunistic pathogens and coliforms) (Chandran and Hatha 2003), high temperatures, low salinities (reducing osmotic shock), pH, and dissolved oxygen (Barrera-Escorcia et al. 1999).

The influence of climatic variation on the microbial water quality in estuaries and coastal lagoons has been observed also in other tropical countries. For example, in India, the high level of fecal coliforms and fecal streptococci was quantified in the rainy season associated with monsoon. The high levels were related to neutral pH, lower temperature and salinity, an increase in nutrient concentrations, and a greater turbidity by greater fluvial contributions (Jayakumar et al. 2013). The survival of fecal microorganisms is influenced by their association with particles, which have a complex hydrodynamic behavior affected by tidal cycles and river flow (Ghaderpour et al. 2014). In coastal lagoons of Brazil, the highest abundances of total coliform, fecal coliform, *Enterococcus*, *S. aureus*, *Vibrio*, and *Salmonella* were also found in the rainy and summer seasons; their presence was related to a high availability of nutrients and organic matter and to the contribution of continental runoff (Gonzalez et al. 2010).

The effect of environmental variables on the distribution and abundance of pathogens and sanitary indicator organisms is explained by their origin in the intestine of man and warm-blooded animals. When fecal microorganisms are discharged in coastal systems, they do not find favorable environmental conditions for their viability. Stewart et al. (2008) determined that the presence, survival, and sometimes the proliferation of enteric bacteria in estuarine–coastal lagoon ecosystems depend on several factors such as biological (competition from other microorganisms, predation by protozoa), chemical (salinity, pH, nutrient concentration), and physical (light, temperature).

The study of microbiological indicators in the coastal lagoons of Mexico has been performed not only in different climatic seasons but also in different environmental matrices: water, sediment, and microorganisms (Tables 4.1 and 4.2). Microbiological contamination has been studied more frequently in water than in sediments or organisms. The main organisms studied are bivalve mollusks such as oysters and clams since they represent a resource of commercial importance.

The presence of coliforms in water ecosystems does not permit their utilization for recreational activities in 33.3% of the analyzed systems, and 29% of the systems cannot be considered for protection of aquatic life. Fecal streptococci presence was found at a relatively low percentage. There are only few studies analyzing the presence of fecal streptococci in Mexico, because Mexican legislation does not include these microorganisms; therefore, results obtained in some analyzed samples are compared only with international criteria (Canter 1977).

Coliform bacteria are found in larger quantities in sediments than in the water column. It has been established that sediments protect the development of bacteria, being the habitat or refuge for these microorganisms and allowing their persistence and growth (Rodríguez-Santiago and Botello 1987). The great amount of organic matter in the sediments is used by some microorganisms like *Escherichia coli* to adapt and to modify their physiological responses facing stressful situations (Munro et al. 1987; Barrera-Escorcia et al. 1999).

The presence of bacteria of fecal origin in water and sediments implies a greater health risk for filter feeders or detritivores, such as oysters and shrimps, because these organisms can easily incorporate them from water or sediment; in fact, in the tissues of these organisms, an abundance of 15,000 fecal coliforms and 9,300 fecal streptococci has been reported. The microbiological quality of the bivalve mollusks is intimately related to sanitary conditions of the surrounding waters where they are cultivated. Mollusks are filter feeders that can concentrate in their tissue particles present in the water by more than fourfold, acting as an important vector for pathogens (Marques-Sousa et al. 2012). Oysters, as filter-feeding organisms, magnify public health problems associated with environmental contamination and their poor sanitary quality, generating important economic losses in the seafood industry in the national market (Fernández-Delgado et al. 2007; Barrera-Escorcia et al. 1998).

The coastal lagoons of Tamiahua, Pueblo Viejo, Mandinga, and Alvarado are the main producers of the oyster in Veracruz, where the sanitary quality of oysters is a serious problem (Franco-López and Chávez-López 1992). The sanitary quality water in Tamiahua and Pueblo Viejo lagoons was analyzed, and both lagoons were reported to be unsuitable for oyster and shellfish culture. Pueblo Viejo lagoon showed that 54.2% of the analyzed samples had values above the limits considered acceptable for total coliforms, 45.8% for fecal coliforms, and 29.2% for streptococci (Barrera-Escorcia et al. 1998). It is important to mention that the levels of microbiological contamination in the coastal zone of the Gulf of Mexico have been associated with morbidity rates due to gastrointestinal and skin diseases, mainly in the infant population, present in high quantity in the coastal areas of Veracruz state (Rodríguez-Santiago and Botello 1987).

In some coastal areas of the Mexican Caribbean, high abundances of microbiological indicators have also been determined (Tables 4.1 and 4.2). Coastal ecosystems of karst regions are particularly vulnerable to eutrophication and microbiological contamination because of freshwater inputs by groundwater, which is highly susceptible to pollution from urban and industrial wastewater, septic tanks, and open sanitary landfills, as well as the use of land in agricultural and livestock activities, adding the uncontrolled use of agrochemicals and the inadequate disposal of waste (Tapia-González et al. 2008). The groundwater of the state of Yucatán presents a bacteriological quality classified as contaminated by 23%, dangerous by 18%, and very contaminated by 14% of the analyzed ecosystems (Pacheco-Ávila et al. 2004). Groundwater being the main source of drinking water supply in this region, the deficient microbial water quality represents a risk to human health and an environmental threat.

4.3.2 Pathogenic Bacteria in Coastal Lagoons of Mexico

Coastal ecosystems normally show the presence of pathogens that may cause diseases and other problems for human health. The results of research carried out in Mexico indicate that estuarine–coastal lagoon systems are contaminated with various types of human bacterial pathogens which might pose a potential serious risk to public health.

The presence of *Escherichia coli*, *Shigella sonnei*, *Salmonella typhi*, *S. paratyphi*, *S. choleraesuis*, *Staphylococcus* spp., *Proteus vulgaris*, *Enterobacter aerogenes*, *Klebsiella pneumoniae*, *Arizona* spp., *Citrobacter* spp., and *Edwardsiella* spp. has been determined in water and clams. The presence of *E. coli*, *K. pneumoniae*, *E. aerogenes*, and *Citrobacter* spp. (Rodríguez-Santiago and Botello 1987; Quiñonez-Ramírez et al. 2000) was observed in sediments. Environmental factors such as higher temperature, dissolved oxygen, nutrients, and saline water are related to the presence of *Salmonella* and *Shigella* spp.; both bacteria cause typhoid fever due to food poisoning, with *Salmonella* being responsible for gastroenteritis (Viau et al. 2011).

Enterobacter aerogenes and *E. cloacae* are opportunistic bacteria causing a variety of infections including pneumonia, urinary tract infections, wound infections, and bacteremia. *Aeromonas* spp. are considered native inhabitants of aquatic environments including seawater, freshwater, and marine waters, and they may be detected in both polluted and unpolluted waters; high levels of *Aeromonas* may increase the risk of wound infection and gastroenteritis in susceptible people associated with aquatic activities (Ghaderpour et al. 2014).

K. pneumoniae is an opportunistic pathogen causing several human diseases such as respiratory, urinary, and wound infections and liver abscess syndrome. *Serratia marcescens* is an opportunistic pathogen causing urinary tract, bloodstream, and pneumonia infections; it is the predominant species isolated from rivers. There are 17 species of *Campylobacter*, and among them, *C. jejuni* and *C. coli* are the most important human pathogens with increased persistence in low dissolved oxygen, low temperature, and low salinity waters (Viau et al. 2011).

Microbial research performed in Mexican lagoons from Sinaloa, Veracruz (Mandinga), and Yucatán (Rosada, Chelem, and Celestún) on bivalve mollusks (clams and oysters) and shrimps revealed the presence of *Arizona hinshawii*, *Salmonella typhimurium*, *S. edimburg*, *S. anatum*, *S. enteritidis*, *Vibrio cholerae* 01, *V. parahaemolyticus*, and *V. alginolyticus* (Quiñonez-Ramírez et al. 2000; Cabrera-García et al. 2004; Castañeda-Chávez et al. 2005; Velázquez-Román et al. 2012; Ortíz-Carrillo et al. 2015).

V. cholerae (causes cholera in humans), *V. parahaemolyticus* (gastroenteritis), and *V. vulnificus* are leading causes of shellfish-related illness and vibrio pathogens most frequently associated with US recreational water outbreaks. Optimal environmental conditions for these pathogens include warmer temperatures (15–30 °C) and mesohaline waters (5–25 ups) (Viau et al. 2011). In coastal areas of Venezuela, the presence of *Proteus mirabilis*, *E. coli*, *Morganella morganii*, and *K. pneumoniae* was also determined in oysters and clams. *P. mirabilis* is one of the most frequent etiological agents associated with urinary tract infections (Fernández-Delgado et al. 2007).

The presence of *Streptococcus faecalis*, *S. salivarius*, *S. mutans*, *V. parahaemolyticus*, *V. alginolyticus*, and *Aeromonas hydrophila* has also been reported in the muscle of fishes of commercial interest. *S. faecalis*, *S. salivarius*, and *S. mutans* release enterotoxins responsible for human diseases. They are opportunistic species favored by the presence of nutrients. *S. faecalis*, the presence of which indicates chronic fecal contamination, can cause peritonitis and biliary and urinary tract infections. *S. salivarius* and *S. mutans* cause tooth decay, tartar formation, and bacterial endocarditis. *V. parahaemolyticus* is associated with acute gastroenteritis, wound infection, ear infection, and secondary septicemia. *V. alginolyticus* is related to acute gastroenteritis, wound infection, ear infection, and primary septicemia; finally, *A. hydrophila* is associated with acute gastroenteritis (Reyes-Valázquez et al. 2010; Romero-Jarero and Negrete-Redondo 2011).

The contamination of shellfish cultivated in coastal marine waters is a global public health concern. Pathogens such as *E. coli* and species of *Vibrio*, *Klebsiella*, and *Salmonella* have been reported from estuarine and marine environments globally (Lee et al. 2011; Ghaderpour et al. 2014). Exposition to marine waters contaminated by microbes generates an estimate of 120 million gastrointestinal infections, 50 million acute respiratory infections, and numerous skin infections each year (Shuval 2003).

Microbial contamination in estuarine–lagoon ecosystems and the presence of pathogens in mollusks, crustaceans, and fishes are threats to public health. Therefore, there is a necessity of applying monitoring programs in a greater number of the coastal lagoons and estuaries in the country. The identification of the sources of contamination as well as the study of the distribution, permanence, and destination of these pathogens is very important since it provides the basis to evaluate possible risks by the consumption of food or by exposition in recreational activities. In most countries, microbial water quality and safety monitoring of coastal and estuarine waters are essential components of the risk management programs (Touron et al. 2007).

In monitoring programs, the use of other microbiological indicators should also be considered because some strains of *E. coli* can survive in marine and brackish waters (Berthe et al. 2013). Alternative indicators cannot multiply under environmental conditions but are present in low concentrations in unimpacted environmental samples and are present in high concentrations in sewage. Some of the microorganisms proposed as alternative indicators are bifidobacteria, *Clostridium perfringens*, human viruses, and F-RNA coliphages (Stewart et al. 2008).

4.4 Vulnerability

The vulnerability of coastal ecosystems is increasing, as these ecosystems are highly exposed to the influence of anthropogenic multistressors such as population growth; urbanization; watershed fragmentation; land and water use alteration by agriculture in surrounded areas; municipal and industrial wastewater discharged with the increasing nutrient enrichment; pollution with organic matter with the consequent increment of the eutrophication phenomenon; introduction of pesticides, heavy metals, hydrocarbons, and pathogenic microorganisms, affecting health at many trophic levels; and depletion of natural resources by fisheries (Robins et al. 2016). Coastal zones are also physically vulnerable, experiencing accelerated erosion, intrusion of seawater, impact of storms, and river inputs, which could increase with the climate change (Dayton et al. 2005). These multistressors and their effects on biodiversity and the consequent ecosystem alteration have been studied mostly in temperate regions and scarcely in tropical regions (Kaestli et al. 2017). There is an enormous interest to understand what happens in tropical regions: "Are they the same stressors?" "Are they the same ecological responses?"

Mexico is a tropical country and possesses an important coastline extension, with different geological, climatic, and orographic characteristics, with the resulting high natural richness, being considered one of the top 5 countries with the biggest biodiversity, owning the tenth part of the worldwide biota. Despite their enormous biodiversity and their recognized ecological, sanitary, and economical importance, coastal ecosystems in Mexico are very vulnerable, and the discharge from the most important rivers Grijalva-Usumacinta, Papaloapan, Coatzacoalcos, and Pánuco affects watersheds in Gulf of Mexico, increasing the amount of nutrients, sediments, and multiple contaminants, among these the pathogenic microorganisms from multiple sources such as runoff, rain, and groundwater discharges, all them with important ecological and economic negative effects on coastal ecosystems (Camacho−Ibar and Rivera-Monroy 2014).

In Mexico vulnerability studies related to microbial communities are scarce; basically, they refer to the impact of episodic storms such as hurricanes. In this sense, in the coastal lagoon of Nichupte-Bojorquéz (Quintana Roo), microbial diversity was analyzed before and after Hurricane Wilma (October 2005). This lagoon has an extension of 48 km^2; in some areas, it presents problems of eutrophication caused by the contribution of nutrients from municipal wastewater. In the water column, the bacteria identified correspond to *Bacteroidetes*, *Flavobacteria*, and *Sphingobacteria*, and the last one included the genera *Cytophaga* and *Flexibacter*. The second most abundant group was assigned to the *Proteobacteria* group (α-, β-, and γ-proteobacteria) and a minor proportion of bacteria that belongs to the *Cyanobacteria* and *Bacilli* class. Members of the phylum *Bacteroidetes* are mostly strict anaerobes. They are considered as fecal indicators and are abundant in the feces of warm-blooded animals. β-Proteobacteria are abundant in freshwater ecosystems, and their presence in the lagoon could adhere to the intrusion of freshwater during the storm. No significant differences were found in the microbial composition after the passage of the hurricane (León-Galván et al. 2009).

The water quality of the Santa Rosa coastal lagoon located in the Caribbean Sea was analyzed to determine the changes after the hurricane Dean. The principal changes observed were a decrease in temperature, salinity, dissolved oxygen, and nitrate concentration and an increase in ammonia and orthophosphates, especially an increase in total and fecal coliforms. Sporadic storms such as hurricanes could be considered the source of pathogen contamination in coastal areas (Torres-Alvarado and Calva Benítez 2011).

Coastal lagoons are important reserves of pathogens; their presence is a risk for human health as well as for the water quality. Pathogens enter these systems by municipal wastewater discharges and runoffs from the surrounding agricultural lands. It is necessary to decrease the impacts of pathogens and indicator microorganisms of fecal contamination by treatment of wastewater discharges to avoid the water quality degradation and to diminish the human health risk in communities located in these areas, as well as to control the microbial contamination of the cultivated or harvested marine species.

Mexico presents common problems as those occurring in other developing countries, where legislation is not correctly applied and in general conservation and sustainable exploitation are not priorities, because there are more pressing social and economic problems to attend. However, the increment of the ecological and social consciousness to preserve the coastal ecosystems is useful to increase funds to study and protect these areas. We should be able to promote sustainable management and conservation strategies, to mitigate ecological disasters and prevent outbreaks of diseases caused by opportunistic pathogens. These strategies are very important because of the economic and ecological human dependence on these ecosystems.

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Chapter 5
Biodiversity Associated with Southern Mexican Pacific Coral Systems

Andrés López-Pérez, Rebeca Granja-Fernández, Omar Valencia-Méndez, Cuauhtémoc Aparicio-Cid, Ana M. Torres-Huerta, Norma A. Barrientos-Luján, Francisco Benítez-Villalobos, and Luis Hernández

5.1 Introduction

Shallow coral reefs worldwide occupy around 284,300 km^2, which is 1.2% of the world's continental shelf area and only 0.09% of the total area of the world's oceans (Spalding et al. 2001). Although scarce in extension, it is a critical resource since

A. López-Pérez (✉)
Departamento de Hidrobiología, Universidad Autónoma Metropolitana-Iztapalapa, Ciudad de México, Mexico
e-mail: alopez@xanum.uam.mx

R. Granja-Fernández
Doctorado en Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana-Iztapalapa, Ciudad de México, Mexico

O. Valencia-Méndez
Doctorado en Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana-Iztapalapa, Ciudad de México, Mexico

Marine and Coastal Ecosystems A.C., Huatulco, Oaxaca, Mexico

C. Aparicio-Cid
Programa de Posgrado. Centro Interdisciplinario de Ciencias Marinas. Instituto Politécnico Nacional, La Paz, B.C.S., Mexico

Marine and Coastal Ecosystems A.C., Huatulco, Oaxaca, Mexico

A. M. Torres-Huerta · N. A. Barrientos-Luján · F. Benítez-Villalobos
Instituto de Recursos, Universidad del Mar. Campus Puerto Ángel, Puerto Ángel, Oaxaca, Mexico
e-mail: blujana@angel.umar.mx; fbv@angel.umar.mx

L. Hernández
Departamento Académico de Biología Marina, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., Mexico
e-mail: lghm@uabcs.mx

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they supply a vast number of people with numerous goods and ecological services (Moberg and Folke 1999). Yet, reefs are degrading rapidly for centuries by overfishing, pollution, and mechanical habitat destruction and recently by species introduction and climate change (Jackson et al. 2001; Hughes et al. 2017).

Goods and ecological services are generated and sustained by biological communities, and these in consequence sustain ecosystem health and resilience (Duffy et al. 2013). In this sense, reef degradation and biodiversity loss may impair the capacity of the reef to provide goods and services and recover from perturbations (Moberg and Folke 1999; Worm et al. 2006; Hughes et al. 2017); therefore, managing reef systems to maintain its biodiversity may provide a way to guarantee their permanence across space and time. Nevertheless, our knowledge of reef-associated biodiversity is still fragmented and often narrow in taxonomic and spatial scope.

The Eastern Pacific is among the most suboptimal areas worldwide for reef development; nevertheless, corals and coral reefs extend from the Gulf of California, México, to Ecuador and the oceanic islands off Western México, Costa Rica, Colombia, Ecuador, and Chile (Glynn et al. 2017). In Western México, coral reef development has been documented at Cabo Pulmo and Bahía San Gabriel inside the Gulf of California (Reyes-Bonilla and López-Pérez 2009), Marías Islands (Pérez-Vivar et al. 2006; López-Pérez et al. 2016a), Ixtapa-Zihuatanejo vicinity (López-Pérez et al. 2012), and in the southern coast of México at Huatulco Bay (Glynn and Leyte-Morales 1997).

By virtue of their extension, reef framework, and structural complexity, the coral systems developing across the coastal expanse of Guerrero and Oaxaca can be considered among the best-developed reef systems from the Eastern Pacific (Glynn and Leyte-Morales 1997; López-Pérez et al. 2012). Despite the above, knowledge of coral-associated biodiversity is still poorly known and fragmented in the area. Currently, most of the biodiversity studies are local in scope (Zamorano and Leyte-Morales 2005; Valencia-Méndez et al. 2017), restricted to well-studied macrofauna such as corals (López-Pérez et al. 2012), echinoderms (Zamorano and Leyte-Morales 2005) and fishes (Juárez-Hernández et al. 2013), incipient studies in some groups (Jarquín-González and García-Madrigal 2010; Humara-Gil and Cruz-Gómez 2018), but fully absent in other taxa.

Here, we synthesize the knowledge regarding the biodiversity of reef-associated organisms including algae, sponges, cnidarians, polychaetes, mollusks, malacostraceans, echinoderms, and fishes across coral systems located in Guerrero and Oaxaca (Fig. 5.1), in the southern Mexican Pacific. A database was constructed from three sources: (a) field data (specimens observed/collected from 2006 to 2018), (b) taxonomical review of the material deposited in biological collections (Table 5.1), and (c) primary literature. We included records in the database solely under the premise that they were collected/recovered in or around reef-building corals.

Integrative databases (such as the current one) resulting from several sources, seasons, sampling techniques, and intensities, assembled to generalize in ecology, without any doubt, are subjected to bias. In particular, bias in sample size and also spatial, temporal, and taxonomical bias may alter the findings and further general-

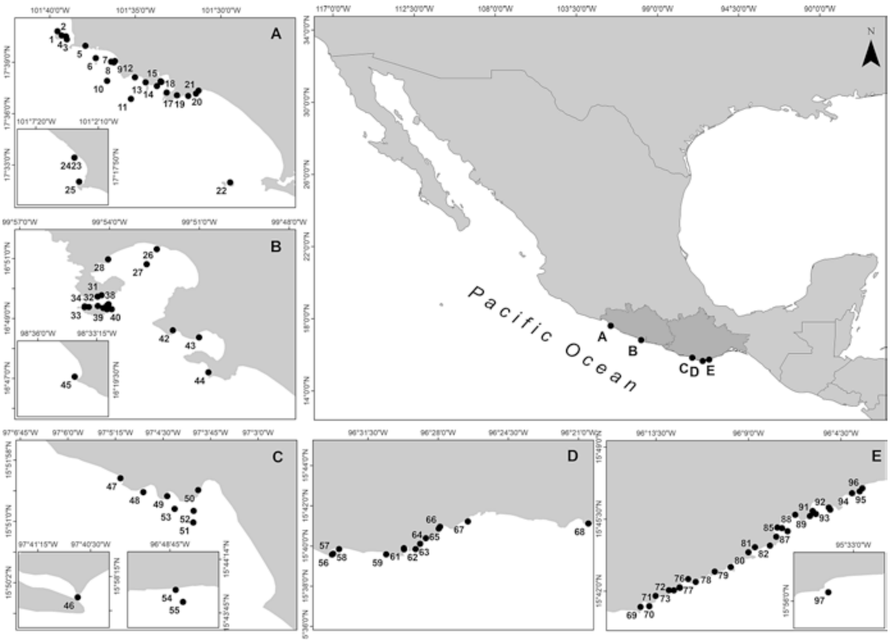

Fig. 5.1 Sampled localities in Ixtapa-Zihuatanejo/Puerto Vicente Guerrero (**a**), Acapulco/Punta Maldonado (**b**), Chacahua/Puerto Escondido/Santa Elena (**c**), Puerto Ángel (**d**), Huatulco/ Tehuantepec (**e**). 1 = Morro de Cerro Colorado, 2 = Playa Coral, 3 = Zacatoso, 4 = Playa Carey, 5 = Playa Don Juan, 6 = El Chato, 7 = Isla Ixtapa, 8 = Morro Tierra, 9 = Pacifica, 10 = Sacramento, 11 = Piedra Sola, 12 = Morro Tigre, 13 = Chololo, 14 = Godornia, 15 = Contramar, 16 = Las Gatas, 17 = Caleta de Chón, 18 = Zihuatanejo, 19 = El Yunque, 20 = Playa Manzanillo, 21 = Riscal, 22 = Morros de Potosí, 23 = Puerto Vicente Guerrero, 24 = Piedra Pelícano, 25 = Atrás Cueva, 26 = El Morro, 27 = San Lorenzo, 28 = Parque de la Reina, 29 = La Angosta, 30 = Zoológico, 31 = Mundo Mágico, 32 = Boca Chica, 33 = Rincón, 34 = Ensenada de Llantos, 35 = Isla Roqueta, 36 = Punta Bruja, 37 = Palmitas, 38 = la Virgen, 39 = El Ripial, 40 = Hawaii 5.0, 41 = Marina, 42 = Pichilingue, 43 = Punta Diamante, 44 = Acapulco, 45 = Punta Maldonado, 46 = Chacahua, 47 = Coral, 48 = Carrizalillo, 49 = Puerto Angelito, 50 = Puerto Escondido, 51 = El Faro, 52 = Punto de Presión, 53 = Zapatito, 54 = Santa Elena, 55 = Agua Blanca, 56 = Punta Cometa, 57 = Mazunte, 58 = Camaroncillo, 59 = Playa del Amor, 60 = Puerto Ángel, 61 = Playa Panteón, 62 = La Guacha, 63 = Estacahuite, 64 = La Mina, 65 = Playa del Muerto, 66 = Boquilla, 67 = La Tijera, 68 = Salchi, 69 = San Agustín, 70 = Isla San Agustín, 71 = Riscalillo, 72 = Jicaral, 73 = Dos Hermanas, 74 = Prima, 75 = Harrys, 76 = La India, 77 = Pomelo, 78 = Copal, 79 = Isla Cacaluta, 80 = El Maguey, 81 = Órgano, 82 = Violín, 83 = La Entrega, 84 = Santa Cruz, 85 = Dársena, 86 = Chahue, 87 = Isla La Blanca, 88 = Tejón, 89 = El Arrocito, 90 = Tangolunda, 91 = Manzanilla, 92 = Casa Mixteca, 93 = Isla Montosa, 94 = Rincón Sabroso, 95 = Copalita, 96 = Conejos, 97 = La Blanca

izations about the species richness associated with southern Mexican Pacific coral systems. In order to reduce those biases from the database, two approaches were followed. First, sampling bias was reduced after eliminating all reference to biomass or abundance data, and hence, analysis was based on incidence-only (presence/absence) data (Clarke and Warwick 2001). Second, even though specimens were identified to the finest possible taxonomic level, bias was reduced by

Table 5.1 Size (ha) of coral communities and reefs in the southern Mexican Pacific. Daniel López (Colegio de la Frontera Sur, México) = Image analysis and echosounder, Eduardo Ramírez (Universidad del Mar, México) = Drone

Locality	Extension (ha)	Method
Ixtapa-Zihuatanejo		
Morro de Cerro Colorado	7.78976	Image analysis
Playa Coral	3.64486	Image analysis
Nudista	1.17586	Image analysis
Zacatoso	2.70432	Image analysis
El Chato	2.95154	Image analysis
Caleta de Chón	1.28666	Image analysis
Manzanillo	8.10079	Image analysis
Puerto Ángel		
Mazunte	6.42759	Echosounder
Estacahuite	2.73068	Echosounder, drone
La Mina	1.77627	Echosounder
Playa del Muerto	0.48707	Echosounder
La Tijera	3.30884	Echosounder
Huatulco		
San Agustín	6.48734	Echosounder, drone
Isla San Agustín	1.12311	Echosounder
Riscalillo	3.51381	Echosounder, drone
Jicaral	1.52033	Echosounder, drone
Isla Cacaluta	1.64828	Echosounder
Maguey	2.80000	Echosounder, drone
Órgano	0.70000	Echosounder, drone
Violín	2.48143	Echosounder, drone
La Entrega	3.23923	Echosounder

using operational taxonomic units (OTUs) (sets of organisms that formed exclusive taxonomic groups) instead of species. Finally, we omitted from further analysis of richness those organisms in the database with incorrect latitude and longitude data or identified as belonging to broad taxonomic groups.

5.2 Environmental Setting

The area (Fig. 5.1) is located in the southern Mexican Pacific, and it is typical of the Eastern Tropical Pacific. The region experiences a dry season that extends from November to April and a rainy season (800–1500 mm year) from May to October. The Eastern Pacific warm pool (SST >28 °C) influences these coastal waters. This oceanographic feature is centered off Guatemala and the southwestern coast of Mexico and is characterized by high temperatures, small annual thermal oscillations

(<2 °C), an average surface salinity of 34, and the presence of a shallow (20–40 m) and quite stable thermocline (Fiedler and Talley 2006).

Due to a paucity of systematic oceanic observations along the southwest coast of México, considerable confusion exists regarding the current system influencing the area and its variability. Kessler (2006) indicated that the anticyclonic flow surrounding the Tehuantepec Bowl (TB) produces a strong southeastward current along the coast of Oaxaca that moves into the Gulf of Tehuantepec and eventually cuts off the Costa Rica Coastal Current (CRCC), forcing it to turn offshore. Concurrently, on the northwest side of the TB, a weak sub-thermocline dome and cyclonic circulation form a poleward coastal flow, called the West Mexican Current (WMC), with a mean speed of about 3 cm s^{-1}. The TB weakens and retreats offshore during July–September. This migration reduces the coastal currents that block the CRCC surface, allowing additional northward flow along the Oaxaca coast in summer. During June–October, the velocity of the WMC speed increases to more than 5 cm s^{-1}, presumably transporting more tropical water northward (Kessler 2006). In addition, Kessler (2006) demonstrated that during winter (January–March), the California Current extends southward past Cabo San Lucas, allowing water from the California Current to penetrate far into the tropics around the TB.

Seasonally, from November through March, high-pressure polar air masses moving into the Gulf of México result in intense wind bursts, collectively called "Nortes or Tehuanos." In México, these wind jets are channeled through the Tehuantepec Jet across the Isthmus of Tehuantepec (Fiedler and Lavin 2017). These winds produce strong changes in the structure of the water column and a complex coastal circulation. Under the influence of Tehuanos, surface water flows offshore, which causes mixing and entrainment of subsurface water, the result of which is a temperature drop of up to 8 °C at the center of the gulf and the formation of a cold-water plume that may stretch over 400 km offshore and be more than 200 km wide (Trasviña et al. 1995). Wind relaxation after Tehuanos results in the formation of mesoscale structures (Chang et al. 2012). Cyclonic and anticyclonic mesoscale structures are highly relevant to coral system development in the Puerto Ángel vicinity but mainly in Huatulco, since they determine the vertical distribution of the physicochemical properties in the water column (Samuelsen and O'Brien 2008); anticyclonic eddies deepen the pycnocline and keep subsurface waters (dissolved inorganic carbon rich, with low pH and near-undersaturated aragonite levels) away from the surface; during cyclonic eddies, on the contrary, upwelling transports subsurface waters toward the surface (Chapa-Balcorta et al. 2015) during which low pH and undersaturated aragonite levels may jeopardy corals and other calcifying organisms.

Finally, the most important source of interannual oceanographic variability along the southern Mexican Pacific is the development of the El Niño-Southern Oscillation (ENSO) phenomenon every 4–5 years (Fiedler and Talley 2006), characterized by a deepening of the thermocline and nutricline, which negatively impacts primary productivity. When ENSO changes to its cold phase (La Niña), the conditions reverse, resulting in reduced depth of the thermocline. Consequently, nutrient-rich waters can come close to the ocean surface, enhancing regional productivity (Pennington et al. 2006).

5.3 Coral Communities and Reefs

Along 882 km of the coastal expanse that comprises Guerrero (314 km) and Oaxaca (568 km) states in southern Mexican Pacific, up to 97 localities have been referred as harboring reef corals. In general, coral communities and reefs clustered around five areas: the bays of Ixtapa-Zihuatanejo, Acapulco, Puerto Escondido, Puerto Ángel, and Huatulco (Glynn and Leyte-Morales 1997; Reyes-Bonilla et al. 2005; López-Pérez et al. 2012).

From west to east, 22 sites corresponded to the Ixtapa-Zihuatanejo vicinity, 3 to Puerto Vicente Guerrero, 19 to Acapulco, 1 to Punta Maldonado, 1 to Chacahua, 7 to Puerto Escondido, 2 to Santa Elena, 13 to Puerto Ángel, 28 to Huatulco (Fig. 5.1), and 1 to Tehuantepec. The presence of large coral systems in Punta Maldonado, Chacahua, and Santa Elena is uncertain; hence, data should be taken with caution.

Overall, coral communities and reefs commonly share south or southeast exposures (Glynn and Leyte-Morales 1997) and are located in embayments or behind rocks or islands that offer shelter from prevailing winds (Reyes-Bonilla 2003; López-Pérez et al. 2012). Six *Pocillopora*-dominated fringing reefs are located in the Ixtapa-Zihuatanejo vicinity (Morro de Cerro Colorado, Playa Nudista, Playa Coral, Zacatoso, Caleta de Chon, and Manzanillo) (López-Pérez et al. 2012), two in Puerto Ángel (La Tijera and Salchi), and ten in Huatulco (San Agustín, Riscalillo, Jicaral, Dos Hermanas, La India, Isla Cacaluta, Maguey, Violín, La Entrega, and Isla Montosa) (Glynn and Leyte-Morales 1997; López-Pérez and Hernández-Ballesteros 2004; López-Pérez et al. 2014). Currently, there are no reefs but just some scattered stony corals in Acapulco (López-Pérez et al. 2012), Punta Mandonado, Chacahua, Santa Elena, Puerto Escondido, or Tehuantepec vicinities.

Reef frameworks in the area are constructed by interlocking branches of pocilloporid corals, intermixed with scattered areas of the typical *Pocillopora* morphotype which form an open framework; meanwhile, in areas where no reef frameworks exist, small coral patches inhabited by *Pocillopora* spp., *Pavona gigantea*, *Porites panamensis*, and rarely *Porites lobata* are common (Glynn and Leyte-Morales 1997; Leyte-Morales 1997; Reyes-Bonilla and Leyte-Morales 1998; López-Pérez et al. 2012). The development of these smaller coral patches is controlled by an arrangement of rock ridges, which served as the primary foundation, similar to the observation elsewhere in the Gulf of California and the Eastern Tropical Pacific (Reyes-Bonilla and López-Pérez 2009; Glynn et al. 2017). However, these patches cannot yet be considered true reefs in a formal constructional sense but coral communities (sensu Alvarado et al. 2005) that host an important biotic community of reef fauna.

Eighteen hermatypic species from seven genera have been reported (Glynn and Leyte-Morales 1997; Reyes-Bonilla et al. 2005; López-Pérez et al. 2012), while communities and reefs exhibit a highly variable live coral cover. Coral cover in the Ixtapa-Zihuatanejo area ranges from 18% to 65%, while in Acapulco, the coral cover is extremely low on average (<4%) (López-Pérez et al. 2012). During mid-1990s, Glynn and Leyte-Morales (1997) addressed that most of the reefs exhibit high (30–50%) to very high (60–90%) live coral cover in the Huatulco area, but data were unknown for the rest of the areas. Current unpublished data (Andrés López, Universidad Autónoma Metropolitana, México) indicates that live coral cover is relatively low in Puerto Escondido (8.7% ± 9.6%), moderate in Puerto Ángel (20.4% ± 18%), and relatively high in the Huatulco vicinity (54% ± 31.5%).

Glynn and Leyte-Morales (1997) and later López-Pérez et al. (2012) addressed the approximate size and shape for a scarce number of coral communities and reefs in Huatulco and Ixtapa-Zihuatanejo, respectively. Recently, López-López (Colegio de la Frontera Sur, México, unpublished data) and Ramírez-Chávez (Universidad del Mar, México, unpublished data) employing bathymetric and remote-operated vehicle approaches have addressed far more accurate size estimates for a relatively large number of coral systems (Table 5.1). Overall, coral communities and reefs extend to 27.7 ha in the Ixtapa-Zihuatanejo area, 14.7 ha in Puerto Ángel, and 23.5 ha in Huatulco, although data are still missing for size and shape for up to 78 (78.8%) coral systems across Guerrero and Oaxaca. Nevertheless, based on expert opinions (Luis Calderón, Centro de Investigación Científica y de Educación Superior de Ensenada; Héctor Reyes and Luis Hernández, Universidad Autónoma de Baja California Sur México), the extent of the communities and reefs across the area may reach up to 120 ha.

Coral communities and *Pocillopora*-dominated reefs in the southern Mexican Pacific are very similar among them and among major coral areas (i.e., Ixtapa-Zihuatanejo, Acapulco, Puerto Escondido, Puerto Ángel, Huatulco) regarding vertical species distribution: encrusting, nodular, and massive species do not intersperse with pocilloporid species within the reef framework, developing instead at the reef base where the latter are less abundant (Glynn and Leyte-Morales 1997). Additionally, coral systems across the area are dominated by *Pocillopora* spp. (>90%) and to a lesser extent by *Pavona* spp. (<5%) and *Porites* spp. (<1%) (Glynn and Leyte-Morales 1997; Reyes-Bonilla and Leyte-Morales 1998; López-Pérez and Hernández-Ballesteros 2004; López-Pérez et al. 2012; Nava and Ramírez-Herrera 2012).

5.4 Biodiversity

To date, up to 989 operational taxonomic units (177 algae, 40 sponges, 36 cnidarians, 131 polychaetes, 196 mollusks, 126 malacostraceans, 73 echinoderms, and 210 fishes) have been recorded in coral systems across Guerrero and Oaxaca in the southern Mexican Pacific (Table 5.2).

Rarefaction curves were constructed to estimate the completeness of sampling effort and, therefore, the reliability of OTUs richness estimates for the reef-associated biodiversity across Guerrero and Oaxaca, southern Mexican Pacific (Fig. 5.2). Except for echinoderms, cnidarians, and to some extent sponges and fishes, no other taxonomic group rarefaction curves reached an asymptote, indicating that the number of sites (97) was insufficient to reliably estimate the total number of OTUs within this habitat and for the overall study area based on these

Table 5.2 Observed and expected OTU diversity associated with coral systems across Guerrero and Oaxaca, southern Mexican Pacific

	Phylum	Class	Order	Family	Genus	OTUs	[a]Expected OTUs	Mexican Pacific/Eastern Pacific
Guerrero								
Algae	4	7	24	40	61	159	---	---
Sponges	1	1	7	15	17	31	35–46	---
Cnidarians	1	2	4	10	12	28	32–43	---
Polychaetes	1	1	5	13	28	49	61–118	---
Mollusks	1	4	16	52	82	111	135–179	---
Malacostraceans	1	1	2	25	40	80	87–117	---
Echinoderms	1	4	14	26	40	64	70–87	---
Fishes	1	2	28	35	118	183	192–223	---
					Total	**701**	**803–1148**	**---**
Oaxaca								
Algae	3	4	12	18	26	36	---	242[b]
Sponges	1	2	6	11	14	20	22–28	17[b]
Cnidarians	1	2	5	13	16	31	35–40	101[b]
Polychaetes	1	1	5	18	62	112	133–190	222[b]
Mollusks	1	4	18	67	122	177	204–263	462[b]
Malacostraceans	1	1	2	33	76	124	134–179	265[b]
Echinoderms	1	4	16	30	44	63	69–85	59[b]
Fishes	1	2	27	59	126	186	206–251	594[b]
					Total	**741**	**864–1147**	**1962[b]**
Overall								
Algae	4	8	25	41	62	177	224–786	232[c]
Sponges	1	2	8	17	21	40	44–55	71[c]
Cnidarians	1	2	5	14	18	36	37–43	75[c]

Polychaetes	1	1	6	21	66	131	157–232	1100[d,e]
Mollusks	1	4	19	71	128	196	216–266	271[c]
Malacostraceans	1	1	2	34	78	133	144–186	122[c,e]
Echinoderms	1	4	17	32	47	73	79–101	79[c]
Fishes	1	2	28	58	138	210	225–254	613[c]
					Total	**989**	**1135–1555**	**2563[c]**

Data source: Algae (López-Valerio 2009; González-Pizá 2013; Vázquez-Texocotitla 2013; Sandoval-Coronado 2016; López et al. 2017; Moncada-García 2018), sponges (Salcedo-Martínez et al. 1988; Carballo et al. 2004, 2007, 2008; Bautista-Guerrero et al. 2006; Cruz-Barraza et al. 2011, 2012, 2014; Carballo and Aguilar-Camacho 2012; Aguilar-Camacho et al. 2013, 2018, Nava et al. 2014), cnidarians (CONABIO HJ029, JF030, https://www.biodiversidad.gob.mx/especies/especies.html, Reyes-Bonilla et al. 2005; López-Pérez et al. 2012, 2014; field work 2005–2018), polychaetes (Conabio HJ029, JF030, https://www.biodiversidad.gob.mx/especies/especies.html; Bastida-Zavala et al. 2016), mollusks (CONABIO HJ029, JF030, https://www.biodiversidad.gob.mx/especies/especies.html; Barrientos-Luján et al. 2017), malacostraceans (CONABIO HJ029, JF030, https://www.biodiversidad.gob.mx/especies/especies.html; Salcedo-Martínez et al. 1988; Ramírez-Luna et al. 2002; Jarquín-González and García-Madrigal 2010; Cortés-Carrasco and García-Madrigal 2013; Hernández et al. 2013; Valencia-Méndez et al. 2017), echinoderms (CONABIO HJ029, JF030, JF047, https://www.biodiversidad.gob.mx/especies/especies.html; Salcedo-Martínez et al. 1988; Benítez-Villalobos 2001; Zamorano and Leyte-Morales 2005, 2009; Granja-Fernández and López-Pérez 2011; Granja-Fernández et al. 2013, 2014; López-Pérez et al. 2014, 2017; field work 2012–2018), fishes (CONABIO HJ029, https://www.biodiversidad.gob.mx/especies/especies.html; Juárez-Hernández et al. 2013; López-Pérez et al. 2013, 2014; Palacios-Salgado et al. 2014; Juárez-Hernández and Tapia-García 2017, 2018; Ramos-Santiago and Tapia-García 2017; Valencia-Méndez et al. 2018)

[a]Chao2, Jacknife1, Jacknife2, Bootstrap

[b]Bastida-Zavala et al. (2013)

[c]Cortés et al. (2017)

[d]Salazar-Vallejo and Londoño-Mesa (2004)

[e]Eastern Pacific

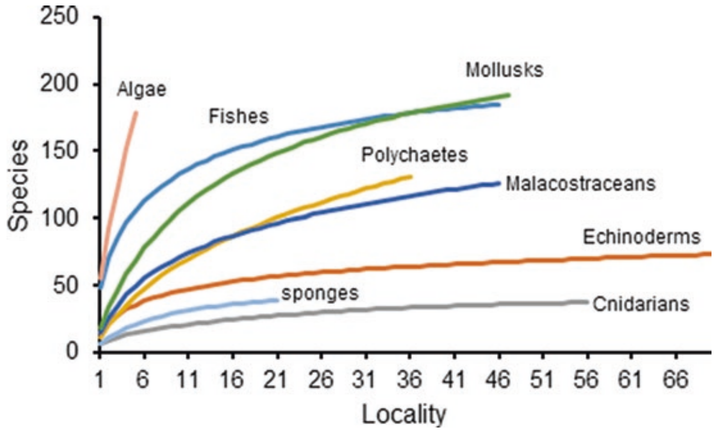

Fig. 5.2 OTU (operational taxonomic unit)-based rarefaction curves across taxa in coral systems located in southern Mexican Pacific

curves; meanwhile, dramatic cases are represented by the scarce number of OTUs recorded in groups such as algae and polychaetes but also in mollusk and malacostraceans (Fig. 5.2).

There is not a single case in which the number of observed OTUs fell inside the expected number of OTUs calculated using Chao 2, Jacknife 1, Jacknife 2, and Bootstrap (Colwell 2015) for the studied area (Table 5.2). When compared to the lower limit of the expected interval, cnidarians (2.7%), fishes (7.1%), and echinoderms (8.2%) are the closest to reach the lower limit of the expected OTU potential; sponges, mollusks, and malacostraceans are 10–14.3% far from reaching the limit, while polychaetes and algae need 26 (19.8%) and 47 (26.5%) OTUs to reach the lower limit of the expected interval in the southern Mexican Pacific. When compared to the upper limit, the observed number of OTUs represents 83.7% of the potential expected OTU richness of cnidarians, 82.6% of fishes, and around 68–74% of poriferans, echinoderms, mollusks, and malacostraceans, but just 56% of the expected polychaetes and scarcely 22.5% of the expected algae associated with southern Mexican Pacific coral systems (Table 5.2).

When data are spatially dissected, the observed number of OTUs related to coral communities and reefs is slightly larger in Oaxaca (741) than in Guerrero (701) (Table 5.2). The trend is deeply rooted in the observed pattern across taxa in the whole area (Fig. 5.3). Except in sponges and echinoderms where the number of observed OTUs is slightly larger in Guerrero, for the rest of the taxonomic groups, the number of observed OTUs is larger in Oaxaca, while in groups such as malacostraceans (34.5%), mollusks (37.3%), and polychaetes (56.3%), the difference between geographic areas is sensibly larger (Table 5.2 and Fig. 5.3). According to nonparametric models, the expected number of OTUs associated with coral systems located in Guerrero ranges from 803 to 1148, while for Oaxaca systems, it ranges from 864 to 1147. The results indicate that the current number of OTUs recorded in coral systems in Guerrero represents 61–87% of the expected richness, while it represents 65–86% of the expected richness in the Oaxaca reef track (Table 5.2).

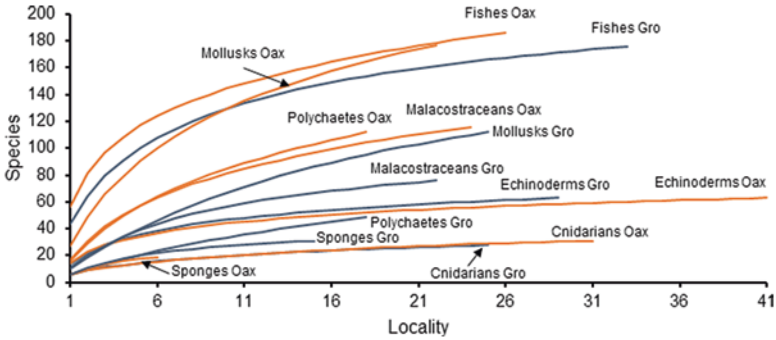

Fig. 5.3 OTU (operational taxonomic unit)-based rarefaction curves across taxa and space (Guerrero vs. Oaxaca) in coral systems located in southern Mexican Pacific

There are few extensive compilations of marine biodiversity associated with coral systems in Mexico and elsewhere in the Eastern Tropical Pacific. Overall, most of the accounts are partial compilations for some taxonomic groups such as polychaetes (Bastida-Zavala 1995), fishes (Álvarez-Filip et al. 2006), ophiuroids (Granja-Fernández et al. 2014), or gasteropods (Barrientos-Luján et al. 2017) or large-scale compilations including all coastal and marine ecosystems (e.g., Honey-Escandón et al. 2008; Tovar-Hernández et al. 2014). In this regard, compared to the recent compilation by Cortés et al. (2017) for the entire Eastern Tropical Pacific coral system (2563) (Table 5.2), the number of taxa addressed in this chapter represents ~39%, a number quite similar to the observed when coral-associated fauna from Oaxaca is contrasted to the coastal and marine biodiversity accounted by Bastida-Zavala et al. (2013) for the same area. Two further data are relevant: if expected species numbers are considered, the breach between Oaxaca accounts reduces to 41%, while compared to southern Mexican Pacific coral systems, the Eastern Tropical Pacific is only 39% larger. The latter number should be considered with caution since there is no detailed account of malacostraceans (Cortés et al. 2017) and polychaetes (Salazar-Vallejo and Londoño-Mesa 2004) associated with coral systems in the Eastern Tropical Pacific; hence, the numerical proximity among areas (39%) may turn smaller.

Overall, we lack strong arguments to support any meaningful OTU richness trend at a smaller spatial scale (i.e., site/locality) in the area since richness was drawn from different sampling techniques, intensities, and times across localities and taxonomic groups; nevertheless, it is useful to identify gaps and sampling bias within and across taxonomic groups.

Algae To date, algae (Chlorophyta, Cyanobacteria, Ochrophyta, and Rhodophyta) have been profusely studied in the southern Mexican Pacific (León-Tejera and González- González 1993; Galindo-Villegas et al. 1997; Fragoso and Rodríguez 2002; Peralta-García and Rosas-Alquicira 2014) since the pioneering work of Dawson (1960); nevertheless, little is known about coral-associated species in the area, either because they have been scarcely sampled in this system (López-Valerio 2009; González-Pizá 2013; Vázquez-Texocotitla 2013; Sandoval-Coronado 2016;

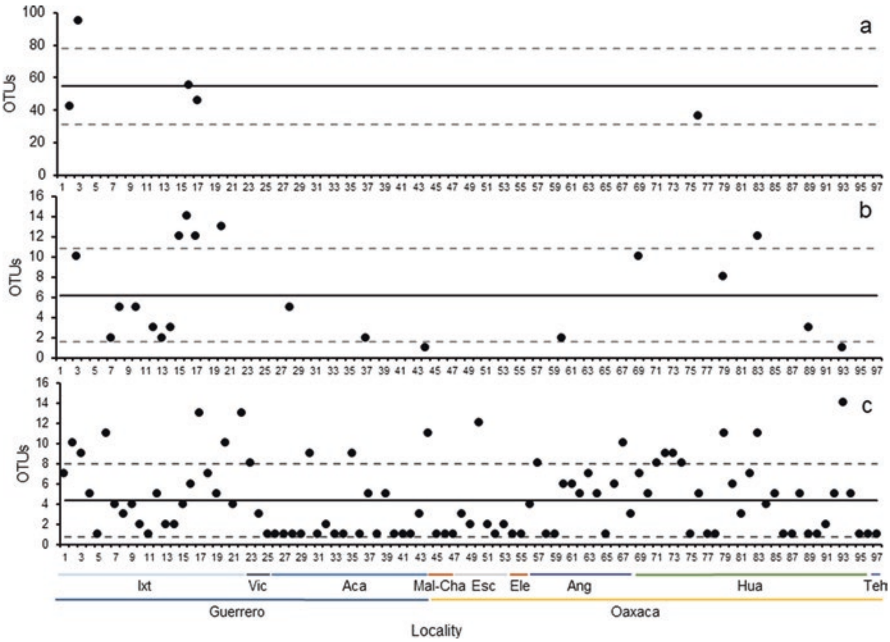

Fig. 5.4 OTU (operational taxonomic unit) richness across coral systems located in southern Mexican Pacific. (**a**), algae; (**b**), sponges; (**c**), cnidarians. Ixt = Ixtapa-Zihuatanejo, Vic = Puerto Vicente Guerrero, Aca = Acapulco, Mal-Cha = Punta Maldonado/Chacahua, Esc = Puerto Escondido, Ele = Santa Elena, Ang = Puerto Ángel, Hua = Huatulco, Teh = Tehuantepec

López et al. 2017; Moncada-García 2018) (Fig. 5.4a) or because their recollection substrate is currently omitted during floristic and taxonomic accounts. Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest, however, that coral systems have a huge potential (>250%) to foster a large number of species from several phyla and morphological groups.

Sponges Except for the Gulf of California (Brusca 1980; Green and Gómez 1986; Gómez et al. 2002; Carballo et al. 2004, 2008), there is a remarkable lack of registers of sponges for the Pacific coast of México. During recent years, however, the distribution patterns of coral reef sponges in southern Mexican Pacific has increased significantly (Fig. 5.4b) as a consequence of studies pertaining to address the capacity of several members of the group to dissolve calcium carbonate substrates such as corals (Carballo et al. 2008). To date, sponge biodiversity has been addressed in up to 21 out of 97 localities (Fig. 5.4b). Most of the records concentrate in Guerrero, particularly in the Ixtapa-Zihuatanejo region (Salcedo-Martínez et al. 1988; Carballo et al. 2004; Nava et al. 2014), moderately in the Huatulco region in Oaxaca (Bautista-Guerrero et al. 2006; Carballo et al. 2007), but scarcely across the Acapulco-Puerto Ángel reef track. Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest that the group has a moderate potential (10–38%) to increase as the extent of ongoing studies included currently unexplored coral systems in southern Mexican Pacific.

Cnidarians By far, Scleractinia, followed by Alcyonacea, are the most extensively addressed cnidarians across Guerrero and Oaxaca reef track (Reyes-Bonilla et al. 2005; López-Pérez et al. 2012; Breedy et al. 2012; Abeytia et al. 2013). While scleractinian corals have been profusely sampled across the whole area (Fig. 5.4c) (Reyes-Bonilla et al. 2005; López-Pérez et al. 2012, 2014), few Alcyonacea (Salcedo-Martínez et al. 1988), Actiniaria, Spitularia, and Leptothecata (Luis Hernandez, filed work data) have been recorded associated with coral systems. Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest that the group has a relatively low potential (3–19%) to increase in the future, particularly in taxa other than reef-building corals.

Polychaetes Most of the polychaete records from the Mexican Pacific come from the Gulf of California or the western coast of Baja California Peninsula (Hendrickx et al. 2005; Bastida-Zavala et al. 2016), while few records are from localities in the large expanse of the central and southern Mexican Pacific, and even fewer of those have been collected associated with reef building corals (Fig. 5.5a) (Gómez et al.

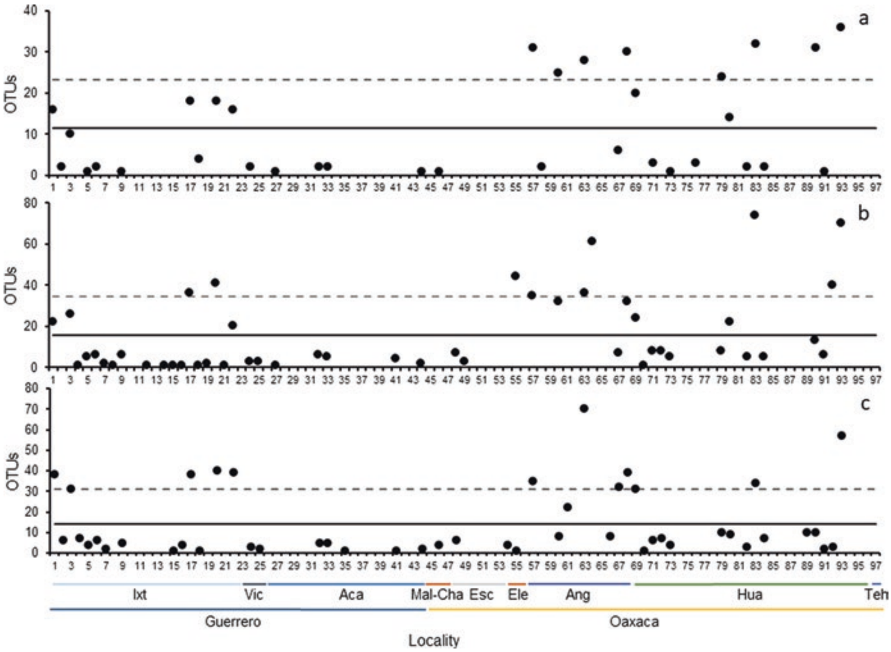

Fig. 5.5 OTU (operational taxonomic unit) richness across coral systems located in southern Mexican Pacific. (**a**), polychaetes; (**b**), mollusks; (**c**), malacostraceans. Ixt = Ixtapa-Zihuatanejo, Vic = Puerto Vicente Guerrero, Aca = Acapulco, Mal-Cha = Punta Maldonado/Chacahua, Esc = Puerto Escondido, Ele = Santa Elena, Ang = Puerto Ángel, Hua = Huatulco, Teh = Tehuantepec

1997; Bastida-Zavala and ten Hove 2003; Bastida-Zavala et al. 2016). Indeed, in only 34 out of 97 localities harboring corals across Guerrero and Oaxaca, polychaetes have been recorded, and in several of those, a scarce number of OTUs are currently reported. To date, OTU richness is larger in coral systems located in Oaxaca (Puerto Ángel and Huatulco), but such numbers are highly biased by sampling intensity since the area is heavily sampled by annelid researchers from the area. Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest that the group has a moderate to high potential (23–81%) to increase in the future, particularly associated with coral communities and reefs located across Guerrero.

Mollusks Although mollusks are among the most dominant invertebrates on coral ecosystems, the taxa have been scarcely studied around Ixtapa-Zihuatanejo (Salcedo-Martínez et al. 1988) and the Huatulco vicinity (Rodríguez-Palacios et al. 1988; Zamorano et al. 2006). Recently, Barrientos-Luján et al. (2017) dissected the spatial variation of the ecological and functional biodiversity of gastropods associated with hermatypic corals in an expanse from Nayarit to Oaxaca, an area of ~1500 km in the Mexican Tropical Pacific region; the carnivorous epifauna was the most important functional group at all studied spatial scales.

Currently, the group has been recorded in 48 out of 99 coral sites mainly located in the Ixtapa-Zihuatanejo and the Huatulco area (Rodríguez-Palacios et al. 1988; Salcedo-Martínez et al. 1988; Zamorano et al. 2006; Barrientos-Luján et al. 2017), while the large expanse from Zihuatanejo to Puerto Ángel has been scarcely sampled (Fig. 5.5b). Overall, OTU richness is larger in coral systems located across Puerto Ángel and Huatulco, in Oaxaca, although such localities have been heavily sampled in recent times (Barrientos-Luján et al. 2017). Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest that the group has a moderate potential (10–36%) to increase in the future.

Malacostraceans Crustaceans, mainly decapods, are among the main cryptofauna components associated with coral systems (Plaisance et al. 2009). To date, 47 out of 97 coral communities and reefs has been surveyed in the area (Fig. 5.5c); among those, 125 Decapoda (Salcedo-Martínez et al. 1988; Ramírez-Luna et al. 2002; Cortés-Carrasco and García-Madrigal 2013; Hernández et al. 2013) and 8 Tanaidacea (Jarquín-González and García-Madrigal 2010) have been recorded.

Malacostraceans have been recovered from localities located in Ixtapa (Guerrero), Puerto Ángel, and Huatulco (Oaxaca) vicinities, the latter area being the richest in OTUs (Fig. 5.5c). Such pattern, however, is highly influenced by sampling bias by researchers from the area (Ramírez-Luna et al. 2002; Cortés-Carrasco and García-Madrigal 2013; Hernández et al. 2013). Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest that the group has a moderate potential (14–48%) to increase in the future particularly in small, cryptic species and species from poorly known groups other than decapods (Jarquín-González and García-Madrigal 2010).

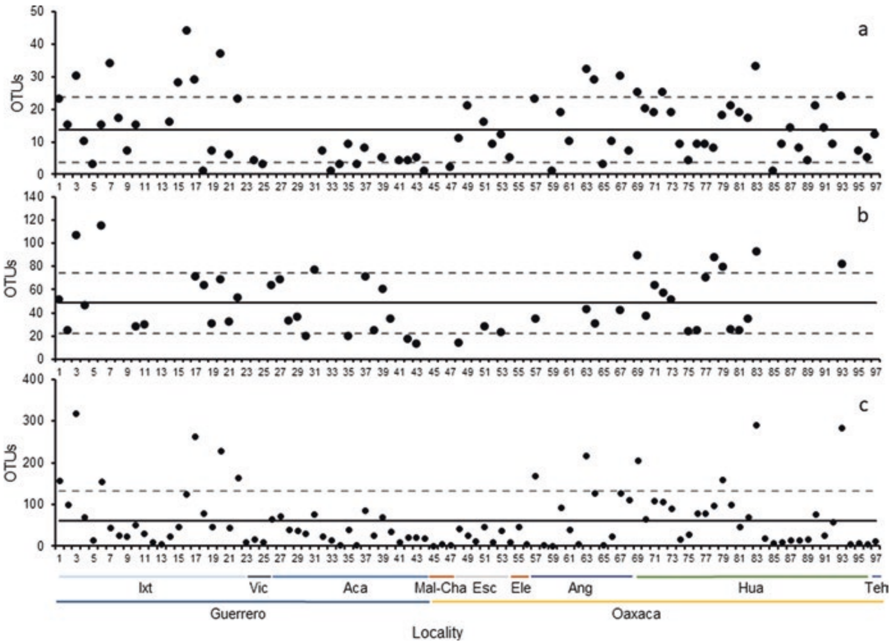

Fig. 5.6 OTU (operational taxonomic unit) richness across coral systems located in southern Mexican Pacific. (**a**), echinoderms; (**b**), fishes; (**c**), overall groups. Ixt = Ixtapa-Zihuatanejo, Vic = Puerto Vicente Guerrero, Aca = Acapulco, Mal-Cha = Punta Maldonado/Chacahua, Esc = Puerto Escondido, Ele = Santa Elena, Ang = Puerto Ángel, Hua = Huatulco, Teh = Tehuantepec

Echinoderms Echinoderms constitute a conspicuous element of the marine invertebrate fauna of coral reefs. Echinoderms have been currently recovered in 77 out of 99 coral systems in the area (Fig. 5.6a), many of those have addressed species richness and distribution through visual censuses of relatively large epibenthic individuals (Salcedo-Martínez et al. 1988; Zamorano and Leyte-Morales 2009; López-Pérez et al. 2014) and cryptic fauna (Benítez-Villalobos 2001; Zamorano and Leyte-Morales 2005; Granja-Fernández and López-Pérez 2011; Granja-Fernández et al. 2014; López-Pérez et al. 2017).

Currently, 73 OTUs are recognized to inhabit coral systems; of those, 30 are holothurians, 17 ophiuroids, 14 echinoids, and 12 asteroids. Overall, the Huatulco area has been heavily sampled (Benítez-Villalobos 2001; Granja-Fernández and López-Pérez 2011; Granja-Fernández et al. 2014; López-Pérez et al. 2014, 2017), but richer localities occurred in the Ixtapa-Zihuatanejo region (Fig. 5.6a). Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest that the group has a low to moderate potential (8–38%) to increase in the future particularly in small, cryptic species such as ophiuroids (Granja-Fernández and López-Pérez 2011; López-Pérez et al. 2017).

Fishes Although fishes are one of the most abundant, conspicuous, and structurally important inhabitants of reef systems, the group has remained largely ignored from biodiversity accounts on the Guerrero and Oaxaca reef tracks. Fishes have been sampled in 48 out of 97 coral systems (Fig. 5.6b), and 210 OTUs are currently recorded (Table 5.2).

Coral-associated fish community has been sampled mainly in the Huatulco vicinity (López-Pérez et al. 2008, 2010, 2013, 2014; Juárez-Hernández et al. 2013; Ramos-Santiago and Tapia-García 2017; Juárez-Hernández and Tapia-García 2017, 2018) but scarcely elsewhere (Palacios-Salgado et al. 2014). Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) suggest that the group has a low to moderate potential (7–21%) to increase in the future particularly in small, bottom, and burrow dweller taxa such as blennies and gobies (Valencia-Méndez et al. 2018).

Overall Biodiversity Across sites, coral-associated biodiversity is highly variable (Fig. 5.6c) as a consequence of sampling bias across taxa and space. Overall, mean OTU richness is relatively low (60), while variance is larger (70). As noticed, most of the sites (64) harbor lower than average OTUs, and in up to 35 sites, richness is larger than average, and in only 12 sites across three regions, the number of recorded OTUs is larger than expected: Morros de Cerro Colorado (157), Zacatoso (318), El Chato (155), Caleta de Chón (263), Manzanillo (228), and Morros de Potosí (164) in Ixtapa; Mazunte (167) and Estacahuite (216) in Puerto Ángel; San Agustín (206), Isla Cacaluta (158), La Entrega (289), and Isla Montosa (284) in Huatulco. On the contrary, for most coral systems from Puerto Vicente Guerrero, Guerrero to Agua Blanca, Oaxaca, OTU richness is lower due to sampling scarcity.

Observed and expected data (Table 5.2, Figs. 5.2 and 5.3) across taxa and space suggest that the current biodiversity represents 61–87% of the expected richness for Guerrero, 65–86% of the expected richness in the Oaxaca reef track, and 63–87% of the expected richness for the whole area (Table 5.2).

5.5 Biodiversity Drivers

Coral reefs are highly complex ecological systems, where multiple processes interact across scales in space and time to create assemblages of exceptionally high biodiversity (Bellwood et al. 2004). Water quality (De'ath and Fabricious 2010), accumulation of carbonates and habitat complexity (Álvarez-Filip et al. 2013; Cabral-Tena et al. 2018), evolutionary history (Johnson et al. 1995), isolation and degree of connectivity (Almany et al. 2009), and reef extent (Chittaro 2002), among many others, are currently suggested as species richness drivers in coral systems; concurrently, drivers change at several spatiotemporal scales (Parravicini et al. 2013) and across taxonomic groups (Mora et al. 2011; Barrientos-Luján et al. 2017; Valencia-Méndez et al. 2018). Nevertheless, those that drive biodiversity in southern Mexican Pacific reefs still scarcely addressed.

Biodiversity in groups such as corals (López-Pérez and Hernández-Ballesteros 2004; López-Pérez et al. 2012), fishes (López-Pérez et al. 2013), echinoderms (López-Pérez et al. 2017), mollusks (Barrientos-Luján et al. 2017), and gobiid fishes (Valencia-Méndez et al. 2018) is hierarchically structured in space across coral systems of

Guerrero and Oaxaca; overall, variations are inversely related to spatial scales: large variations occurred at smaller spatial scales, while variation turns smaller when spatial scale increases. Additionally, for taxa such as echinoderms (López-Pérez et al. 2017) and gobiid fishes (Valencia-Méndez et al. 2018), large-scale biodiversity is mainly explained by β-diversity across the area. Concurrently, there are only two examples addressing the environmental effect upon the reef biota in the southern Mexican Pacific. López-Pérez et al. (2013) observed that biodiversity changes of reef-related fish assemblages were associated with substrate differences on the scale of hundreds of meters to kilometers, as well as with major changes on oceanographic variables throughout time. Meanwhile, Barrientos-Luján et al. (2017) found that gastropods associated with coral systems in Guerrero were affected by the Mexican Warm Pool, while those located in Oaxaca were mainly driven by the relatively high biological productivity produced by coastal upwelling.

Although scarcely investigated, connectivity may play an important role in species composition and richness in coral systems located in southern Mexican Pacific. The earliest accounts of reef-building fauna from Guerrero (López-Pérez et al. 2012) and Oaxaca (Reyes-Bonilla and López-Pérez 1998; Leyte-Morales et al. 2001) suggested the immigration or dispersal of coral larvae from the coast of Central America through the poleward flow of the Western Mexican Current and Costa Rica Coastal Current during most of the year, and from the entrance of the Gulf of California during the winter through the California Current (Kessler 2006), bringing waters from the tip of the Baja California peninsula, Nayarit, Jalisco, Colima, and Michoacán into Guerrero. Additionally, disjoint distribution of echinoderms (*Acanthaster planci*, Glynn 1974; *Euapta godeffroyi*, Granja-Fernández et al. 2013) and corals (*Leptoseris papyracea*, Leyte-Morales et al. 2001; *Porites lobata*, Carriquiry and Reyes-Bonilla 1997; *Pocillopora effusa*, *Pocillopora inflata*, *Pavona varians*, and *Pavona clavus*, López-Pérez et al. 2012), along with recent records in fishes (Zepeta-Vilchis et al. 2013) and decapods (Valencia-Méndez et al. 2017), indicates the recurrent arrival of taxa to southern Mexican Pacific coral systems.

Recently, through the use of Lagrangian particle-tracking algorithm coupled offline with an ocean-circulation numerical model, the northern (i.e., the Revillagigedo Archipelago, Gulf of California, central Mexican Pacific) potential arrival of larvae and fauna into the coral systems located in Guerrero was addressed (López-Pérez et al. 2016a) and also supported by genetic evidence (Paz-García et al. 2012; Saavedra-Sotelo et al. 2013). Meanwhile, Lequeux et al. (2018) demonstrated that systems located in Huatulco were demographically connected with coral reef aggregations located in the Eastern Pacific equatorial region. Overall, the aforementioned evidence (López-Pérez et al. 2016a; Lequeux et al. 2018) provided not only the mechanism to explain the species composition associated with coral communities and reefs across Guerrero and Oaxaca but also the means by which biodiversity may increase in the future (Table 5.2).

Contrary to mechanisms that increase biodiversity, coral system degradation impoverishes species richness (Bellwood et al. 2004). To date, mainly in Acapulco (El Jardín, Las Palmitas, Punta Bufadora, El Ripial, La Hierbabuena, and Hawaii 5.0) but also in Puerto Escondido (Carrizalillo and Puerto Angelito), Puerto Ángel

(Mazunte, Playa Panteón, and Estacahuite), and Huatulco (Riscalillo, La India, Violín, La Entrega, Santa Cruz, Manzanilla, and Isla Montosa), abundant remains of small patch reefs possessed an advanced eroded condition, characterized by scattered live colonies of the encrusting form of *P. panamensis*, the massive *P. gigantea*, and occasional pocilloporids (López-Pérez and Hernández-Ballesteros 2004; López-Pérez et al. 2012). Highly eroded reefs in areas such as Acapulco, Puerto Escondido, Puerto Ángel, and Huatulco resulted from land use change and marina, road, and hotel construction as the major destructive agents (López-Pérez and Hernández-Ballesteros 2004; Nava and Ramírez-Herrera 2012), while coral extraction for jewelry and souvenir trades (Glynn 2001) also contributed to the virtual elimination of pocilloporid-dominated reefs from Acapulco (López-Pérez et al. 2012) and Puerto Escondido (Eladio Spindola and Andres Pacheco, pers. comm. 2018; Luis Hernández, pers. obs.). Additionally, ENSO events (Glynn and Leyte-Morales 1997; Reyes-Bonilla et al. 2002; López-Pérez et al. 2016b), hurricanes and tropical storms (Lirman et al. 2001), and sea urchin mortalities (López-Pérez et al. 2002; López-Pérez and Hernández-Ballesteros 2004; Benítez-Villalobos et al. 2009) also contributed to reef degradation.

Reef degradation translates into habitat loss and fragmentation and reef flattening. The species–area relationship was the central paradigm of reserve design in the 1970s and early 1980s and has been used to estimate local species richness (Abele 1976; Abele and Patton 1976; Chittaro 2002) and to predict the effect of habitat loss and fragmentation on reef biodiversity (Bonin et al. 2011). Abele (1976) and Abele and Patton (1976) evaluated the number of coral-associated decapod crustacean species against the size of *Pocillopora damicornis* coral heads in Panama; overall numbers of species and individuals of decapods were highly correlated with the area of the coral head. Regarding fish assemblages, Chittaro (2002) addressed a positive relationship between species richness of reef fish and coral reef area in St. Croix; indeed, the author addressed that area explained 66–96% of the variation in species richness. Meanwhile, empirical studies to date suggest that habitat loss has large, consistently negative effects on biodiversity, while habitat fragmentation per se has much weaker effects on biodiversity that are at least as likely to be positive as negative (Fahrig 2003; Bonin et al. 2011). Additionally, reef corals deposit calcium carbonate to build their skeletons and form complex three-dimensional structures as part of their growth (Carricart-Ganivet et al. 2012; Norzagaray-López et al. 2015), while the loss of morphologically complex corals such as *Acropora* (Álvarez-Filip et al. 2013) or *Pocillopora* (Cabral-Tena et al. 2018) has severe repercussions for associated biodiversity and ecosystem structure, function, and stability. Regarding the Eastern Pacific, for example, a shift in coral species dominance driven by environmental variability, as previously reported (Manzello et al. 2008; Manzello 2010), may cause coral community calcification to drop to 85% (Cabral-Tena et al. 2018) and hence compromise structural integrity and overall reef functionality. Nevertheless, the synergy between the expected coral community calcification drop at a regional scale (Cabral-Tena et al. 2018) and the observed reef habitat loss across Guerrero and Oaxaca (see above) and its effects upon the overall reef-associated biodiversity are still unaddressed but are in urgent need.

5.6 Future Research Agendas

During the last two decades, species inventories have increased considerably in southern Mexican Pacific reefs in conspicuous and well-studied macroinvertebrates (corals and echinoderms; Glynn and Leyte-Morales 1997; Zamorano and Leyte 2009; López-Pérez et al. 2012, 2014) and vertebrates (reef-associated fishes, López-Pérez et al. 2010; Palacios-Salgado et al. 2014), while cryptic invertebrate fauna inventories in taxonomic groups such as sponges, polychaetes, mollusks, crustaceans, and ophiuroids growth at a slower pace (Cortés-Carrasco and García-Madrigal 2013; Cruz-Barraza et al. 2014; Granja-Fernández et al. 2014; Bastida-Zavala et al. 2016; Barrientos-Luján et al. 2017). Additionally, for some taxonomic groups, initial steps have been taken for octocorals (Breedy et al. 2012; Abeytia et al. 2013), hydroids (Humara-Gil and Cruz-Gómez 2018), and peracarids (Jarquín-González and García-Madrigal 2010).

It is remarkable to signal that the increase in reef biodiversity expected by the nonparametric models is 15–57% larger than the current biodiversity (Table 5.2). The expected increment, however, is not at the expense of unrecorded taxa that remain absent from local (Bastida-Zavala et al. 2013) and regional (Cortés et al. 2017) biodiversity accounts such as reef-associated prokaryotes and viruses, cnidarians other than reef building corals, marine worms other than polychaetes, mollusks other than gastropods and bivalves, crustaceans other than decapods and small, bottom and burrow dwellers fishes, but in already recorded groups such as algae, sponges, cnidarians, polychaetes, mollusks, malacostraceans, echinoderms and fishes. In particular, a large number of records are expected to occur in groups such as algae, polychaetes, and mollusks; a moderate increase in sponges, cnidarians, and malacostraceans; and a minor increment in echinoderms and fishes, as a consequence of the larger number of rare species (i.e., occurring in less than two sites) (Fig. 5.7) in the database.

Additionally, several interdependent communities and habitat niches (zooplankton, soft bottoms, and rhodolith beds) that make up coral ecosystems (Cortés et al. 2017) are still scarcely prospected. In southern Mexican Pacific, rhodoliths occur in Playa Manzanillo and Playa Carey in Ixtapa-Zihuatanejo, Guerrero, and Isla Cacaluta in Huatulco, Oaxaca (Peralta-García and Rosas-Alquicira 2014), but only a handful number of ophiuroids (Granja-Fernández et al. 2014) have been reported in this habitat. On the other hand, Granja-Fernández and López-Pérez (2011), Granja-Fernández et al. (2014), and Barrientos-Luján et al. (2017) accounted for the ophiuroid and mollusk biodiversity, respectively, of soft bottom habitats associated with coral systems of a reduced number of localities.

Finally, it is expected that future sampling of unprospected habitats, sites, and taxa employing traditional and novel techniques such as DNA barcoding (Plaisance et al. 2011) may render far more species than expected. Additionally, biodiversity should be seen as a master variable for practically evaluating both the health of ecosystems and the success of management efforts and hence a standardized method such as ARMS (Autonomous Reef Monitoring Structures, noaa, https://www.pifsc.

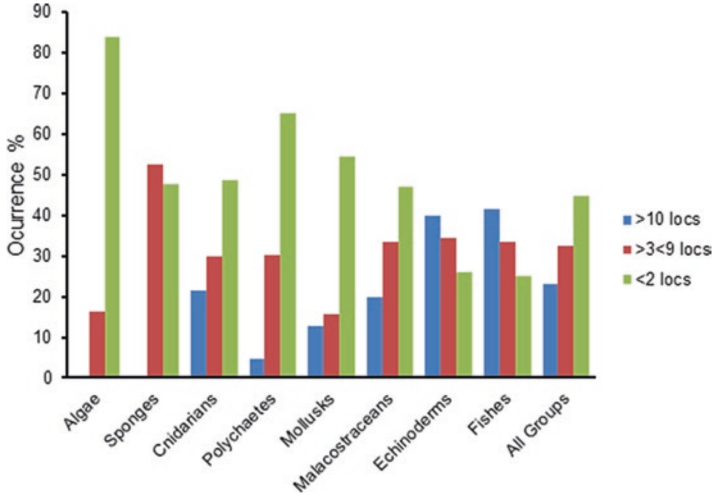

Fig. 5.7 OTU (operational taxonomic unit) distribution across coral systems in southern Mexican Pacific

noaa.gov/cred/survey_methods/arms/overview.php), and systematic monitoring protocol under a marine biodiversity observation network is necessary for effective reef management (Duffy et al. 2013; Ransome et al. 2017).

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Chapter 6
Fish Fry Stocking in Epicontinental Aquatic Systems: The Production Policy

Ana Laura Ibáñez and Eduardo J. Tlalpan

6.1 Introduction

Mexico's geographical position, straddling tropical and subtropical regions, between the Atlantic and the Pacific oceans, and with altitudes ranging from 0 to >5000 m above mean sea level (AMSL), provides it with extreme rain (22.3–5179 mm/year) and temperature (−20 to +54 °C) conditions (Challenger 1998). Approximately one million hectares of lakes, wetlands and reservoirs are distributed across this complex environmental landscape that comprises several ecological zones (Castillo and Toledo 2000; García 2004) and provides the country with more than 150,000 tonnes of freshwater fish products.

Centuries before the discovery of America, the diet of Mexico's inhabitants included – in various degrees of importance – fish products from inland waters (Valle 2000; Boege 2008; Rojas 2009). Even today, native fish species form an important part of the diet of the rural ethnic communities (Gatti 1986; Brockman 2004), though alien species have become increasingly prevalent.

Seventeen new species were introduced (Mendoza-Alfaro and Alvarez-Torres 2003) to exploit a proliferation of reservoirs constructed mainly for agricultural purposes in the twentieth century, especially from the mid-1940s to the mid-1970s when the impounded volume increased tenfold (COPESCAALC-FAO 1986). During this period, the need to increase food availability through aquaculture-based fisheries was recognised, a practice that is very common in many countries nowadays as a millenary tradition in aquacultural areas (Huang et al. 2001) and others that have adopted this practice as a component of development (van der Mheen 1994; Fonticella et al. 1995). In line with many other countries, the species that have been mainly introduced are carp and tilapia because of their high production poten-

A. L. Ibáñez (✉) · E. J. Tlalpan
Universidad Autónoma Metropolitana-Iztapalapa, Departamento de Hidrobiología, Mexico City, Mexico
e-mail: ana@xanum.uam.mx

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tial (Ruddle and Zhong 1988). One of the first fish stocking events took place in 1893, with 5000 trout stocked in a fish farm in Mexico (Carranza 1953). The common carp *Cyprinus carpio* Linnaeus 1758 was the first non-native species to be introduced into Mexican waters. Chinese carp were brought from China between 1965 and 1979 (Ramírez-Granados 1974), and tilapia were acquired from the Auburn University, Alabama, USA, in 1964 (Morales 1991). Stocking became extremely widespread and was carried out uncritically.

Since the 1970s, the production of exotic fish species has surpassed the production of native species (SIC 1973–1975; DEPESCA 1979; SEPESCA 1979–1993; SEMARNAT 1994–1999; SAGARPA 2000–2003). This change came through the creation of fish farms throughout the country, especially to produce cichlids and cyprinids. These actions were partly explained by the need to increase food availability, particularly for the poor and undernourished part of the population (Verduzco 2005), according to national fisheries policies. This purpose has been consistently mentioned in institutional programmes since the 1930s and was supported by rural culture-based fisheries projects that included stocking carp, black bass and trout in waterbodies in Central Mexico (Ramírez-Granados 1974; Medina-Gándara et al. 1976). In 1974, 23 fish farms were operating with a production of fry of 14 million (Medina-Gándara et al. 1976). Between 1976 and 1982, and within the Mexican Food System (Sistema Alimentario Mexicano) (Barquera et al. 2001), there was an intensification of certain stocks, especially tilapia and carp (Juárez 1985). In 2001, 36 fish farms were operating with a production of fry of 140 million. Nowadays, the federal government supports 10 fish farms that produce an average of 20.5 million fry per year, 50.7% of which are tilapia, 42.5% are carp and the remaining 6.8% are 11 other species, 9 of which are native.

The current fishery policy is based on the National Sustainable Fishing and Aquaculture Law (LGPAS) and management tools, such as the National Fisheries Chart (CNP), that provide status indicators for species under exploitation. Despite the presence of culture-based fisheries in Mexico for almost a century, very little information is available. It is possible to consult fish stocking data on the national scale (from 1975) and specific digitised information on each stocking event from 2001 to 2013. For the later years, assessments may be rough.

Considering the scarcity of information and the occasional need to use indirect data, the purpose of this study was to address the following specific questions: What species have been used in stocking freshwater areas in Mexico? Is fish stocking related to yield? What are the strategies the Mexican government has followed for fisheries based on fish stocking? What is the general tendency of fisheries based on fish stocking in Mexico?

Historical data on national inland waterbodies were obtained from the Fishery Statistical Yearbooks from 1973 to 2014 (DEPESCA 1979; SEPESCA 1979–1993; DEPESCA 1981; SEMARNAT 1994–1999; SAGARPA 2000–2003; SAGARPA 2000–2014). Information on the national scale (mainly, the number of specimens and of species stocked; the region, month and year stocked; the name, surface area and location of the reservoir) was obtained from the Comisión Nacional de Acuacultura y Pesca (CONAPESCA National Commission on Aquaculture and

Fisheries) in order to identify relationships between stocking practices and fish yields. The relationship between fry stocking and production was tested along a 1-year lag period because of the grow-out time for fish from the fry stage to harvest. This was tested for the period 2001–2013 for the seven geo-economic regions established in the Mashbitz proposal analysed by Bassols (1967), namely, Northwestern (NW), Northern (N), Central-Western (CW), Central (C), Gulf of Mexico (G), Yucatán Peninsula (Y) and Southern (S), in order to identify regional differences between stocking and yield. The data were restricted to 2001–2013 because of the varying reporting procedures. The area of water available for stocking in each state was obtained from an inventory of waterbodies (CNP 2006) and examined to test for impacts generated by fish production.

6.2 Recent History of Fisheries Policies

The main promoter and introducer of fish farming in Mexico, Esteban Cházari Esperón, is recognised through his 1884 publication *Piscicultura de Aguas Dulces* (Freshwater Fish Farming) where he proposed the activity be developed and formal and 'scientific' fish farming be started (Cifuentes-Lemus and Cupul-Magaña 2002; Contreras 2012). This author stated the bases for the establishment of an organisation for the culture of fish in continental waters. However, it was not until 1950 that the federal government exerted a preponderant role in the management, organisation and regulation of fish culture in the continental waterbodies of the country.

Thus, present-day aquaculture in Mexico acquired institutional character in 1950 with the establishment of the Comisión para el Fomento de la Piscicultura Rural (Commission for the Promotion of Rural Fish Farming) of the Secretaría de Marina (Marine Secretariat). One of the fundamental objectives of this commission was the construction of federal centres for the production of fish fry (Sevilla 1987). The number of federally owned aquaculture centres increased from 17 to 54 centres between 1950 and 1987, respectively. Starting in 1987, and during the administration of the then president Carlos Salinas (1988–1994), the number of aquaculture centres decreased in a trend that continued with his successors and left only 10 federally owned working aquaculture centres in the country by the year 2016.

The offices in charge of fisheries administration also went through various changes. At the start of the year 1950, the office responsible for the management of fish farming in continental waters was the Secretaría de Marina (Marine Secretariat), where the Comisión para el Fomento de la Piscicultura Rural (Commission for the Promotion of Rural Fish Farming) was formed. Two years later, this commission was assigned to the Secretaría de Industria y Comercio (SIC, Industry and Commerce Secretariat) that created the Comisión Nacional Consultiva de Pesca (National Advisory Commission on Fisheries), all during the administration of Adolfo López-Mateos (1952–1958).

By 1970, the SIC created the Subsecretaría de Pesca (Undersecretariat of Fisheries) and, within it, the Instituto Nacional de la Pesca (National Institute of Fisheries) during the presidential administration of Luis Echeverría (1970–1976).

During the time of the then President José López-Portillo (1976–1982), all fisheries administration passed directly to the newly formed Departamento de Pesca (Department of Fisheries), when fisheries research was promoted, and the first intensive fry production farms were created. In 1982, this department became the Secretaría de Pesca (Secretariat of Fisheries), and fisheries production markedly increased during the 6-year presidential period of de la Madrid (1982–1988). The administration of Carlos Salinas (1988–1994) favoured the participation of both national and foreign private entities through the creation of a new Ley de Pesca (Fishing Law), of which the main objectives were the growth of aquaculture infrastructure and the promotion of greater investment and interest on the part of the private sector. In addition, the farming of species with a 'greater commercial value', such as shrimp, was favoured, leaving aside species grown in inland waters.

This trend of changes and re-evaluations of the fishing sector through political will and the efforts of institutions were interrupted by the arrival of the presidency of Ernesto Zedillo (1994–2000), when the Secretaría de Pesca (Secretariat of Fisheries) returned to being an undersecretariat within the newly created Secretaría del Medio Ambiente, Recursos Naturales y Pesca (SEMARNAP, Secretariat of the Environment, Natural Resources and Fisheries). After this and during the administration of Vicente Fox (2000–2006), federal fisheries activities passed from SEMARNAP to the present Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA, Secretariat of Agriculture, Cattle Raising, Rural Development, Fisheries and Food), and the management of fisheries passed to the Comisión Nacional de Acuacultura y Pesca (CONAPESCA, National Commission on Aquaculture and Fisheries), de-centralising the sector and changing its address from Mexico City to its present location in Mazatlán, Sinaloa, on the Pacific coast. In 2004, the Mexican government and the CONAPESCA prepared an action plan, partly based on the Código de Conducta para la Pesca Responsable (CCPR, Code of Conduct for Responsible Fisheries) of the FAO (Food and Agriculture Organization), marking the importance of recreational fishing as an environmental administrator for the sustainable conservation of fish habitats (FAO 2010).

The next administrations headed by Felipe Calderón (2006–2012) and Enrique Peña (2012–2018) were characterised by offers of economic support or subsidies for communities to negotiate with civil organisations or private and academic groups, the training, technical management and development of projects. In addition, as is presented further on, aquaculture changed from extensive to intensive during these years, resulting in an increased production in inland aquatic environments. This may be observed in the world statistics where Mexico has appeared, for the first time in the 2018 FAO report, in 16th place among the 18 most productive countries (FAO 2018). Thus, the fishing sector has undergone changes in its organisation and administration, both at the level of fishermen and cooperatives and at the level of the government institutions in charge of organising this activity. Recently, these policies have increased production, with most of the production of fry for aquaculture and/or restocking passing from the federal government to private producers.

6.3 Species Used in Freshwater Stocking

Of 24 species farmed in federal aquaculture centres between 2001 and 2013, 87.5% were fish. Carp and tilapia were the two groups of species with the greater production volumes. Among the fish species, tilapia fry represented 50.7% of the fry produced in government-funded freshwater fish farms (GFFF), basically with 3 species and 1 hybrid (Table 6.1). In turn, carp fry production was represented by 9 taxa and constituted 42.5% of the total production. In consequence, 93.2% of the fry were generated by tilapia and carp on the national scale. Thus, exotic species predominated among the species produced in the GFFF (Table 6.1). Native stocked species

Table 6.1 Species cultured in federal aquaculture centres of the Federal government during 2001–2013

Common name	Scientific name	Production (%)	Origin
Pisces			
Tilapias		50.7	
Nile tilapia	*Oreochromis niloticus* (Linnaeus 1758)		Exotic
Blue tilapia	*Oreochromis aureus* (Steindachner 1864)		Exotic
Mozambique tilapia	*Oreochromis mossambicus* (Peters 1852)		Exotic
Rocky mountain tilapia	*Oreochromis rocky mountain* (*O. aureus* X *O. niloticus*)		Exotic
Carps		42.5	
Common carp	*Cyprinus carpio* (Linnaeus 1758)		Exotic
Mirror carp	*Cyprinus carpio specularis* (Lacepède 1803)		Exotic
Israel carp	*Cyprinus carpio var. specularis*		Exotic
Bighead carp	*Hypophthalmichthys nobilis* (Richardson 1845)		Exotic
Black carp	*Mylopharyngodon piceus* (Richardson 1846)		Exotic
Grass carp	*Ctenopharyngodon idella* (Valenciennes 1844)		Exotic
Silver carp	*Hypophthalmichthys molitrix* (Valenciennes 1844)		Exotic
Freshwater bream	*Abramis brama* (Linnaeus 1758)		Exotic
Amur carp	*Cyprinus carpio rubrofuscus* (Chen and Huang 1977)		Exotic
Breams		0.40	
Bluegill	*Lepomis macrochirus* (Rafinesque 1819)		Exotic
Firemouth	*Amphilophus macracanthus* (Günter 1867)		Native?
Three spot cichlid	*Cichlasoma trimaculatum* (Günter 1867)		Native
Other fish			
Rainbow trout	*Oncorhynchus mykiss* (Walbaum 1792)	2.71	Native**
Chanel catfish	*Ictalurus punctatus* (Rafinesque 1818)	1.16	Native**
Largemouth bass	*Micropterus salmoides* (Lacepède 1802)	0.49	Native**

(continued)

Table 6.1 (continued)

Common name	Scientific name	Production (%)	Origin
Alligator gar	*Atractosteus spatula* (Lacepède 1803)	0.22	Native*
Pátzcuaro chub	*Algansea lacustris* (Steindachner 1895)	0.04	Native*
Amphibian		0.16	
Leopard frog	*Lithobates megapoda* (Taylor 1942)		Native+
Bullfrog	*Lithobates catesbeianus* (Shaw 1802)		Native
Crustacean		1.52	
Giant freshwater prawn	*Macrobrachium rosenbergii* (De Man 1879)		Exotic

Modified from Ibáñez et al. (2011)
Native* = native but have been planted outside its original distribution; Native** = native, but the crop has been sustained with copies of the USA, South America and Australia; Native? = native species, possibly confused with "*Cichlasoma*" *urophtalmus*; Native+ = under protection according to the NOM-059-ECOL-2001. Production refers to the total national percentage of offspring, for the sum of the period 2001–2013

were the rainbow trout *Oncorhynchus mykiss* (Walbaum 1792), largemouth bass *Micropterus salmoides* (Lacépède 1802) and channel catfish *Ictalurus punctatus* (Rafinesque 1818), and farmed stocks were supported mainly by organisms imported from the USA, South America and Australia (Ibáñez et al. 2011).

The introduction of species raised production in many areas of the country, together with the risk of environmental disturbance. However, as tilapia and carp species considerably resist handling and manipulation, as well as pollution and changes in environmental conditions, fish stocking with these species ensured that fish production would be achieved even under extreme conditions (Bowen 1988; Moreau 1988), notwithstanding that they could damage and threaten ecosystems and biodiversity. Mexico in particular has reported tilapia invading the environment in several sinkholes and waterbodies of the state of Quintana Roo where endemism is important (Schmitter-Soto and Caro 1997). Tilapia has also appeared in coastal lagoons along the Western Gulf of Mexico (Gaspar-Dillanes and Barba-Torres 2004; Díaz-Ruiz et al. 2003), such as Laguna de Alvarado in the state of Veracruz where it supports fishery in the lower-salinity areas. The disturbance of habitats by the introduction of exotic species was well documented by Contreras-Balderas and Escalante-Cavazos (1984), Zambrano et al. (1999) and Tapia and Zambrano (2003). In addition to the problems generated by the use of exotic species in extensive systems, hybridisation, introgression and loss of genetic diversity have also been recorded (Barriga-Sosa et al. 2004). Accordingly, it has become necessary to control the loss of native species and the presence of undesirable species. It is also necessary to carry out restorations with a full understanding of the implications and potential effects of manipulation. Thus, it is important that the energy flow; the relationships between the physical, chemical and biological components; and the functioning of the ecosystems under management are analysed. Regarding native species, several efforts to farm them, including two cichlids (*Mayaheros urophthalmus* (Gunter 1862) and *Petenia splendida* (Gunter 1862)), two gar species (*Atractosteus spatula* (Lacepède 1803) and *Atractosteus tropicus* (Gill 1863)) and three silverside species (*Chirostoma jordani* (Woolman 1894), *Chirostoma estor* (Jordan 1880) and *Chirostoma humboldtianum* (Valenciennes 1835)), are currently taking place (Dávila-Camacho et al. 2018).

6.4 Distribution of Tilapia and Carp Stocking from 2001 to 2013

Figure 6.1a shows the abundance of tilapia stocking for the 2001–2013 period when stocking took place intensively with 437.7 million fry throughout the country, except for the region of Yucatán where only 2.6 million fry were provided.

The regions most intensively stocked with tilapia in Mexico are the Northwestern (NW) and the Northern (N), regions with a reduced natural availability of water (2000–5000 m^3/per capita/year). This is explained as, according to reports in the CONAPESCA database, 65% of fish stocking events take place preferably during the rainy season (June to October) where 78% of the annual rainfall occurs, with 67% of fish stocking on surfaces smaller than 1 ha and 84% on surfaces smaller than 5 ha. The stocking frequency average increased in June, July and August (45%), while 44% of stocking events took place during the dry season (November to May), at which time reservoirs have lower volume levels (Hernández-Avilés et al. 2007). The timing of stocking should be considered in order to take advantage of exponential fish growth (Cowx 1999; Ibáñez 2004). Stocked *Oreochromis* spp. presents a low growth rate in temperate environments, highland areas and the Northern regions of Mexico (Ibáñez 2004). Similarly, a low growth rate has been recorded for tilapia, as this predominantly tropical species has been stocked in the temperate environment of high plateau areas (Gómez-Márquez 1998; Ibáñez 2004) and of the Northern regions of the country (Kapetsky 1997).

Although in general, as will be shown later, there is a close relationship between fry stocking and capture, other factors also affect yield, an example of which is the low temperature in the Northern region of the country during the autumn and winter. Captures may be influenced by two factors: on the one hand, a hot climate that encourages a high growth rate that makes it possible to have two harvests per year and, on the other hand, the fact that the CW and G regions harbour a great number of private producers and fish farms financed by the states, as is the case of the state of Michoacán on the Pacific coast in the CW region (Fig. 6.1b).

With respect to carp, stocking density is presented in Fig. 6.2a. Tents have been stocked intensively with 362.0 million fry throughout the country, except for the NW region and Yucatán where fish stocking provided 246,350 and 10,733 fry, respectively. The regions most heavily stocked are the CW and C where water availability is average. Despite this, the C region harbours the largest aquaculture centre for carp (Tezontepec de Aldama, Hidalgo). In general, stocking of fry takes place in the states where an aquaculture centre is located. In addition, the CW and C regions are the most productive, followed by the N region (Fig. 6.2b). The production of common carp in Mexico takes place in most of the temperate region, whereas tilapia is produced mainly in the coastal areas.

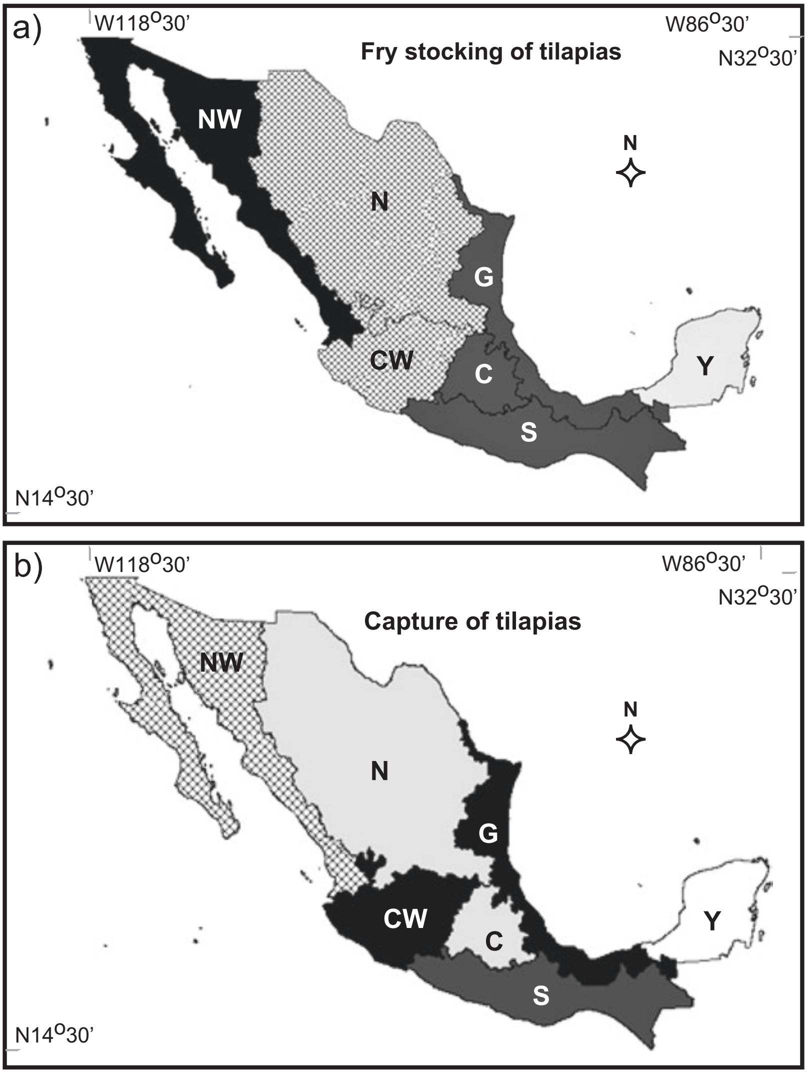

Fig. 6.1 (**a**) Fry stocking of tilapias (millions of fry) for the period 2001–2013 for the seven geo-economic regions. Tone key: very low in white ≤1; low in grey light = between 1.1 and 30; medium in grey dark = between 30.1 and 60; high in grid = between 60.1 and 90; very high in black >90. (**b**) Capture of tilapias (tonnes) for the period 2001–2013. Tone key: very low in white ≤10,000; low in grey light = between 10,001 and 60,000; medium in grey dark = between 60,001 and 110,000; high in grid = between 110,001 and 160,000; very high in black >160,001

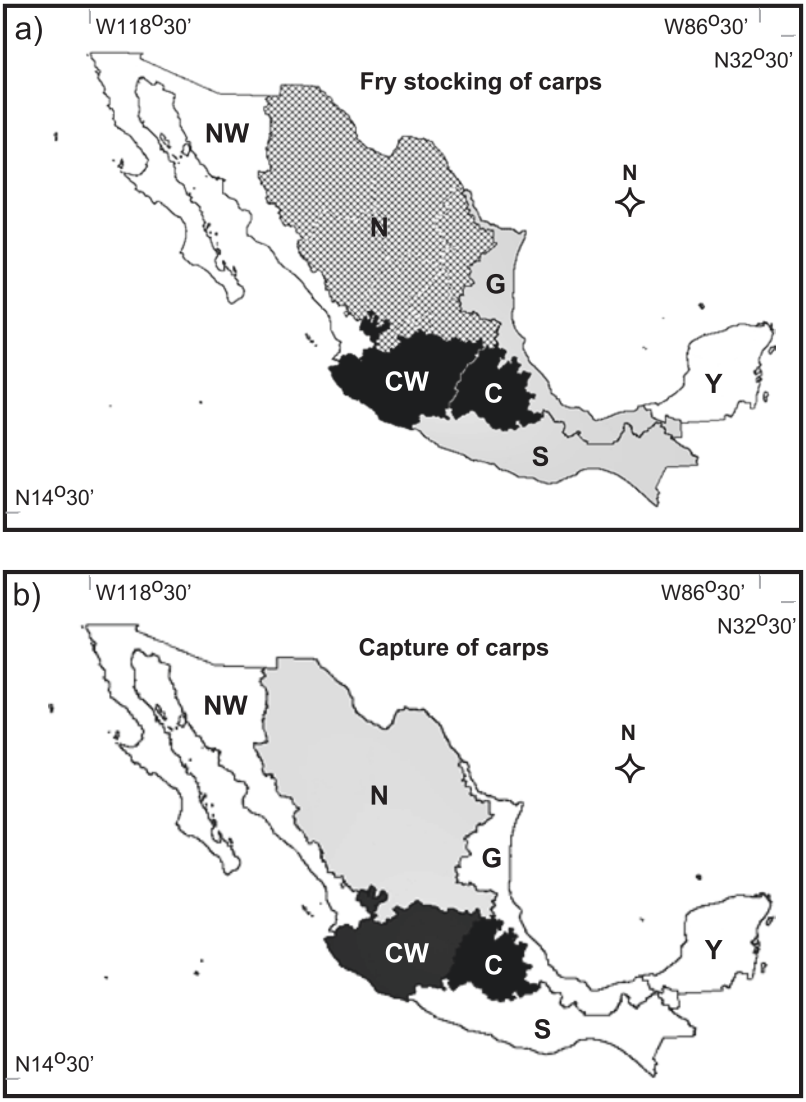

Fig. 6.2 (**a**) Fry stocking of carps (millions of fry) for the period 2001–2013 for the 7 geoeconomic regions. Tone key: very low in white ≤1; low in grey light = between 1.1 and 30; medium in grey dark = between 30.1 and 60; high in grid = between 60.1 and 90; very high in black >90. (**b**) Capture of carps (tonnes) for the period 2001–2013. Tone key: very low in white ≤10,000; low in grey light = between 10,001 and 60,000; medium in grey dark = between 60,001 and 110,000; high in grid = between 110,001 and 160,000; very high in black >160,001

6.5 Fish Fry Stocking Versus Inland Production

6.5.1 Fish Stocking Versus Inland Fish Production at the National Level from 1974 to 2014

Production in inland waterbodies increased from 1973 to the late 1990s, decreasing thereafter to around 100 tonnes per annum during the 2000s (Fig. 6.3), when a marked drop in catches was recorded from 1997 to 2003. A highly significant relationship ($r^2 = 0.88$) was recorded between the number of fry stocked 1 year and inland fish production the following year for the years 1974–2003. This was largely driven by a massive increase in fry production in the 1980s, especially between 1986 and 1988, when there was a large expansion in aquaculture infrastructure, with two new fish farms opened and 39 farms refurbished. The number of fish farms in operation increased from 24 in 1976 to 39 in 2003 (Table 6.2). Stocking density substantially increased in all economic regions, mainly the Central region. The region with the greatest increase in the number of fish farms was the Gulf of Mexico region, followed by the Northern and Central-Western regions. A negative correlation ($r^2 = -0.49$) was recorded when fry production declined in 2001, after which fish production steadily rose from 2003 to 2013 (Fig. 6.3).

The CONAPESCA reported that it refocused the work carried out in the aquaculture centres belonging to the public sector in order to transform them into reference centres dedicated to the production and maintenance of products of recognised quality regarding genetics and health and to the development of research to improve

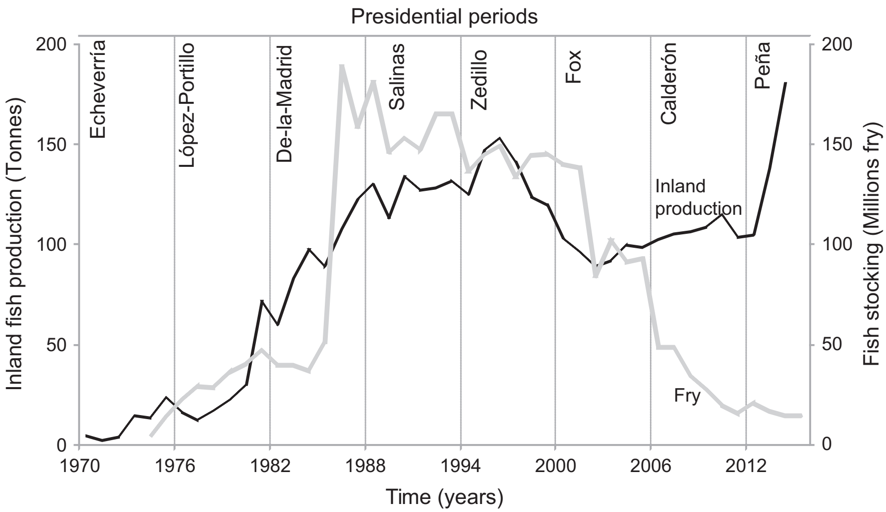

Fig. 6.3 Trends in inland fish production and fish stockings between 1970 and 2014. Presidential periods are indicated by vertical lines and the name of the president in turn. (Modified from Ibáñez et al. (2014))

Table 6.2 Number of government freshwater federal aquaculture centres (GFFF) by geographic zone during the period 2001–2013

Year	NW	N	CW	C	G	Y	S	Total
2001	3	7	8	5	7	0	6	36
2002	3	8	9	6	7	0	6	39
2003	3	7	9	5	7	0	6	37
2004	3	7	9	5	6	0	6	36
2005	3	7	9	5	6	0	6	36
2006	3	7	9	4	6	0	5	34
2007	3	7	9	6	5	0	4	34
2008	2	7	8	6	5	0	3	31
2009	2	7	6	6	5	0	3	29
2010	2	6	5	4	4	0	2	23
2011	2	3	2	3	2	0	1	13
2012	2	4	2	3	1	0	1	13
2013	2	4	2	3	1	0	1	13
2014	1	3	2	3	1	0	2	12
2015	1	3	2	3	1	0	1	11
2016	1	3	2	3	0	0	1	10
Máx	3	8	9	6	7	0	6	39
Mín	1	3	2	3	0	0	1	10

existing production systems for the benefit of the country's producers (CONAPESCA 2009). To our knowledge, this transformation has not taken place, while the number of GFFF decreased from 39 active fish farms in 2002 to only 10 in 2016 (Table 6.2).

Since 2013, it has been very difficult to obtain statistics on fish stocking, as the staff in charge of this task has been reduced below the operational level. This information is thus no longer available. Also, since 2014, the CONAPESCA has not released the fishing yearbooks that provide information on the state of the fisheries in the country. This is the result of a substantial reduction in the personnel that records fishery statistics in the country. Thus, the post-2014 information has been obtained from annual government reports or journalistic notes in which government officials provided some details. As a result of all this, currently (2018), there are 9230 aquaculture farms, of which 4623 are for tilapia (50.1%), 1843 are for rainbow trout (20.0%), 447 are for shrimp (4.8%) and the rest are for other species.

6.5.2 Fish Stocking Versus Inland Fish Production at the Geoeconomic Level from 2001 to 2013

Stocking and fisheries yield at the geoeconomic level recorded an overall positive relationship ($r = 0.71$), though this was not consistent in all regions (Fig. 6.4a). The strongest relationship between stocking and yield was recorded for the

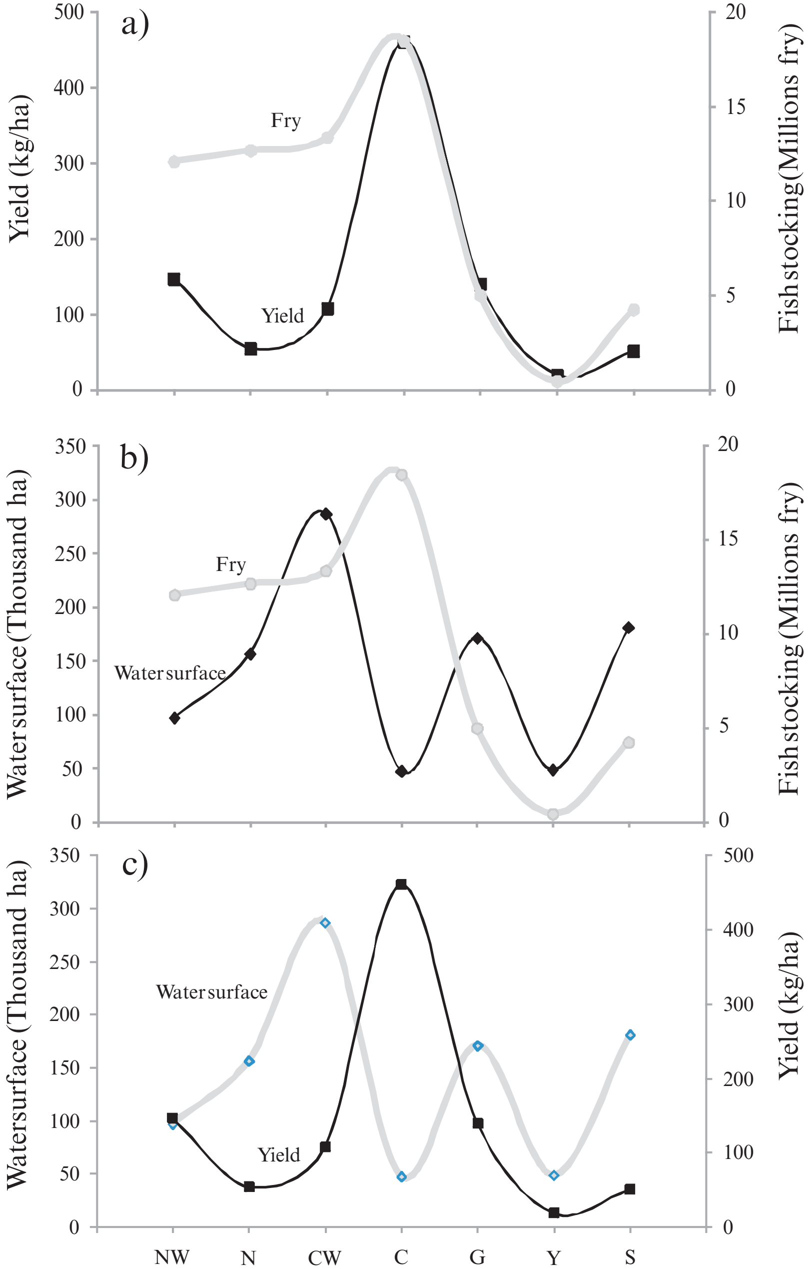

Fig. 6.4 Analysis of freshwater results in a geoeconomic scale for the 2001–2013 period. (**a**) Yield vs. Fish fry stocked; (**b**) fry stocked vs. reservoirs area; (**c**) yield vs. reservoirs area. Geoeconomic regions. NW Northwestern region, N Northern region, CW Central-Western region, C Central-Eastern region, G Gulf of Mexico region, Y Yucatán Peninsula region, S Southern region

Central region. This region has the smallest water surface area distributed over a large number of small waterbodies (Hernández-Avilés et al. 2007). Stocking in small waterbodies has generally tended to be more effective than that in large waterbodies (Quirós 1994, 1998; Fonticella et al. 1995). The Central and Gulf regions are associated with large internal markets, especially those in Mexico City, while the federal government reduced the number of farm units supplying stocking material from 6 in 1976 to 3 this year (2018) (Table 6.2). The weaker relationships between stocking and yield recorded in other regions may be explained in several ways. Recreational fisheries are more prominent than fisheries for food in the Northern region, where the value of sport fishing exceeds two million USD and specifically targets the tourist sector (CONAPESCA 2000). The Gulf region is characterised by high tropical temperatures throughout the year that increase growth potential; however, some fisheries are supported by considerable, undocumented stocking by the private sector that skews any possible relationship. Fisheries yields recorded for Mexican continental waters lie within the range of production estimates reported by Welcomme and Bartley (1997), where the NW, CW and G regions fall into the 'natural production with stocking' category and the N region is located in the temperate region of the country. The Central region exceeds the national yields of the 'natural production with stocking regions' and the 'extensive stocked unfertilised regions'. This may be related to the intensive farming systems that are increasingly being used. The range of enhancement techniques involves increasing the level of human input and control that significantly raises productivity and also raises costs. Cases of positive relationships between fish stocking and yield have been previously reported for extensive systems (Sugunan and Katiha 2004; Jayasinghe et al. 2006). The reasons for these relationships may include the shape of a dam, the size of the stocked fry (also related to mortality) or the size of fish at the time of capture, among others (Lorenzen 1995).

A moderate positive relationship was recorded between fish stocking and water surface area ($r = 0.51$), when anomalous data for the Central region were omitted. This region has the highest stocking density, followed by the Central-Western, Northern, Northwestern and Gulf of Mexico regions. The Southern region and the Yucatán Peninsula have the lowest stocking density (Fig. 6.4b). Yield is not associated with the area of available waterbodies ($r = -0.38$). The Central region has the lowest water availability and the greatest yield (Fig. 6.4c).

6.6 Freshwater Fisheries Policies

The number of fish fry farms in the country decreased from 36 in 2001 to 10 in 2016. The Central-Western (CW), Gulf of Mexico (G) and Northern (N) regions suffered the largest loss of fish fry farms (Table 6.2). The number of aquaculture centres began to decrease in 2001 during the administration of President Fox, and the loss of centres was dramatic during the administration of President Calderón, particularly between the years 2010 and 2011 (Table 6.2). It was in the administration of President Fox that fry began to be sold in federal aquaculture centres. This constituted a turning point in the policies of fish stocking in the country. Thus, the administrations of presidents Fox, Calderón and Peña have been characterised by a progressive abandon of federal aquaculture.

A significant increase in the number of people engaged in intensive systems, for marine and freshwater activities, took place over the last years (AEP 2000–2014), with about 20,000 people in 2006 and about 60,000 over the years 2012–2014, whereas staff working with fish stocks (fish stocks and repopulation or extensive systems) decreased from 250,000 over the years 2000–2010 to 200,000 over the years 2010–2014 (Fig. 6.5a). Similarly, freshwater fish production in intensive

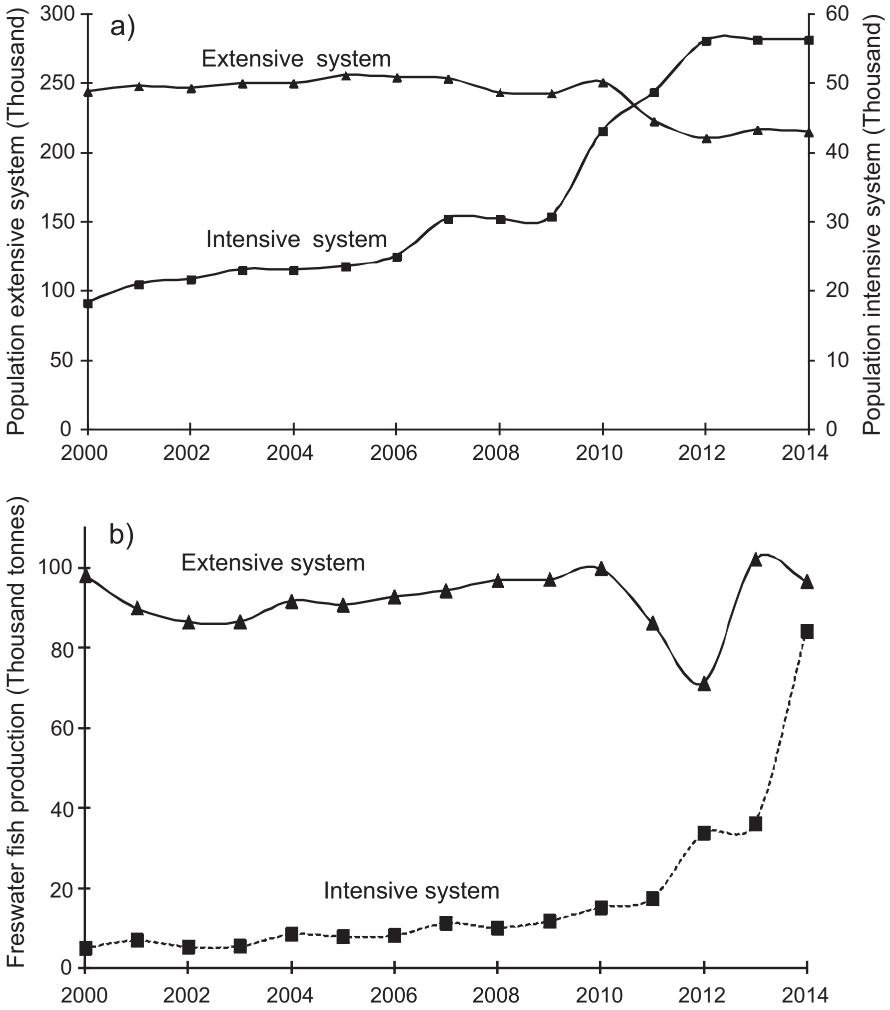

Fig. 6.5 (**a**) National population engaged, for marine and freshwater activities, in extensive and intensive systems. (**b**) Freshwater fish production by extensive and intensive systems

systems increased from 2000 to 80,000 tonnes for the period 2000–2014, while extensive production remained stable around 80–100 thousand tonnes (Fig. 6.5b).

Over the last 18 years, fry production by the GFFF was almost abandoned and the promotion of intensive crops of mostly trout and tilapia resulted in a proliferation of private farms where the production of fry may be linked to the consumer in an expanding market. These increasing intensive private farms that produce alien species cause an increased and widespread deterioration of biodiversity in epicontinental aquatic systems nationwide. This, together with the loss of habitats and the introduction of exotic species, is one of the major causes of the extinction of native species (Allan and Flecker 1993; Clavero and García-Berthou 2005). This situation is aggravated even more by the lack of control of other accidentally introduced species, such as *Hypostomus plecostomus* (Linnaeus 1758), and several little known species, mainly of the genus *Pterygoplichthys*, of the family Loricariidae.

Summarising, production of fish in inland waters in Mexico increased rapidly from about 14,000 t to about 120,000 t from the early 1970s to the late 1980s and fluctuated between 120,000 and 170,000 tonnes thereafter. This trend in fish production is largely explained by fish stocking and the expansion of the water surface area generated by the proliferation of reservoirs since the 1950s. The stabilisation of fish production after 1990 appears to be associated with a decline in the construction of reservoirs (Table 6.3), overexploitation of fish in some large reservoirs (Jimenez-Badillo 2004), the fact that most fisheries had reached their point of maximum exploitation, environmental perturbations (urban-industrial pollution) and, possibly, an increase in sediment runoff (generating turbidity) caused by deforestation. Despite this, there are success stories regarding aquaculture management in small waterbodies (Hernández-Avilés et al. 2007) linked to subsistence or commercial fishing in some regions. The Mexican government is committed to supporting the growth of aquaculture as a replacement for overfished wild stocks but has not addressed the underlying causes of overexploitation through, for example, fishery regulations (Cowx 1999). Alvarez-Torres et al. (2002) recorded 51% of inland fisheries as overexploited and 38% as deteriorating. Consequently, in order to increase

Table 6.3 Stocking fry density (sum of the 13-year period between 2001 and 2013) and number of federal aquaculture centres in operation in each geoeconomic region

Region	Stocking fry density Thousand $(km^3)^{-1}$		Number of federal aquaculture centres	
	1979[a]	2013[b]	1976[c]	2016[b]
NW	40	317	2	1
N	190	134	4	3
CW	260	222	6	2
C	1540	1746	5	3
G	90	10	1	0
Y	0	0	0	0
S	130	236	6	1

From [a]DEPESCA (1981); [b]our study; [c]Medina-Gándara et al. (1976)

production, it will be necessary to intensify the management of individual fisheries, which may probably be best achieved by returning management to the local communities, coupled with better focused stocking activities.

6.7 Conclusions

What are the most important problems arising from fish stocking? Stocking modifies aquatic ecosystems, changes nutrient cycles in lakes and causes population declines and a loss of genetic diversity (Cowx 1999; Halverson 2008). In Mexico, native and endemic freshwater fish have deteriorated because of basin degradation and introduction of exotic species (Alvarez-Torres et al. 2002). The aquaculture of tilapia cannot continue unrestricted without further exacerbating damage to native fish species and biodiversity. Farming indigenous species and restricting the culture of tilapia to closely managed, controlled ponds, while exclusion is preferred when possible, are recommended. On the other hand, *Oreochromis* spp. and *Cyprinus* spp. resist environmental alterations and pollution, thereby guaranteeing fish production even in critical environments (Bowen 1988). Stocking practices have adopted these species rather than native or endemic ones. There is no national plan for the production of the fry of native species (white fish, native cichlids, catfish).

The Mexican government has recommended stocking for aquaculture as a replacement for overfished wild stocks but has not addressed the underlying causes of overexploitation through, for example, fishery regulations. Regulated and valid methods for inland fish and fisheries that include data collection and database management are needed.

Fish stocking is no longer related to continental fisheries production following a decrease of approximately 90% in the number of fry produced (from the year 2001 to 2013), together with a significant rise in production in intensive systems over the last years that has exceeded production in extensive systems. However, no detailed information is available to analyse fishery yields.

It is essential to count on available and adequate information in order to carry out the necessary analyses that may lead to proper decision-making. Currently, fisheries and aquaculture statistics are provided with a delay of 3–4 years. The last available yearbook at the time of writing this text (October 2018) is for the year 2014. Considering that it is necessary to be able to consult these statistics on a regular and reliable basis, it is suggested that the Instituto Nacional de Estadística y Geografía (INEGI, National Institute of Statistics and Geography) or SAGARPA through its Servicio de Información Agroalimentaria y Pesquera (SIAP, Processed Food and Fisheries Information Service) be in charge of this task. In a country where an efficient use of water is a priority, it is important to coordinate efforts for the evaluation, diagnosis and management of limnological resources. In addition, the market demand for tilapia in Mexico is growing rapidly. Management by CONAPESCA of aquaculture centres for fry production is practically null, and freshwater fish fry management has been transferred to the private sector or to local administrations. Fisheries yields recorded for Mexican continental waters are within the FAO estimates, with the exception of the Central region of the country where national yields are exceeded. This suggests that intensive farming systems are being increasingly adopted. An improved performance of inland fisheries estimates would facilitate policy-making, and a more effective management aimed at making fisheries sustainable. Fish production has increased because of the rise of intensive systems; however, it would be interesting to carry out a rigorous 'impact assessment', a technique that measures the before and the after of the state of social and economic phenomena.

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Chapter 7
Tuna Fisheries and Global Warming in Mexico

Enrique Ayala-Duval and María del Carmen Maldonado-Monroy

7.1 Introduction

Currently, a major concern mainly for oceanographers, fishery biologists, and earth scientists is the current issue of global warming (GW). There is enough evidence showing that the temperature has been rising around the entire globe since several decades ago (Philips and Pérez-Ramírez 2017; IPCC 2001).

Global warming could be considered a major issue for twenty-first-century science. Hundreds of publications have been written and symposiums have been held, trying to collaborate in the understanding of this problem and its possible mitigation.

The ocean is directly impacted by GW, causing physical, chemical, and biological changes; its effects are also reflected in the structure of marine food webs (Edwards 2009; Garzke et al. 2015), affecting the tuna species in their population structure and, therefore, their fisheries, for example, by changing their distribution or the habitat size and fisheries productivity (FAO 2011).

The aim of this chapter is to follow and examine what is known at present on the effects of GW on the related species to the Mexican tuna fisheries. We will also explore what effects and responses could be expected from the thermal physiology of tunas and some of their biological aspects such as migrations, spawning grounds, and feeding, also on the recruitment to the adult stock, all of these to visualize what changes could be expected for this fishery economically important for many countries, including Mexico.

Mexico has a tuna fishery based on several species in the Pacific Ocean, Gulf of Mexico, and Caribbean Sea (Table 7.1). Most of them are highly migratory, so they are common with other countries, meaning that the welfare of these species is a matter of the countries that share them.

E. Ayala-Duval (✉) · M. del C. Maldonado-Monroy
Universidad Autónoma Metropolitana-Iztapalapa, Departamento de Hidrobiología, México City, Mexico
e-mail: ead@xanum.uam.mx

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Table 7.1 Species that inhabit Mexican waters and their respective FAO Area

Species	FAO names	Area 31	Area 77	References
Scomber japonicus (Houttuyn, 1782)	Chub mackerel	x	x	a
Acanthocybium solandri (Cuvier 1832)	Wahoo	x	x	b
Scomberomorus cavalla (Cuvier, 1829)	King mackerel	x		a
S. concolor (Lockington, 1879)	Monterey Spanish mackerel		x	a
S. regalis (Bloch, 1793)	Zero	x		a
S. maculatus (Mitchill, 1815)	Atlantic Spanish mackerel	x		a
S. brasiliensis (Collette, Russo & Zavalla-Camin, 1978)	Serra Spanish mackerel	x		a
S. sierra (Jordan & Starks, 1895)	Pacific sierra		x	a
Sarda sarda (Bloch, 1793)	Atlantic bonito	x		a
S. orientalis (Temminck & Schlegel, 1844)	Striped bonito		x	a
S. chiliensis (Cuvier, 1831)	Eastern Pacific bonito		x	a
Auxis rochei (Risso, 1810)	Bullet tuna	x	x	a
A. rochei rochei (Risso, 1810)	Bullet tuna	x		c
A. rochei eudorax (Collette and Aadland 1996)	Bullet tuna		x	c
A. thazard (Lacepède, 1800)	Frigate tuna	x	x	b
A. thazard thazard (Lacepède, 1800)	Frigate tuna	x		c
A. thazard brachydorax (Collette and Aadland 1996)	Frigate tuna		x	c
Katsuwonus pelamis (Linnaeus, 1758)	Skipjack tuna	x	x	a; b
Euthynnus alletteratus (Rafinesque, 1810)	Little tunny	x		a; b
E. lineatus (Kishinouye, 1920)	Black skipjack		x	a; b
Thunnus thynnus (Linnaeus, 1758)	Northern bluefin tuna	x	x	a; d
T. alalunga (Bonnaterre, 1788)	Albacore	x	x	a; b
T. obesus (Lowe, 1839)	Bigeye tuna	x	x	a; b
T. albacares (Bonnaterre, 1788)	Yellowfin tuna	x	x	a; b
T. atlanticus (Lesson, 1831)	Blackfin tuna	x		a; b
T. orientalis (Temminck & Schlegel, 1844)	Striped bonito		x	b

References are a = Collette and Nauen (1983); b = Collette (2003); c = Collette and Aadland (1996); and d = Bayliff (1994)

7.2 Tuna Fisheries: A Brief History

Tuna fisheries are one of the oldest in the world, with records dating from 2000 years BC, with Phoenician trap fisheries (Maguire et al. 2006). In the Pacific Ocean, the tuna fishery had its origin in the United States (USA) in 1903, with bait boats fishing yellowfin tuna *Thunnus albacares* for canning, with the industry developing rapidly in California (Miyake et al. 2004).

In 1914, the tuna harvest reached about nine million tonnes, diminishing toward 1916, so the producers decided to include the skipjack *Katsuwonus pelamis* in the tuna cans; after this, to increase the tuna production, the US tuna vessels explored toward southern California (Coan 2001), and they found that the catches increased when they fished further south (Wild and Hampton 1994). In 1923, the catches from the new areas exceeded those from the Californian waters; thence, the US fleets increased their number of vessels, which landed about 32 million tonnes in 1929; so new areas were explored to find more tuna banks and discovered that in the area of the Revillagigedo Islands (Coan 2001; Wild 1994), Marias Islands, and Alijos Rocks, the tuna fishing was possible all year-round (Muhlia-Melo 1987).

7.3 The Beginning of the Tuna Fishery in Mexico

In Mexico, the tuna-fishing activities started in 1937, with the bait boat and purse seine fisheries (Muhlia-Melo 1996); the catches from 1937 to 1965 were between 340 and 3528 tonnes per year; in 1970, Mexico had 15 tuna vessels, harvesting 11,328 tonnes annually, and this level was sustained until 1972. The Mexican fleet increased to 19 tuna vessels in 1973 and the harvests accounted for 17,495 tonnes each year. In 1974, with 23 vessels, the catches reached up to 21,615 tonnes annually, and from 1975 to 1981, the average catches ranked between 35,000 and 40,000 tonnes, when the fleet was formed by 55 vessels; in 1985, there were 61 vessels with a carrying capacity of 46,200 tonnes; at the end of 1986, the catches reached more than 100,000 tonnes (Muhlia-Melo 1987).

From 1985 to 1993, the carrying capacity of the Mexican tuna fleet was, for purse seine (Miyake et al. 2004), between 42.6 and 46 thousand tonnes and, for bait boat, between 0.69 and 1.5 thousand tonnes (Muhlia-Melo 1996).

Later, in 2003, the tuna fleet had 79 vessels, harvesting 183 thousand tonnes as a historical record (CONAPESCA 2014; DOF 2018). From 2004 to 2013, the total catches per year (Table 7.2) were less productive (CONAPESCA 2014).

The sport fishery in Mexico began in the 1950s with the tourist industry; since the 1990s, the most important sport fishing areas in the Pacific coast of Mexico included the southern tip of the Baja California Peninsula (Miyake et al. 2004), Mazatlán in Sinaloa, San Blas in Nayarit, Puerto Vallarta in Jalisco, Manzanillo in Colima, and both Ixtapa-Zihuatanejo and Acapulco in Guerrero (Muhlia-Melo 1996).

In the 1950s, the longline fishery also began in Mexico (Miyake et al. 2004), when the Japanese fleet extended the activities of this fishery toward the eastern

Table 7.2 Total tuna landings in Mexico by year in thousands of tonnes

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Landings	183	141	156	110	139	128	129	131	133	125	153

Data source: CONAPESCA (2014); DOF (2018)

Pacific, and high catch rates of tuna and other big pelagic fish were taken from an area formed by the Revillagigedo Islands, the southern portion of the Gulf of California, and northwest off Baja California Sur to the north of Magdalena Bay (Muhlia-Melo 1996). In 1963, the Gulf of Tehuantepec was pointed as an area where there were substantial fisheries (*Thunnus albacares* and *Katsuwonus pelamis*) by the United States (Blackburn 1969) and that the purse seine fishery was incipient until 1959 (Blackburn 1963; Coan 2001). At the end of the 1960s, the most important area in Mexico (where fisheries had more activity) was the northwestern coast of the Baja California Peninsula (Blackburn 1969).

In the Pacific coast of Mexico, five kinds of devices are being used in the tuna and billfish fisheries, namely, Troll (sport fishing), pole and line (bait boat), purse seine, longline, and drift gillnet (Muhlia-Melo 1996). As the fleets increased the number of vessels and their carrying capacity, farther areas were exploited; thus, from the northern-west area of Baja California, the catches were increasingly taken toward the central Pacific coast of Mexico (Miyake et al. 2004) and later to Central America and Peru and as far as 140 °W (Muhlia-Melo 1987).

With the increasing tuna fishery activities around the world, the need for scientific information about the marine resources (the tuna resource in this case), the inequality of carrying capacities by each country, and with the affectation to other species (mammals, sharks, turtles, and others), the need for coordinators and regulatory institutions becomes apparent; thus, several institutions were organized.

The Food and Agriculture Organization of the United Nations (FAO) was founded in October 1945; presently, 196 countries are members of this organization; it leads international efforts to overcome hunger in the world. It serves to both developed and developing countries and acts as a neutral forum where all nations meet as equal to negotiate agreements and debate policy. In order to organize and coordinate all the 196 member countries, the FAO has divided the world ocean into 27 major fishing areas for statistical purposes (FAO 2018), where Mexico is between the Area 77, which covers the Eastern Tropical Pacific, and Area 31, covering Gulf of Mexico, western Atlantic Ocean, and Caribbean Sea (Fig. 7.1).

A few years later, the Inter American Tropical Tuna Commission (IATTC) was established in 1950, by international convention, and it is responsible for the conservation and management of fisheries for tunas and other species taken by tuna-fishing

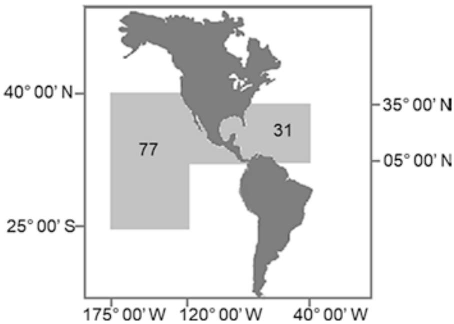

Fig. 7.1 Schematic representation of fishing areas 77 and 31 related to Mexico (from the FAO World's major fishing areas). (Modified from the downloadable map at: http://www.fao.org/3/a-az126s.pdf. Accessed on August 2018)

vessels, in the eastern Pacific Ocean (IATTC 2009). A total of 21 countries are members of this organization, including Mexico since 1964, plus five cooperating nonmember countries (IATTC 2009; Okamoto and Bayliff 2003).

The Scripps Tuna Oceanography Research program was undertaken by the Scripps Institution of Oceanography, funded largely by the US Bureau of Commercial Fisheries, to sample the Eastern Tropical Pacific and to learn how the oceanography of the region influences to the very valuable fishery resources of the region (Fiedler and Lavín 2006).

In the same way, as a counterpart in the Atlantic Ocean, The International Commission for the Conservation of Atlantic Tunas (ICCAT) was funded in 1969 and is an intergovernmental fishery organization responsible for the conservation of tunas and tuna-like species in the Atlantic Ocean and its adjacent seas, and there are 52 member countries, including Mexico since 2002, according to the last update (ICCAT 2018).

The Indian Ocean Tuna Commission (IOTC) was established in 1993 (IOTC 2018a), and has areas of competence, those defined by the FAO as areas 51 and 57, adjacent seas, and north of the Antarctic, as far as necessary to protect those species that immigrate to, or emigrate from, the Indian Ocean (IOTC 2018b).

The fishing pressure on tuna species has been constantly increasing through the years, with more efficient methods, by using either fishing flotsam and aggregate devices (FADs), whose importance has increased greatly in recent years (Girard et al. 2004; Itano and Holland 2000), or sophisticated detection techniques, such as satellites (Kuno et al. 2000), which detect oceanographic conditions (Andrade 2003; Matsuura et al. 1997) such as temperature ranges, water mass fronts, and tuna schools by their warmer bodies than the surrounding water, which produces a contrast in the infrared spectrum, where the tuna species are frequently found. Such sophisticated techniques are being used to achieve larger catches with less effort and cost (Schaefer and Fuller 2005). For this reason, the policies of the involved institutions must be carefully sustained with more scientific knowledge, such as periodic monitoring of the life history of tunas (Maguire et al. 2006; Young et al. 2006), and the continuously changing marine conditions.

7.4 What Do Tuna Species Prey On?

The diet of tunas must support a high metabolic rate, which is common to all tunas, and produces a rapid digestion (Allain 2005; Graham and Dickson 2004). Such diet, as well as for many other fish, varies according to their developmental stage (larva, juvenile, or adult), even between the same stages in different species; for example, larvae of some scombrids like chub mackerel *Scomber japonicus* consume mainly appendicularians, copepods, and fish larvae, whereas larvae of the Japanese Spanish mackerel *Scomberomorus niphonius* (Cuvier, 1832), typical from the northwest Pacific, fed almost exclusively on fish larvae and a very small proportion of invertebrates (Shoji et al. 2001); thus, the kind of food ingested by the larval stages depends on the size of the mouth (Margulies et al. 2001; Shoji et al. 2001), size of larva (Margulies 1993), and the color of the prey (Sánchez-Velasco et al. 1999).

Studies of two species of larval tuna from the southern hemisphere, such as southern blue fin tuna *Thunnus maccoyii* (Castelnau, 1872) and *Katsuwonus pelamis*, predating on microzooplankton (mainly grazers between 20 and 200 μm), have shown that scombrid larvae can affect the abundance of microzooplankton (Gerking 1994).

Larvae of two species, *Thunnus maccoyii* and *T. alalunga* (Bonnaterre, 1788), were found having Copepoda nauplii, Calanoida, Cyclopoida, and Cladocera in their stomachs as the main prey, but in different proportions; in the case of *T. maccoyii*, in the post-flexion stage, it also preys on its own species. Larvae of *Katsuwonus pelamis*, as a third tuna species, had appendicularians and fish larvae (Young and Davis 1990). When there is competition for limited food resources, a reduced growth could be caused (Wexler et al. 2007). This is common in the Eastern Tropical Pacific (ETP) coasts of Panama, which have seasonal upwelling: during this period (January to March), larvae of *Thunnus albacares* are found well fed, which is opposite to the season of upwelling absence, when the larvae are found starving and malnourished (Frommel et al. 2016; Lauth and Olson 1996).

Katsuwonus pelamis from 26.3 to 75.7 cm preys mainly on fish (herring, flying fish, and other small tunas like *Auxis*), mollusks (squids), and crustaceans (Stomatopoda), although zooplankton is also found in their stomachs (Batts 1972).

The larvae of black skipjack *Euthynnus lineatus* (2.0–9.9 mm) and *Auxis* (from 2.0 to 7.9 mm) have been found to feed mainly on copepod nauplii, copepodites, crustacean eggs and appendicularians (*Oikopleura dioica*), and other minor items (Sánchez-Velasco et al. 1999). The northern bluefin tuna *Thunnus thynnus* larvae between 2.6 and 8.7 mm in standard length (SL) inhabiting the Mediterranean spawning grounds in the Balearic Archipelago are diurnal feeders; copepod nauplii dominated the diets of earlier stages, whereas larvae of 5.0–6.0 mm SL exhibited positive selection of cladocerans over other prey. Larvae progressively selected larger prey. Appendicularians were found in the diet of larger larval sizes (>6 mm SL), but no fish were observed (Catalán et al. 2011).

The importance of appendicularians as food for tunas resides in the continuous production of their filter-feeding houses (Catalán et al. 2011), which, by gathering microparticles, creates shortcuts in the carbon flux through the marine food web (Troedsson et al. 2013). When both appendicularians and their houses are ingested by tuna larvae, they take advantage of a high energy input to improve their growth related to the development of structures for capture and locomotion and then acquiring the ability to chase prey at the stage of flexion.

Gelatinous zooplankters (jellyfish, ctenophores, and salps) are also eaten by adult tunas such as *Auxis rochei*, *Euthynnus alletteratus*, *Sarda sarda*, *Scomber scombrus*, *Thunnus alalunga*, and *T. thynnus*; given the high amount of gelatinous zooplankton in the stomachs of adults, it is considered that this food intake is opportunistic, and the reason why this kind of food is eaten by tunas is still unknown, due to the low energetic value provided to adults (Cardona et al. 2012).

7.5 Effect of pH, Temperature, Salinity, and Dissolved Oxygen on the Survival of Tuna

It is well known that some oceanographic conditions at sea are altered by human activities. Input of CO_2 and other gases classified as having greenhouse effects (methane, ozone, nitrous oxide, and others, like those related to sulfides) in the atmosphere, all of them and their derivatives, finally end up in the world ocean, regardless of the route they have followed.

Ocean acidification and its warming are just some of the known effects on seawater, which can cause, for instance, toxic algae blooms and hence hypoxia, by increasing the oxidation of organic matter affecting the zooplankton biomass within which there are some of the prey for tuna larvae (Gerking 1994; Shoji et al. 2001; Young and Davis 1990). It has been seen that internal organs such as the eye, liver, kidney, pancreas, and muscle of *Thunnus albacares* larvae are damaged by experimental seawater acidification at pH values of 7.6, 7.3, and 6.9 (Frommel et al. 2016).

The chemical behavior of the ocean pH is complex, since many factors (physical, chemical, and biological) are involved in its value at a given zone. According to Sverdrup et al. (1942) and Garrison and Ellis (2015), pH values in the sea vary between 7.5 and 8.4; the highest values are related to the surface (8.1 to 8.3) where the CO_2 is in equilibrium with the atmosphere, though higher values may occur due to the fact that photosynthesis has lowered the CO_2 concentration. At a deeper level (≈800 m), usually all the O_2 has been practically consumed, and the CO_2 concentration is high; the pH has a trend to the value of 7.5, and this is known as the oxygen minimum zone (OMZ), characterized by a very low oxygen concentration ($<$0.5 mL O_2 L^{-1} or 22 μmol kg^{-1} or 7.5% saturation) (Gallo and Levin 2016). Below the deeper limit of the OMZ, the pH tends to have a slight increase in its value with depth, but near the bottom (≈4000 m), H_2S is produced by bacterial activity, and the pH value may be found near to 7.0 or a bit lower in the acid range (Sverdrup et al. 1942).

Distribution and properties of OMZs have been studied by Helly and Levin (2004) and Gallo and Levin (2016); these authors have pointed out that the OMZs are a product of the euphotic layer productivity, water mass age, and a slow circulation. A thicker OMZ is caused when there are increased upwelling and the productivity is high, so the oxygen demand is also high; a slower circulation also contributes to form a thicker OMZ (Helly and Levin 2004).

In the eastern Pacific, the top and bottom edges of the OMZs vary according to latitude; thus, between 40 and 60 °N, such OMZ borders are located between 200 and 1480 m depth; in the range of 0–30 °N, the OMZ extends from 30 to 1260 m depth, and between 0 and 20 °S, the boundaries range from 20 to 800 m in depth (Helly and Levin 2004).

Due to the high metabolic rate and the subsequent high oxygen demand by tunas, it is likely that the species which carry out the deepest diel vertical migrations do it to avoid the low oxygen concentrations of the OMZs; for instance, adults and larvae of *Thunnus thynnus* make diel vertical migrations at depths greater than 1000 m (Cornic et al. 2018).

Dam (2013) points out that marine zooplankton is being stressed by the changing conditions of seawater due to GW; considering that each stressor must be viewed as evolutionary selection pressure, the author argues that some zooplankton can respond to these changes by phenotypic plasticity or genetic adaptation and highlights the importance of considering combined factors in further experiments for studying the possible future responses of zooplankton to such changing conditions of seawater.

Environmental variables such as pH, temperature, salinity, and dissolved oxygen influence the biological processes of tuna species and thus determine their survival, spatial distribution, and densities (Arrizabalaga et al. 2015; Boyce et al. 2008). Thus, larval stages of blackfin tuna *Thunnus atlanticus* and *T. albacares* and the bigeye tuna *T. obesus* and *T. thynnus* from the northern Gulf of Mexico have been found under different environmental conditions; for instance, Cornic and collaborators have found that *T. atlanticus* and *T. obesus* have had the highest larval densities with salinities greater than 36 and *T. albacares* at a salinity of 27; *T. atlanticus* and *T. obesus* tend to be in areas with salinities between 28.3 and 38.6 but have been found in higher densities where salinity is greater than 36. The same authors also found that the larvae of *T. thynnus* are distributed in areas with salinities of 36, and at depths greater than 1000 m (Cornic et al. 2018).

Thunnus atlanticus is widely distributed throughout the Atlantic Ocean; this species spawns mainly in the Gulf of Mexico, and this activity is low in the northwestern part of the Atlantic Ocean (Muhling et al. 2014); its preferred temperature range is between 21.9 and 26.6 °C; and most of the time (90%), it swims between 0 and 57 m depth (Fenton et al. 2015).

The water temperature determines the time of spawning of *Thunnus albacares* and was observed in the waters of Panama that it spawns between 23.3 and 29.7 °C (Margulies et al. 2007). Yolk sac and first-feeding larvae of this species showed lethal conditions at temperatures below 21 °C and greater than 33 °C and at dissolved oxygen values lower than 2.2 mg O_2 L^{-1} and between 26 and 29 °C (Wexler et al. 2011). Adults of this species (and also *Katsuwonus pelamis*) usually limit their dives to depths where water temperatures are not colder than 8 °C of those values from the surface and no less than a concentration of 3.5 mL O_2 L^{-1} (Brill et al. 2005). The oxygen levels in seawater play an important aspect in the ecology of fish, whereas adult tuna need from three to five times more dissolved oxygen than most of any other fish due to their high metabolic rate (Barkley et al. 1978). Studies on adult tunas have shown, for instance, that the lowest limit for *K. pelamis* is 4 mL O_2 L^{-1}, while for *Euthynnus affinis* is 2 mL O_2 L^{-1} (Dizon 1977), 3.5 mL O_2 L^{-1} for *T. albacares*, and 1.0 mL O_2 L^{-1} for *Thunnus obesus* (Graham and Dickson 2004).

Thunnus obesus with a worldwide tropical and subtropical distribution (Collette and Nauen 1983) has a peculiar depth distribution and vertical migration ranges; these fish usually swim at the surface layer at night and, at dawn, descend beyond 500 m depth, following the diel vertical migration of zooplankton and small nekton of the deep scattering layer, taking advantage from these organisms as a food resource (Hays 2003), although the mean depth range of vertical migrations is greater for the larger fish than for the smaller ones (Schaefer and Fuller 2005).

Temperature at their maximum depths is about 5 °C, and this species has an exposure to temperatures 20 °C colder than in the surface layer, and oxygen concentrations of less than 1.5 mL O_2 L^{-1} (Brill et al. 2005).

The ranges of spatial distribution of tuna species are related to their physiological tolerance to temperature (Boyce et al. 2008), so climate change can cause the loss or deterioration of the habitat of the species and generate physiological and behavioral responses that affect larval survival, growth, recruitment (Muhling et al. 2015), reproduction, distribution, and abundance (Perry et al. 2005). For instance, larvae of *Thunnus atlanticus* are very sensitive to temperature. Processes like growth and swimming capacity to catch prey or to avoid predators are the result of the influence of the sea surface temperature (SST) and salinity; thus, values between 29 and 30 °C have positive effects for the larvae of this species in the Gulf of Mexico (Cornic and Rooker 2018).

By developing habitat models from fishery data, it has been possible to speculate that an increase in water temperature would lead to the alteration on the distribution of adults and both spawning season and spawning areas, as well as the larval growth, feeding, and survival. In this way, it has been predicted, for instance, an anticipated beginning and term of the spawning season in *Thunnus thynnus*, as well as a change in their planktonic prey and density of predators, as a possible future scenario in the Gulf of Mexico (Muhling et al. 2011).

Adults of *Thunnus thynnus*, *T. albacares*, *T. atlanticus*, and *Katsuwonus pelamis* migrate through the Atlantic to spawn in the Gulf of Mexico; physiologically, *T. thynnus* is more vulnerable to an increase in water temperature than *T. albacares*, *T. atlanticus*, and *K. pelamis*; all the three species spawn during spring in the Gulf of Mexico (Cornic et al. 2018; Muhling et al. 2014). A possible future scenario of climate change effects for the years 2050 and 2090 would result in a wider distribution of larvae of *T. albacares*, *T. atlanticus*, and *K. pelamis* and one more restricted for *T. thynnus* in the Atlantic Ocean and Gulf of Mexico (Muhling et al. 2014). Later, Richardson et al. (2016) have found that *T. thynnus* in addition to the well-known spawning areas in the Mediterranean Sea and Gulf of Mexico, there is another spawning area in the Slope Sea, between the Gulf Stream and northeast US continental shelf, meaning that this species is diversifying its spawning areas.

In the Pacific Ocean, *Katsuwonus pelamis* is affected according to the water temperature and the size of the fish in the following way: individuals of less than 3 kg or 50 cm in length can inhabit all the Eastern Tropical Pacific above the oxycline, but as the fish size increases, when weighing 8 kg or 70 cm in length, it can be excluded from Cabo Corrientes, Jalisco and San Blas, and Nayarit in Mexico, and from there to Panama, because at this size and weight, it shows a lesser tolerance to warmer temperatures (NOAA 1974).

Since tunas are a food resource of high value, the pressure of fishing through several decades, the most demanded species have been overexploited (Tidd et al. 2018; Cornic et al. 2018). In addition to overexploitation, the effects of climate change causing a zooplankton biomass reduction (Häder et al. 1998), from which larval fish are fed (Gerking 1994), the increasing of density of other zooplankters that are favoured with the increase of the water temperature and an acidified pH, such as the appendicularians that are consumed by some species of tuna in their larval and juvenile stages (Marsac 2017; Troedsson et al. 2013).

The increase in jellyfish and ctenophores also favored by warm waters (Purcell 2005), which prey on zooplankton including eggs, larvae, and juvenile of tuna (and of course on other fish that are prey of adults) (Marsac 2017). Without a doubt, some of the stocks of tuna in Mexican waters and in the world ocean will significantly decrease because of all of these situations.

7.6 Other Threats for Tuna Species from Human Origin

It has been found that microplastics can be transferred through food webs, and their ingestion can be accompanied by several pollutants (Lima et al. 2016); this kind of pollution can affect human health (Rochman et al. 2015). Plastic debris can also be transferred from one area to another, when it is ingested by migratory species such as tunas (Lima et al. 2016). In this way, microplastic debris have been found in gut contents of *Thunnus obesus* adults, although in a low proportion (9% of 35 stomachs analyzed) (Choy and Drazen 2013); also, microplastics have been found in the gut of *T. obesus* and *Katsuwonus pelamis* in Saint Peter and Saint Paul Archipelago, in the Equatorial Atlantic (Lima et al. 2016). No microplastics were found in adult specimens of *Thunnus albacares* (Choy and Drazen 2013), *K. pelamis* in Indonesia, and in both *Scomber japonicus* and *Thunnus alalunga* from the US market (Rochman et al. 2015); then, microplastic debris could be a threat to the health and survival of tuna species, although studies on its effects are currently scarce and should be focused on Mexican waters.

As we have seen above, tuna species are pelagic and highly migratory (Maguire et al. 2006) and capable to undertake transoceanic migrations; for instance, the striped bonito *Thunnus orientalis* and *T. albacares* that move between the western Pacific (WPO) and the eastern Pacific (EPO) (Glaser et al. 2015; Olson et al. 2016) and the juvenile of *T. orientalis* migrate through waters of the Kuroshio and California Currents (Olson et al. 2016; Pacific Bluefin Tuna Status Review Team 2017); with this argument, the Pacific Bluefin Tuna Status Review Team has pointed that the possibility of an extinction risk of *T. orientalis* could be minimized, given its wide distribution, migratory capacity, and their generalist feeding strategy (Pacific Bluefin Tuna Status Review Team 2017). Also, other tuna species migrating through the 77 and 31 FAO Areas could diminish their several threats by changing among different environmental conditions, but their fragile early-life stages are exposed to a greater predation, cannibalism, starvation, microplastic debris pollution, and therefore, a low recruitment to the adult stock. Finally, it can be deduced that GW and its consequences are a great threat for the early-life stages of tuna species.

Currently, the most dangerous environmental threats for tuna fish seem to be the warming and the acidification of the seawater, which affects the internal organs of larvae (Frommel et al. 2016). In addition to the effect of GW and overfishing, other threats such as oil spills, and construction of new ports in the Gulf of Mexico and Mexican Pacific, will cause damage to the spawning and nursery grounds, and will affect the welfare of adult tuna fish, by impacting the recruitment process, and consequently the future size of adult stocks of some tuna species.

Mexican authorities and institutions related to tuna exploitation must consider a regulatory structure of care and preservation of the spawning and nursery areas, since these are the places where the fragile part of the life cycle of tuna species begins, mainly those related to oceanic fronts and upwelling areas.

In the near future, worldwide monitoring will be essential for understanding the GW impact on the biology and spatiotemporal distribution of adult and larval tunas, as well as detecting overexploited stocks, and providing the necessary protection for the most vulnerable species to overfishing.

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Chapter 8
Fishery Resource Management Challenges Facing Climate Change

Francisco Arreguín-Sánchez, Mirtha O. Albañez-Lucero, Pablo Del Monte-Luna, and Manuel J. Zetina-Rejón

8.1 Introduction

Climate change is a natural cyclical phenomenon, with a frequency of approximately 70 years; and even when its effects and consequences are assumed, they are not clearly identified and characterized in the marine environment. The consideration of climate change effects for the management of living marine resources has not been incorporated into daily fishing practices. In the first instance, this has been due to the difficulty of identifying and separating the two sources of variation of stock abundances in a highly variable environment; second, the evidence of the effects of climate change has not been recognized in a timely manner. Although the regime shift was recognized by the late 1970s and early 1980s, it was not until 1984, at the World Conference on Fisheries Management and Development (FAO 1984), that the exploration of this phenomenon was suggested. Later, in 1995, Agenda 21 (ONU 1995) and the Code of Conduct on Responsible Fisheries (FAO 1995) included recommendations for governments to consider the effects of climate change on fishing activities; however, it was not until 2001, at the Reykjavik Declaration (FAO 2002), and in 2002, at the World Summit on Sustainable Development in Johannesburg (ONU 2002), that countries formally agreed to consider the climate change phenomenon within their policies, establishing a commitment to promote the implementation of measures to mitigate its effects. With this agreement, countries formally committed to attending to the effects of climate change, which, regarding fishing, was approximately 20 years after the regime change.

In this context, the state of knowledge of fisheries, the lack of background on the effects of climate change, and the absence of data, trends, and empirical evidence

F. Arreguín-Sánchez (✉) · M. O. Albañez-Lucero · P. Del Monte-Luna · M. J. Zetina-Rejón
Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, La Paz, Mexico
e-mail: farregui@ipn.mx

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used by science have caused a delay in the provision of management advice. Additionally, before the 1980s, management practices were closely linked to the available science, which was, in general, based on the static nature of the models, assuming a stable population carrying capacity, and therefore of the ecosystems; consequently, fishing was assumed to be the main or only driver of changes in the trends of stock abundance. Under these conditions, if a stock is fully exploited, that is, harvested to the limit of its maximum capacity of production, the change in abundance caused by climate change was not recognized at that time, and such effects were attributed to fishing. In this way, since the stock declined due to a cause other than fishing and the high harvest rates were maintained at the level corresponding to the limit of the stock production capacity, a certain degree of overfishing was generated; the impact of that overfishing may be more or less severe, depending on the life history of the populations and the accumulation of this effect over time.

Under this scenario, a number of fish stocks around the world appear overfished; but now, we know that environmental conditions are a key factor inducing these abundance decreases. On the other hand, the fact that the global effect shows a decreasing trend for many resources is because, also in global terms, the warming trend is associated with a reduction in primary production (Roxy et al. 2016; Gu et al. 2017); and, if the tendency of the latter is to decrease over time, the abundance of the populations will also, in general, tend to decrease. Of course, since this process is propagated through the food web, some stocks will decrease, and others will increase in abundance, but global production is expected to decline. This is the case that is illustrated in Fig. 8.1, which represents the ecosystem evolution of the continental shelf of Campeche in the southern Gulf of Mexico from late 1950–2010.

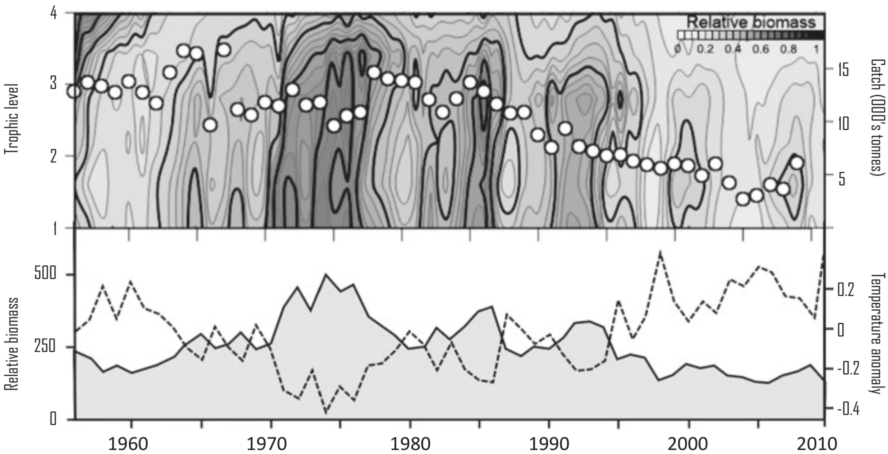

Fig. 8.1 Effect of climate change on the ecosystem of the southern Campeche Bank. Species in ecosystems are represented by their trophic level. Isolines reflect relative production along the ecosystem structure and through time. Note that maximum production occurs by the late 1980s with the regime shift when a cooling period ends and a warming period starts. Also note a decadal fluctuation that follows the long-term pattern of declining carrying capacity with a warming trend

The current challenge for science is to maintain the sustainability of exploited populations and ecosystems that change and evolve over time, defining adaptable management strategies by, for example, considering biological interdependencies, effects on habitat, changes in currents' circulation patterns, and metabolic stresses, among others. These types of questions require science that promotes active management actions, which allows for the continued generation of information and a continuous implementation of strategies in time and space in order to maintain sustainability independent of the evolution of stocks and ecosystems.

According to Arreguín-Sánchez (2012) and Arreguín-Sánchez et al. (2015), the Campeche Bank shows clear evidence of the effects of climate change, and in this region, consequences have been clearly reported for some of the main fisheries. In the following sections, three of the most significant regional fisheries are discussed: two of them have been negatively affected by climate change, with an official diagnosis of deterioration and overfishing, and one stock has been positively impacted, and yields have progressively increased. In all cases, we briefly discuss the consequences of adopting a management strategy based on an adaptability policy.

8.2 The Campeche Bank and the Evidence of Climate Change

One of the marine regions of Mexico that best reflects the effects of climate change on fisheries resources and that requires a new approach to fisheries management is undoubtedly the Campeche Bank (Fig. 8.2). In this region, a climate regime shift occurred in the late 1970s and the beginning of the 1980s, as shown by the anomalies of several environmental variables, such as temperature, salinity, primary production, mean sea level, and some climate indexes, such as the North Atlantic Oscillation, NAO, and the Atlantic Multidecadal Oscillation, AMO (Fig. 8.3) (Arreguín-Sánchez 2012; Arreguín-Sánchez et al. 2015). Additionally, the dominant effect of the 67-year harmonic component of temperature, which is characteristic of a climate change cycle, was demonstrated for this region, and this explains approximately 60% of the total variation in temperature (Del Monte-Luna et al. 2015).

The Campeche Bank behaves like a semi-closed marine system with respect to the rest of the Gulf of Mexico (Fig. 8.2). The bank contains an extensive continental shelf of approximately 140,000 km^2, which extends north and west of the Yucatan Peninsula for more than 200 km of coastline. In the peninsula, there are no rivers, except at the southern limit; its influence, because of the coastal currents, is manifested toward the western region outside the Campeche Bank. In this way, the contribution of terrestrial nutrients is limited to the adjacent area close to the mangrove systems along the coast; as a result, most primary production in the region comes from phytoplankton. The marine currents are, generally, of low intensity and provide a poor contribution to production because of the effect of turbulence that limits nutrient availability. On the other hand, the exchange of masses of water with the adjacent ocean, from the central Gulf of Mexico, is largely controlled by six eddies

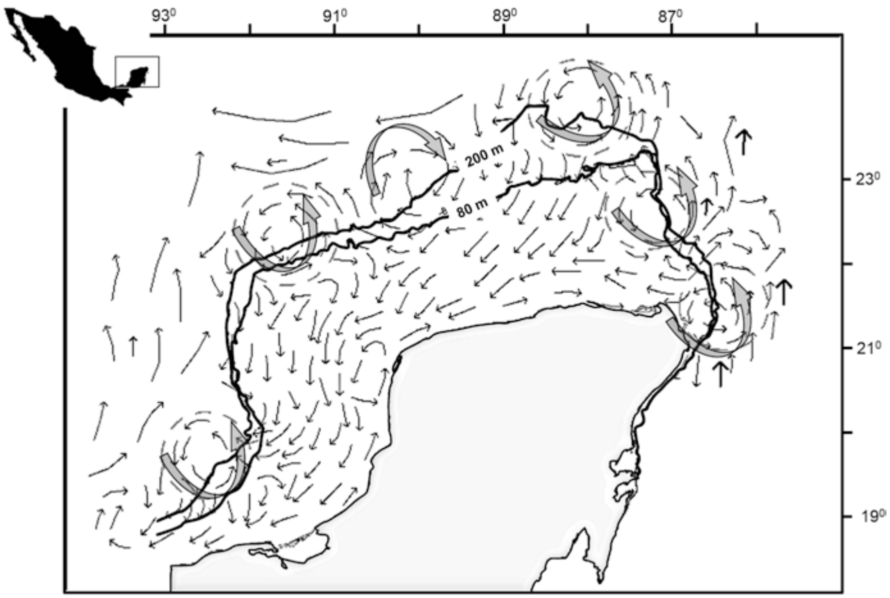

Fig. 8.2 Map showing the Campeche Bank indicating the limits of the continental shelf and the eddies around it (large transparent arrows). Thin arrows indicate Ixtoc I was the direction of the marine currents. It can be seen that most of the eddies act as a natural barrier with respect to the central Gulf of México

over the limit of the continental shelf, five of them anticyclonic gyres, which transport water outside the Bank of Campeche, and only one cyclonic gyre with the opposite effect (see Fig. 8.2). One important aspect to be taken into account for spatial and seasonal dynamics is that the entire system responds to seasonal pulses of primary production; one such pulse is associated with the region of the Laguna de Términos, is manifested just after the rainy season (July), and is characterized by the departure of a large number of species that migrate from the breeding areas to the sea (Yáñez-Arancibia and Day Jr 1988; Arreguín-Sánchez 1992; Zetina-Rejón 2004); another pulse is associated with the seasonal upwelling on the northeast of the continental shelf of the Yucatan Peninsula, occurring in April (Merino 1996; Pérez et al. 1999; Piñeiro and Giménez-Hurtado 2001). This dynamic results in east-west seasonal movements of many species; these are processes that have been documented by several authors (i.e., Arreguín-Sánchez 1992; Arreguín-Sánchez et al. 1995; Arreguín-Sánchez and Pitcher 1999; Pérez et al. 1999; Piñeiro and Giménez-Hurtado 2001).

The above processes explain ecosystem and population responses to climate change. In general, the warming period starting in the 1980s has caused a diminishing trend in primary production (Fig. 8.3) manifested as a general drop in the ecosystem carrying capacity (Fig. 8.1). This process has marked the evolution of the ecosystem over the last six decades and, in general, has led to a decreasing trend in global production.

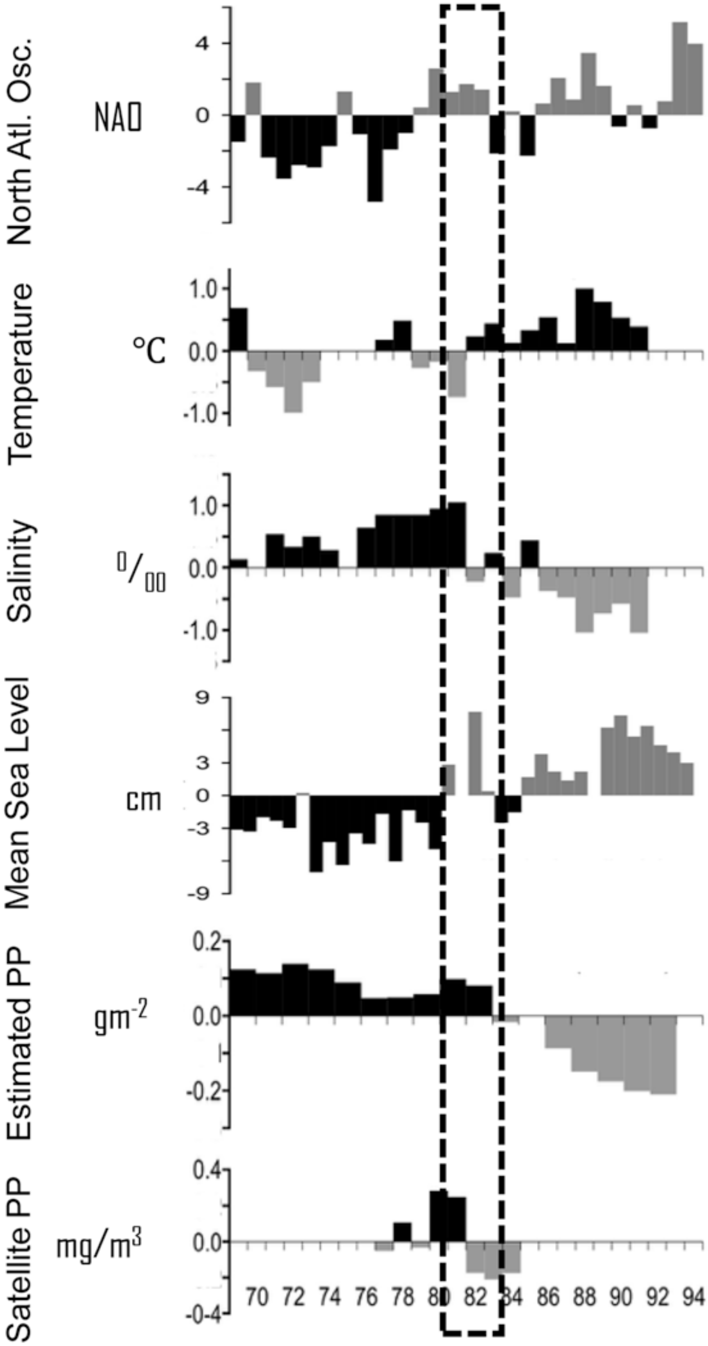

Fig. 8.3 Anomalies of several environmental variables affecting the Campeche Bank, where the change of phase indicates the regime shift moment

8.3 About the Management Tools

On the other hand, the management policies and tools are, conventionally, fixed, not dynamic. This is because fishery science has been conventionally based on the assumption of a stable carrying capacity and ecosystems. This assumption was acceptable for about six decades before the 1980s (Arreguín-Sánchez 2012), though it still persists in many cases, despite the evidence of the effect of climate change. The reason seems clear; the acceptance of climate change effects implies the commitment of governments to explicitly adopt management policies that incorporate dynamic management or an adaptable policy, which is a very complex process because it implies changes in the governance schemes that have been in place for many years. Additionally, the implementation of such a policy also depends on governments' scientific capacities to advise new forms of management. These tasks constitute a very strong challenge that must be faced. A recent approach to ecosystem-based management could help with this new form of management; such scientific developments suggest combining three interesting concepts: the harvest rate as a proportion of the stock that is retained by fishing; the noxicline, which defines the harvest rate limit before fishing affects ecosystem function; and the harvest rate that corresponds to the maximum production capacity of the resource (Arreguín-Sánchez et al. 2017a, b). In this sense, a constant harvest rate could be functional since it represents a proportion of the stock retained by fishing, that is, when the stock is large, a fishery can retain a certain proportion of that high biomass, and if the stock size is low, fishing will retain the same proportion of biomass.

In the following sections, three examples of the challenges imposed by climate change in this transition in the management approach are shown, using as an example some fisheries in the Campeche Bank.

8.4 The Pink Shrimp Fishery (*Farfantepenaeus duorarum*)

The current state of the pink shrimp fishery of the Campeche Bank is that it is collapsed and highly deteriorated (DOF 2012). Annual yields in the 1950s to the early 1970s averaged 18,000 t, while at present, they are lower than 2000 t. In 1995, when the state of the fishery was officially diagnosed as collapsed, the main hypotheses were overfishing and the disturbance of nursery and breeding habitats, among others. However, it has been shown that the decrease in the pink shrimp stock was strongly linked to climate change (Ramírez-Rodríguez et al. 2003, 2006; Arreguín-Sánchez et al. 2015).

Present knowledge indicates that the recruitment rate had been decreasing since the mid-1970s, following the same decreasing trend in primary production in the Campeche Bank, which was inversely related to the increasing trend in temperature (Arreguín-Sánchez 2012). Since fishing effort was not adjusted to the state that the shrimp stock acquired over time, the stock decreased, and the assumption was that

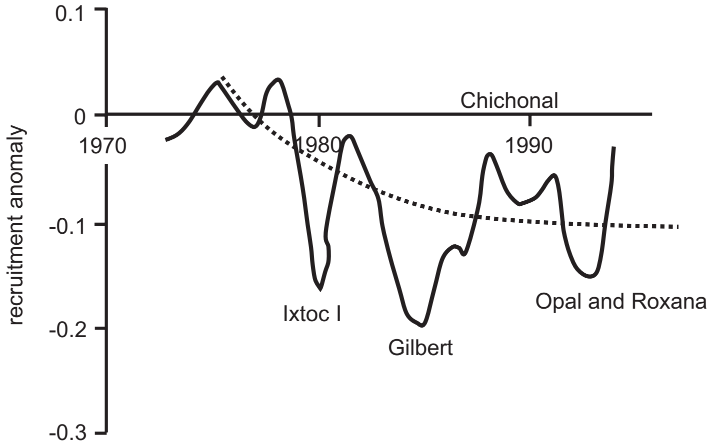

Fig. 8.4 Decreasing trend of the anomaly of the pink shrimp recruitment rate, over time, from the mid-1970s. Several falls in recruitment are shown, caused by hazardous phenomena: Ixtoc I was an oil spill; Gilbert, Opal, and Roxana were hurricanes; and Chichonal was an ash eruption. Recovery after each impact denotes the stock resilience. (Arreguín-Sánchez et al. 2008)

the decrease was the result of overfishing; however, the industry was not aware of this. This happened because, since January 1, 1980, Cuban and US shrimp trawlers ended their operations in Mexican waters, and after that, between 1982 and 1984, the Mexican fleet reduced its fishing efforts during the process of transferring fleet ownership from the private sector to cooperative societies. The net effect was a reduction in fishing mortality by approximately 50% by the mid-1970s; and the observed decreasing yields during the 1980s were attributed to these events. However, by the early 1990s, the fleet normalized its operations, and the low yields continued until 1995 when fishery collapse was recognized. Following the long-term trend in the recruitment rate, it can be observed that the decline started by the mid-1970s; during the 1980s, such decline in the recruitment rate was lower because of the reduction in fishing mortality, which returned to the long-term (higher) declining rate once the fleet operations were normalized (Fig. 8.4).

The management strategy implemented since the late 1990s was to avoid growth and recruitment overfishing; recovery was the main goal for the shrimp stock, which would be the first step toward returning the stock to the level of abundance that existed in the 1990s and, eventually, to the previous stock size that existed in the mid-1970s (DOF 2012). These measures have persisted from the mid-1990s to the present day, with no change in the stock abundance. In this context, the shrimp sector generated expectations of recovery. Of course, the measures were correct for maintaining the spawning stock in the best condition possible to maximize recruitment; however, since the shrimp stock has not been recovered after 20 years, it has generated distrust, which severely affects governance.

Currently, in terms of an ecosystem approach, an intensity of fishing equivalent to a harvest rate (the proportion of the available biomass taken by fishing) of

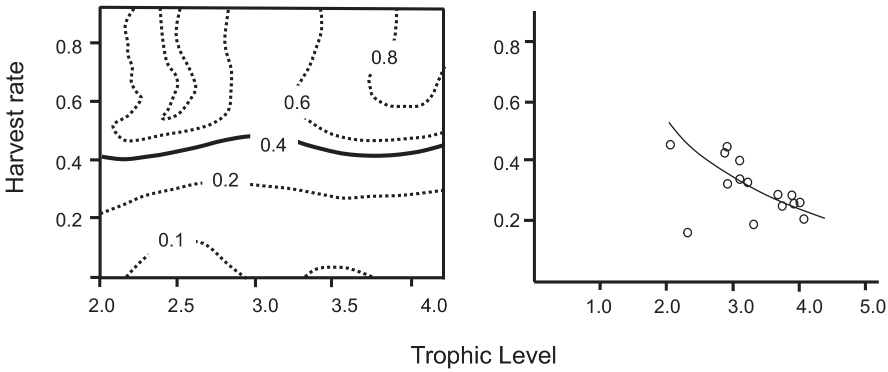

Fig. 8.5 Left, the bold isoline represents the noxicline, the limit reference level of fishing to affect ecosystem function given by the gain ecosystem entropy when biomass is extracted. The limit reference level can be defined by the harvest rate applied to each species (represented by their trophic level). Right, the isoline represents the balanced catch for the species within the ecosystem and the correspondent harvest rate. Both pictures represent the north continental shelf of the Yucatan

HR = 40% can be applied to the existing biomass, which meets both criteria: to use the maximum production capacity of the resource and to keep fishing mortality below the limit so as not to affect ecosystem function (Fig. 8.5).

In this case, there are three aspects to the management challenge: (i) generate the necessary knowledge about the contribution of climate change to the stock abundance trend and differentiate it, explicitly, from that induced by fishing; (ii) incorporate this information into fishery models to identify the harvest rate scenarios necessary to maintain the existing shrimp stock at its maximum production capacity, giving the stock the possibility of increasing when the environmental conditions are favorable; and (iii) communicate and involve the fishermen in this knowledge and in the management strategies to generate confidence and move, from the point of view of governance, toward a socially accepted condition.

8.5 The Red Grouper (*Epinephelus morio*) from the Campeche Bank

The grouper of the northern continental shelf of the Yucatan is one of the most important fisheries in the Gulf of Mexico, and it is currently diagnosed as deteriorated (DOF 2017). Three fleets to which a catch quota is assigned participate in the fishery: an artisanal fleet and a medium-sized fleet from Mexico and a Cuban fleet with greater autonomy. Toward the end of the 1970s, yields averaged approximately 18,000 t per year, while presently, they are approximately 8000 t. Red grouper is a species that presents reproductive concentrations in the winter in the eastern region of the continental shelf of the Yucatan with a hard bottom (Albañez-Lucero and

Arreguín-Sánchez 2009). The fleets took advantage of this behavior, which is when the resource is more vulnerable to fishing (Arreguín-Sánchez and Pitcher 1999), but the situation changed after the implementation of a closure aimed at protecting the reproductive process (DOF 2017).

There is an inherent risk for populations when reproductive concentrations are exploited (Sadovy 1999; Sadovy and Domeier 2005). For the red grouper, a closure to prevent recruitment overfishing was implemented by the mid-1990s; at that time, the stock did not yet display signals of overfishing, even though yields were lower than those in the previous decade. By the early 1990s, there were signals of a fully exploited stock, exhibiting the first evidence of interference from the fleets due to the catch-per-unit of effort trends. Despite the closure and the control of fishing effort, the stock continued decreasing. It has been documented that red grouper needs relatively low temperatures for a successfully reproductive period (Zupanovic and González 1975; Giménez-Hurtado et al. 2003), which has not the case because the influence of the warming period that began in early 1980s. The highest frequency of mature females occurred at of 22 ± 1 °C, while temperatures above 24.5 °C tend to inhibit gonadal maturation, which when accumulated over time, as during a warming period, will promote a decreasing trend in stock abundance.

On the other hand, catchability patterns indicate that vulnerability to fishing increases with size/age. In addition, before the late 1980s, these patterns could clearly be interpreted through the biological behavior of the species, evidencing bottom-up control (Arreguín-Sánchez and Pitcher 1999). Such patterns changed years later (Gimenez-Hurtado 2005), reflecting fleet behavior, changing to a top-down control (Fig. 8.6), which has been interpreted as a response to a diminished stock abundance, which was initially assumed to be a consequence of fishing but is now recognized as a combined effect of climate change (the warming period) and fishing.

Currently, management measures include a minimum legal size, a catch quota for the Cuban fleet, a limited number of fish permits, and a closure for all fleets; the

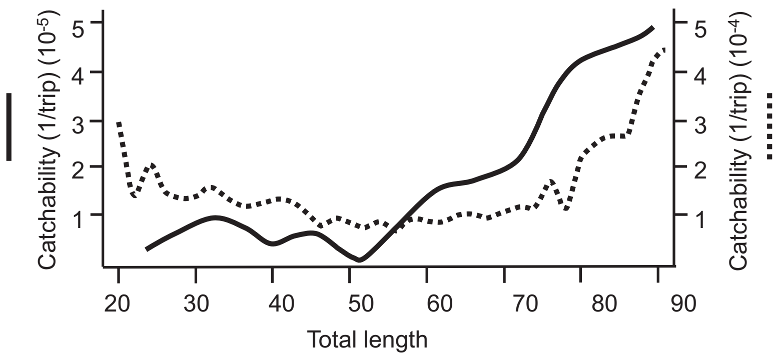

Fig. 8.6 Catchability patterns before and after the early 1990s, showing a shift from bottom-up to top-down control expressed by the interactions between the stock and the fleet. Such a change is associated with the change in the stock condition, which, in turn, is associated with the regime shift

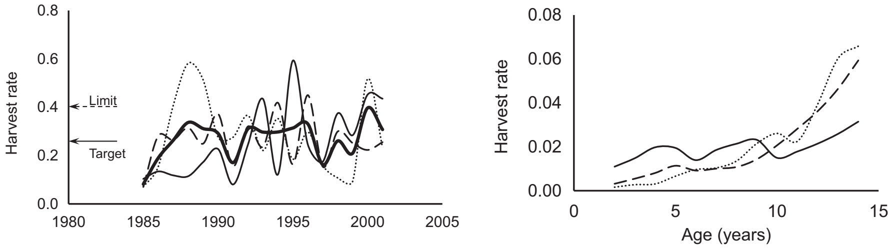

Fig. 8.7 Harvest rates for the red grouper fishery per fleet (thin black line for artisanal fleet, dashed line for mid-sized fleet, dotted line for Cuban fleet, and bold line for all fleets). Left historical trend; note that the historical pattern has been relatively stable; the thin arrow on the left indicates the target (recommended) harvest rate HR = 25%; the dashed arrow indicates the harvest rate corresponding to the limit reference point (see text for explanation). The right figure shows the average harvest rate per age, showing an increase for adult and older fishes

last measure is aimed at protecting the reproductive event. However, these measures are part of a static management scheme, in contrast with a population that is affected by climate change interfering, negatively, in the reproductive process. In this sense, the management challenge is to turn it into a dynamic management scheme that considers, in addition to the protection of the reproductive stock, a harvest rate that will be reviewed year to year and is coordinated with stock availability. In this sense, according to Arreguín-Sánchez et al. (2017a), a harvest rate of HR = 25% (meaning captures can be 25% of the existing biomass) that maximizes the productivity of the resource is suggested (Fig. 8.7), with a limit reference point represented by a HR = 40%, after which exploitation can affect ecosystem function. The values between both harvest rates imply a lower stock productivity level than the maximum that is possible.

8.6 The Red Octopus (*Octopus maya*) Fishery

The octopus fish resource in the Campeche Bank is currently composed of two species: the red octopus (*O. maya*), which is an endemic species (Voss and Solís-Ramírez 1966), and *O. vulgaris*, which began to be registered in the catches in 1998. The red octopus is captured by the artisanal fleet using sticks with strings at the end of which a crab is placed as bait. When the octopus accesses the bait, it is lifted on board. These operations do not require any technology, and many vessels operate without an outboard engine in shallow waters. The yields of the fishery in the 1980s were stable at approximately 8000 t per year; then, there was a gradual increase over time to approximately 20,000 t in the last two decades (Fig. 8.8).

It is known that the red octopus population is concentrated near the coast just after the rainy season (early August) where it searches for food, mainly crustaceans that migrate from inner waters to the sea. The change in feeding favors gonadal maturation and reproduction that occurs some few months later. According to

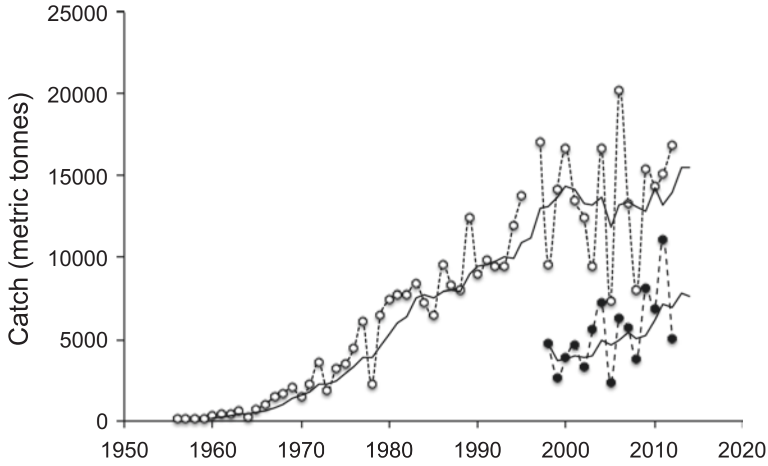

Fig. 8.8 Historical catch records of the octopus fishery in the Campeche Bank. White dots for *Octopus maya* and black dots for *O. vulgaris*

Arreguín-Sánchez (1992) and Solís-Ramírez et al. (1997), a similar event appears to occur toward the middle of the spring and is synchronized with the seasonal upwelling on the eastern edge of the continental shelf of the Yucatan (Merino 1996; Pérez et al. 1999; Piñeiro and Giménez-Hurtado 2001); the number of organisms that will aggregate in coastal waters the next year is based on the success of the reproduction of the spring cohort. According to laboratory experiments, increases in temperature and radiation favor the growth and robustness of *O. maya* (Van Heukelem 1976). In addition, a significant relationship has been found between these variables and fishing yields, which explains the continuous increase in stock abundance and the large increase in annual catches in the last three to four decades. This relationship is associated with the climate change trend documented for the Campeche Bank (Arreguín-Sánchez 2012; Arreguín-Sánchez et al. 2015). Another indirect effect is presumably the reduction of predation on *O. maya* by *E. morio* whose stock abundance has also declined as a result of climate change. Such a predation effect was demonstrated by Solís-Ramírez and Arreguín-Sánchez (1984) who indicate that predation can impact octopus yields up to 3000 t over the octopus' maximum sustainable yield.

According to Arreguín-Sánchez et al. (2017a), and using an ecosystem approach, a harvest rate of HR = 35%, which maximizes the stock production, is suggested with a limit reference represented by a HR = 40%, after which ecosystem function could be affected.

In terms of management, the access to the fishery is through fishing permits, which are limited in number based on the stock biomass. In this case, contrary to what happened in the previous examples, the red octopus population was favorably impacted by climate change; this consequence is reflected in the high yields obtained year after year. This condition caused a high demand for fishing permits, which, when granted in a limited manner, caused some governance problems in some fishing seasons since fishermen felt they could get better benefits.

The current state of management is rather precautionary, applying a minimum legal size, a closure from January to July, and fishing permits; it is estimated that the resource is being exploited to its maximum production capacity. The precautionary approach is applied because it is well known that the *O. maya* stock is highly sensitive to environmental changes and because it is highly important from the social point of view. The management challenge in this fishery is in maintaining a sustainable use of the stock given the uncertainty imposed by climate change. In such a case, a dynamic scheme with fishing mortality adapted, year to year, to the available biomass could be a good option.

8.7 About Management Challenges

Changes in the three fisheries mentioned above are linked to the effects of climate change. In the cases of pink shrimp and red grouper, the productivity of the resources has declined, while the productivity of red octopus has increased. The first two cases are critical because the effects of climate change were not identified until a couple of decades ago, though the effects are the result of a warming period that began in the early 1980s. Since both fisheries were fully exploited at that time, a certain and unknown degree of overfishing was caused because fishing mortality was not adjusted to the new stock sizes; this overfishing was not recognized at that time. Pink shrimp is a nice example of the necessity for clear management policy when facing climate change. When fishing mortality decreased approximately 50% for several years, the stock responded immediately, as expected of an "r-strategy" species; however, the long-term decreasing recruitment rate continued, but with a lower velocity. This suggests that the harvest rate should be continuously adapted to the new stock sizes year after year.

For the red grouper stock, changes in the interaction between the stock and fishing effort appear to be relevant since the stock tends to be highly vulnerable during warming periods since this condition reduces the efficiency of the reproductive success. The management's suggestion to maintain a harvest rate of 25% could improve the fish stock. With this in mind, a simulation based on such a constant harvest rate suggests that the stock size could have been approximately 20% higher than the present size.

In the case of octopus, the management strategy, even when it is not explicitly defined, corresponds approximately, in a reserved manner, to maintaining a constant harvest rate, which was easily implemented through an increase in the number of fishing permits since the stock abundance was increasing. However, in recent years, annual yields have stabilized, showing a relatively high interannual variability. Under such conditions, it is highly relevant to formalize a management strategy, especially because fishermen must be prepared to reduce fishing mortality or to reduce access to the fishery when the stock size decreases.

Before the effects of climate change were recognized, the management strategy based on annual harvest rates seemed to be adequate. With such a definition of harvest rates, it will be possible to contend with climate change effects from the biological point of view. However, governance must be strengthened because, when stock abundance is clearly lower than that in other years, the access rules must change, the access rules must be clearly defined, the access must be provided equitably, and the strategy must be accepted by fishermen. All of this must be developed with enough time in order to permit the planning of alternatives. This is an unusual scheme at the moment, but it is of fundamental importance in order to avoid overfishing.

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Chapter 9
Emerging Aquatic Alien Invasive Species: Trends and Challenges for Mexican Fisheries in the Extended Gulf of Mexico Basin

César Meiners-Mandujano, Roberto González-Gómez, Lourdes Jiménez-Badillo, Gabriela Galindo-Cortes, and Piedad S. Morillo-Velarde

9.1 Introduction

The introduction of alien species and its posterior spread as wild populations constitutes the second strongest threat related to biodiversity loss and ecosystem degradation at a global scale (Vitousek et al. 1996; Leung et al. 2002; Millennium Ecosystem Assessment 2005). Generally, the introduction of aquatic invasive species, may it be on purpose or incidentally, is formally registered years after the initial colonization (Geller et al. 1997; Lohrer 2001), and by the time they are detected (through direct interactions with productive activities like fishing or scuba diving), they have usually developed big populations, making their total extirpation almost impossible (Bax et al. 2001).

The Gulf of Mexico (GoM) and adjacent areas shared by Mexico, Cuba, and the United States cannot escape from the biological and ecosystemic transformation

C. Meiners-Mandujano (✉) · L. Jiménez-Badillo · G. Galindo-Cortes
Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico
e-mail: cmeiners@uv.mx

R. González-Gómez
Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

Posgrado en Ecología y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

P. S. Morillo-Velarde
Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Boca del Río, Veracruz, Mexico

CONACyT – Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Benito Juárez, Mexico City, Mexico

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processes derived from the simultaneous proliferation of alien species, may them be mainly marine or from inland hydrological systems, that drain into the marine ecosystem. In order to properly assess the invasive processes and their potential impacts, it is important to point that the Mexican portion of the GoM and its associated hydrological basins cover an extensive area of nearly 1,444,550 km^2. Approximately 53% (~762,653 km^2) of this area corresponds to the Mexican exclusive economic zone (EEZ), while the other 47% (681,897 km^2) includes the hydrological basins that drain into the Mexican western coastal plain and flow into the GoM (CONAGUA 2016), from Rio Bravo in the border with the United States to the northwestern wetlands of the Yucatan Peninsula (Fig. 9.1). This is comparable to the total extension of the Great Marine Ecosystem of the Gulf of Mexico.

From the total area of the Mexican EEZ in the GoM, nearly 30% corresponds to an extensive environmentally heterogeneous continental shelf, with a gradient from terrigenous substrates in the northwest to carbonated ones in the southwest (Antoine et al. 1974). The shelf is also characterized by a staggered presence of coral formations (Tunnell 1988; Jordán-Dahlgren 2002) and a strong deltaic influence of mangrove forests (Lot and Novelo 1990). Several directed and multispecific fisheries are exercised on it, accounting for an approximate volume of 217,000 t per year (Jiménez-Badillo et al. 2017). On the other hand, the main hydrological basins that flow into the GoM in this region are the Grijalva-Usumacinta, the Papaloapan,

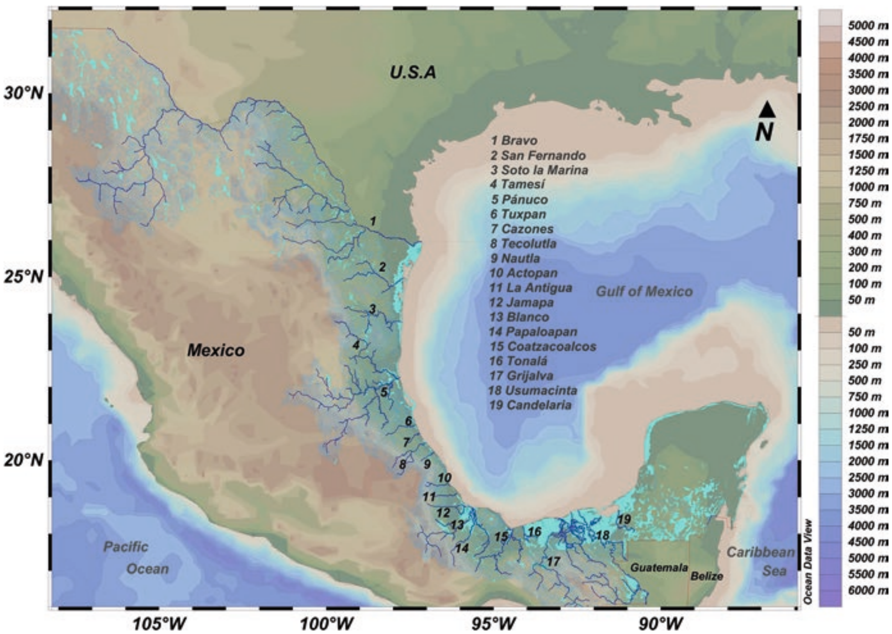

Fig. 9.1 Study area. Mexican basin of the GoM showing main characters of associated hydrological basins. Orography and bathymetry in color scale, main rivers (dark blue), secondary runoff (light blue), and wetlands (turquoise blue). Dotted line indicates the Mexican exclusive economic zone (EEZ)

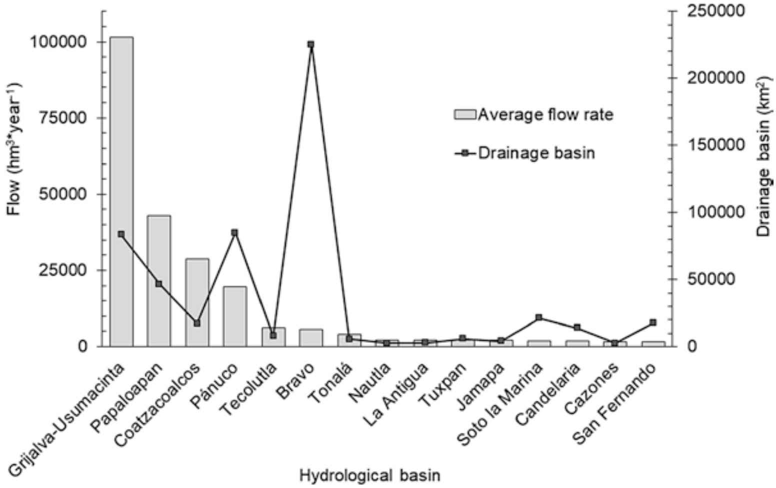

Fig. 9.2 Average annual flux (hm^3*year^{-1}) and area (km^2) of the main hydrological basins draining into the waters of the GoM. Order of basins corresponds to their contribution to the total flux

the Coatzacoalcos, and the Pánuco (CONAGUA 2016) (Fig. 9.2). Together, these basins are responsible for 86% of the annual runoff to the GoM from Mexican territory, and despite only representing 42% of the extension of the hydrological basins in this area, they are subject of an intensive artisanal multispecific fishing activity based mainly on fish and decapod crustaceans (Espinoza and Mendoza 2015; Espinoza et al. 2015).

During the last two decades, a rapid colonization and proliferation of two fish species complexes and two decapod alien species has been documented in this area. Because of their rapid expansion and potential direct interaction with the fishing sector and ecosystem structure, they must be analyzed as a single unit and from a big basin integrated perspective. The main invasive alien species recorded in these hydrological basins include the species complex of armored catfishes of the genus *Pterygoplichthys* (Siluriformes: Loricariidae), including *Pterygoplichthys pardalis* (Castelnau 1855), *Pterygoplichthys disjunctivus* (Weber 1991), and *Pterygoplichthys multiradiatus* (Hancock 1828) and the Australian red-claw crayfish *Cherax quadricarinatus* (von Martens 1868) (Decapoda, Parastacidae). In regard to coastal and marine environments, they are represented by the lionfish complex *Pterois volitans* (Linnaeus 1758) and *P. miles* (Bennett 1828) and the giant tiger shrimp *Penaeus monodon* (Fabricius 1798; Fig. 9.3). The occurrence dynamics and geographic dispersion of these species have been reported mainly through new records on scientific publications; however, the interactions, geographic expansion, and impacts on native populations and the ecosystem have been addressed mainly in gray literature, with a more restricted circulation and a narrower scope.

One of the main concerns for the Mexican public administration, both for the segment in charge of conservation policies for habitats, ecosystems and biodiversity, and for the one in charge of fisheries and aquaculture production, is the

Fig. 9.3 Emerging aquatic alien invasive species of hydrological basins draining into Mexican waters of the Gulf of Mexico. *Pterygoplichthys* complex (upper-left panel) composed by *P. pardalis* (lower left), *P. disjuntctivus* (lower middle-left), and *P. multiradiatus* (lower left) and Australian red-claw crayfish *Cherax quadricarinatus* (right panel)

quantification and forecast of the effects derived from the population expansion of these invasive alien species. Under this perspective, this chapter presents an explicitly spatial-detailed integration of the four emergent species/complexes that have invaded the Mexican portion of the extended GoM basin, as well as the temporal evolution of the process. The immediate and medium-term implications for the structure of the fishing systems of the region and the stability of the natural systems on which these are developed are also discussed.

9.2 Data Source and Analysis

To achieve this goal, data was gathered from several complementary sources. First, occurrence records of the four emergent invasive species/complexes were obtained from the public access databases *United States Geological Survey* (USGS), *Nonindigenous Aquatic Species database* (USGS 2018), and *Naturalista* (CONABIO 2018). Second, these records were verified and complemented with an exhaustive search of indexed scientific publications in SCOPUS® leading to studies on these species for this particular region, and, lastly, detailed information found on other regional research products was also incorporated. These included reports from research projects, conference papers, book chapters of national publishers, and bachelor and master theses from superior education institutions and research centers of the region. Regardless of the source, all data considered were spatially and temporally explicit, with at least, annual resolution. Regarding records from the *Naturalista* database, only the ones associated to the "research" degree were considered and, in the case of complementary literature reports, photographs of reported specimens were available in all cases.

The compiled records of the four emergent invasive species/complexes were segregated to the lowest possible taxonomic level and used to generate distribution maps. These included layers of the main distinct elements of the hydrological basins and the bathymetry of the area. At the same time, the temporal progression of dispersion and settlement of the invasive taxa were evaluated by monitoring the annual and accumulated frequency of occurrence of the records.

9.3 Invasive Threats for the Mexican Hydrological Basins Draining into the Gulf of Mexico

The main invasive process affecting the hydrological basins draining into Mexican waters of the GoM is related to the species complex of armored catfish of the genus *Pterygoplichthys* and, to a lesser extent, at the moment, to the Australian red-claw crayfish *C. quadricarinatus* (Fig. 9.3).

Species of the genus *Pterygoplichthys* belong to the family Loricariidae, which encompasses almost 80 genera and over 700 species. They are native to the Amazonas and Orinoco basins in South America (Weber 1992) and, to a lesser extent, to basins in Panama and Costa Rica in Central America (Armbruster and Page 2006). They inhabit freshwater streams from the coastal plain up to 3000 m (Nelson 1994). Their quick adaptability to captivity conditions and popularity among aquarists for more than two decades have led to their introduction and dispersion in non-native distant ecosystems (Wakida-Kusunoki et al. 2007). They are very efficient invaders with a large geographic distribution, currently known to inhabit North and Central America, some islands of the western Caribbean (Guzmán and Barragán 1997; Nico and Fuller 1999; Hoover et al. 2004; Chávez et al. 2006; Hubilla et al. 2007; Wakida-Kusunoki et al. 2007; Hossain et al. 2008; Levin et al. 2008; Krishnakumar et al. 2009; Mendoza et al. 2009; Nico et al. 2009a; Trujillo-Jiménez et al. 2010; Wathsala and Upali 2013), Southeast Asia (Bunkley-Williams et al. 1994; Nico and Martin 2001; Tan and Tan 2003; López-Fernández and Winemiller 2005; Chávez et al. 2006; Page and Robins 2006; Gibbs et al. 2008; Hubbs et al. 2008; Neal et al. 2009; Nico et al. 2009b), and eastern Europe and Near East (Ozdilek 2007; Keszka et al. 2008; Simonović et al. 2010; Emiroğlu et al. 2016).

Mexico has not escaped the invasive process of *Pterygoplichthys*. It was recorded for the first time in 1995 in the Balsas River's basin (Guzmán and Barragán 1997) which drains into the Pacific Ocean and again in 1998 in the Infiernillo Dam (Arroyo-Damián 2008). Later on it has been also recorded in the Amacuzac River in the Mexican Plateau (Trujillo-Jiménez 2003) and, for the first time, in systems draining into the GoM in the basin of the Grijalva-Usumacinta in the Catazajá and Medellín lagoons (Ramírez-Soberón et al. 2004), Tecpatán (Mendoza-Alfaro et al. 2009) and in the lower part of the basin in the locality of Frontera (Wakida-Kusunoki et al. 2007), and in the Palizada River (Wakida-Kusunoki and Amador del Ángel 2008).

Although not all records of *Pterygoplichthys* are segregated to the species level, as shown in Fig. 9.4, it is clear that *P. pardalis* is the most abundant and geographically extended taxon, having invaded two main basins of the GoM, Grijalva-Usumacinta and Coatzacoalcos, and a minor one, Jamapa-Cotaxtla, all of them located in the southern part of the study area. Moreover, *P. disjunctivus* secondarily contributes to the invasive process in the same hydrological basins and in part of the Tamesí River, within the Pánuco Basin, in the northern part of the study area. Finally, there is a minor contribution of *P. multiradiatus* records, mainly from the system of interdunary lagoons of the City of Veracruz, in the Jamapa-Cotaxla Basin (Cruz-León 2016) and a single record form the Grijalva-Usumacinta (Ramírez-Soberón et al. 2004).

Since the first occurrence records in the region in the 2000s, the occurrence dynamics of *Pterygoplichthys* was characterized by a rapid increment in the number

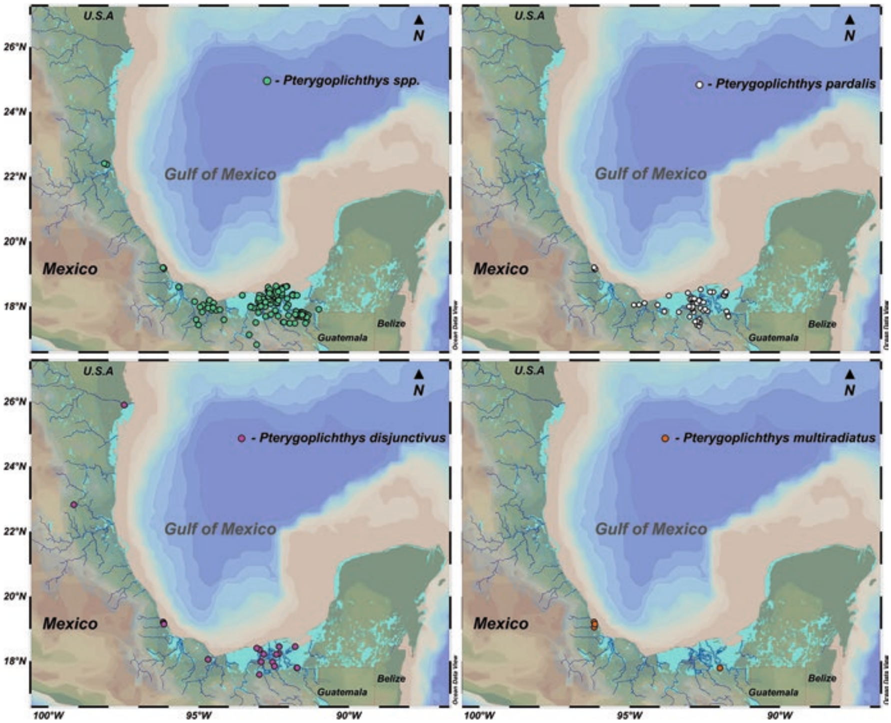

Fig. 9.4 Spatial distribution of records of the armored catfish invasive complex *Pterygoplichthys* in the Mexican hydrological basins draining into the GoM

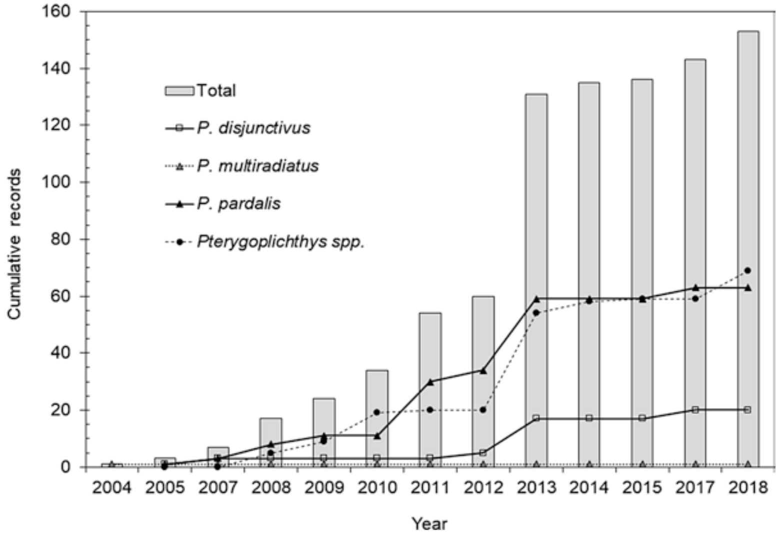

Fig. 9.5 Annual cumulative frequency of records of the armored catfish invasive complex *Pterygoplichthys* in the Mexican hydrological basins draining into the GoM

of records during 2009–2015, stabilizing around 160 different occurrence records from then. The main relative contribution to the occurrence dynamics is dominated by *Pterygoplichthys* spp. (45%) and *P. pardalis* (41%), secondarily by *P. disjunctivus* (13%) and marginally by *P. multiradiatus* (<1%; Fig. 9.5).

The *Pterygoplichthys* complex has colonized and successfully developed in the hydrological basins Grijalva-Usumacinta, Papaloapan, Coatzacoalcos, Bravo, and Jamapa-Cotaxtla, which carry up to 81% of the freshwater runoff into the GoM. In contrast, the occurrence records and settlement of the Australian red-claw crayfish *C. quadricarinatus* are focalized, to date, in the Pánuco and Soto la Marina basins, both located in the northern portion of the region (Fig. 9.6).

The Australian red-claw crayfish is a decapod crustacean from the family Parastacidae. It is an omnivorous physically robust species, characterized by a gregarious behavior, fast growth, moderated high-frequency fecundity, direct development, and a wide tolerance to variable environmental conditions (Karplus et al. 1998; Lin et al. 1999; Jones et al. 2000). It is native to northern Australia and southern Papua New Guinea (Holthuis 1986; Jones 1995; Sagi et al. 1997; Edgerton and Owens 1997; Munasinghe et al. 2004; Bláha et al. 2016). However, given its high culture potential (Jones 1990), the species has been successfully introduced for aquaculture purposes elsewhere, posteriorly colonizing several tropical and subtropical regions of the world, mainly in the Caribbean (Todd 2005; Williams Jr et al. 2001; Azofeifa-Solano et al. 2017), Southeast Asia (Ahyong and Yeo 2007; Belle and Yeo 2010; Patoka et al. 2016), and South Africa (De Moor 2002; Nunes et al. 2017).

The Australian red-claw crayfish was originally introduced in Mexico for experimental culture in research facilities in the mid-1990s (Arredondo 2004), but some

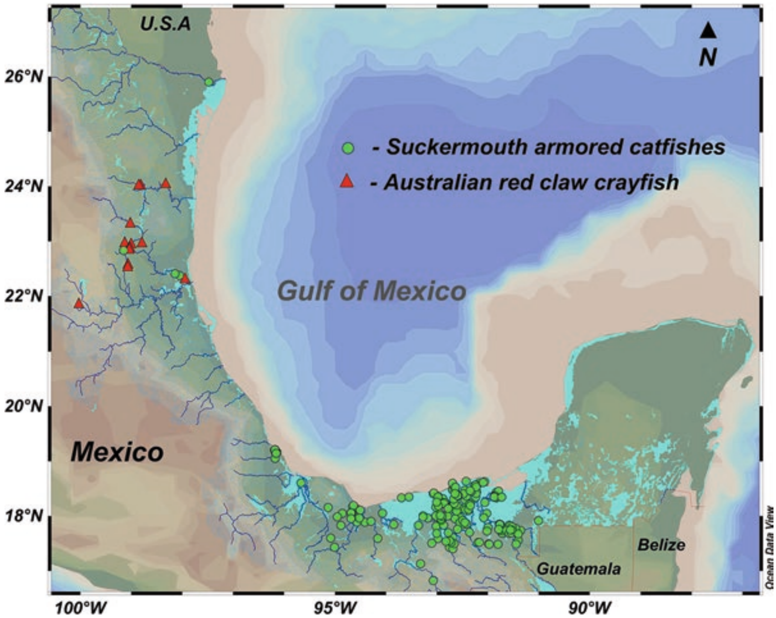

Fig. 9.6 Spatial distribution of the armored catfish invasive complex *Pterygoplichthys* and the Australian red-claw crayfish in the Mexican hydrological basins draining into the GoM

commercial experiences with moderate results were also developed afterward in localities of the plateau, northern and southern Mexico (Ponce-Palafox et al. 1999). From 2000, the culture of the red-claw crayfish has been diversified in several areas of the country, especially nearby Ciudad Mante and Ciudad Victoria, in the state of Tamaulipas (northwest) (Mendoza-Alfaro et al. 2011). This diversification of culture experiences at a commercial level coincided with the first records of occurrence and settlement for the species in the natural habitat, first in the state of Morelos (central Mexican plateau) in 2000 and 5 years later in southern Tamaulipas, in freshwater streams and agricultural irrigation channels adjacent to the culture facilities (Bortolini et al. 2007).

The annual trend of occurrence records for *C. quadricarinatus* in this region is irregular, but the positive slope of the cumulative curve suggests that the dispersion process is in an initial growing state (Fig. 9.7) and, currently, clearly geographically focalized (see Fig. 9.6).

Records of settlement and dispersive invasion in this region, both for the invasive *Pterygoplichthys* complex and the Australian red-claw crayfish, are coincident in time (around 2005); however, the *Pterygoplichthys*'s invasion is much more intense, successful, and geographically extended that the one of *C. quadricarinatus*. This contrast depends mainly on the different origins of the vectors responsible for the development of wild populations. It is highly probable that *Pterygoplichthys* may have had multiple original vectors in the wild coming from aquaculture escapes and

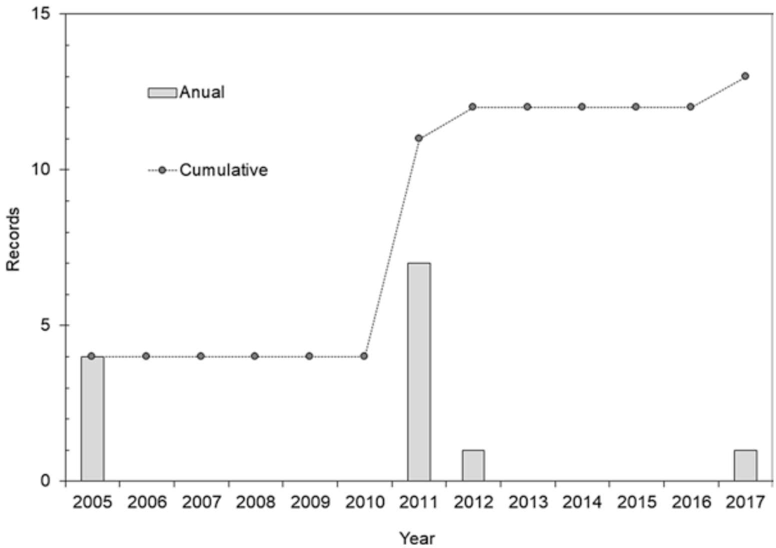

Fig. 9.7 Cumulative annual frequency of Australian red-claw crayfish records in the Mexican hydrological basins draining into the GoM

from the "Nemo effect" by punctual intentional liberations of organisms coming from home aquaria (Mendoza et al. 2007) of the main urban centers of the area, such as Villahermosa, Coatzacoalcos-Minatitlán, Veracruz-Boca del Río-Medellín de Bravo, and Tampico-Madero, which together, host a population of over 2.5 million people (INEGI 2015). In contrast, origin points for the vectors of *C. quadricarinatus* are determined by the proximity of commercial culture facilities, which limit the origin points.

9.4 Coastal-Marine Invasive Threats in the Mexican EEZ of the Gulf of Mexico

The main emergent invasive pressures in the coastal-marine environment of this region currently come from the settlement of wild populations of the lionfish complex of the genus *Pterois*, mainly *Pterois volitans*, and the giant tiger shrimp *P. monodon* (Fig. 9.8).

One of the most relevant examples of an efficient and extremely successful aquatic invader is the lionfish complex of the genus *Pterois*. These are tropical and subtropical fishes native to the Indo-Pacific (Schultz 1986) that were incidentally introduced to the east coast of North America in the early 1980s (Morris Jr and Whitfield 2009) and constitute the first invasive reef fish species to be established in the Caribbean and the western central Atlantic (Gómez-Lozano et al. 2013).

Fig. 9.8 Emerging aquatic alien invasive species into Mexican waters of the Gulf of Mexico. One of the members of lionfish complex, *Pterois volitans* caught in the Veracruz Reef System (upper panel) and giant tiger shrimp *Penaeus monodon* caught off Coatzacoalcos, Veracruz (lower panel)

Three decades later, the lionfish has already spread across the eastern American Coast, the Bahamas, the Great Caribbean, and, more recently, the GoM (Whitfield et al. 2007; Schofield 2009, 2010).

In the Mexican littoral of the GoM, the species was first detected in 2009 off the Yucatan Peninsula (Aguilar-Perera and Tuz-Sulub 2010), and 3 years later one specimen was also captured in the Veracruz Reef System (VRS) (Santander-Monsalvo et al. 2012) and in the Lobos-Tuxpan Reef System (LTRS) (González-Gándara et al. 2012). Since then, records of important aggregations of lionfish became widespread, covering almost every shallow-water reef of the Yucatan shelf (Aguilar-Perera et al. 2012), the VRS, the Campeche bank (Acevedo-Lezama 2015; USGS 2018; CONABIO 2018), and even some mesophotic reefs (>35 m depth) in the southeast of the GoM (Aguilar-Perera et al. 2016). Moreover, the potential bathymetric distribution range of the lionfish could be much broader, considering that several specimens were recently recorded on the outer edge of the shelf and upper slope (>200 depth) of Bermuda and Roatan in the western Atlantic (Gress et al. 2017).

Therefore, not only has the lionfish colonized the main reef systems of the Mexican Exclusive Economic Zone (EEZ) of the GoM but also diversified the invaded habitat toward nonreef coastal areas associated with artisanal fishing off Soto la Marina (Tamaulipas) (Arellano-Méndez et al. 2017) and with shrimp trawls (42–73 m depth) in muddy bottoms off Tecolutla, Laguna Verde, Coatzacoalcos, and Agua Dulce in Veracruz and Chiltepec in Tabasco (Oviedo et al. 2014) (Fig. 9.9). This means the lionfish has successfully colonized almost all the Mexican continental shelf of the GoM. This successful and geographically extended colonization is also shared by the giant tiger shrimp, *P. monodon*, although in this case it is more related to coastal areas and associated to the commercial fishery of shrimps that are native to the GoM (Fig. 9.9).

The giant tiger shrimp is a widespread penaeid shrimp species which, like the lionfish, is native to the Indo-Pacific, from the coasts of east Africa and the Arabian

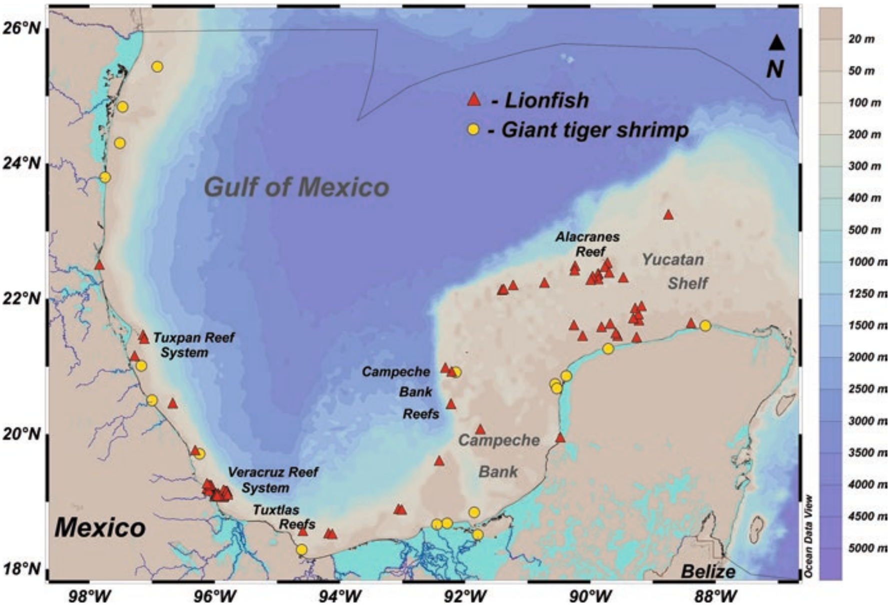

Fig. 9.9 Spatial distribution of the lionfish invasive complex and the giant tiger shrimp in the Mexican exclusive economic zone (EEZ) of the Gulf of Mexico

Peninsula to Southeast Asia and northern Australia (Holthuis 1980). It is the largest commercially exploited shrimp species in the world, with females reaching up to 33 cm total length (TL) and typically being 25–30 cm TL and weighing 200–320 g (Holthuis 1980; FAO 2005).

The giant tiger shrimp has been extensively cultured in Southeast Asia since the early 1970s (Gillett 2008), rapidly extending toward distant regions from its original distribution range, such as the western African coasts, the east coast of North America, and the Caribbean (Fuller et al. 2014; Knott et al. 2018). Due to escapes from aquaculture facilities, the species is now established in many areas including the east coast of the United States from North Carolina to Florida, the northern GoM from Alabama to Texas (Fuller et al. 2014), western Africa from Senegal to northern Angola, some localities of the Caribbean (Knott et al. 2018; Giménez-Hurtado et al. 2013; Alfaro-Montoya et al. 2015), and South America from Colombia to Brazil (Fausto-Filho 1987; Coelho et al. 2001; Santos and Coelho 2002; Aguado and Sayegh 2007; Altuve et al. 2008; Gómez-Lemos and Hernando-Campos 2008; Cintra et al. 2011).

In Mexico, the species was first recorded in Pacific waters, in the Huizache-Caimanero lagunar system (Córdova-Murueta et al. 1994), but since 2012, some incidental captures have also been recorded in shrimp trawls in the southern GoM, off the coasts of Tamaulipas, Tabasco, and Campeche (Wakida-Kusunoki et al. 2013; Oviedo et al. 2014), along the coast of Veracruz (Morán-Silva et al. 2014; Oviedo et al. 2014) and off the coasts of the Yucatan Peninsula (Wakida-Kusunoki et al. 2016a, b).

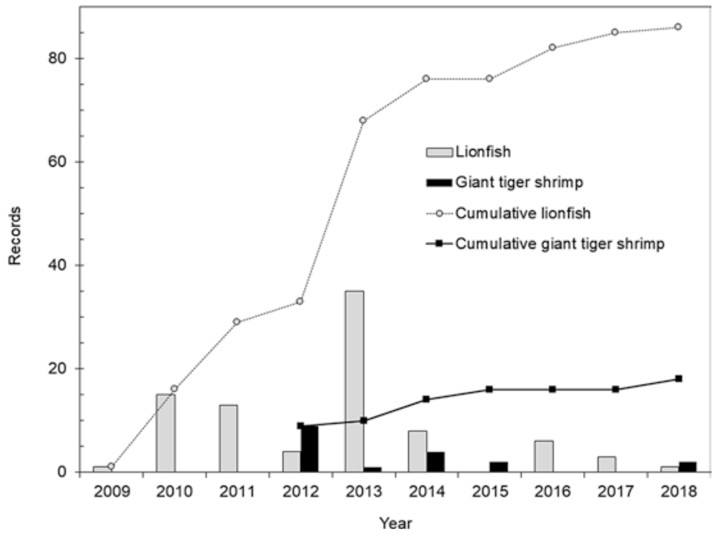

Fig. 9.10 Annual and cumulative frequency of records the lionfish invasive complex and the giant tiger shrimp in the Mexican exclusive economic zone (EEZ) of the Gulf of Mexico

Comparatively, the temporal window of lionfish and giant tiger shrimp occurrence is very similar, with the first records at the beginning of the decade of 2010 for both taxa; however, as in the case of the records for the emergent invaders in the hydrological basins of this zone, the *Pterois* ictic complex records (90) are almost one order of magnitude higher than those of the invasive crustacean *P. monodon* (18). Nearly 10 years after the detection of the settlement and dispersion of both invaders in this area, it seems evident that the trend of new records is still growing (Fig. 9.10), even though the geographic dispersion already covers the entire study area, as shown in Fig. 9.8.

The Mexican part of the GoM constitutes the last portion of the west central Atlantic be invaded by the lionfish and the giant tiger shrimp. This circumstance is not a coincidence because besides being the furthest portion from the initial invasive points reported by Schofield (2009) and Fuller et al. (2014), the basin has a semi-closed condition that restricts water and suspended material exchange with adjacent areas. These characteristics are determined by the Loop Current (LC), which dominates the GoM's circulation and is formed as the waters of the pre-Gulf Stream flow from the Caribbean Sea through the eastern portion of the GoM on its way to the Atlantic (Sturges 2005).

In line with this, Wakida-Kusunoki et al. (2016b) have proposed two plausible ways to explain the settlement of the giant tiger shrimp in the Mexican waters of the GoM, which may be extensible to the lionfish also; on one hand, the release of larvae transported in ballast water taken onboard from native or previously invaded areas, and on the other hand, through direct migration from areas where wild populations are already well-stablished. Under this second route, the most important migratory flow of *P. monodon* is more likely to come from the northern GoM (Alabama, Mississippi, Louisiana, and Texas), where most abundant sightings have been reported (USGS 2018). Regarding the lionfish, besides in northern GoM, its occurrence densities are also high from the Mexican Caribbean to the Yucatan shelf, on both sides (USGS 2018).

9.5 Challenges for Mexican Fisheries in the Extended Gulf of Mexico Basin

Ideally, comprehensive high-resolution databases must be available in order to conduct rapid assessments, test scientific hypothesis, and validate predictive models on invasive species' dispersion and their effects on natural and productive systems (Ricciardi et al. 2000). The advent of some public-access databases such as the USGS Nonindigenous Aquatic Species database (USGS 2018) and Naturalista (CONABIO 2018) helps toward the achievement of this goal, encouraging teamwork among specialists, public administration, and the general public. However, to date, several of these databases still lack enough record resolution for several regions, such as the southern GoM, which results in a biased perception about the heterogeneity of the real distribution of the invading taxa.

In the absence of an intensive, frequent, and geographically representative monitoring program of these emergent aquatic invaders, fishery data can be a robust data source. Not only can it offer occurrence records but also information related to relative abundance, biomass, population structure, seasonal and interannual variability, or even species interactions. Regarding the Mexican fisheries of the extended GoM's basin, they are mainly small-scale ones, with artisanal fleets using nonmechanical fishing gear and working normally on the continental shelf, often on lagunar and estuarine systems (Quiroga-Brahms et al. 2002; Salas et al. 2007). There are only three industrial coastal fleets in this area; the grouper fleet of the Yucatan shelf (Monroy et al. 2010; Monroy-García et al. 2014; Coronado and Salas 2011), the tuna surface-longline fleet operating in the EEZ beyond the continental shelf, and the shrimp trawl fleet (Wakida-Kusunoki et al. 2006, 2010; Jiménez-Badillo et al. 2017). Due to their fishing strategy, the first two do not interact with any of the invasive taxa mentioned before; in contrast, it is known that the shrimp trawl fleet, which operates with bottom trawls over extensive areas of the GoM's shelf, interacts both with the lionfish and the giant tiger shrimp, as it has been responsible for several occurrence records of both invasive species (Wakida-Kusunoki et al. 2013; Oviedo et al. 2014).

Mexican artisanal fleets are characterized by targeting multiple species in many different and sometimes faraway habitats (Caso et al. 2004; Aldana-Arana et al. 2013), from the middle sections of the hydrological basins, mainly the Grijalva-Usumacinta system (de Oliveira-Leis et al. 2019), to lagunar systems and the adjacent coastal zone (Quiroga-Brahms et al. 2002; Salas et al. 2007) and even some reef systems (Jiménez-Badillo 2008; Jiménez-Badillo et al. 2008). Therefore, artisanal fleets represent the mandatory way to assess the progression and immediate impact of the emergent invasive species over native species in this area. Moreover, they can gather information about those that were introduced several decades ago and incorporated into the local productive systems afterward, such as the African and Centroamerican cichlids of the Mexican southeastern hydrological basins (Ayala-Pérez et al. 2003; Amador-del Ángel et al. 2009, 2012; Amador-del Ángel and Wakida-Kusunoki 2014).

Most relevant impacts documented to date on local fisheries refer to the negative impact of the *Pterygoplichthys* complex on fishery production levels inside the hydrological basins, mainly in the Grijalva-Usumacinta (Mendoza et al. 2009) and surrounding areas (Amador-del Ángel et al. 2016). The relative abundance of *Pterygoplichthys* in relation to total captures oscillates between 25% and 75%, depending on the basin (Wakida-Kusunoki and Amador-del Ángel 2011; Castillo-Capitán et al. 2014; Cruz-León 2016). In order to mitigate the negative impact caused by this invasive complex, while diversifying the local economic activity at the same time, the public administration has begun to promote some emergent programs that seek the exploitation of this resource, such as the production of flour and silage for agricultural and livestock farming purposes (Mendoza et al. 2009). This process represents an inflection point in which the *Pterygoplichthys* complex needs to be considered, not as an enemy of the system or the fishing activity, but as an obligate resource instead, for which an adequate capture technology must be developed in order to maximize its containment and develop added value for the fishing sector.

Lionfish records come mainly from recreational self-contained underwater breathing apparatus (SCUBA) divers and free-diving fishermen in reef systems that normally have some protection status, may it be environmental like the Alacranes Reef (Aguilar-Perera and Tuz-Sulub 2010; López-Gómez et al. 2012; Aguilar-Perera et al. 2012; USGS 2018; CONABIO 2018) and the Veracruz Reef System (Santander-Monsalvo et al. 2012; Acevedo-Lezama 2015; Aguilar-Perera et al. 2016; USGS 2018; CONABIO 2018), or due to oil exclusion like the Campeche Bank Reef systems (USGS 2018; CONABIO 2018).

To date, the greatest concern regarding the lionfish focuses on the possible modification of the trophic chain's structure of Mexican reef systems, given that its main prey consist of small fishes (Morris and Akins 2009; Acevedo-Lezama 2015) which are, in turn, prey for bigger ones. Moreover, in a prey-reduction case scenario, the lionfish diet could include juveniles of commercially and ecologically important species such as groupers, grunts, and snappers (Albins and Hixon 2008, 2013; Morris and Akins 2009).

Several previous experiences in the Bahamas and the Caribbean to promote direct exploitation of the lionfish (Gómez-Lozano et al. 2013) have served as a model for the use of this resource in Mexico. In particular, with the support of the National Commission of Marine Protected Areas (CONAMP), some GoM localities encourage recreational divers and commercial fishermen to specifically target this invasive species with the aim of promoting its consumption as a measure of population control. This way an invasive species is promoted as a gourmet delicacy, becoming a highly demanded fish among tourists (Hernández-Matus and Caballero-Vázquez 2015; Carrillo-Flota and Aguilar-Perera 2017; Moreno-Munar and Sanchez-Aponte 2017). Therefore, unlike in *Pterygoplichthys*, the economic value of the lionfish is an incentive for coastal artisanal fishermen to invest their time and effort in this invasive species, thus making money, mitigating the impacts on the ecosystem, and avoiding negative effects over other important commercial species.

In the case of the two emergent crustacean invaders, *C. quadricarinatus* and *P. monodon*, both can be considered as well-established populations along the study area; however, they still represent a low impact risk, given the focalized distribution of *C. quadricarinatus* in a single hydrological basin (Pánuco) and the absence or low abundance of *P. monodon* juveniles associated to shrimp trawls and artisanal fishing in coastal lagunar systems (Wakida-Kusunoki et al. 2016a, b). Most immediate concerns about the settlement of these species include, on the one hand, direct competition with native species, predation, and habitat modification and, on the other hand, the transmission of pathogens to native populations (Durand et al. 2000; Chapman et al. 2004; Bortolini et al. 2007; Molnar et al. 2008; Wakida-Kusunoki et al. 2016a). In this sense, the dispersion of *Penaeus monodon* would have serious effects on the amount and quality of the GoM's shrimp catches, which represent the GoM's most important fishery (Wakida-Kusunoki et al. 2006, 2010), with an average annual income of 45 million dollars (Jiménez-Badillo et al. 2017) from both the industrial and artisanal fleet.

Finally, the main challenge that the Mexican fishery sector and associated decision-makers are currently facing in the extended GoM basin consists of their ability to become the main providers of real-time spatially explicit population information on the invasive taxa that interact with the fishing activity. Besides, the development of operative, technological, or even regulatory adaptations to develop primary and transformed products from the invasive taxa could open new possibilities for new market niches. By doing so, some benefits could be seen in the long term in the attempt to neutralize the effect of these aquatic emergent invasive alien species.

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Chapter 10
HABs (Harmful Algal Blooms) Analysis, Their Cost, and Ecological Consequences

Mónica Rodríguez-Palacio, Cruz Lozano-Ramírez, and Sergio H. Alvarez-Hernández

10.1 Introduction

Almost three fourths of the Earth is covered by water. In these huge bodies of water thrive countless tiny life forms—plankton. Some of these organisms are able to transform sunlight into chemical energy—phytoplankton. This process, called photosynthesis, is essential for the maintenance of life on Earth and is characterized by carbon fixation at the same time that oxygen is released (Janssen et al. 2014). Phytoplankton comprises the primary producers, the basis of the trophic web.

Some species of phytoplankton can produce toxins that affect the biota; this phenomenon is called harmful algal bloom (HAB). This event is produced through a combination of physical, chemical, and biological circumstances (Herrera-Sepúlveda et al. 2008). The term HAB was adopted by the Intergovernmental Oceanographic Commission (IOC), which is dependent on the United Nations Educational, Scientific, and Cultural Organization (UNESCO), and is currently accepted throughout the world to refer to any proliferation of microalgae that generates a negative impact.

In Mexico and other parts of the world, HABs are recurring events that have affected the ecosystems, fishing, aquaculture, and tourism, registering in some cases economic losses (Smayda 1997; Hernández-Becerril et al. 2007a, b; Anderson et al. 2009; Band-Schmidt et al. 2011).

HABs are multifactorial generated events; coastal eutrophication, the transfer of cysts of dinoflagellates in ballast water, global warming, among others, may propitiate the triggering of the rapid multiplication of microalgae. Investigations on this subject are now in progress (Hallegraeff 1993; Cortés-Altamirano 1998).

M. Rodríguez-Palacio (✉) · C. Lozano-Ramírez · S. H. Alvarez-Hernández
Laboratory of Applied Phycology, Departamento de Hidrobiología, Universidad Autónoma Metropolitana, Mexico City, Mexico
e-mail: mony@xanum.uam.mx

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According to Steidinger (1983), the triggering of HABs is generated in four stages:

1. The existence of a bed of cysts caused by marine currents and carried to the surface.
2. Growth and asexual reproduction supported by favorable ecological factors such as temperature, light, nutrients, and salinity.
3. Maintenance of high cell densities with the emergence of interspecific competence and release of chemical agents.
4. The last stage is the ending of HAB, where the grazing increases, the ecological conditions that originated the event disappear, and cysts are produced that eventually travel to the ocean floor.

HABs are generated by different hydrological events, among which we can mention upwellings, convection cells, internal waves, and front zones, among others. HABs can be transported by these circumstances away from their point of origin.

Upwellings are generated by surface winds that produce deep currents; these are generally formed by cold, nutrient-rich waters that come to the surface near the coasts. Convection cells are circulation systems formed between two masses of water with different densities, temperatures, and salinities. Under the influence of the internal waves, many organisms migrate and concentrate just where the ecological conditions are favorable (Estrada 1986; Cortés-Altamirano 1998).

10.2 First Records of Harmful Algal Blooms in Mexico and the World

Of the 4000 species described, only 200 species of phytoplankton are considered toxic (Zingone and Enevoldsen 2000); of the harmful species, most of them are dinoflagellates and to a lesser extent raphidophytes, prymnesiophyta, diatoms, ciliates, and cyanobacteria (Balech 1988, 2002; Cortés-Altamirano et al. 1997; Cortés-Altamirano and Licea-Duran 1999).

The first recorded case of poisoning by consumption of organisms contaminated by a HAB was in 1793 on Vancouver Island by sailors who explored the coasts. Numerous other cases have been described from the coast of North America and Alaska to the Gulf of California (Medcof et al. 1947; Needler 1949; Medcof 1972), as well as in South Africa, New Zealand, Belgium, Germany, France, England, and Ireland (Bondeanu and Usurelu 1979).

From these events, research began to focus on the organisms that produce HABs and the toxins they produce, these toxins have been classified according to the type of disorder they produce in people who are poisoned through PSP (intoxication paralyzing by mollusks), DSP (diarrheal poisoning by mollusks), ASP (amnesic poisoning), NSP (neurological affectation), and CFP (ciguatera fish poisoning) for marine species. In the case of fresh water, they are classified as hepatotoxic, neurotoxic, cytotoxic, and dermatoxic (Pérez-Morales et al. 2016).

The first report of HAB in Mexico dates from 1539 in the region of the Gulf of California, when the Spaniards explored the territory and named the area as the Bermejo Sea because of its frequent reddish coloration, which is thought to be due to HAB since in the Gulf these blooms prevail especially in the areas of Mazatlán, Mochis, Topolobampo, Yavaros, Port of Guaymas, Kino Bay and the northern zone of Angel de la Guarda Island, due to its coincidence with upwelling zones (Cortés-Altamirano 1998).

The main cause of these HABs was the ciliate *Myrionecta rubra*, but other species have been reported in the area over the years, such as *Gymnodinium catenatum*, *Gonyaulax polygramma*, *Gonyaulax polyedra* (Gilbert and Allen 1943; Cortés-Altamirano 1998), and *Noctiluca scintillans* (Allen 1937; Gárate-Lizárraga 1991), among others (Table 10.1 and Fig. 10.1).

In the Mexican Pacific there is not much information until 1989, where there was a first record of an event caused by *Pyrodinium bahamense* var. compressum near the coasts of Chiapas; after this event, there has been recorded the presence of numerous species that proliferate as *Cochlodinium polykrikoides*, which have been reported to form blooms from Bahia de la Paz (Garate-Lizarraga et al. 2001a, b); Manzanillo, Colima (Morales-Blake et al. 2000, 2001); Bahia de Mazatlán (Cortes-Altamirano and Nuñez-Pasten 1991); Michoacán (Rodriguez-Palacio et al. 2009) in Acapulco, Guerrero (Rodriguez-Palacio et al. 2009, 2010). However, high cell densities have not been reached, such as those occurring in the Gulf of Nicoya in Costa Rica (Hargraves and Viquez 1981; Vargas-Montero et al. 2006).

Species of the genus *Neoceratium* have also been reported in the waters of the Acapulco Bay and the Pacific waters (Cortes-Altamirano and Nuñez-Pasten 2000; Vargas-Montero and Freer 2004; Rodríguez-Palacio et al. 2010), the studies in the Pacific have helped to update the floristic listings, there are records of new species in the area that are potentially toxic or harmful, and there is a description of new species (Hernández-Becerril 2003; Hernández-Becerril et al. 2007a, 2008, 2010, 2013; Uribe-Hernández et al. 2010; Rodríguez-Palacio et al. 2011, Esqueda-Lara et al. 2005, 2013).

In the Gulf of Mexico, particularly in the city of Veracruz, the oldest records of HAB occurred in the year 1797, where there was a high mortality of fish and humans when consuming them. In 1969, the causative organism of these toxic events was identified as the dinoflagellate *Karenia brevis* (*Gymnodinium brevis*) (Brongersma-Sanders 1957). Currently there is strong monitoring in the Gulf of Mexico area by SEMAR (Navy and Army of Mexico), COFEPRIS (Federal Commission for the Protection Against Sanitary Risks), and the Fishing Secretary. Since toxic events continue to occur, reaching Mexico from the everglades of Florida and down the coast of Matamoros to the area of Tampico, Tamaulipas, and sometimes reaching the Port of Veracruz (Table 10.1, Fig. 10.1), it can be said that these events have been formed by the same species *Karenia brevis* and sometimes combined with the cyanobacteria *Trichodesmium erythraeum*.

In continental waters, only records from the last decades are available, and due to the growing eutrophication of these, uncontrolled proliferations of phytoplankton, mainly cyanobacteria, are frequent (Tomasini-Ortiz et al. 2012). The genera involved

Table 10.1 HAB-producing organisms in several localities of Mexico since 1987

Organism	Toxin	Locality, State	References
Akashiwo sanguinea Toxicity reported: low oxygen concentration; lobster, abalone, snail, fish and oyster culture mortality	N.R.	Tortugas Bay and Punta Abreojos, Baja California Sur	Turrubiates-Morales (1994), Gómez-Tagle (2007), Gárate-Lizárraga et al. (2007a, 2008), Núñez-Vázquez et al. (2011)
Akashiwo sanguinea Toxicity reported: nontoxicity Action: no action implemented	N.R.	Tortugas Bay, Baja California Sur	COFEPRIS (2012)
Alexandrium catenella Toxicity reported: bivalves	STX	Concepción Bay, Baja California Sur	Gárate-Lizárraga (1996), Morquecho-Escamilla et al. (1997), Herrera-Silveira (1999), Lechuga-Devéze et al. (2000)
Alexandrium monilatum *(=Gonyaulax monilata)* Toxicity reported: bivalves	STX	Mazatlán Bay, Sinaloa	Cortés-Altamirano and Nuñez-Pastén (1992)
Alexandríum sp. = *Gonyaulax* sp. Toxicity reported: N.R.	N.R.	Bacochibampo Bay, Sonora; Mazatlán, Sinaloa; Nayarit	Cortés-Altamirano et al. (1995a, b, c), Herrera-Silveira (1999)
[1]*Alexandríum* spp. = *Gonyaulax* sp. Toxicity reported: N.R.	N.R.	Tonala and Puerto Madero, Chiapas; Acapulco Bay, Guerrero; Bacochibampo, Sonora; Mazatlán, Sinaloa; Nayarit	COFEPRIS (2009, 2010, 2014), Cortés-Altamirano et al. (1995a, b), Herrera-Silveira (1999)
Alexandríum spp. Toxicity reported: N.R. Action: fishery closure	STX	Morales lagoon in Soto la Marina municipality and Brazil lagoon and Carrizal river, Tamaulipas	COFEPRIS (2010)
Alexandrium catenella Toxicity reported: bivalves	STX	Salina Cruz and Huatulco, Oaxaca	Saldate-Castañeda et al. (1991)
Alexandrium digitale Toxicity reported: N.R.	N.R.	Baja California	Blasco (1977)
Alexandrium polygrama Toxicity reported: fish mortality due to oxygen depletion	N.R.	Los Angeles Bay, Baja California, and Gulf of California, Mexico	Millán-Nuñez (1988), Cortés-Altamirano et al. (1996), Herrera-Silveira (1999)

Alexandrium verior Toxicity reported: N.R.	N.R.	Concepción Bay, Baja California Sur	Morquecho-Escamilla et al. (1997)
Amylax triacantha Toxicity reported: N.R.	N.R.	Mazatlán Bay, Sinaloa	Cortés-Altamirano et al. (1995a, b, c), Herrera-Silveira (1999)
Ceratoperidinium falcatum Toxicity reported: N.R.	N.R.	La Paz Bay, Baja California Sur	Gárate-Lizárraga (2014)
Chaetoceros spp. Toxicity reported: gill obstruction, crustacean mortality and fish death by asphyxia	N.R.	La Paz Bay, Baja California Sur	López-Cortés et al. (2006), Gárate-Lizárraga et al. (2007b), Núñez-Vázquez et al. (2011) López-Cortés et al. (2015)
Chaetoceros sp. Toxicity reported: nontoxicity Action: no action implemented	N.R.	Santiago and Manzanillo Bay, Colima	COFEPRIS (2012)
Chatonella sp. Toxicity reported: fish, mollusks, and crustaceans	NSP	Cabo San Lucas, La Paz Bay, Baja California Sur; Kun Kaak Bay, Sonora; Sinaloa coast; Lagoon Tampico, Tamaulipas	Herrera-Silveira (1999), Barraza-Guardado et al. (2004), García-Hernández et al. (2005), Band-Schmidt et al. (2005), García-Hernández (2008), Cortés-Altamirano et al. (2006a, b), Martínez-López et al. (2006), Rodríguez-Palacio et al. (2011)
Chattonella marina Toxicity reported: ichtyotoxicity Action: fishery closure	N.R.	Kino Bay, Sonora	COFEPRIS (2003)
Cochlodinium catenatum Toxicity reported: fish mortality Action: fishery closure	N.R.	Mazatán Bay, Sinaloa; Ensenada Bay, Baja California; Banderas Bay, Jalisco-Nayarit; Perula Bay, Jalisco; Manzanillo Bay, Colima; Tapachula, Pijijiapan, Tonalá, Chiapas	Orellana-Cepeda et al. (1993), Cortés-Lara et al. (2001), COFEPRIS (2007, 2013)
[2]*Cochlodinium polykrikoides* Toxicity reported: nontoxicity, fish mortality Action: no action implemented	N.R.	Acapulco Bay, Guerrero; Mazatlán, Sinaloa; Santiago and Manzanillo Bay, Colima; Tapachula, Chiapas; El órgano beaches, Punta Colorada, Santa Cruz Bay, Tangolunda, Cacaluta, Oaxaca; El Gancho beach in Suchiate, Chiapas; La Paz Bay, Baja California Sur; Banderas Bay, Jalisco-Nayarit	COFEPRIS (2007, 2008, 2012, 2014), Gárate-Lizárraga et al. (2001a, b, 2004a, 2011), Cortés-Lara et al. (2001, 2004), Núñez-Vázquez et al. (2003), Rodríguez-Palacio et al. (2010)

(continued)

Table 10.1 (continued)

Organism	Toxin	Locality, State	References
Cylindrotheca closterium Toxicity reported: fish mortality Action: no action implemented	N.R.	Río Lagartos in San Felipe, Yucatán; Centla, Tabasco	Álvarez-Góngora and Herrera-Silveira (2005), Herrera-Silveira and Morales-Ojeda (2009), COFEPRIS (2011)
Cylindrospermopsis cuspis Toxicity reported: nontoxicity	N.R.	Términos Lagoon, Campeche; Southeastern Gulf of Mexico	Poot-Delgado et al. (2016)
Dinophysis spp. Toxicity reported: N.R. Action: fishery closure	DSP	Manzanillo Bay, Colima; San Quintin Bay, Guerrero Negro Lagoon, Rincón de Ballenas, Todos Santos Bay, Baja California; Santiago Bay, Colima; Tapachula, Chiapas; Palo María at Vallarta Port, Jalisco	COFEPRIS (2010, 2012, 2014)
Dinophysis acuminata Toxicity reported: N.R.	N.R.	Ensenada Bay, Baja California; Guasave, Sinaloa	Orellana-Cepeda et al. (1993), Martínez-López et al. (2001),
Dinophysis caudata Toxicity reported: N.R.	DSP	Concepción Bay, Baja California Sur; Tamiahua Lagoon, Veracruz	Morquecho-Escamilla et al. (1997), Figueroa-Torres and Weiss-Martínez (1999), Lechuga-Devéze et al. (2000)
Dinophysis caudata Toxicity reported: fish and crab mortality Action: fishery closure	Okadaic acid	Tehuamixtle, Vallarta Port, Barra de Navidad, La Manzanilla Bay in Jalisco; Manzanillo and Santiago, Colima	COFEPRIS (2007, 2008, 2014)
Dinophysis tripos Toxicity reported: nontoxicity Action: no action implemented	N.R.	La Paz Bay, Baja California Sur	COFEPRIS (2012)
Dolichospermum flos-aquae Toxicity reported: nontoxicity	N.R.	Alvarado Lagoon, Veracruz	Aké-Castillo and Campos-Bautista (2014)
Eutreptiella marina Toxicity reported: fish mortality	N.R.	Banderas Bay, Jalisco	Cortes Lara et al. (2010)
Fibrocapsa japonica Toxicity reported: nontoxicity Action: no action implemented	N.R.	Altata Bay, Sinaloa	COFEPRIS (2008)

Gambierdiscus spp. Toxicity reported: human intoxication, presence of ciguatera toxins assumed but organisms not recorded regularly	CFP	Rocas Alijos, El Pardito Isle, Baja California Sur; Quintana Roo	Parrilla-Cerrillo et al. (1993), Barton et al. (1995), Lechuga-Devéze and Sierra-Beltrán (1995), Núñez-Vázquez et al. (2000, 2008)
Gambierdiscus toxicus Toxicity reported: fish mortality	CTX	Rocas Alijos and El Pardito Isle, Baja California Sur; Isla Mujeres, Cozumel Bojorquez lagoon, Cancún, Quintana Roo	Lechuga-Devéze and Sierra-Beltrán (1995), Cortés-Altamirano et al. (1996), Herrera-Silveira (1999), Popowski-Casañ et al. (2000), Heredia-Tapia et al. (2002)
Guinardia striata Toxicity reported: nontoxicity Action: no action implemented	N.R.	Río Lagartos, Yucatán	COFEPRIS (2008)
Gymnodinium breve = *Ptvchodiscus brevis* Toxicity reported: N.R.	N.R.	Veracruz	Cortés-Altamirano et al. (1996)
[2,3]*Gymnodinium catenatum* Toxicity reported: human intoxication; bivalve, crustacean, and fish mortality; shrimp in culture mortality Action: fishery closure	STX PSP	Kino Bay, Sonora; Acapulco Bay; north coast of Guerrero, Guerrero; Lázaro Cardenas Port, Michoacán; San Quintin Bay, Guerrero Negro Lagoon, La Paz Bay, San Felipe Puertecitos, Baja California; Tapachula, Pijijiapan, Tonalá, Chiapas; Mazatlán, Urias Estuary, Sinaloa; Santiago Bay, Manzanillo Bay, Colima; La Ventosa Bay, Santa Cruz Bay, Tangolunda, Cacaluta, El órgano beaches, Punta Colorada, Oaxaca; Santiago and Manzanillo Bay, Colima; Vallarta Port, Nuevo Vallarta, Pérula Bay, Jalisco	De la Garza-Aguilar (1983), Mee et al. (1986), COFEPRIS (2003, 2004, 2005, 2007, 2008, 2010, 2011, 2012, 2013, 2014), Saldate-Castañeda et al. (1991), Cortés-Altamirano and Nuñez-Pasten (1991, 1992), Cortés-Altamirano et al. (1995a, 1996), Gárate-Lizárraga (1996), Manrique and Molina (1997), Cabrera-Mancilla et al. (2000), Morales-Blake et al. (2000), Morquecho-Escamilla et al. (2000), Figueroa-Torres and Zepeda-Esquivel (2001), Ramírez-Camarena et al. (1996, 1999, 2002), Alonso-Rodríguez and Páez-Osuna (2003), Gárate-Lizárraga et al. (2001b, 2004b, 2005, 2006), Band-Schmidt et al. (2005, 2006, 2010), Rodríguez-Palacio et al. (2006), Hernández-Sandoval et al. (2009)

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Table 10.1 (continued)

Organism	Toxin	Locality, State	References
Gymnodinium mikimotoi Toxicity reported: N.R. Actions: fishery closure, 3.2 tons oyster incinerated	PSP	Manzanillo Bay, Colima	COFEPRIS (2007)
Gymnodinium peridinium Toxicity reported: N.R.	N.R.	Acapulco Bay and Puerto Marqués, Guerrero.	Cortés-Altamirano et al. (1996)
Gymnodinium sanguineum Toxicity reported: N.R.	N.R.	San Hipólito, Baja California; Tortugas Bay, Magdalena Bay, Concepción Bay, Baja California Sur	Orellana-Cepeda et al. (1993), Cortés-Altamirano et al. (1996), Gárate-Lizárraga (1996)
Gymnodinium sp. Toxicity reported: N.R. Actions: fishery closure, 3.2 tons oyster incinerated	PSP	Manzanillo Bay, Colima	COFEPRIS (2007)
Gymnodinium splendens Toxicity reported: N.R.	N.R.	Mazatlán Bay, Sinaloa; Chametla Bay, Jalisco	Cortés-Altamirano et al. (1996), Herrera-Silveira (1999)
Gymnodinium tripos var. *ponticum* Toxicity reported: N.R.	N.R.	Mazatlán Bay, Sinaloa	Cortés-Altamirano et al. (1996)
Gyrodinium instriatum Toxicity reported: N.R.	N.R.	Acapulco Bay, Guerrero; Mazatlán Bay, Sinaloa	COFEPRIS (2014) Gárate-Lizárraga et al. (2013)
Gyrodinium spirale Toxicity reported: N.R.	N.R.	Tamiahua Lagoon, Veracruz	Figueroa-Torres and Weiss-Martínez (1999)
Heterosigma sp. Toxicity reported: nontoxicity Action: no action implemented	N.R.	Mazatlán Bay, Sinaloa	COFEPRIS (2012)
Karenia spp. Toxicity reported: human eye and respiratory irritation/fish death	N.R.	Veracruz Port	Aké-Castillo et al. (2010)

Karenia brevis Toxicity reported: human intoxication, fish and dolphin mortality	NSP	Gulf of México; Dzilam Port, Yucatán; Carmen-Machona Pajonal lagoon and Mecoacán lagoon, Tabasco; San Fernando, Bagdad shore, Matamoros, Miramar, Tamaulipas; Centla, Tabasco; Pánuco, Tuxpan, Tamiahua Lagoon, Veracruz; north and center coast of Campeche	COFEPRIS (2003, 2005, 2008, 2009, 2011), Cortés-Altamirano et al. (1995b, 1996), Figueroa-Torres and Weiss-Martínez (1999), Ramírez-Camarena et al. (1999, 2006), Cervantes-Cianca et al. (2002), Magaña et al. (2003), Borbolla-Sala et al. (2006), Terán-Suárez et al. (2006)
Lingulodinium polyedrum Toxicity reported: nontoxicity Action: no action implemented	N.R.	Todos Santos Bay, San Hipólito, Concepción Bay, Baja California; Costa Chica Acapulco, Guerrero	COFEPRIS (2012) Blasco (1977), Orellana-Cepeda et al. (1993), Cortés-Altamirano et al. (1996), Gárate-Lizárraga (1996), Morquecho-Escamilla et al. (2000), Ruiz-de la Torre et al. (2013), Pérez-Cruz et al. (2015)
[4,5]*Myrionecta rubra* Toxicity reported: N.R. Action: fishery closure	N.R.	Mazatlán Bay, Sinaloa; North Gulf of California; Punta Prieta, San Lorenzo Channel, La Paz Bay, Cabo San Lucas, Baja California; Barra de San Francisco, Zicatela Bay, Puerto Escondido, Oaxaca; Manzanillo and Santiago, Colima; Tizate and Manzanilla beaches in La Cruz de Huanacaste municipality, Nayarit	COFEPRIS (2008, 2009, 2011, 2012, 2013, 2014) Hernández-Becerril (1987), Cortés-Altamirano et al. (1995a, b, 1996), Gárate-Lizárraga (1996), Alonso-Rodríguez et al. (1999), Herrera-Silveira (1999)
Neoceratium balechii Toxicity reported: N.R. Action: fishery closure	N.R.	Acapulco Bay, Guerrero	COFEPRIS (2012)
Neoceratium dens Toxicity reported: N.R.	N.R.	Ensenada, Baja California; Concepción Bay, Baja California Sur; Mazatlán Bay, Sinaloa; Manzanillo, Colima; del Carmen Lagoon, Tabasco	Blasco (1977), Orellana-Cepeda et al. (1993), Cortés-Altamirano et al. (1995b, 1996), Herrera-Silveira (1999), Lechuga-Deveze et al. (2000)
Neoceratium dens Toxicity reported: N.R.; fish, lobster, and echinoderm death due to oxygen depletion Action: no action implemented	N.R.	Salsipuedes Bay, Todos Santos Bay and Eréndira Village, Baja California; Santiago Bay, Colima	COFEPRIS (2007, 2011)

(continued)

Table 10.1 (continued)

Organism	Toxin	Locality, State	References
Neoceratium divaricatum Toxicity reported: oxygen depletion; lobster, sea star, crab, and fish mortality	N.R.	Bahía de Ensenada, Baja California	Orellana-Cepeda et al. (2007)
Neoceratium furca Toxicity reported: N.R., oxygen depletion, tuna in culture mortality	N.R.	Bahía de Ensenada, Baja California	Orellana-Cepeda et al. (2004)
Neoceratium furca Toxicity reported: N.R.; fish, lobster, and echinoderm death due to oxygen depletion Action: no action implemented	N.R.	Salsipuedes Bay, Todos Santos Bay and Eréndira Village, Baja California; Santiago Bay, Colima	COFEPRIS (2007, 2011)
Neoceratium fusus Toxicity reported: N.R.	N.R.	Baja California Sur: Concepción Bay	Lechuza-Deveze et al. (2000)
Neoceratium lineatum Toxicity reported: N.R.; fish, lobster, and echinoderm death due to oxygen depletion Action: no action implemented	N.R.	Salsipuedes Bay, Todos Santos Bay, and Eréndira Village, Baja California	COFEPRIS (2007)
Neoceratium teres Toxicity reported: N.R. Action: no action implemented	N.R.	El Corralero lagoon in Pinotepa Nacional municipality, Oaxaca	COFEPRIS (2014)
Neoceratium tripos Toxicity reported: N.R.; fish, lobster, and echinoderm death due to oxygen depletion Action: no action implemented	N.R.	Salsipuedes Bay, Todos Santos Bay, and Eréndira Village, Baja California	COFEPRIS (2007)
Neoceratium tripos var. ponticum Toxicity reported: N.R.	N.R.	Concepción Bay, Baja California Sur; Mazatlán Bay, Sinaloa	Cortés-Altamirano et al. (1995b), Herrera-Silveira (1999), Lechuga-Deveze et al. (2000)

Nitzschia spp. Toxicity reported: N.R.	ASP	Zihuatanejo Bay, Guerrero	Cortés-Altamirano et al. (1996)
Nitzschia longissima Toxicity reported: nontoxicity Action: no action implemented	N.R.	Cuyo, Sisal, Chelem, Chixchulub and Progreso ports, Yucatán	COFEPRIS (2008)
Nitzschia pungens Toxicity reported: fish mortality	Ammonia	Ensenada Bay, Baja California	Orellana-Cepeda et al. (1993)
Noctiluca millliaris Toxicity reported: N.R. Action: no action implemented	N.R.	From Coromuel beach to Pichilingue beach in La Paz municipality, Baja California Sur	COFEPRIS (2013)
Noctiluca scintillans Toxicity reported: nudibranch mortality	Ammonia	La Paz and Concepción Bay, Baja California Sur	Gárate-Lizárraga (1991), Orellana-Cepeda et al. (1993), Cortés-Altamirano et al. (1995a, b, 1996), Gárate-Lizárraga (1996), Morquecho-Escamilla et al. (1997), Herrera-Silveira (1999), Figueroa-Torres and Weiss-Martínez (1999), Gárate-Lizárraga et al. (2001a)
Noctiluca scintillans Toxicity reported: N.R. Action: no action implemented	N.R.	Santiago Bay, Colima; Altata Bay, Sinaloa; from Coromuel beach to Pichilingue beach in La Paz municipality, Baja California Sur	COFEPRIS (2011, 2012, 2013)
Oscillatoria erythraea Toxicity reported: N.R.	N.R.	Concepción Bay, La Paz Bay, Baja California Sur; Mazatlan Bay, Sinaloa; Peñasco Port, Sonora	COFEPRIS (2012) Cortés-Altamirano et al. (1995a, b), Gárate-Lizárraga (1996), Morquecho-Escamilla et al. (1997), Herrera-Silveira (1999)
Oxyphysis oxitoxoides Toxicity reported: N.R.	N.R.	Tamiahua Lagoon, Veracruz	Figueroa-Torres and Weiss-Martínez (1999)
Peridinium quinquecorne Toxicity reported: nontoxicity Action: no action implemented	N.R.	San Francisco de Campeche Bay, Campeche	COFEPRIS (2008)
Proboscia alata Toxicity reported: N.R.	N.R.	Magdalena Bay, Baja California Sur	Gárate-Lizárraga and Siqueiros-Beltrones (1998)

(continued)

Table 10.1 (continued)

Organism	Toxin	Locality, State	References
Prorocentrum spp. Toxicity reported: N.R.	N.R.	Bacochibampo Bay, Sonora; Baja California Sur; Chametla Bay, Jalisco; Superior Lagoon, Oaxaca; Manzanillo and Santiago, Colima; San Quintin Bay and Guerrero Negro Lagoon, Rincón de Ballenas and Todos Santos Bay, Baja California; Vallarta Port and Nuevo Vallarta, Jalisco	COFEPRIS (2008, 2010, 2012, 2013) Cortés-Altamirano et al. (1995a, b, 1996), Gárate-Lizárraga (1996)
Prorocentrum compressum Toxicity reported: N.R.	N.R.	Concepción Bay, Baja California Sur	Lechuga-Devéze et al. (2000)
Prorocentrum compressum Toxicity reported: presence of okadaic acid Action: fishery closure	Okadaic acid	El Coyote Estuary at Punta Abreojos, Baja California Sur	COFEPRIS (2014)
Prorocentrum dentatum Toxicity reported: fish mortality	Okadaic acid and DTX-I	Bacochibampo Bay, Sonora; Mazatlán Sinaloa	Cortés-Altamirano et al. (1995b), Cortés-Altamirano and Núñez-Pastén (2000)
Prorocentrum gracile Toxicity reported: N.R. Action: fishery closure	Okadaic acid	Carmen-Machona Lagunar complex, Tabasco	COFEPRIS (2007)
Prorocentrum lima Toxicity reported: N.R.	DSP	El Pardito Isle, Baja California Sur	Heredia-Tapia et al. (2002), Núñez-Vázquez et al. (2003)
Prorocentrum lima Toxicity reported: N.R. Action: no action implemented	NSP	Dzilam Port, Yucatán	COFEPRIS (2003)
Prorocentrum mexicanum Toxicity reported: N.R.	N.R.	Concepción Bay, Baja California Sur; Mazatlán, Sinaloa	Gárate-Lizárraga and Martínez-López (1997), Morquecho-Escamilla et al. (1997), Cortés-Altamirano and Nuñez-Pastén (2000), Lechuga-Devéze et al. (2000)

Prorocentrum micans Toxicity reported: toxicity to bivalves	N.R.	San Hipólito, Baja California; Concepción Bay, Baja California Sur; Mazatlán, Sinaloa; Tamiahua Lagoon, Veracruz; Banderas Bay, Jalisco	Blasco (1977), Orellana-Cepeda et al. (1993), Figueroa-Torres and Weiss-Martínez (1999), Herrera-Silveira (1999), Lechuga-Devéze et al. (2000), Cortés-Altamirano and Nuñez-Pastén (2000), Cortés-Lara et al. (2010)
Prorocentrum micans Toxicity reported: nontoxicity	N.R.	Manzanillo and Santiago, Colima; Santa Cruz Bay, Tangolunda, Cacaluta, El órgano beaches and Punta Colorada, Oaxaca	COFEPRIS (2008, 2011, 2012)
Prorocentrum micans Toxicity reported: presence of okadaic acid Action: fishery closure	Okadaic acid	Estero El Coyote Estuary at Punta Abreojos and La Bocana Estuary in Mulege municipality, Baja California Sur	COFEPRIS (2014)
Prorocentrum minimum Toxicity reported: nontoxicity	N.R.	Guasave and Mazatlán Bay, Sinaloa; Ballenas Bay, Baja California Sur	COFEPRIS (2012), Cortés-Altamirano and Agraz (1994), Cortés-Altamirano et al. (1996, 1997), Cortés-Altamirano and Licea-Durán (1999), Lechuga-Devéze et al. (2000), Martínez-López et al. (2001), Núñez-Vázquez et al. (2003), Sierra-Beltrán et al. (2005a), Martínez-López et al. (2008)
Prorocentrum triestinum Toxicity reported: N.R.	N.R.	Mazatlán, Sinaloa	Cortés-Altamirano and Nuñez-Pastén (2000)
Protoperidinium sp. Toxicity reported: N.R. Action: no action implemented	N.R.	Santiago and Manzanillo Bay, Colima	COFEPRIS (2012)
Protoperidinium conicum Toxicity reported: N.R.	N.R.	Tamiahua Lagoon, Veracruz	Figueroa-Torres and Weiss-Martínez (1999)
Pseudo-nitzschia spp. Toxicity reported: bird and marine mammal mortality, fish death by asphyxia	ASP	Cabo San Lucas, Loreto, Baja California Sur; Todos los Santos Bay, La Paz Bay, Gulf of California	Sierra-Beltrán et al. (1997), Herrera-Silveira (1999), Gárate-Lizárraga et al. (2007b) García-Mendoza et al. (2009), López-Cortés et al. (2015)

(continued)

Table 10.1 (continued)

Organism	Toxin	Locality, State	References
[1]*Pseudo-nitzschia* spp. Toxicity reported: N.E. Action: fishery closure	ASP	Rincón de Ballenas, Punta Abreojos, Coyote Estuary, La Paz Bay, Baja California; Tapachula, Pijijiapan, Puerto Madero, Chiapas; Tehuamixtle, Jalisco	COFEPRIS (2004, 2005, 2006, 2007, 2009, 2010, 2012, 2013, 2014)
Pseudonitzschia australis Toxicity reported: seabird, fish, marine mammal mortality	ASP	Gulf of California; Guasave Sinaloa and Nayarit	Sierra-Beltrán et al. (1997, 1999, 2005b), Meave-del Castillo et al. (2000), Martínez-López et al. (2001)
Pseudonitzschia cf *multiseries* Toxicity reported: N.R.	N.R.	Guasave, Sinaloa	Martínez-López et al. (2001)
Pseudo-nitzchia delicatissima Toxicity reported: icthotoxicity Action: fishery closure	ASP	Dzilam Port, Yucatán	COFEPRIS (2003)
Pseudo-nitzchia seriata Toxicity reported: N.R. Actions: fishery closure and monitoring distribution centers	N.R.	La Paz Bay, Baja California Sur	COFEPRIS (2006)
Ptychodiscus brevis Toxicity reported: N.R.	N.R.	Tamaulipas; Veracruz; Gulf of Mexico and Yucatán	Cortés-Altamirano et al. (1996), Herrera-Silveira (1999)
Pyrodinium bahamense var. *bahamense* Toxicity reported: nontoxicity	N.R.	Tamiahua Lagoon, Veracruz; Gulf of México and Mexican Caribbean	Cortés-Altamirano et al. (1996), Gómez-Aguirre and Licea (1998), Herrera-Silveira (1999)
Pyrodinium bahamense var. *compressum* Toxicity reported: toxicity to bivalves (clams, mussels, and oysters), fishes, and turtles Actions: fishery closure, confiscation of oysters (17.5 kg) in Tapachula	STX PSP	Rincón de Ballenas, Baja California; Tapachula, Chiapas; Santa Cruz; Carmen-Machona Lagunar complex, Tabasco; Huatulco Bay, La Ventosa Bay, La Colorada in Santiago Astata, La Ventosa Bay in Salina Cruz and Punta Colorada Beach in San Pedro Mixtepec, Oaxaca; Guerrero coast; Santiago Bay, Colima	COFEPRIS (2004, 2006, 2007, 2010, 2011, 2012, 2013), Saldate-Castañeda et al. (1991), Sotomayor-Navarro and Domínguez-Cuellar (1993), Parilla-Cerillo et al. (1993), Cortés-Altamirano et al. (1996), Ochoa et al. (1998), Orellana-Cepeda et al. (1998), Ramírez-Camarena et al. (1996, 2002), Licea-Durán et al. (2006), Meave-del Castillo and Rodríguez Vargas (2006), Núñez-Vázquez et al. (2007), Gárate-Lizárraga et al. (2008, 2009, 2011, 2012)

Rhizosolenia spp. Toxicity reported: N.R. Action: no action implemented	N.R.	Champotón, Campeche	COFEPRIS (2013)
Scripsiella spp. Toxicity reported: N.R.	N.R.	La Paz Bay, Baja California Sur	COFEPRIS (2013)
Scripsiella trochoidea Toxicity reported: N.R.	DSP	Dzilam Port, Yucatán; Río Lagartos in San Felipe municipality, Yucatán; Centla, Tabasco	COFEPRIS (2003, 2011), Orellana-Cepeda et al. (1993), Cortés-Altamirano et al. (1995a, b), Alonso-Rodríguez et al. (1999), Figueroa-Torres and Weiss-Martínez (1999), Álvarez-Góngora and Herrera-Silveira (2006), Herrera-Silveira and Morales-Ojeda (2009)
Skeletonema costatum Toxicity reported: nontoxicity	N.R.	Mazatlán Bay, Sinaloa; Manzanillo, Colima	Herrera-Silveira (1999), Figueroa-Torres and Zepeda (2000)
Stephanopyxis palmeriana Toxicity reported: N.R.	N.R.	Kino Bay, Sonora: Gulf of California	Molina et al. (1996)
Thalassiosira eccentric Toxicity reported: fish death by asphyxia	N.R.	La Paz Bay Baja California Sur	López-Cortés et al. (2015)
Trichodesmium erythraeum Toxicity reported: N.R. Action: no action implemented	N.R.	From Coromuel beach to Eréndira beach, Baja California Sur	COFEPRIS (2010)

N.R.: nonreported,[1] Events in December 2009 and January 2010,[2] Double event in 2007 (Acapulco, Guerrero),[3] Double event in 2010 (Manzanillo Bay, Colima),[4] Double event in 2008 (Manzanillo Bay, Colima),[5] Double event in 2012 (Santiago and Manzanillo Bay)

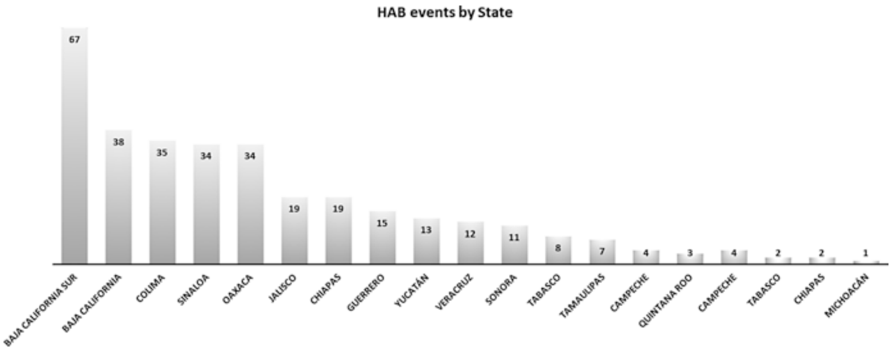

Fig. 10.1 Species that have been producing HABs since 1987 in several locations

are *Anabaena*, *Anabaenopsis*, *Cylindrospermopsis*, *Microcystis*, *Nodularia*, *Phormidium*, *Planktothrix*, and *Pseudanabaena*. These genera produce cyanotoxins that cause adverse effects on different species, affecting animals and humans (Pérez-Morales et al. 2016).

10.2.1 Records of HAB Events in Mexico Since 1987

This revision is based on the reports made by Ochoa et al. (2002) and Ochoa (2003), who made the first revision in scientific literature in Mexico. Another work used was published by Band-Smith et al. (2011), which is the last revision made in our country. This revision included reports in congress, symposia, and expert boards in Mexico and integrated also the reports in scientific journals up to 2018. Also, we reference the data published by national organization COFEPRIS, the one responsible for controlling potential intoxication in our coasts due to the presence of harmful algal blooms. The information from COFEPRIS only covers 2003–2014.

From the analysis of all the information, we can say that the total number of events up to 2018 was 431. This is without distinguishing between toxic and non-toxic events because the presence of many species can have a long-term impact on the food chain and can cause further human intoxication. To obtain a better vision on which genera were implicated in a higher frequency of event, we classified the event as a HAB by genera with a frequency of more than 15 events registered (Fig. 10.2).

We can point out the high frequency in species of *Gymnodinium*, *Prorocentrum*, and *Pyrodinium*, particularly attributed to *Gymnodonium catenatum* and *Pyrodinium bahamense* var. *compresum*, a saxitoxin producer organism. The HAB of these organisms had produced toxicity along the coast of the tropical Mexican Pacific and had caused the incineration of various tons of marine food products (COFEPRIS 2004, 2006, 2007, 2010, 2011, 2012, 2013). *Pyrodinium bahamense* var. *compresum* is also present in the coast of Gulf of Mexico. However there are not reports of

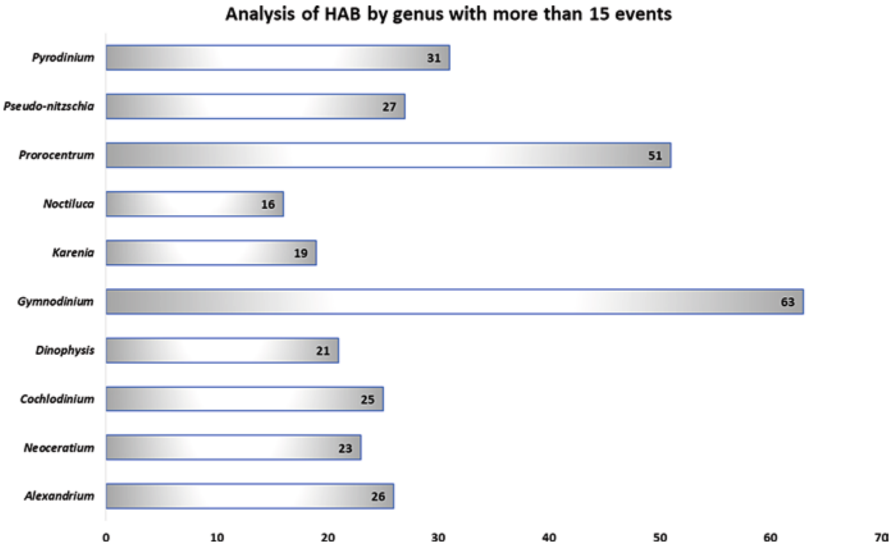

Fig. 10.2 Genera of phytoplankton organisms with more than 15 recorded events

human poisoning (Gómez-Aguirre and Licea 1998; Herrera-Silveira 1999) the same information was registered about the toxicity of *Prorocentrum* species, some of this event or *Prorocentrum* spp. where reported as nontoxic, while others, like *P. lima*, *P. compresum*, and *P. gracile*, has been reported the presence of okadaic acid and the actions were fishery closures in a prevention action for avoid human intoxication (COFEPRIS 2003, 2007, 2014).

The diatom Pseudo-nitzchia also have presented toxicity events in mexican waters. Some reports have associated the presence of this organism with mortality of birds and marine mammals. This diatom can produce amnesic shellfish poisoning (ASP), however the fish mortality are primary related with the obturatrion of fish gills. Pseudo-nitzchia delicatissima and Pseudo-nitzchia seriata were responsible for toxicity events in 2003 and 2006, respectively. COFEPRIS actions were fishery closur for prevent further health impacts on human populations. Other genera with considerable frequency of HAB events were Cochlodinium (25), Alexandrium (26), Dinophysis (21) and Karenia (19). In most of these events the authorities have suspended fishery activities. The species of *Noctiluca* and *Neoceratium* genera had nonreports on toxic molecules synthesis; the mortality caused by these organisms was due to asphyxia on fishes.

The genera that have presented 6-15 events of HAB are *Myrionecta*, a species of ciliates, and *Scripsiella*, a dinoflagellate. Both genera have not presented reports of toxicity, but they can cause fish mortality due to anoxia phenomenon (Fig. 10.3).

Other toxic genera have low frequency of toxic events, such as *Lingulodinium*, *Gambierdiscus*, and *Akashiwo*. This last genera, particularly *Akashiwo sanguinea*, has been related with lobster, abalone, snail, fish, and oyster culture mortality. In the

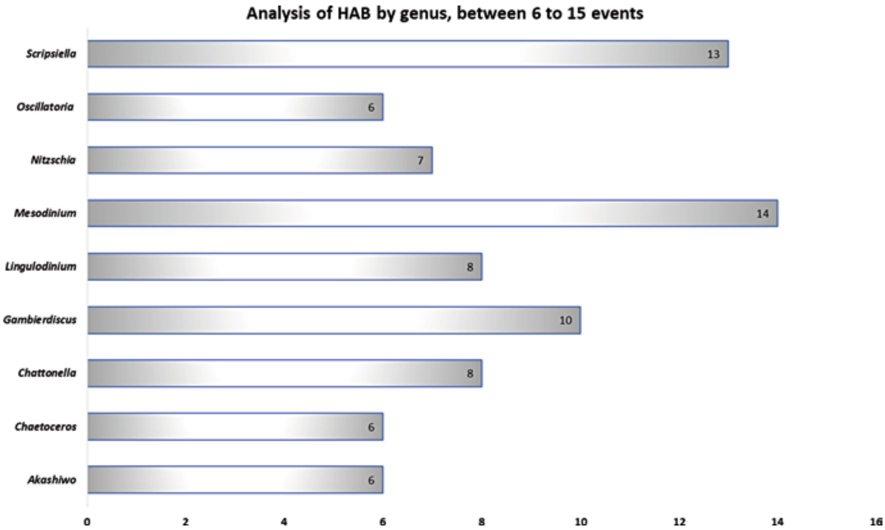

Fig. 10.3 Genera of phytoplankton organisms with 6–15 recorded events

coast of Baja California Sur, the authorities had implemented fishery closure in order to prevent intoxication. The diatoms *Chaetoceros* and *Nitzchia* had reports of nontoxicity, and they can only cause mortality via anoxia. Also, nontoxic event is related to the HAB of the cyanobacteria *Oscillatoria*.

Many genera had a single report of HAB. Only the diatom *Cylindrotheca* has four events in Yucatán, and only one of them provokes fish mortality due to gill obturation. The dinoflagellate *Gyrodinium* has three reports, but they only concern nontoxicity associated with its HAB (Fig. 10.4).

It is necessary to note that we consider as important HAB events those where a species is related to more ten events. The number of events in this category was 202, wich constitutes 47% registered since 1987.

The greatest portion of HAB events is represented by Gymnodinium catenatum (25%) followed by *Pyrodinium bahamense* var. *compresum* (14%) and Pseudo-nitzchia spp (10%) (Fig. 10.5). These species can account for a 50% of the total events registered until now and can contribute to the presence of toxicity or human health risk in our country.

Finally, we analyze the number of events taking into consideration the geographical places (states) in Mexico. We can observe that Baja California Sur is the state with the higher number of events of HAB with diverse composition of species. In general, there are more reports in the Mexican Pacific coasts than in the Gulf of Mexico. We cannot be sure whether there are more occurrences or whether there are less reports in Gulf of Mexico coasts, but indirectly we can observe that there are more reports on human intoxication or preventive action in the Pacific coast than in the Gulf and in the continental waters.

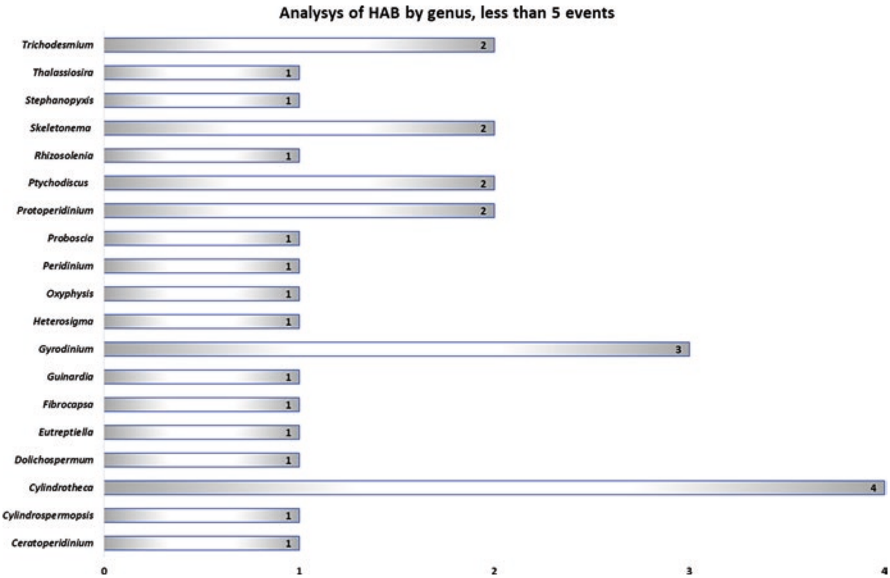

Fig. 10.4 Genera of phytoplankton organisms with less than 15 recorded events

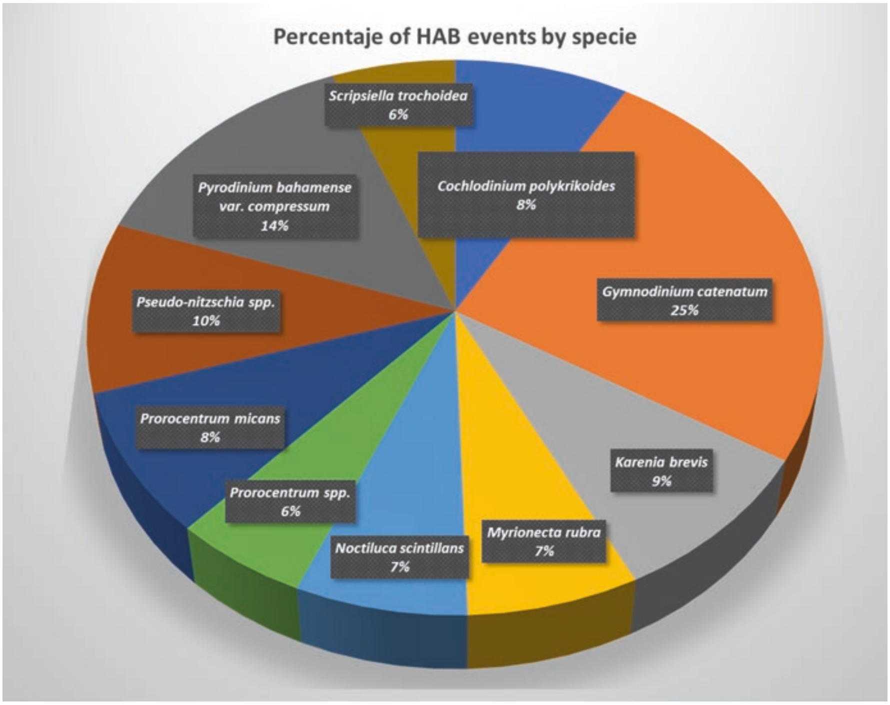

Fig. 10.5 Percentage of HAB events by species

10.3 Ficotoxins, Human Poisoning

Toxins can affect human health in various ways and degrees dependeing on the form of exposure. The exposure can be direct contact: when the flowering occurs in fishing or recreation places and the people who perform these activities touch these waters, resulting in skin irritation, nasal mucosa, ocular irritation, dermatitis, or more severe symptoms. Or people can be affected by HAB toxins through indirect contact: by means of an indirect vector such as a bivalve mollusks; since these are bioaccumulators and can filter and bioaccumulate large amounts of toxin, this type of poisoning is more dangerous as it can cause from mild discomfort to death.

10.3.1 Types of Toxins and Their Treatments

PSP (intoxication paralyzing by mollusks). Mechanism of action includes blockade in the transport of Na + (in channels). Symptoms are classified as mild, severe, or extreme. In the case of mild intoxication, there is perioral paresthesia, tingling sensation around the mouth passing to the hands and feet, headache, vertigo, vomiting, diarrhea, nausea, and numbness of the face and neck. Severe intoxication presents the symptoms of mild intoxication plus incoordination when talking, paresthesias in the arms and legs, inordordination of extremities, adynamia, alteration of the pulse, and respiratory distress. Serious poisonings also include flaccid muscular paralysis, pronounced dyspnea and sensation of breathlessness, respiratory arrest, and death. As for the treatment, it is necessary to consult a physician if there was ingestion of bivalve mollusks in the last hours or minutes before beginning to feel discomfort. In the hospital, gastric lavage is recommended, as well as determining the cause of vomiting, keeping the respiratory tract permeable, treating respiratory insufficiency, providing artificial respiration, controlling vital signs, and keeping the resuscitation team on alert (Borison and McCarthy 1977; Galvão et al. 2009; Osterbauer and Dobbs 2009; Smith et al. 2012; Cusick and Sayler 2013; Seymour et al. 2015).

NSP (neurological affectation). This is caused by brevetoxins. This toxin is called a spray because it is released into the environment and penetrates the body through the skin, nose, or eyes. A person can also be poisoned by the consumption of mollusks or contaminated fish. The symptoms and treatment are the same as with PSP poisoning (Acheson 2009; Jong 2017).

DSP (diarrheal poisoning by mollusks). This affects phosphorylation and phosphatases (electrolyte balance). Symptoms range from mild to severe. Diarrhea is the main symptom, followed by nausea, vomiting, and abdominal pain. These symptoms start from half an hour or less of consuming the contaminated food.

Chronic exposure can present serious symptoms such as the formation of tumors in the digestive system. Treatment should focus on correcting electrolyte imbalance. Patients can recover in a short time, approximately in three days (Chand 2009; Matsushima et al. 2015; Chun-Hung et al. 2016).

ASP (amnesic poisoning). The mechanism of action is the blocking of glutamic acid acceptors at the level of the central nervous system due to domoic acid (DA) wich is similar in chemical terms to glutamic acid and therefore competes with it for the corresponding acceptors producing physiological alterations in the hippocampal region cerebral, so that the gastrointestinal symptoms are nausea, vomiting, diarrhea, abdominal cramps, headache, the neurological ones are decreased deep pain, short-term memory loss, disorientation, confusion, bronchial secretion, respiratory distress, loss of balance, attacks, coma, and death. The treatment must be symptomatic since there is no antidote (Chand 2009; Jong 2017).

CFP (ciguatera fish poisoning). The mechanism of action involves the blocking of Ca^{++}. Neurological symptoms include numbness of the hands and feet, loss of balance, low blood pressure and heart, rash or rash, death from respiratory failure. There is no antidote. Neurological symptoms can prevail for months and years; calcium and mannitol can help reduce symptoms (Hallegraeff 1993; Cortés-Altamirano 1998; Seymour et al. 2015).

There are species called reactive oxygen species (ROS) that produce substances that cause serious environmental damage during HABs. O_2 radicals include superoxide and hydroxyl anions, which cause oxidative damage during the functioning and structuring of cells. The gills of the fish reduces oxygen transfer capacity (Chen et al. 1993; Whyte et al. 2009; Coelho et al. 2002). In the case of humans, it causes irritation of the skin, nasal mucosa, ocular irritation, dermatitis in general, which are considered minor complaints that do not require specialized treatment (Vargas-Montero and Freer 2004).

The toxins produced by cyanobacteria are classified as hepatotoxic, neurotoxic, cytotoxic, and dermotoxic. Exposure to these toxins can cause mild health problems such as dermatitis and gastric disorders to serious problems such as liver damage, nervous system damage and cancer (Pérez et al. 2008; Perez- Morales et al. 2016).

The hepatotoxins called microcystins, nodularins, and cylinrospermopsins are phosphatase blocking and produce hemorrhage in the liver, with potential cumulative carcinoma damage. The neurotoxins known as anatoxin cone, homoanatoxin and saxitoxins cause blockade of postsynaptic depolarization, acetylcholinesterase, and sodium channels. Cytotoxin or dematoxins cause blockage of protein synthesis, causing inflammation in the skin and in the gastrointestinal tract (Kaebernick and Neilan 2001; Wiegand and Pflugmachaer 2005).

The toxins produced by microalgae and cyanobacteria have specific variations according to the species that produces them and differences in chemical characteristics and therefore vary the effect of intoxication in humans (Table 10.2).

Table 10.2 Toxins produced by microalgae and cyanobacteria

Toxin type	Source organisms	Characteristics	Effects on other organisms	References
PSP (paralytic shellfish poisoning)	Dinoflagellates: *Alexandrium catenella*, *A. minutum*, *A.tamarense*, *Gymnodinium catenatum*, *Pyrodinium bahamense* Cyanobacteria: *Aphanizomenon*, *Planktothrix*, *Cylindrospermopsis*, *Lyngbya*, and *Scytonema*	Saxitoxin (STX) and its derivatives cause poisoning commonly referred to as paralytic pufferfish poisoning following bioaccumulation and ingestion. Include more than 50 structurally related tricyclic guanidium alkaloids. Saxitoxin binds to voltage-gated sodium channels within cell membranes, inhibiting membrane depolarization and blocking the proliferation of action potentials. Because this toxin molecule is not a protein, it is more stable in extreme temperature and pH. It has a lethal human dose of approximately 0.2 mg for the average adult and is approximately 1000 times more toxic than the chemical warfare agent sarin. Saxitoxins cross the blood–brain barrier, and sodium channel blockade in the central nervous system therefore contributes to its paralytic effects.	Saxitoxins are produced in freshwater and marine environments. In marine environments, they are often referred to as PSPs. Most human saxitoxin toxicoses have been associated with the ingestion of marine shellfish, which accumulate saxitoxins produced by marine dinoflagellates. In fresh waters, saxitoxins are produced by cyanobacterias and can accumulate in freshwater fish such as tilapia. Physiological effects of these channel blockades develop into a paralytic syndrome characterized by descending peripheral and central paralysis that begins with facial involvement, which results in paresthesia of the lips mouth, face, and neck and then progresses to involve the diaphragmatic muscles wherein respiratory failure may ensue. Alterations in the central nervous system (CNS) are also apparent, with cardiac disturbances, ataxia, drowsiness, and lack of motor coordination also being reported. Rapid cardiac failure in cats after administering high intravenous doses of saxitoxin with diverse arrhythmias, including ventricular and atrial fibrillation and hypotension that preceded rapid cardiac arrest within minutes, has also been shown. In addition, it is known that excretion of the toxin is entirely renal and that no metabolic machinery exists to process saxitoxin in mammals.	Borison and McCarthy (1977), Galvão et al. (2009), Osterbauer and Dobbs (2009), Smith et al. (2012), Cusick and Sayler (2013), Seymour et al. (2015)

NSP (neurotoxic shellfish toxins)	Dinoflagellate: *Karenia* Raphidophyceae: *Chattonella marina*, *Fibrocapsa japonica*	Brevetoxin may act on TRPV1 channels in nerve cell membranes, affecting thermal and pain sensation. Brevetoxins are polycyclic ethers that bind to and stimulate Na + flux through voltage-gated Na + channels in nerve and muscle. These toxins are depolarizing substances that open voltage-gated Na + ion channels in cell walls, leading to uncontrolled Na + influx into the cell.[4] This alters the membrane properties of excitable cell types in ways that enhance the inward flow of Na + ions into the cell.	It is known to kill fish, invertebrates, seabirds, and marine mammals (e.g., manatees). About 1–6 hours after ingestion of contaminated shellfish, the affected person will experience paresthesias, reversal of hot and cold temperature sensation, ataxia, nausea, vomiting, and diarrhea. When the toxin is aerosolized in rough surf, exposed people can develop a syndrome consisting of conjunctivitis, rhinorrhea, and a nonproductive cough. It causes sickness in humans lasting several days. However, it is not fatal to humans.	Acheson (2009), Jong (2017)
DSP (diarrhetic shellfish poisoning)	Dinoflagellates: *Dinophysis acuminata*, *Dinophysis caudata*, *Prorocentrum lima*	Dinophysistoxins (DTXs) and pectenotoxins (PTXs) are severe gastrointestinal illnesses producers caused by the consumption of shellfish contaminated with diarrhetic shellfish toxins (DSTs). Based on their structures, DSTs were initially classified into three groups: okadaic acid (OA)/dinophysistoxin (DTX) analogues, pectenotoxins (PTXs), and yessotoxins (YTXs). OA and its analogues, dinophysistoxin-1 (DTX1) and − 2 (DTX2), are the most important toxins due to their causing severe diarrhea. DTXs encompass several toxin derivatives (Fig. 10.1); however, only OA and DTX analogues such as DTX-1, DTX-2, and “DTX-3” are the major toxins that induce intoxication. “DTX-3” is a group of fatty acid ester derivatives caused by acylation of DTX-1 in the digestive gland of seafood. Moreover, “DTX-3” metabolically transforms back to DTX-1 in human stomach after consumption of contaminated bivalves. Therefore, “DTX-3” does not exist in microalgae. These toxins are lipophilic and accumulate in shellfish and are potent inhibitors of serine/threonine protein phosphatases 2A (PP2A), 1B, and 2B, which are vital for the regulation of cell metabolism, DNA replication, transcription, RNA splicing, cell cycle progression, differentiation, and oncogenesis through the dephosphorylating phosphor-serine and phosphor-threonine residues of their substrates; these toxins are potential tumor promoters in the human digestive system. Moreover, OA induces apoptosis, cytotoxicity, DNA adduct formation, chromosome loss, DNA breaks and cell cycle arrest, as well as changes in neuropeptide Y.	These toxins have been shown to be potent phosphatase inhibitors, a property that can cause inflammation of the intestinal tract and diarrhea, possibly leading to tumor promotion. Because PTXs and YTXs do not cause diarrhea, they are now not considered to be members of the DST group. Because OA/DTXs and PTXs are produced by toxic dinoflagellate *Dinophysis* spp., DSP is a self-limited diarrheal disease without known chronic sequelae. Gastroenteritis develops shortly after ingestion and generally lasts 1–2 days. There is no evidence of neurotoxicity, and no fatal cases have ever been reported. Diarrhea was the most commonly reported symptom, closely followed by nausea and vomiting, with onset 30 minutes to 12 hours from ingestion. Complete clinical recovery is seen even in severe cases within 3 days.	Chand (2009), Matsushima et al. (2015), Chun-Hung et al. (2016)

(continued)

Table 10.2 (continued)

Toxin type	Source organisms	Characteristics	Effects on other organisms	References
ASP	Diatoms *Pseudo-nitzchia* and *Nitzchia*	They are produced by domoic acid and are structurally similar to the excitatory neurotransmitter glutamate. Lesions in the human brain, with necrosis of the glutamate-rich hippocampus and amygdala in autopsied cases, have been reported in ASP cases and are similar to those seen in rats after intravenous administration. When rats are exposed experimentally to domoic acid and its analogues, they experience limbic seizures, memory and gait abnormalities, and degeneration of the hippocampus. In animals, domoic acid is 3 times more potent than kainic acid and 30–100 times more potent than glutamic acid. This neurotoxic synergism may occur through a reduction in the voltage-dependent Mg2+ block at them *N*-methyl-d-aspartate (NMDA) receptor-associated channel, following activation of non-NMDA receptors by domoic acid. In humans, domoic acid appears to cause a nonprogressive acute neuronopathy involving anterior horn cells or a diffuse axonopathy predominantly affecting motor axons. The acute neuronal hyperexcitation syndrome presumably results from the stimulus of central and possibly peripheral neurons, followed by chronic loss of function in neural systems susceptible to excitotoxic degeneration (hippocampus and anterior horn cells of spinal cord).	Gastrointestinal symptoms (nausea, vomiting, abdominal cramps, and diarrhea) occur within 24 hours after the toxic ingestion, and neurologic symptoms (headache, seizures, hemiparesis, ophthalmoplegia, abnormal state of arousal ranging from agitation to coma, and antegrade memory loss) become manifest within 48 hours after the ingestion.	Chand (2009), Jong (2017)

CFP (ciguatera fish poisoning)	Dinoflagellate: *Gambierdiscus toxicus*	These are lipid-soluble cyclic polyethers structurally similar to brevetoxins. Several variants occur; however, the most common and potent is ciguatoxin-1. Although water-soluble toxins, such as maitotoxin, coexist with ciguatoxinsin *G. toxicus* and can be isolated from digestive tracts of herbivorous fish, the concentrations in muscle tissues are so low that they are deemed unlikely to be a major cause of toxicosis in people who eat fish. Ciguatoxins act as agonists at receptors on voltage-gated sodium channels of neuromuscular junctions, sensory neuron membranes, and other excitable cells. Both cholinergic and α-andrenergic receptors are affected by ciguatoxins. Like brevetoxins, they act on site 5 of the alpha subunit of the sodium channel receptor to increase excitability and prolong refractory periods of sensory and motor nerves.	The hemodynamic and cardiac effects are specifically attributed to ciguatoxins' inhibitory action on vasomotor centers innervated by the vagus nerve, thus preventing regulatory stimulation and removing sympathetic tone that establishes normal peripheral vascular resistance and cardiac rhythm. Case studies have documented severe and prolonged cardiac symptoms lasting as long as 4 days despite corrective care. The extended duration of symptoms—both the uncommon cardiac effects and more characteristic neurological symptoms—has been postulated to be due either to the lipophilic structure of the toxin allowing accumulation and preventing elimination or the fact that ciguatoxin modulation of sodium channels is a permanent effect with relief relying on the development of new receptors.	Solter et al. (2013), Seymour et al. (2015)

10.4 Some Ecological Considerations About Microalgae Toxins

In 1984, Rice described allelopathy as any beneficial or harmful effect produced by a plant and exerted on another plant, microbe, or fungus. This effect must be produced by the action of a chemical agent.

In 1996, the International Allelopathy Society defined allelopathy as any process induced by secondary metabolites produced by bacteria, fungi, algae, and plants that affect the growth and development of biological or agricultural systems (Zak et al. 2012).

Allelopathy produces different ecological consequences, and it is hard to be tested. The classical works on Californian chaparral shrubs done by Muller (Muller and Del Moral, 1966; Muller et al. 1964; Muller et al. 1968) show us that this phenomenon is not obvious. In aquatic environments, allelopathy could be more difficult to test. It is necessary to take into account several aspects to decide if an ecological circumstance is produced by allelopathy. Some effects that an allelopathic agent can produce on microalga or other organisms are as follows:

(a) It affects other algae around.
(b) It affects its own growth.
(c) It affects microbes associated with the algae.
(d) It could affect higher plants around.
(e) Accumulation and availability of nutrients can influence the distribution and establishment of other organisms (Inderjit and Dakshini 1994).

Algae can affect others in the vicinity, including favoring their growth, killing them, or reducing their growth, nutrition level, or reproduction rate. Sometimes the concentration of the chemical allelophatic agent is so high that it produces a harmful effect on the organism that produces it; this is called autotoxicity. The effect that algae can produce on higher plants may perhaps be seen more frequently in freshwater environments because of the presence of higher plants there. One of the scarce examples of higher plants in the ocean is the sea grasses.

Some researchers think that allelopathy is not the only or the most important factor that can influence the HAB event. The effects of HABs are presumably due to the strength of toxicity of these chemicals. The ecological advantage of allelopathic species could be related to its defense mechanism against plankton eaters, pathogens, or parasites. Allelopathy does not necessarily kill the menace organism; however, it could reduce its ecological efficiency. Using the metaanalysis approach, it is suggested that under field conditions where cell density and turbulent water currents make difficult the high concentrations of chemical agents, allelopathy as a direct factor for HAB is unlikely (Jonsson et al. 2009).

Several ecological conditions like increase in temperature, availability of nutrients, or stratification in the column of water, among others, are indicated as facilitators of this phenomenon (Anderson et al. 2009; Caroppo et al. 2005; Paerl and Huisman 2008; Pitcher et al. 2010). The manifestation of these allelopathic effects may be related to subtle physical-chemical changes of the aquatic environment, such as temperature and salinity. *Pseudo-nitzschia* can produce domoic acid (DA), a potent neurotoxic substance that causes shellfish poisoning disease. It has been found by means of bioassays that DA and nutrient addition to a phytoplankton community in a low salinity environment, the inhibition of cryptophytes was negatively correlated with the salinity when AD was added. This type of studies throw new knowledge in relation to allelopathy phenomena (Meerssche et al. 2018). There are persistent species of dinoflagellates whose success is presumed to be caused by cyst bed distribution and cyst abundance, deterrence of zooplankton grazing, and high nutrient concentration due to human activity. Another possibility is the chemicals they release, such as in the case of *Alexandrium fundyense* along the North American East Coast (Hattenrath-Lehmann and Gobler 2011). These authors have found during laboratory experiments that *A. fundyense* shows an inhibition effect on *Rhodomonas salina*, *Thalassiosira pseudonana*, and *Thalassiosira weissflogii*, which was dependent on the density of both donor and target species. In field conditions, *Alexandrium* produced a decrease in the abundances of a diatom and a nanoflagellate. Legrand et al. (2003) said that allelopathy is an ecological phenomenon mediated by chemical agents when there is competition for scarce resources. Some resources can be very specific, when two species are very similar in their needs the competition can be very intense. Some toxins produced by HAB producers are not proved to be allelopathics; an exception is the karlotoxins, which have shown to have an inhibition effect on the growth of competitor species and a moving immobilization effect for a later depredatory behavior depending on the chemical composition of the cellular membrane of the target species (Sheng et al. 2010).

This level of specificity is not surpriseng, many chemical interactions are highly specific. The allelopathic power of these substances is not always the same. It has been observed that five genetic strains of *Karenia brevis* produce a different impact on *Asterionellopsis gracilis*, a competitor species. The results indicate that the harmful effects can be from very strong to very weak or even be slightly stimulating. Metabolomes of *K. brevis* were analyzed, and a variation of chemical composition related to the effect exerted on target species was found. Allelopathic effect was characterized by high concentration of fatty acids, aromatics, and other polyunsaturated compounds (Poulin et al. 2018). This circumstance indicates the subtlety and dynamism of chemical relationships related to the allelopathy phenomenon.

Manifestations of algae allelopathy are especially difficult to prove in natural conditions. However, we must consider that in order to talk about this topic, we must reflect on the following points: persistence time in the environment of the allelochemical agent, biological active concentration, way of renewability, static and dynamic availability, and its variation over time considering the seasons of the year, site, habitat and many other environmental factors (Inderjit and Dakshini 1994).

The biological communities are very complex scaffoldings where each integrant affects its neighbor. When one species lives very closely to another and the biological fitness of one is affected by the other, it is called symbiosis.

In its original meaning, as originally coined by Anton De Bary (1879), symbiosis is the coexistence together of differently named organisms. This definition does not

Table 10.3 Type of interaction

Type of Interaction	Result for the participating species	Comment
Competition	0 – or – –	Species A can exclude species B. Competition in which A and B coexist (Kalmykov and Kalmikov 2013; Nguyen and Yin 2016)
Predation	+ –	Carnivory: A typically kills B. Herbivory: A typically bowses on but does not kill B (Dhanker et al. 2012; Place et al. 2012).
Parasitism	+ –	A is parasite; B is host (Park et al. 2013).
Commensalism	+ 0	A is beneficiated, while B has no effect (Ramanan et al. 2016).
Detritivory	+ 0	B is dead prior to interaction, so incurs no cost (Mincks et al. 2008).
Mutualism	+ +	Both A and B are beneficiated (Cooper and Smith 2015).
Neutralism	0 0	

Modified from Halliday (1996)

indicate if any of the parties is benefited or harmed (Douglas 2002). Some researchers have differentiated several types of symbiosis depending on the benefits or harm to each of the participating species (Table 10.3).

Paralytic shellfish poisoning (PSP) is produced by contact with the paralytic shellfish toxins (PSTs) produced by several species of the genera *Alexandrium*, *Pyrodinium*, *Gymnodinium*, and *Catenella*, among others. Another group of organisms that produce these toxins are cyanobacteria of the genera *Aphanizomenon*, *Anabaena*, and *Lyngbya.* Evidence suggests that some of these dinoflagellates can maintain bacteria inside themselves and some metabolites of bacteria can act as promoters for the production of PST and vice versa. Experiments have shown different results when the dinoflagellates have been cultivated with bacteria in the same culture system as when they have been cultivated axenically. This could indicate a very complex relationship between the biochemical signals of dinoflagellates and the bacteria (Gallacher and Smith 1999). It has been seen that some substances have a harmful effect on phytoplankton elements. Some free fatty acids are toxic as they cause leakage of intracellular K^+ as a result of damage of the cellular membrane, lysis, and liberation of phycobilines. Apparently, this is because of change in membrane permeability and dissociation of phycobilines from the thylacoids (Wu et al. 2006). Cyanobacteria produce a large number of substances that show a wide variety of biological activities. *Lyngbya majuscula* generates nitrogen-containing compounds, polyketides, cyclic peptides, etc. *L. majuscula* has substances that can act as protein kinase C activator and tumor promoters called lyngbyatoxins and aplysiatoxins, inhibitors of microtubulin assembly (curacin A), and a blocker of sodium channel (kalkitoxin) (Shimizu 2003). This type of substances may have a relevant ecological role; many protozoa depend on the ability to produce tubulin for movement. Inhibition in the production of this protein can stop the movements of scapes, turning them into prey.

Emiliania huxleyi, a forming coccolithophorid bloom, produces chemical defenses against grazing. These defenses include the production of dimethylsulfoniopropionate (DMSP) by the enzyme DMPS lyase to yield dimethylsulfide (DMS) and acrylate. Several ciliates and heterotrophic dinoflagellates showed a diminished feeding rate when they were in the presence of high-level DMSP lyase activity *E. huxleyi* strains (Strom et al. 2003).

The chemical-ecological activities of the phytoplankton are hardly known. It is clear that competition, allelopathy, predation, herbivory, parasitism, etc. are ecological phenomena that have generated evolutionary responses in order to increase the biological fitness. Coevolution is the evolutionary response to the emerging evolutionary characteristics of the interacting species. The production of chemical agents to obtain an ecological advantage is clearly involved in the production of HABs.

Chemical and physical characteristics of the column of water are related to the HAB phenomena. It is worrisome that global climatic change favors the increasingly frequent appearances of HABs.

The phytoplankton community is a very complex system, and it is necessary to do more research on ecological chemistry to understand, predict, and perhaps control to some extent this phenomenon.

10.5 Mitigation and Control of HABs

For years, HAB studies have focused on detecting which species formed these blooms, the probable causes of these phenomena, the duration and frequency of them in certain areas, and the type of toxins they produced. But it was only until the beginning of the twenty-first century that work on how to control and mitigate these events to avoid the damage they cause to man and the environment was began.

HABs have created such an impact on the economy, the environment, and human health that systematic monitoring, prevention, and mitigation strategies have been implemented to evaluate their probable effects (Band-Schmidt et al. 2011; http://geohab.org/).

Ways to manage the impact of HABs include prevention (reduction of their incidences and scope), control (stopping or controlling flowering), and mitigation (measures to minimize their impact). However, controlling of the HABs presents a series of technical and economic difficulties since the costs are high, effectiveness is low, there are many environmental implications, and there is little knowledge about mitigation strategies (Herrera-Sepúlveda et al. 2008).

The mitigation of the impact of HABs involves several areas of attention, such as the correct implementation of regulatory measures, the development of monitoring techniques for harmful biotoxins and microalgae, the generation of basic and applied information on the physiology and ecology of harmful species, as well as the implementation of management plans for species with commercial importance susceptible to be affected by the HAB, among others. The most used control methods are grouped into four basic types: nutrient control, mechanical methods, chemical methods, and biological methods (Cobo 2015).

Therefore, the use of clays (as flocculating agents), herbicides, chelating agents (Cu_2SO_4), and surfactants, as well as other methods such as artificial turbulence, ultrasonic probes, ozonation, aeration, and biological control (using parasites, viruses, bacteria, and zooplankton) are considered. However, many of these methods are not practical, their costs are high, and they can have side effects on the ecosystem (Anderson et al. 2001).

Biological research methods include the use of organisms, materials and natural substances derived from them. A great variety of aquatic and terrestrial organisms have been considered and studied based on predation, parasitism, or the liberation of metabolites. In the case of cyanobacteria, barley straw has been used, which suppresses their growth (Cobo 2015, Ball et al. 2001). Some studies have focused on the effect of macroalgae and macrophytes on phytoplankton, such is the case of macroalga Ecklonia kurume, wich has shown a limiting effect on species that generate HABs as *Cochlodinium polykrikoides*, *Karenia mikimotoi*, *Chattonella antiqua*, among others through the production of florotannins (Nagayama et al. 2002; Nagayama et al. 2003; Addisie and Calderon-Medellin 2012). Others focus on the use of barley straw, whole or fractionated, which have been efficient in mitigating the flowering of certain species of phytoplankton (Newman and Barret 1993; Everall and Less 1997; Nagayama et al. 2003; Butler et al. 2005; Drábková et al. 2007).

In shallow lakes, wetlands, or intensive farming systems, the growth of aquatic plants has been promoted, which slows the development of phytoplanktons because they absorb nutrients from water and sediments, competing with phytoplanktons and limiting the availability of light for them. In addition, macrophytes reduce sediment and nutrient resuspension caused by wind, which limits turbidity, and serve as a refuge for zooplanktons during their horizontal diurnal migrations, allowing predation on phytoplanktons to remain (McComas 2002).

However, there is also an area of study that has been dedicated for years to demonstrating the allelopathic effects (defining this as the biochemical interactions between aquatic primary producers (Gross et al. 2007)) of some species of macrophytes, submerged, mainly of the genus *Chara*, resulting in inhibition on the growth of some phytoplankton species (Berger and Schagerl 2003; Cooke et al. 2005; Mulderij et al. 2003, 2006; Erhard and Gross 2006; Gross et al. 2007; Addisie and Calderon-Medellin 2012).

Therefore, numerous laboratory-scale or microcosm studies have been carried out to test this inhibitory activity in the growth of cyanobacteria using aquatic plants such as *Elodea canadensis*, *E. nuttallii*, *Ceratophyllum demersum*, and *Vallisneria spiralis* (Gross et al. 2003, 2007; Qiming et al. 2006).

Since this part of the mitigation and control of HAB research is still in the making, more work is required on a pilot scale to analyze the relevance of the measures and their impact on the environment.

10.6 International and National Monitoring Programs

Most seafood-producing countries have implemented monitoring programs for HABs to protect public health and to reduce the risk of exposure to toxins.

These programs include monitoring of oceanographic conditions (climate, currents, and nutrients), checking of toxic microalgae and toxin content in shellfish, and monitoring of confined areas, cultivation sites, and coastal zone.

There are many organizations that manage these programs, and the most important are IOC Intergovernmental Panel on Harmful Algal Bloom (IPHAB), Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB), ICES-IOC Working Group on Harmful Algal Blooms Dynamics (WGHABD), IOC Science and Communication Center on Harmful Algae (IOC SCC), and IOC-IEO Science and communication center on Harmful Algae-Vigo (http://hab.ioc-unesco.org/; http://geohab.org/).

The IOC Harmful Algal Bloom program focuses on promoting the effective management of HABs and their scientific research in order to understand their causes, predict their incidence, and mitigate their effects (http://hab.ioc-unesco.org/).

The working model of the GEOHAB includes various aspects of biodiversity, ecology and biogeography that include the availability of nutrients for organisms, eutrophication processes in different types of water bodies, adaptive strategies of populations, comparison of the functioning of ecosystems, but above all it generates models to be able to predict the behavior of HABs (http://geohab.org/).

The work model of GEOHAB includes studies on biodiversity and biogeography, nutrients and eutrophication, adaptation strategies, comparison of ecosystems, and finally, conjugating all of the above, observation, modeling, and prediction (http://geohab.org/).

In regard to biodiversity and biogeography, the work model studies the relation between the distribution of species, their diversity, and environmental changes and also analyzes genetic variability in relation to toxicity, population dynamics, and biogeography. It determines biogeographic changes that are caused naturally or by human activities. It also studies variations in the composition of species in response to environmental changes.

The strategies of adaptation handle them as the characteristics that determine their intrinsic growth potential, the quantification of biological and physical interactions at the scale of individual cells, determines the variation of the species composition in relation to environmental changes.

The relationship of nutrient discharges to water bodies with eutrophication processes is also studied. The model likewise compares ecosystems and identify which mechanisms regulate population dynamics in ecosystems. And since species have a natural response to environmental factors, it also defines which functional groups in communities integrate toxic and noxious species. The objective in obtaining and analyzing all these data is to be able to predict HAB events, observe them in situ, and develop models to describe and predict them (http://geohab.org/).

The IOC Intergovernmental Oceanographic Commissionmanages three aspects in this program: scientific, operational and educational. The educational aspect acquires great importance in developing countries where training is a pressing need (http://www.ioc-unesco.org/).

These courses provide updates on the definition of the phenomenon, local species that are toxic or noxious, distribution of these, and the areas most exposed to this phenomenon. Scientific aspect implies the creation of multisisciplinary and interinstitutional research groups among the governments of different nations in order to acquire a comparative knowledge of the biology and ecology of toxic microalgae, sampling methodology, intercalibration of techniques of counting, and evaluation of toxins. It is necessary that these programs have a direct link with the academy to achieve success at a global level.

Due to the large number of HABs organizations such as Mexican Society of Harmful Algal Blooms (SOMEFAN) and the Network of Harmful Algal Blooms (Redfan) were founded (https://redfan.cicese.mx/Secciones/inicio). From these meetings arise several work groups and teams driven by the common goal of studying the HAB in all its edges. The Mexican Society of Harmful Algal Blooms (SOMEFAN) was founded and a network of harmful algal blooms (Redfan) (https://redfan.cicese.mx/Secciones/inicio) was formed, where researchers from different institutions, industries, organizations, health sector participate to publicize their progress, receive support, and continue in this task.

In Mexico, SEMAR participates in monitoring programs with oceanographic cruises along coasts and with specific sampling in irrigation sites. Likewise, COFEPRIS participates by implementing preventive fishing prohibitions in case of a HAB.

During a HAB event, the authorities should avoid people having contact with the toxin, preventing people from swimming or consuming contaminated products, and signaling places at risk.

In addition to all this, the participation of citizens is necessary to take mitigation and prevention measures. Likewise, it is necessary to form teams with qualified personnel to identify the toxic species as well as the ecological factors that favor the appearence of HAB events.

10.7 Potential for Use and Biotechnological Applications with HAB-Forming Species

The HAB forming species are capable of reaching high population densities in natural environments and also in controlled environments. This fact is interesting because a large quantity of potentialy useful substances can be harvested for industrial and pharmaceutical uses as well as for cleaning the environment.

Such is the case of some dinoflagellates. *Prorocentrum lima* and *P. belizeanum* produce high amounts of okadaic acid and are used today to study cellular processes such as signal transduction, memory, cell division, and apoptosis; neurosciences is also concerned with toxin to treat neurodegenerative diseases and antipsychotic properties. Dinoflagellates of the genus *Amphidinium* are used to study L1210 mouse lymphoma, as well as KB cells of human epidermal carcinoma (Gallardo-Rodríguez et al. 2012; Assunção et al. 2017).

Symbiodinium dinoflagellate that grows associated with corals has shown activity against human colon cancer as well as against leukemia in mice. Simbiodimine and neo-symbiodimine are potentially useful against osteoporosis in humans (Gallardo-Rodríguez et al. 2012; Assunção et al. 2017).

Purified toxins such as saxitoxin can be used as topical anesthetic; tetratoxin is used as treatment against addictions to strong drugs such as heroin. Okadaic acid is also used in neurosciences for the treatment of psychotic and neurodegenerative diseases (Gallardo-Rodríguez et al. 2012; Assunção et al. 2017).

The dinoflagellate *Crypthecodinium cohnii* is commercialized in the United States of America as a source of polyunsaturated fatty acids (decosahexaenoic) (Ratledge et al. 2010).

Other groups such as cyanobacteria also have the hability to multiply excessively. These have been cultivated in order to obtain potentially useful metabolites with high commercial value. This is how numerous studies focus on the production of bioplastics from various polyhydroxybutyrate (PHB)-producing organisms that have similar mechanical properties to petroleum-based plastics, with the advantage of being biodegradable, biocompatible, and produced from sources renewable. Therefore, this polymer can be obtained and produced by bacteria and cyanobacteria (Segura et al. 2007; Ibrahim and Steinbuchel, 2010; Kadiyala 2014).

Several species of cyanobacteria accumulate considerable amounts of PHB such as *Gloeocapsa* sp., *Spirulina platensis*, *Aphanothece* sp., *Synechococcus* sp., and *Synechocystis* sp. Therefore, the industrial use of PHB-producing cyanobacteria would have advantages ranging from the production process, since they consume CO_2 (greenhouse effect gas) as a carbon source for their metabolic functions and could grow in wastewater effluents, being also a biodegradable product (Segura et al. 2007; Kadiyala 2014).

Likewise, some toxic species such as *Microcystis* sp. are considered to be the future of promising sources of biofuels and bioproducts. The algal carbohydrates can be fermented to bioethanol after pretreatment process. Efficient pretreatment of the biomass is one of the best requirements for commercialization of the algal-based biofuels (Vijayakumar 2012).

These are just some of the potential applications for these microorganisms, so we can take advantage of the HAB phenomena to obtain bioproducts that benefit the environment.

10.8 Perspectives

There are many investigations in relation to HAB events. However there are areas still little studied.

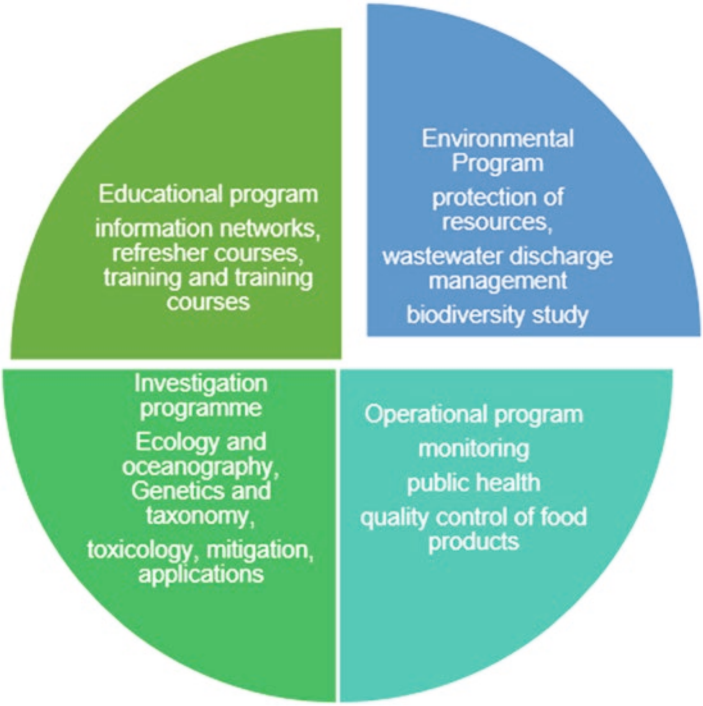

Fig. 10.6 Main points that a HAB management program should include

Advances in basic and applied research go hand in hand with those of other countries, as well as the integration of multidisciplinary and multiinstitutional research groups. However, economic support is required to be able to carry out a complete and timely investigation, for a good management of the HAB requires multidisciplinary, integrative, and nonexclusive work (Fig. 10.6).

The REDFAN is an important instrument to support a permanent monitoring programs in critical areas of the country. REDFAN is a fertil field to train researchers and students as well as inform people about the HABs.

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Chapter 11
The Importance of Aquatic Protected Areas and Other Policy Instruments in Fisheries Management

David Gutierrez-Carbonell and Juan E. Bezaury-Creel

11.1 Introduction

There is a large debate in México about marine protected areas (MPAs) and particularly no-take zones for the sustainable management of fisheries, with the debate hinging on if this tool is the best for migratory species like tuna supported by scientific studies and not only on ecosystem functionality. Both sides, environmetalists and ecology related governmental institutions versus fishermen and fisheries related governmental institutions, like Coallition for Sea Protection (CODEMAR) and National Commission of Protected Areas/Ministry of Environment (CONANP) versus large tuna and shrimp fishermen enterprises and Fisheries Institute (INAPESCA) and National Commission of Fisheries (CONAPESCA)/ Ministry of Agricultura and Fisheries (SAGARPA) have exposed arguments in favor of or in opposition to the promotion of new MPAs, both supported by ecological or fisheries-derived scientific information.

In Mexico, MPAs are based on The Environmental Law (Ley General del Equilibrio Ecológico y la Protección al Ambiente, or LGEEPA), where the purposes of each category, strict conservation, recreation-oriented categories, multiple-use categories, and zoning, are established. In addition, it is necessary to elaborate a management plan with clear rules of which activities are allowed and which are prohibited in each part of the MPA. Historically MPAs were established to protect species or ecosystems only after the exertion of much societal pressure and requests for a conservation tool. Thus, in the past, many efforts around the world concentrated on threatened or rare species (Hooker and Gerber 2004). In Mexico, for

D. Gutierrez-Carbonell (✉)
National Commission of Protected Areas, Mexico City, Mexico
e-mail: daguti@conanp.gob.mx

J. E. Bezaury-Creel
The Nature Conservancy Mexico (TNC), Mexico City, Mexico
e-mail: jbezaury@tnc.org

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example, several marine and terrestrial reserves have been established, such as the Monarch Butterfly Reserve for butterflies, and the Upper Gulf of California Biosphere Reserve for the endangered marine mammal *Vaquita marina*. It is not until recently that international agreements between countries have established goals and targets to be followed, such as those achieved at Aichi, Japan, in 2010 for the Convention of Biodiversity, where all signatory countries agreed on the Strategic Plan 2011-2020, and established, in Target 11, that by 2020, at least 10% of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, would be conserved through effectively and equitably managed, ecologically representative, and well connected systems of protected areas and other effective area-based conservation measures, and integrated into wider landscapes and seascapes (https://www.cbd.int/sp/targets/).

After that agreement many countries devoted a great deal of energy to establishing the largest MPAs in history; for example, the Ross Sea Region in the Antarctic, of 206,005,800 hectares; the Réserve Naturelle Nationale des Terres australes françaises in the Pacific Ocean, of 165,499,900 hectares; and the Papahānaumokuākea Marine National Monument around the Hawaiian Islands, of 151,655,700 hectares (https://www.protectedplanet.net/marine#distribution). This initiative has led to an increase in the number of MPAs, and an increase in their surface area of up to 6.6% of the oceans at present, from only around 2% eight years ago.

Mexico followed that initiative of establishing large MPAs; in December 2016 the largest MPA in the country was created: the “Pacífico Mexicano Profundo” Biosphere Reserve (Deep Mexican Pacific), with a surface area of 57,786,214 hectares, with the main objective being to protect sea bottoms, submarine mountains, and hydrothermal vents; though later this MPA was reduced to 43 million hectares to strengthen the Revillagigedo Islands to constitute Revillagigedo National Park with its marine portion as a no-take zone (DOF 2016).

Biosphere reserves are a multiuse category, with a core and buffer zones, with great acceptance in Mexico, because all the country is inhabited and the land does not belong to the government, so these reserves are a good instrument to protect biodiversity and they give landowners opportunities to make sustainable use of their resources. In the case of the Pacífico Mexicano Profundo, the declaration allows fishing activities, as long as fishing gear, such as trawling nets or dredges, does not damage the bottom of the ocean. This biosphere reserve covers from 800 meters depth to the sea bottom, leaving a good space in the water column for most superficial fishing, a requirement that was requested by the National Institute of Fisheries (INAPESCA).

National parks are more restrictive than biosphere reserves, and are oriented mainly for conservation and recreational activities. Revillagigedo National Park was established in November 2017 to protect the islands; in particular the marine realms were established as a no-take zone, excluding tuna fisheries and all kinds of sport fishing, with the main objectives being the conservation of natural resources and environmental services and the prevention of degradation or pollution arising from human activities (DOF 2017).

Protected areas in Mexico have a long history, starting in 1917 with President Venustiano Carranza declaring “Desierto de los Leones” National Park. Policies for national parks reflected United States policies for many years, being oriented to protect temperate forests for recreation, but there was no staffing and no funds to manage these areas until the 1990s; until then they were called “paper parks” for experts. Many national parks were also established in the 1930s by President Lázaro Cárdenas.

11.2 Marine Conservation in México

The history of marine conservation in Mexico is short, in contrast with the development of fisheries supported by Mexican policies for decades, particularly since the 1970s to 1990s and the first decade of this century. In the 1980s the Institution in charge on environment was under the Ministry of Urban Development was weak for compared with the Underministry for Fisheries, which had been strong since the 1970s (Guzmán del Pro 2012); in1982, a Ministry of Fisheries was created, followed by a National Aquaculture and Fishing Commission (Comisión Nacional de Pesca y Acuacultura; CONAPESCA) in 2000.

Conservation efforts were focused on species rather than on ecoregions or ecosystems as a whole. The first MPA was Ojo de Liebre Lagoon (Complejo Lagunar Ojo de Liebre), designed to protect the lagoons of Baja California, where the gray whale reproduces. The second MPA was established mainly to protect a geological feature, sand falls in front of Los Cabos, Baja California Sur. It was not until the concept of Biosphere Reserve in the UNESCO’s Man and the Biosphere (MAB) Programme in the 1970s when Mexico started to plan and develop policies that were regionally and ecologically oriented. The new concept fitted Mexican reality, where land does not belong to the government but mainly to communities and “ejidos”, (social organization established by law that not allows to sell land under any circumstances), so it is necessary to gain agreement from land owners for any kind of restriction of land use. In 1986, the Sian Ka’an Biosphere Reserve was declared; it has a substantial amount of marine surface in order to protect coral reefs, mangroves, and marine grasses (DOF 1986), and its total extent is 528 million hectares, 153 million hectares of which are coastal and marine.

Today 49 of Mexico’s 60 MPAs for marine environments are coastal, and they protect 90 million marine hectares, but the no-take area is only Revillagigedo National Park, consisting of a little more than 14 million hectares (Fig. 11.1).

Fisheries refuges (FRs) are supported by the Fisheries and Aquaculture Law (LGPAS) and are defined as: waters, and additionally their surrounding environment, of federal jurisdiction with the purpose of conservation, natural or artificial, to promote and develop fisheries resources for reproduction, growth, or species recruitment (DOF 2007). So finally an FR can be compared with an MPA, functioning as a conservation instrument if designed properly (Table 11.1).

But the FR instrument was not implemented until 2012 with very small steps in numbers and surface, and inside a biosphere reserve, losing the opportunity to test this new figure by itself. It is obvious that zoning in a biosphere reserve can establish core zones or preservation zones equivalent to an FR.

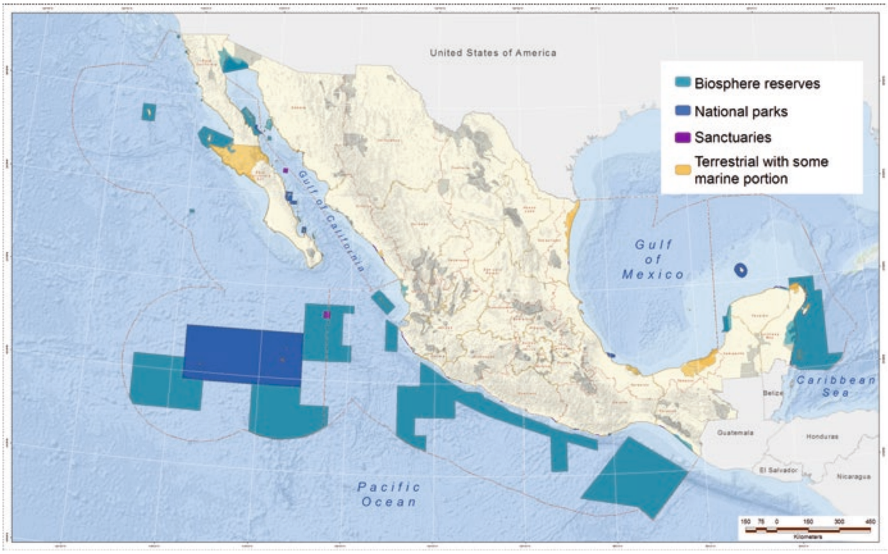

Fig. 11.1 Marine protected areas (MPAs) in Mexico

Table 11.1 Marine protected areas and fisheries refuges in Mexico

	MPA	Fisheries refuge (FR)
Established	Presidential declaration	Ministerial agreement
Actual surface area (hectares)	69, 458, 748	2007, 242[a]
Validity	Permanent	5 Years[b]
Actual number	49	40[c]
Declarations or agreements	49	8

[a]Golfo de Ulloa FR consists of 1993, 1,993,200 hectares, covers 99% of all FRs
[b]Golfo de Ulloa FR had a validity of 2 years in 2016 and was renewed for 5 years in 2018
[c]Several FRs in one agreement

There are some advantages in FRs; they are more flexible than MPAs, in the sense that a presidential declaration is not needed, but only a Ministry one. The FRs are not perpetual but have a temporary effective date, established by the Fisheries Authority, of between 2 and 5 years, with the possibility of extension or termination. An MPA must be declared by the President and is supposed to be for life, unless another President changes that situation, but this has never happened in Mexican history.

The first Ministerial FR was: "Acuerdo por el que se establece una red de zonas de refugio pesquero en aguas marinas de jurisdicción federal ubicadas en el área de Sian Ka'an, dentro de la Bahía Espíritu Santo en el Estado de Quintana Roo" (DOF 2012). This refuge established eight polygons; unfortunately, seven of them were 6 hectares on average, covering 40 hectares in all, too little for the ocean, considering the dynamics of the sea due to ocean currents and natural day-to-day

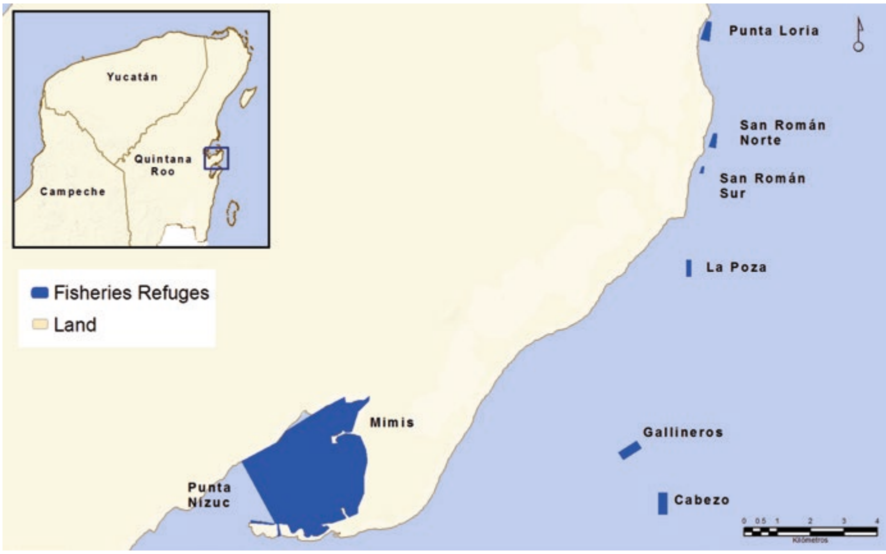

Fig. 11.2 First fishery refuge in Mexico, inside the Sian Ka'an Biosphere Reserve, established in 2012, with eight polygons, with a surface of approximately 1000 hectares

changes in marine conditions, and only one polygon covered around 1000 hectares in a bay. If the FR were established to protect sessile species or coral reefs then this FR would make some sense; instead, it was established "to protect reproduction processes for fisheries resources (like fishes and spiny lobsters), reduce mortality and promote biomass recovery". It is logical that these species cannot be considered permanent residents of the area, particularly because of its small size (Fig. 11.2).

11.3 Fisheries in México

Mexico's fisheries are definitively in crisis. A recent Organisation for Economic Co-operation and Development (OECD) estimate derived from studies of 54 Mexican fisheries has concluded that 63% of fisheries are at their maximum capacity, 20% are overfished, and 17% still have limited potential for growth (Costello et al. 2012).

Mexico's official information provided by the 2010 National Fisheries Chart supports this estimate, with percentages of 67%, 16%, and 16%, respectively, for 477 species. A national policy for sustainable fisheries is urgent, a policy that goes beyond the official speech of responsible authorities in research (National Institute of Fisheries and Aquaculture; INAPESCA) and management (CONAPESCA).

Arreguín-Sánchez and Arcos (2011) also used the National Fisheries Chart to analyze data, from 1956 to 2009, identifying five categories: collapse, over-fishing, maximum use, developing, and underdeveloped, concluding that the overall state of the fisheries has remained roughly unchanged since the late 1990s. However, they identified a higher proportion of resources tending to over-fishing; for 46.3% of the resources the use was maximum; over-fishing was considered to occur for 28.6% of resources, 6.9% of resources were in the development stage, and 18.3% had collapsed. The region with the highest proportion of deteriorated resources was the Central Pacific Coast and the region with the lowest proportion was the Eastern Gulf of California. Almost three-quarters of fisheries are developed by industrial fleets focused on tuna, sardine, and shrimp, the remainder of more than 400 species are caught by artisanal fishermen.

11.4 Protected Areas or Fisheries Refuges

We cannot be blind to the fact that most fisheries resources in Mexico are deteriorating, although some of them are improving; therefore immediate measures must be taken to recover fisheries stocks and damaged ecosystems that are in danger of losing functionality. We ask the questions: Are MPAs or FRs more important? Or are they complementary? And which other measures or regulations must be implemented?

Worldwide, MPAs are recognized as one of the better instruments used for marine conservation biology, and their numbers have been increasing constantly over the years (Fig. 11.3).

A number of authors have debated the need for MPAs, and their roles and effectiveness (Claudet et al. 2008; Agardy et al. 2010; Mills et al. 2010). Many factors have been identified, e.g., size, time duration of their function, particular characteristics of any ecoregion or ecosystems involved, size of marine ecoregions, human

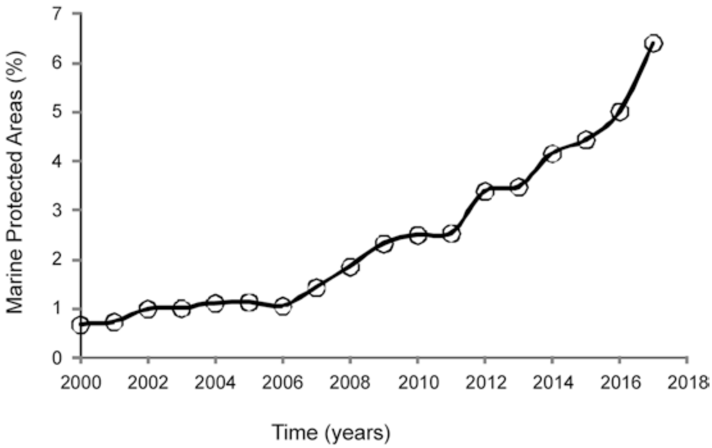

Fig. 11.3 Growth of marine protected areas (MPAs) in the last 15 years. Actual surface protected is 6.4% vs. less than 1% 15 years ago. (Source: https://www.protectedplanet.net/marine#distribution)

activities and governance, social opportunities or restrictions needed, available scientific information for deep analysis of each place, empirical information from local communities, flexibility to establish one large or several small areas, network designing, larval connectivity, magnitude of movements for migratory species, and local or regional conservation priorities. Establishing an MPA is not sufficient for biodiversity conservation; also, if expectations are not fulfilled this can lead to frustration, and critics may put the existence of the MPA at risk. If the MPA is not well designed or is not large enough to protect identified values or to protect people displaced from their residences, or to protect against lost economic activities relevant for local communities, then those issues will act against the viability of a particular MPA in the short or long term.

Mills et al. (2010) add to the debate the concept of networks; if conservation is possible not only is an MPA necessary, but several are required in an ecoregion to assure connectivity, genetic exchange, and viable populations. In general, there is common cause between experts that large MPAs are preferable to several small ones, particularly if they are no-take reserves; several authors have suggested a minimum size of 50,000 hectares, with results that are easily verifiable in the short term (Agardy et al. 2010; Halpern and Warner 2003; Russ et al. 2012). Nevertheless, there are some species with a high range of movement, such as tuna and sharks, where even a very large MPA adds little for conservation purposes; in such cases before starting a process to establish a large MPA that could affect artisanal fisheries or essential livelihoods for local communities (Palumbi 2003; Planes et al. 2008; Harrison et al. 2012), it is necessary to consider other scales for oceanographic conditions, such as ocean currents for larval transportation, and reproductive areas or feeding grounds. Even in an MPA designed to understand whether fish larvae remain locally or are transported or recruited over long distances, it is necessary to improve existent scientifc data in order to take decisions for the future, like if a protected area needs to be changed in its dimensions or regulations (Hooker and Gerber 2004; Christie et al. 2010; Almany et al. 2007; Cudney et al. 2009; Planes et al. 2008).

There is no acceptance of MPAs between fisheries people, scientists, and producers because they do not see clear evidence of benefits; there is a need for the best scientific information to be available at all times and over long periods of time, and such resources are not always available (Sale et al. 2005). Locally there is much more evidence in ecosystems such as coral reefs, where the larvae of many species remain (Christie et al. 2010; Hooker and Gerber 2004; Almany et al. 2007).

There are other sets of legal instruments in Mexican national laws besides MPAs and FRs; for example, temporary or permanent closures, Mexican Official Norms, and capture quotas. Also, while it is not necessary for environmental protection or fish population recovery, maintaining the prices of products, to protect the way of life of certain coastal communities, could reduce conflicts between groups of fishermen, could help to facilitate scientific research, and could help to diversify local economies looking for productive alternatives while a closure is in progress (FAO 2012). The establishment of no-take zones against industrial fishing is well documented to benefit artisanal fishermen or wildlife; for example, in South Africa, industrial fishing was devastating for penguin prey and as a consequence penguin populations were reduced to half their former size, but once a no-take zone was established the population recovered relatively rapidly (Pichegru et al. 2012). Other scientists are convinced that no-take reserves are the only viable long-term regulation against multiuse protected areas, and a very strict closed area is the only way for marine life replenishment (Jones 2007; Lester and Halpern 2008; Pichegru et al. 2012; Roberts 2012; Sale et al. 2005)

11.5 Networks of Marine Protected Areas

Gaines et al. (2010) are more optimistic and are designing networks for protected areas and also for FRs. Although some evident results of some no-take zones have shown repeatedly that such zones are able to enhance the abundance, size, and diversity of species, these benefits do not occur for most marine species, because, typically, the individual protected areas are small. Hence, there is a need for networks with a regional view, rather than taking into account only some target species or the life cycles of commercial species, so knowing the basic ecology and oceanography of an ecoregion, it is possible to design a network of desirable size and spacing. One of the best examples is in The Great Barrier Reef in Australia, a live laboratory where 100 years of theories have been piloted, confirming that MPAs are tools that help to manage fisheries (Almany et al. 2007; Planes et al. 2008; Roberts 2012).

11.6 Governance

One of the last points to consider is governance. Theoretical planning of size, spacing, target species, or time in effect sometimes does not take people into consideration. People are one of the main issues to be considered in the equation in developing countries, as the worst enemies of a process are misunderstanding, fake news, or rumors that provoke delays or even the end of a project. In Mexico public consultation is mandatory by law in all kinds of processes, particularly for Indigenous peoples, but sometimes political considerations that require short-term results lead to disastrous results. MPAs undoubtedly are promoted as an important marine ecosystems management tool; however, serious challenges have been raised with regard to their effectiveness (Jentoft et al. 2007). Fisheries refuges in Mexico have been so small in size that they have provoked no reaction against them by fishermen, with the exception of the large one at “Golfo de Ulloa FR”; this refuge, was renewed by five more years with great rejection of artisanal fishermen, besides there are not a strong regulations, had a validity time for 2 years and the time for evaluations was at all views insuffcent to obtain serious scientific conclusions.

As mentioned before, there are three main industrial fisheries in Mexico, sardine, tuna, and shrimp; the first being the most fished in volume and the last the most important economically. Around 70–75% of the national fish product comes from the Gulf of California. More than 400 other species are fished mainly by artisanal fishermen, so it is needed to be taken into account for governance to consider the large amount of artisanal fishermen and not only the big entrepreneurs. For example, every September a war is started by artisanal and industrial fleets fishing for shrimp, although it would be relatively simple to establish measures to divide the resource for all, with benefits for all. There are cases in other countries where the planning of an MPA network was established on a regional scale – essential and complex available information was distributed to stakeholders, scientists, and policy makers with different areas of technical expertise and knowledge, and the initiative focused on compiling relevant information on the ecological and socio-economic context of the region (Gleason et al. 2010).

In Mexico there is an exemplary case study. Artisanal fishermen asked for a multiuse MPA with a core no-take zone around Cedros Island in the Eastern Pacific as a measure to avoid conflicts with industrial fishermen. In 2003 they sent an official letter to the government for the area; in 2005 the government published, in the Official Newspaper a notice of intent to start public consultation, and, after years of debate, the “Islas del Pacífico de Baja California” Biosphere Reserve was declared (DOF 2016). It took more than 10 years to get information to support the initiative and to demonstrate benefits for local communities, and local fishermen will be the main actors and beneficiaries of this MPA success.

Some basic elements need to be considered for good governance; namely, among others, involving all groups and interests in project designing, sharing information and responsibility with stakeholders for management, fostering participatory decision making, fostering adaptive decision making, deciding on process guidelines before attempting to make substantive choices, promoting decision-maker accountability, establishing advisory committees, making MPA rules and boundaries clear, building accountability into enforcement, making the punishment for illegal activities, and measuring both biological and social performance (De Santo 2013; Jentoft et al. 2007; McCay and Jones 2011; Mascia 2003).

11.7 Management Effectiveness

The best way to solve any debate is by taking advantage of information – the best available scientific and empirical information – and that will lead processes. With the selection of proper indicators, it is easier to check results. Elements developed by the World Wildlife Fund for Nature have been integrated in RAPPAM methodology (Rapid Assessment and Priorization of Protected Area Management; Ervin 2003). This methodology involves:

Funding. Inadequate funding is the major weakness in any system.

Staffing. Lack of funding can be the indirect cause of staffing inadequacies, but capacity building, coaching, and study levels are other factors involved.

Research and monitoring. The best science and the best knowledge, both biological and social, provide the basis for the best decisions.

Natural resource inventories. Where are the resources, and what is their condition, abundance, and risks?

Community relations. The best management plan is useless if there is no support for allies and stakeholders.

11.8 Conclusions

There is no one regulation that is better than any other, but, rather, there is a proper one for every case. After all, regulations can work as complementary tools, and we need to apply the tools depending on the challenge, but if we do not allow the tool to be tested, do not give it time, and do not make an effectiveness analysis, then it is useless to continue arguing whether MPAs or FRs are superior vehicles for fisheries management. Unfortunately, in Mexico FRs are a simulation, because they have been established without a strong information basis, are small in scale, have only short-term validity, and entail no process of effectiveness analysis.

The first step to identifying a fisheries problem is with the best available scientific information. There must be well defined objectives for replenishment, population recovery, and ecosystem conservation. Also, the size of the problem area must be identified, and it must be defined whether it is local or regional, a large marine ecoregion or a small reef, or oceanic or coastal. Then a logical follow up will appear if one or several areas is needed or a network, size of each one and distance between them. Stakeholders, scientists, local authorities, and environmentalists must be involved before decisions are taken.

There has been no time to sufficiently evaluate either MPAs or FRs in Mexico, and we need time and effort for this evaluation before proceeding with establishing new MPA or FR, or modifying the actual ones. Two to 5 years in nature is almost nothing for a serious evaluation and this time span is even more insufficient if the area in question spans many hectares.

There are other tools to complement those noted above, such as permanent or temporary closed seasons or areas set aside for reproductive reasons or to protect juveniles. Fisheries management can be planned according to species, with, for example, minimum legal sizes, capture quotas, and Official Norms. Harmonizing all instruments and policies will help to achieve the optimal and sustainable use of natural resources.

But nothing will work, absolutely nothing, if there is no law enforcement with strong fines and punishments (Campbell et al. 2012). In the Upper Gulf of California many instruments have been applied over the years: an MPA, a large closed area for fisheries, a wildlife refuge, large subsidies, boat buy outs, temporary permits leases in fishing equipment, and the promotion of activities other rather than fishing. But nothing worked for saving the *Vaquita marina*, because of failure in the enforcement of environmental and fisheries laws.

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