Cuatro Ciénegas Basin: An Endangered Hyperdiverse Oasis

Valeria Souza
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Luis E. Eguiarte *Editors*

Conflicts Between Biodiversity Conservation and Humans

The Case of the Chihuahua Desert and Cuatro Ciénegas

Springer

Cuatro Ciénegas Basin: An Endangered Hyperdiverse Oasis

Series Editors
Valeria Souza, Universidad Nacional Autónoma de México
Ecology Institute, Mexico City, Mexico

Luis E. Eguiarte, Universidad Nacional Autónoma de México
Ecology Institute, Mexico City, Mexico

This book series describes the diversity, ecology, evolution, anthropology, archeology and geology of an unusually diverse site in the desert that is paradoxically one of the most phosphorus-poor sites that we know of. The aim of each book is to promote critical thinking and not only explore the natural history, ecology, evolution and conservation of the oasis, but also consider various scenarios to unravel the mystery of why this site is the only one of its kind on the planet, how it evolved, and how it has survived for so long.

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Editors
Valeria Souza
Instituto de Ecología
Universidad Nacional Autónoma de
México (UNAM)
Mexico City, Mexico

María C. Mandujano
Instituto de Ecología
Universidad Nacional Autónoma de
México (UNAM)
Mexico City, Mexico

Irene Pisanty
Facultad de Ciencias
Universidad Nacional Autónoma de
México (UNAM)
Mexico City, Mexico

Luis E. Eguiarte
Instituto de Ecología
Universidad Nacional Autónoma de
México (UNAM)
Mexico City, Mexico

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Preface

Agua ¿a dónde vas?
Federico Garcia Lorca
1898–1936
Spanish poet and playwrither,
who was executed during the Spanish Civil War.

Agua, ¿dónde vas?
Riendo voy por el río
a las orillas del mar.

Mar, ¿adónde vas?
Río arriba voy buscando
fuente donde descansar.

Chopo, y tú ¿qué harás?
No quiero decirte nada.
Yo…, ¡temblar!

¿Qué deseo, qué no deseo,
por el río y por la mar?

(Cuatro pájaros sin rumbo
en el alto chopo están).

============
Water, where are you going?
Laughing I go by the river
to the shores of the sea.

Sea, where are you going?
Upriver I am looking for
a fountain where to rest.

Poplar, and you, what will you do?
I don’t want to talk to you.
I … tremble!

What I wish, what I don’t wish,
for the river, for the sea?

(Four aimless birds
in the high poplar they are).

Editors translation

Life is wonderful; life arose in water; life is amazing and beautiful without doubt. So says literature and music, so says painting and sculpture, so says everyday experience. Scientific knowledge says this also, despite a general hesitance to perceive science as a powerful and creative tool to describe and analyze nature in a lovely way. Life is also complicated, for what we have the chance to see with plain eyes, it is the result of long, complex interacting processes that are the product of ancient and, at the same time, recent processes that occur at short, medium, and long time terms.

However, life, in all of its complexity is sustained by a few basic components, among which water is outstanding because no simple or complex form of life can develop or survive without this simple molecule. Many organisms need oxygen to live, but there are also those which thrive without it, in anoxic conditions. All organisms need nutrients, but some can survive with very little amounts of some of them. However, absolutely all organisms that inhabit our blue planet need water to survive, even if it is only available from time to time.

Water is, in many ways, the “holy breath” of life. All levels of biological complexity, all levels of organization of life depend on water availability. Even the most drought-resistant organisms need at least a certain amount of water. As a consequence, many amazing adaptations have evolved among all types of organisms to withstand both too little and too much water. Therefore, life cannot be indifferent to water by itself, then water is, in a way, life.

Needless to say, as any living creature, including us humans, need water to survive. Our livelihoods depend on water as much as ourselves. Contrasting with all other organisms, we need additional water to irrigate our food and our food’s food. We also need water for our machines, that provide electricity, transportation, and all sorts of products. Water is present in absolutely everything we are and do as individuals and as societies. Water sustains all that we humans are. Consequently, we consider that it should be evident that water is precious to our species, to say the least.

As a vital element, water has been worshiped through deities in many cultures, Asiaq in the Inuit from northern Canada, Tó Neinilii of the Navajo pueblo, Tlaloc for the Aztecs, Chaak in the Mayan culture, Yemaya in the Yoruba religion of West African, Qebhet a deity who gave freshwater to souls in Egypt. This is true all over the world. Please, imagine how additionally important rain deities are in arid and semi-arid zones, where water cycles determine absolutely everything.

Modern times move and evolve beyond gods and goddesses, and in many ways also beyond natural limitations, thanks to what seems a never-ending development of all sorts of technologies. Water is made available to humans and their activities through things that even the ancient gods would not have imagined. However, no matter how much water we collect in dams, how much water we divert from a river or lake, or how much of this precious liquid we desalinate from the ocean, we still have a basic, and inalienable need: freshwater. No matter how much technology we can develop, we will always be biological humans—unless we all turn into robots or computers—and humans are simply "rational" animals that depend on basic natural processes. Therefore, we cannot eliminate water or air we breathe (or many other basic natural things) from our lives.

The importance of water for life is part of the most basic knowledge necessary to survive. Prehistoric people knew it well; the nomads looked for water and food, just like the first farmers and ranchers. Furthermore, both empiric and scientific knowledge understand this very well. Every day great efforts are made to make water available. How, then, is it possible that freshwater has been so mismanaged so many times, over and over again in many places on the planet? How water went from being one of the four different elements of mythology that shaped the world, and passed from being an endless renewable resource in the 1960s, to being non-renewable in the present, an element so scarce, that freshwater has become part of the stock market? Why have so many places in the world been abandoned? Is it because of lack of water due to pollution and overexploitation? In fact, the answers are complex and become even more complicated due to the variety of contradictory answers these questions have received, but no one will answer "Oh, well, we evolved as a species and we no longer need water, so we can do whatever."

Our modern power-driven society is one that believes in technology, but we do not realize that, we are no different from the Easter Island (Chile, Isla de Pascua)—Rapa Nui society, which used all its resources to pray to the stone gods in order to bring water to their ravaged dry islands. Nowadays, we are just worshiping different gods; they have the heart of a machine and we pay them with money and our language towards those modern deities is complex and sounds more like lawyers talk. However, the ply is the same; we need more water, now. Today, the ever-increasing demand for water has been accompanied by all kinds of regulations, including, of course, economic considerations. Nevertheless, fresh, clean water is becoming a precious jewel, more valuable than money in dry regions with overexploited aquifers. As a result, water wars and all kinds of conflicts could be just around the corner and, in fact, are already happening in some localities.

Overexploitation and mismanagement of aquifers have affected many regions of the world. What a few decades ago seemed like a triumph of human engineering that turned the dry desert into green agriculture through the use of pumps and dams has had enormous effects on arid and semi-arid lands, where water was already scarce for all living things, including humans. Water extracted from ecosystems needs integrity of the system to be available.

Let us remember that some very arid zones, such as the Gobi and Atacama deserts, are almost deprived of life, but there are still wonderful creatures adapted to these extreme environments, all of them showing incredible adaptations towards these extremely harsh environments. Other deserts are different because due to several causes they are not so dry, but can be very seasonal and unpredictable, and can harbor a surprising diversity. Also, some deserts have more water than might be expected due to localized water sources, as sometimes a river crosses them, sometimes oases are made up of desert springs, or in other cases complex hydrological systems create discrete water habitats in the middle of a desert. These remarkable sites have strong local and often regional ecological effects and can create conditions for successful human settlements that thrive on the availability of the basic element of life, water.

However, these desert oases have been devastated around the world by human greed for more water and now face dramatic disturbances that can—and have—completely destroyed many of them, along with all their ecological significance and beneficial effects for humans. This is certainly far from sustainable.

In this volume, a group of specialized authors review some of the many aspects of water mismanagement and conflicts in a region that is unique in so many senses: the Cuatro Ciénegas Basin (CCB), a hyper-diverse oasis located in NE Mexico. The water springs of CCB are current windows to the past and future of life, and now they are at risk of being lost forever. The many extraordinary physical and biological features of this site have been thoroughly explored in the previous five volumes of this series. In this last volume, we focus on the complex relationship between humans and water, and the consequences of how different recent decisions made by different stakeholders have affected the basin and its astonishing biodiversity, and will continue to do so, unless conflicts between the people's daily life and the conservation of an ecosystem that profoundly influences them are resolved in a direction that allows a fair protection of both human beings and the ecosystems.

This book comprises 11 chapters. In the first one, Alberto Búrquez, regarded as one of the best desert experts of Mexico, makes a masterful description of the beauty and power of the deserts of North America and the lasting impression they cause. Alberto in particular explains how the deserts of northwestern Mexico and southwestern USA originated, how their flora and fauna evolved, and how the humans colonized and used the deserts in different ways, and how recent human activities are destroying these paradoxically fragile environments because of the water scarcity. Building from this ecological and historical perspective, Yuri Leopoldo De la Rosa Gutiérrez, in Chap. 2, describes, from an archeological perspective, the early human inhabitants of the deserts of North America, in particular of the actual state of Coahuila in Mexico. Yuri explains how they managed not only to survive but to prosper in this harsh and seasonal environment, and their relationships with water, based all this in his own studies of their cave paintings and arts, artifacts, and other remains of their activities.

In Chap. 3, Carlos Manuel Valdés Davila, Claudia Cristina Martínez García, and Ana Sofía Rodríguez Cepeda retake the history of the desert of Coahuila after the Spanish arrival to the area. The history of the Spanish colonization of the area is far more complex than what we usually suspect, as different religious and civilian groups from different areas of Spain arrived with different cultural experiences, methods of dealing with always scarce water and food production to the region, starting with Franciscan friars in 1567 and an administration originally form the

Basque country. The authors go to an astounding effort of disentangling this complex history from the fragmentary information in available archives, describing the complex and dramatic changes and declines of Native American populations, and in particular of the complex and long history of the town of Cuatro Ciénegas, the focal area of this and the rest of our collection of books.

Indeed, water management has always been a problem for the arid lands of Mexico. In Chap. 4, Miguel Angel Sorroche Cuerva describes how water has been managed in the country, from the pre-Hispanic ancestral practices to the methods and their implementation by the Spaniards, based on their own experience from living also in a dry country, derived both from medieval Muslim and Christian traditions, but in many cases disrupting the pre-Hispanic dynamics. In this chapter, water management techniques and their changes in time in a desert area are exemplified with the history of the mission of Baja California. In the next Chap. 5, the complex and in many cases contradictory laws regarding water use and management and environmental conservation of Mexico, from the independence to the present, are carefully reviewed by Teresa Souza Bosh. In this chapter, Teresa also reviews the legal status of the Cuatro Ciénegas protected area and discusses how to better use the available legislation to protect this and other wetlands and their water.

The water of Cuatro Ciénegas is precious for all its remarkable diversity of plants, animals, fungi, and microbes, and for this reason, Oscar Adrián Leal Nares, Gabriela Rendón Herrera, and Mauricio de la Maza Benignos describe in Chap. 6 their original study aimed to analyze the legal status and the available water resources of the Cuatro Ciénegas protected area. After their analysis, they concluded that the Mexican water authority (CONAGUA) should exercise its powers to reverse the water overexploitation in the area and to reestablish the water balance of the Cuatro Ciénegas aquifer to ensure its long-term environmental sustainability. In a dramatic Chap. 7, Evan W. Carson carefully describes how the water slowly disappeared from the Churince system and how the animals, microbes, and plants that only lived there also died. Churince was one of the most diverse and better studied water systems of the Cuatro Ciénegas basin; in Chap. 8, Irene Pisanty and colleagues analyze in detail the populations dynamics of three plant species, *Samolus ebracteatus* var. *coahuilensis*, *Flaveria chlorifolia*, and *Schoenus nigricans* and how little by little their populations changed and finally almost disappeared, acting as the “canaries in the mine” of the environmental degradation of the area due to the progressive loss of water. They concluded that the loss of water in the Cuatro Ciénegas Basin is still ongoing, and now it is time for everyone to respond before all this precious water is gone forever.

Microbe species and populations can also become extinct, despite the fact that they have been around for millions of years. In Chap. 9, Manuel II García-Ulloa and colleagues describe the population and evolutionary dynamics of two species of bacteria, *Pseudomonas otitidis* and *Bacillus coahuilensis* that used to be frequent and abundant species that have now completely disappeared in the Churince system. The authors also analyze how the high diversity and endemicity and local distribution of the microbes of Cuatro Ciénegas make it very vulnerable to extinctions, thus risking its unique microbiota that has survived eons.

In a more optimist note, Héctor Fernando Arocha-Garza and Andrés Espinosa Montes in the next chapter discuss the roles of education and of the children in conservation of water and of the biodiversity of Cuatro Ciénegas, in particular the effort done at the local high school, the CBTA 22, and other local social initiatives.

The last chapter of the book, by Valeria Souza, Gabriela Olmedo, and Luis E. Eguiarte discusses the perspectives derived from the different chapters of the book, describing how the Cuatro Ciénegas basin started to lose water in the last century, and how their research program started and developed. They mention the future perspectives for the conservation of water and biodiversity, in addition to ensuring the development and health of the human populations in the basin. The authors also are concerned about how to use the lessons learned from Cuatro Ciénegas for future water conservation in arid lands of Mexico and the world.

Humanity as a whole needs to rethink water, recognize it as a vital and limited resource and, in a sense, return to the worship that this liquid received as sacred. Water originated, as well as all the chemical elements, in ancient supernova explosions, and while water it is one of the most abundant molecules of the universe, it is generally unavailable for life, as it is frozen or salty. Our blue planet, that pale blue dot in a solar system, in a galaxy we call the Milky Way, is rich in liquid water: let's keep it where it belongs, clean and available for future generations of humans, as well as other organisms—plants, fungi, animals, and microbes, and for those that will follow us.

Mexico City, Mexico

Valeria Souza
María C. Mandujano
Irene Pisanty
Luis E. Eguiarte

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Contributors

Hector Fernando Arocha-Garza Genesis 4C, Cuatro Ciénegas de Carranza, Coahuila, Mexico

Alberto Búrquez Departamento de Ecología de la Biodiversidad, Instituto de Ecología, Universidad Nacional Autónoma de México, Hermosillo, Sonora, Mexico

Evan W. Carson San Francisco Bay-Delta Fish and Wildlife Office, US Fish and Wildlife Service, Sacramento, Albuquerque, CA, USA

Biology Department and Museum of Southwestern Biology, University of New Mexico, Albuquerque, NM, USA

Gabriel Cervantes-Campero Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

Yuri Leopoldo Dela Rosa Gutiérrez Centro Instituto Nacional de Antropología e Historia (INAH), Saltillo, Coahuila, Mexico

Luis E. Eguiarte Departamento de Ecología Evolutiva, Instituto de Ecología, Universidad Nacional Autónoma de México (UNAM), México City, Mexico

Andrés Espinosa Montes Plan Cuatro Ciénegas 2040, Cuatro Ciénegas de Carranza, Coahuila, Mexico

Manuel García-Ulloa II Departamento de Ecología Evolutiva, Instituto de Ecología, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

Oscar Adrián Leal Nares Pronatura Noreste AC, Monterrey, Mexico

María C. Mandujano Departamento de Ecología de la Biodiversidad, Instituto de Ecología, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

Claudia Cristina Martínez García Facultad de Ciencias Sociales e Investigación y Difusión del Patrimonio, Universidad Autónoma de Coahuila, Saltillo, Coahuila, Mexico

Mauricio de la Maza Benignos Pronatura Noreste AC, Monterrey, Mexico

Gabriela Olmedo-Alvarez Laboratorio de Bacteriología Molecular y Ecología Microbiana, Departamento de Ingeniería Genética, CINVESTAV – Unidad Irapuato, Irapuato, Mexico

Cynthia Peralta-García Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

Irene Pisanty Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

Gabriela Rendón Herrera Strategic Communication Planning of the Executive Committee of the Permanent Forum on Binational Waters, College Station, TX, USA

Ana Sofía Rodríguez Cepeda Facultad de Ciencias Sociales e Investigación y Difusión del Patrimonio, Universidad Autónoma de Coahuila, Saltillo, Coahuila, Mexico

Mariana Rodríguez-Sánchez Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

Miguel Ángel Sorroche Cuerva Department of Art History, University of Granada, Granada, Spain

Valeria Souza Departamento de Ecología de la Biodiversidad, Instituto de Ecología, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

Teresa Souza Bosh Consultoria Legal Ambiental, Ciudad de Mexico, Mexico

Carlos Manuel Valdés Dávila Facultad de Ciencias Sociales e Investigación y Difusión del Patrimonio, Universidad Autónoma de Coahuila, Saltillo, Coahuila, Mexico

Chapter 1
A Land of Illusions and Thin Air

Alberto Búrquez

In 1901, John Van Dyke, a New Jersey professor of art history, following his doctor's advice, traveled west seeking a cure for his chronic respiratory ailments. He moved from the civilized, temperate world of the east coast to the wildest of places in the southwestern deserts. At the time, the dry, desert air and the abundance of sunshine were the only cure for lung disorders. He became smitten by the desert landscapes and the astonishing atmospheric effects. He wrote: *The deserts should never be reclaimed. They are the breathing space of the west and should be preserved forever*. In his famous essay, *The Desert* (Van Dyke 1901), he later added: *To speak about sparing anything because it is beautiful is to waste one's breath and incur ridicule in the bargain*. [However,] *The aesthetic sense, the power to enjoy through the eye, the ear, and the imagination—is just as important a factor in the scheme of human happiness as the corporeal sense of eating and drinking; but there has never been a time when the world would admit it*. Van Dyke's message is as valid today as it was in the days when he was traversing the drylands of the southwestern USA and northwestern Mexico. At the time, the world had five times fewer people, and Mexico had only one-tenth of its present population. The deserts were almost pristine, and Van Dyke's claim to protect them was fulfilled more by their remoteness than by any human effort.

The desert, with deceiving horizons and mountains that seem closer than they are, is not an easy place for living or working. In the summertime, the weather is almost always too hot. Later in the year, winter days bring that cold that goes through your bones, and on days when the temperature is bearable, it turns too dry. Once rainfall arrives, it comes as a deluge with roaring arroyos and flooded plains.

A. Búrquez (✉)
Departamento de Ecología de la Biodiversidad, Instituto de Ecología, Universidad Nacional Autónoma de México, Hermosillo, Sonora, Mexico
e-mail: montijo@unam.mx

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At the start of the summer rains, it turns into a sultry, humid, and oppressive sauna. For the discerning newcomer, the desert induces an unavoidable state of trance, where perception is defeated by the sparkling blue skies and the spotless landscapes, sometimes colored by gaudy ochre and red and sometimes by subduing pastel hues. Desert daily rhythms start with the sunrise, fresh and promising at dawn, dilutes into fata morgana mirages as the day progresses, and ends in a violent display at sunset. Then, twilight comes while deceivingly peaceful night falls. At night, everything seems quiet, but plants and animals keep busy. Some desert plants silently transform carbon dioxide into chemical 4-carbon molecules inside their cells. The next day, these will be transformed into sugars by the process of photosynthesis, miraculously fixing light into organic matter. Some animals will harvest seeds or run after small prey while scurrying under a starry sky. Time is the main ingredient to get an understanding of the desert. As time passes, we better appreciate its aesthetics and richness and forget about the discomfort.

What we call Mexico today is mainly a territory of deserts and mountains in the north and tropical forests in the south. A jigsaw puzzle of different biological, geological, climatic, and cultural landscapes, a set of environments moving to new positions throughout its evolutionary history. In deep time, these blocks—which were in other places assembling other continents—came together in a tectonic dance to build southern North America. By the Cretaceous, North America was relatively simple, Laramidia to the west and Appalachia to the east. A shallow seaway separated both subcontinents. The south, called by some Deep Mexico, is much more complex. It is formed by terranes—blocks—with names like Chortis, Maya, Guerrero, and Oaxaquia. Some of these are in turn the result of even older accretion of blocks.

Earth, ironically, is mainly sea. The continental terranes made of lighter elements are prehistoric Noah's arks carrying their biota, sometimes isolated, across the marine realm. The case of the Baja California Peninsula illustrates well how pieces of the continent split and drift. The peninsula started a slow divorce from the continent millions of years ago. It has been carrying a biological treasure of unique, sequestered species. Geologists indicate that the small seaport of San Felipe, near the Colorado River delta, will be near the Golden Gate in a few million years. On their pilgrimage, reassembling fragments of the light continental crust, sometimes end capturing pieces of ancient seas. For example, during the Ediacaran and Early Cambrian, about 600 million years ago, evaporites of the Salt Range Formation in the Pothohar Plateau produced the coveted Himalayan pink salt derived from old shrinking seas.

In what is now North America, the fragments of the Western Interior Seaway ended trapped in northern Mexico by the accretion of terranes during the Late Cretaceous. The convergence center of these wandering terranes (Guerrero, Oaxaquia, Central, and others) happens somewhere in the Northern Mexican Plateau, not far from the area some people call The Lost Paradise. A place of stark mountains, desolate desert, and crystal-clear blue lagoons. In a sense, John Milton's remark about nature gifts is highly appropriate for the region: *Wherefore did Nature pour her bounties forth, With such a full and unwithdrawing hand, Covering the* *earth with odours, fruits, flocks, Thronging the seas with spawn innumerable, But all to please and sate the curious taste?* The whole region, seemingly arid and dry, on second thoughts, has an amazing richness of environments, flora, and fauna as well as varied mineral deposits.

In addition to the deserts of northern Mexico, whose niche partitioning—as ecologists call the apportioning of the available resources among species—happens mainly across horizontal gradients of temperature and water availability, there are two other prominent terrestrial regions of Mexico: tropical forests where niche partitioning primarily occurs along vertical light gradients and temperate forests distributed across the extensive mountain ranges typified by extremely low temperatures during winter and a diverse Nearctic tree flora. Given the broken topography across the country, these three broad units are geographically related and share three biogeographic origins. The very old North American elements (Paleoamerican), the more recent Northern Hemisphere properly (Nearctic), and those of tropical origin, including the remains of the tropical flora which flourished in North America during the Tertiary. All these are present in varying proportions across the country and produce the richest biodiversity hotspot of the continent.

Mexico, with its southern powerful rivers and prominent mountain ranges flanking both coasts, is the Sweet Land (*La Suave Patria*) where the *sky is filled with heron's flight and the green lightning of parrots' wings*. However, the poet López Velarde, who speaks of a land of mountains, mines, green jungles, and maize fields forgot to mention that more than half of the country comprises drylands where few dared to go, even with the promise of Cibola and the Golden cities. A place where herons journey among distant, isolated oases, and parrots live in deep Sierran canyons.

On the environmental background of ancient, vanished seas and wandering geological blocks that shaped the Sweet Land, a few human bands arrived into a pristine territory only 20 to 30 thousand years ago. Some say that across the frozen Bering Sea, others now claim that sailing along the western North American coast, and some invoke perplexing migrations paths after finding Aboriginal Australian genetic signatures in South American native people. As happens with the dispersal of plants and animals, at first these early migrants, being few, left little remnants. Some include the mammoth that Emil Haury excavated in the border between Arizona and Sonora in 1952 (Haury 1953) and the gomphothere remains at *El Fin del Mundo*, an ancient locality in the Sonoran Desert (Sánchez et al. 2014), both associated with Clovis spear points. About 60 years ago, in the Cuatro Ciénegas region of the state of Coahuila, in northern Mexico, two well-preserved human footprints more than 10,000 years old were found in tuff deposits near the Sierra San Marcos y Pinos, and recently more footprints have been recorded near the lagoons (Felstead et al. 2014).

It is not difficult to imagine these early humans finding the lagoons in the middle of the desert while chasing ancient bison, gomphotheres, mammoths, and other large mammals. They were inadvertently witnessing the end of an era. At the end of the last glacial—known in North America as the Wisconsin glaciation—after a long summer day, they might have jumped into the balmy thermal waters of the lagoon. A big relief following a strenuous walk stalking prey. Unknowingly, they disturbed the rich bacterial communities that thrived in the translucent waters. The hunter-gatherers of the end of the last glaciation traversed across conifer forests in the high sierras, and mesquite, oaks, junipers, and pinyon pines in the lowlands (Van Devender and Burgess 1985). These assemblages were plant and animal communities of which we have no contemporary analogs. Biomes where desert and temperate species freely mixed (Minckley et al. 2019). Today, plant communities are markedly drier. Creosote bush (gobernadora, *Larrea tridentata*) is now dominant, especially in the extensive old alluvial valleys. Yuccas and prickly pears, along with a seemingly infinite number of lechuguilla agave, form extensive succulent and rosette desert scrub communities. Even in the high ranges, most of the temperate species have disappeared, and the ones left behind are fast climbing the highest mountains to escape the accelerated warming of climate change.

Since the conquest of Tenochtitlan, the endless deserts of the arid north were the challenging frontier to dominate. Soon after the conquest, Europeans started traveling along already ancient roads. The *Camino Real de Tierra Adentro*—the Inland Road to the North—was the main artery communicating Mexico City with San Juan Pueblo, north of Santa Fe. It traversed the Chihuahuan Desert, and its trace can still be followed along the highways linking the major cities of northern Mexico and New Mexico. These pathways were well trodden by Native Americans carrying much commerce and goods exchange across long distances. For example, the Sonoran Desert toad has been associated with Mayan rituals in the Peten and Yucatán peninsula (Davis and Weil 1992), and the tropical scarlet macaws were traded and bred in the North American Southwest (Minnis et al. 1993).

These old paths were once traveled by Alvar Núñez Cabeza de Vaca and three companions in an epic saga of discovery and survival (Núñez Cabeza de Vaca 1555). Cabeza de Vaca was part of the ill-fated Pánfilo de Narváez expedition. A storm destroyed their ships and drowned most of the expeditionary force near Galveston Island. Narváez set sail in a makeshift raft never to be seen again, and about 80 survivors were marooned ashore. Between 1528 and 1538, Cabeza de Vaca, trying to find a way back to Mexico, walked south, crossed the Rio Grande, and found a native settlement he called *San Luis* or *San Luisito* (present-day Monterrey). The Sierra Madre Oriental, part of the extensive American Cordillera, was a formidable barrier that shifted Cabeza de Vaca path toward the endless plains of Baján, south of Monclova. Most likely, he followed the busy indigenous roads leading to the Cuatro Ciénegas region. As happened with the first Native American settlers, we can think of him taking a respite of the hardships of travel in the warm, blue mirrors of the desert. After resting, he and his companions traveled through present-day Coahuila, Chihuahua, and New Mexico, probably crossing again the Río Bravo (known by many different native Prehispanic names and also known as Río Bravo del Norte and Río Grande del Norte. After the separation of Texas it was officially named Río Grande in the USA; Carroll 1995). He traveled westward, across the continental divide, entering the Pacific watershed and slowly moving into the margins of the much warmer Sonoran Desert. Finally, he was able to travel south following the ranges and rich valleys west of the Sierra Madre Occidental. Southward, into the tropics, he reached the city of Culiacán, by then ruled by the tyrant Nuño Beltrán de

Guzmán. Captured among hundreds of indigenous people in slave raids, Cabeza de Vaca and his three companions, wiry and sunburnt, marveled the Spanish soldiers when they started speaking Castilian.

In the northern deserts, the low desert productivity kept population density relatively low. Settlements were limited to the riverbanks, or the well-irrigated plains, just as the Hohokham of the Sonoran Desert, the Pueblo of the Northern Plateau, and many other now-vanished cultures did long ago. Desert villages comprised small communities, like the Hopi and O'odham in the northwest, or southern desert dwellers like the C*oahuiltecos*, *Guachichiles*, *Zacatecos*, and *Tobosos*. All are descendants of the original immigrants of the end of the Pleistocene whose environmental footprint led to or speeded up the great megafaunal extinction of the last glacial period (Martin 1973; Surovell et al. 2016). The powerful depiction of a mammoth hunting party, guessed from remains found in Santa Isabel Ixtapan, is exhibited in one of the halls of the Museo Nacional de Antropología.[1] At the time, biological desert communities changed by the gradual temperature increase and retreat of glacial ice and by the disappearance of the large herbivores—landscape architects modeling the composition and structure of plant communities. With the megafaunal extinction and increasing population density, a new equilibrium on the biological communities was reached. It was a short-lived, precarious equilibrium that modern native indigenous desert people lived at the time of Cabeza de Vaca pilgrimage.

The transition from the period of conquest to the colony happened through royal land grants, sometimes coming along with a nobility title. Being a landlord, the owner of a hacienda with a few hundred or thousands of acres and the peasants to work that land, was the sign of high social rank and influence. The first to receive such a grant was Hernán Cortés in 1529, when he was appointed Marquis of the Valley of Oaxaca by the Emperor Charles V. In comparison with the lands of the Central Plateau, by its remoteness and isolation, the *Lost Paradise* remained almost unchanged. The next remarkable change in ecological and cultural landscapes of the northern deserts happened during the times of Porfirio Díaz, a dictator that modernized Mexico at the end of the nineteenth century. Don Porfirio, as he was called, with the help of new technology, modernized colonial practices and supported the *Sistema de Haciendas* through the appropriation of vast tracts of land by the Mexican elite and the injection of foreign capital to transform and control land. Less than 1000 families controlled political power. They had millions of acres of cultivated land as well as extensive forests and cattle range and a monopoly on finances, telephony, railroads, goods and services, and food production. The state of Coahuila, home of the Cuatro Ciénegas region, was not the exception. With the arrival of the railroad in 1880, the whole region turned from being one of the poorest, less populated, and most isolated into a strategic raw materials supplier. Its plentiful coal mines propelled the nascent Mexican industrial revolution, and new markets for extensive agriculture and livestock quickly developed (González Galindo 2016).

[1] Some anthropologists suggest that the mammoth was already dead when butchered.

The last chapter on the history of change and development of the spectacular ecosystems of the Mexican arid north has been written by land developers pushing the agricultural-livestock dryland frontiers. The plains and rivers of Sonora and Sinaloa were channeled by elite capitalists, the so-called agrotitanes, for irrigation. The cotton and later the dairy farming industry of the *La Laguna* region rapidly increased at the expense of drying aquifers. The farmers of the northeast cleared the rich and unique Tamaulipan thornscrub. Throughout the drylands, livestock growers with extensive cattle and goat herds repopulated the desert with the newly imported European megaherbivores. Landowners, and later agro-industries, saw the environment as the frontier to conquer, depleting biotic resources and using technology and the great energetic value of cheap oil—López-Velarde's "springs deeded by the devil"—to dam rivers, to search for deep-well fossil water, and to open the fertile river deltas and valleys for agriculture. This is the dilemma that the fragile desert ecosystems face. All these actions, along with the higher-order factors of transformation due to global climate change, are rapidly shifting the unstable equilibrium of the desert. Unless we find a way to change consumption and production patterns, the recovery and better use of drylands, the replenishment of the ancient sea, remains of the blue lagoons, will be a consequence of the ever-closer human society collapse. Time ticks fast. Perhaps is time to heed the words of Van Dyke (1901) about the desert: "*a land of illusions and thin air. [Where] The vision is so cleared at times that the truth itself is deceptive*."

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Chapter 2
The Cosmovision of the Ancient Inhabitants of the Desert: A Look Through the Cave Painting

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Yuri Leopoldo Dela Rosa Gutiérrez

2.1 Introduction

We, archaeologists, in general, during our professional work, spend a lot of time searching, finding, recording, and recovering evidence and materials from the cultures of the past. Once we obtain the information, generally in arduous field seasons, we return to our offices to analyze calmly and serenely all the evidence and traces of the culture of the ancient inhabitants of the most diverse regions of the world. This exercise in analyzing the information leads us to bring together all the data previously obtained from all the archaeological materials of our sites as well as the contexts where they were found, in order to venture hypotheses on what the life of these people who lived in the past was like.

Particularly in the desert region of northern Mexico, the ancient inhabitants were groups of nomadic hunter-gatherers and left very particular evidence: they drew and filled with color the rocky walls of caves, shelters, and rocky fronts, expressing in them their cosmovision (Fig. 2.1).

This special form of expression and archaeological evidence has its own particular language, and the way to "read" it is the archaeological interpretation, where the archaeological record (the obtaining of the information), the natural context (the desert and its inhabitants), and of course the cultural background or the cosmovision of the interpreting researcher are brought together.

Y. L. D. R. Gutiérrez (✉)
Centro Instituto Nacional de Antropología e Historia (INAH), Saltillo, Coahuila, Mexico

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Fig. 2.1 Junco Canyon, in the background gypsum dunes and Cuatro Ciénegas. Photo Yuri De la Rosa

2.2 The Task of Obtaining the Information

The objective of archaeology as a science is the construction of the archaeological data through the material evidence, and this process of methodological construction implies the analysis and synthesis that lead us to offer argued answers to the basic questions of archaeological investigation like what type of material evidence is located in the area to investigate, where is this type of natural and cultural material, what possible temporality can be attributed to the registered material, how does the material evidence behave, etc. Later, through the synthesis, we intend to work with the constructed data, elaborated from the elementary field record. The intention of the synthesis is the elaboration of plausible stories that can be disseminated to society in general and that contemplate truthful information about the societies that inhabited this region in pre-Hispanic and historical times.

It is important to point out the need to produce basic, systematized, explicit, unified, and easily accessible information so that other researchers can use these archaeological data and form their own archaeological synthesis.

In our case, in order to find the answers to the above questions, it was necessary to design and employ archaeological research techniques and methods according to the particular characteristics of the area of study, in this case the Chihuahuan Desert, where archaeological contexts are normally found in natural cavities. Within this desert, a particular site took our interest, the valley of Cuatro Ciénegas in the state of Coahuila, Mexico. This is an extraordinary place in many ways, it is an oasis and a unique wetland, a protected area that includes canyons and wide fans, alluvial plains saturated with salt, with some low hills, and an important area of gypsum dunes, unique in its kind in Mexico. Given the particularities and problems of registering this type of context, it is necessary to be as meticulous as possible in relation to the priorities and objectives of the projects for which the sites are registered.

2.3 The Ancient Inhabitants of the Desert

Thanks to multiple archaeological investigations, including those of the Cuatro Ciénegas Archaeological Project directed by Leticia González and the large number of references in historical sources, we know that for thousands of years the Coahuila Desert, and particularly the Cuatro Ciénegas area, was inhabited by groups of hunter-gatherers, most probably since the continent began to be occupied by migratory waves from different places. These groups or families were nomadic, traveling through the different desert landscapes during the different seasons of the year taking advantage of the natural resources that the environment offered them. Hunting was one of the main activities; they hunted big and small prey such as deer, rabbits, some birds, and reptiles, and since this is a wetland, endemic fish were also included in their diet; plants were used in many ways, some as food, while others were used for the manufacture of baskets and textiles such as mats, nets, and ropes.

As they were nomads, at different times they occupied the different places in the desert, sometimes they made camps in the valleys and the low areas, in others they inhabited the wave and deep caves that exist in the high parts of the mountains always according to the climatic conditions as well as the quantity and quality of the resources necessary to survive.

The funeral ritual of these people is well known because the desert has preserved and mummified the bodies of the dead, which were deposited and half-buried, sometimes in the caves and crevices of the mountains. These were prepared for their journey to the other world in a burial bundle that apart from the body contained some personal objects; all this was wrapped in a rucksack and secured with ropes and knots.

For thousands of years these hunters-gatherers made and manufactured a great variety of objects and artifacts, some ornamental like earrings and necklaces, others domestic like baskets, and finally those that were used in activities like hunting and fishing. Sometimes they held big meetings with other groups of hunter-gatherers, where they ate, danced, got drunk, and probably consumed some hallucinogens such as peyote; these meetings had a social and ritual meaning but also served for the exchange of some goods.

These particular characteristics of living in these arid regions are the basis for what archaeologist Leticia Gonzalez Arratia has called *The Culture of the Desert* :

"The interrelationship between the material aspects of subsistence and the manifestations of a symbolic nature in a scenario such as the desert, I call it desert culture. It includes the series of artifacts, marks in the desert and the technology derived from the capacity of the groups of hunter-gatherers-fishermen to conceptually select and order the natural elements and transform them by means of different processes, in such a way as to allow them to survive.

I circumscribe the term desert culture to the archaeological material mostly manufactured and used by human groups organized around the social formation of hunters, gatherers, fishermen who lived in and from the products offered by the desert; which occupied the widest geographical space known in pre-Hispanic societies and whose great temporal depth (8,000 years at least of reproduction as such) is also the most extensive (Taylor 1966)" quoted in (González Arriata 2004: 370)

In general, we can mention that the archaeological sites that characterize the Culture of the Desert are.

Outdoor sites: these are those that functioned as temporary camps for the specific use of some natural resource that the environment could provide; some were work sites with rocks and minerals for the elaboration of lithic artifacts (projectile tips, scrapers, etc.); some of these camps had fireplaces, which sets of burned rocks that served for the preparation of food, and in some others there are mortars on the mother rock where food was also prepared.

Of very particular characteristics are the sites with petroglyphs; they are places in the hills and slopes of the hills where thousands of rocks show representations of geometric type in their majority, but also animals, weapons, and even motives of the colonial or historical period are represented already after the contact with the Spaniards that indicate us the presence of these groups by stationary periods (Fig. 2.2).

Fig. 2.2 Pictographs site el Junco II. Photo David Jaramillo

2.3.1 Caves, Mountains, and Shelters

2.3.1.1 Cave Painting

In these sites the nomadic groups drawn abstract figures that represent the way they saw the world and their relationship with the supernatural, as they observed some extraordinary phenomena of nature. Some of these sites have numerous representations in red, yellow, white, and black colors. They were created using various techniques and diverse tools such as brushes of vegetable fibers and the fingers themselves for the application of the pigment. In some sites you can also find what could be astronomical representations (suns, moons, stars, and concentric circles), in others, anthropomorphic and zoomorphic representations, but generally they are straight lines, in zigzag and geometric figures that in most cases are combined (Fig. 2.3).

Fig. 2.3 Pictographs site Lagartija Canyon. Photo Yuri De la Rosa

2.3.1.2 Incisions on Mother Rock in Layers

These are made with some lithic instrument, and the representations are found both in small and aligned sets and in large quantities and without any special order. In most cases they are related to sites with cave paintings, but the purpose of these incisions on the rock is being discussed (Fig. 2.4).

2.3.1.3 Habitation Caves

Generally, these caves are found in the upper parts of the mountains; they are large and very deep with traces of fireplaces. We can also distinguish in those specific places for certain activities, such as the preparation of food or the manufacture of lithic tools. Here, the inhabitants of the desert sheltered themselves from the cold seasons and took advantage of the resources they found in the mountains. Some sites present cave painting (Fig. 2.5).

Fig. 2.4 Pictographs Cueva Pinta Site. Photo David Jaramillo

Fig. 2.5 Pictographs site of the Lagartija Canyon. Photo Yuri De la Rosa

2.3.1.4 Funeral Caves

These are places previously selected, both for their geomorphological characteristics[i] and for their location in relation to the mountains. Here the groups of hunter-gatherers left their dead where they were worshipped as part of a complex ritual characterized by the previous preparation of the body and its place of deposition (Fig. 2.6).

2.4 A Millenary Life in the Desert of a Highly Successful Culture

During the numerous archaeological investigations in the Cuatro Ciénegas Valley, dates have been set at four different sites, giving us results ranging from 10,500 thousand years before the present to 600 before the present. Chronologically as they were made known, during the 1940s the American archaeologist Walter W. Taylor carried out excavations in what is known as Cueva de la Espantosa, which is described as a cave for housing. The results of this work were published in 2003 and include radiocarbon dating of different materials including coprolites, sandals, and other textiles; he obtained a sequence of dates that indicate a long occupational

Fig. 2.6 Pictographs site Cueva Pinta. Photo David Jaramillo

sequence in this particular cave and, therefore, in the region from 8900 to 1300 years before the present (Taylor 2003).

In 2002, as part of the work of the Cuatro Ciénegas Archaeological Project directed by Leticia González Arratia, a mortuary cave was excavated where a child's mortuary bundle had been previously removed. From this excavation, in addition to lithic and textile materials, a series of carbon fragments were recovered, which were later analyzed, throwing up for the "occupation of the cave 603 years ago BP" (González Arratia 2004).

In another expedition, during 2006, the Desert Museum, having as a background a couple of human fossil footprints found in travertine from the valley of Cuatro Ciénegas, and on display in the Regional Museum de la Laguna in Torreon, were studied by the Archaeological Project Cuatro Ciénegas and from there in collaboration with the INAH Center Coahuila and the Project of the early Man in Mexico, the Museum of the Desert and the University John Moores of Liverpool carried out works in the site Huellas Tierra Blanca, their dating shows an age of 10,477 years ago.

More recently, as part of a new museography and restoration project at the Casa de la Cultura in Cuatro Ciénegas, a series of studies were carried out in conjunction with the Early Man Project in Mexico on the materials shown in their displays in the archaeology room, that has material taken from the caves in the Cuatro Ciénegas area. Of these materials, a couple of carbon 14 dating, carried out by the Laboratory of Mass Spectrography of the UNAM, stand out. These studies were done on a yarn placed on deer antlers and a net woven with vegetable fibers, which presumably come from the same cave; they were 4000 years old (De la Rosa et al. 2016). This cave is located in one of the mountains of the valley of Cuatro Ciénegas. All these results together show that this amazing wetland has been inhabited at least for 12,500 years and, most of the time, by nomadic people.

2.5 The Worldview of the Ancient Desert Dwellers

In the intellectual sphere, the humans who inhabited the Cuatro Ciénegas desert developed a complex system of experiences, knowledge, ideas, and ways of conceiving the world around them and their interaction with it, both in everyday and extraordinary events, and a particular cosmogony developed over thousands of years by the people of the desert. Leticia González explains it in the following way:

> "It should be added that all his activities, both productive and social, included the intellectual construction of a world of supernatural beings and events. They developed a cosmogony that is reflected in the archaeological material (González Arriata 2004:77–78) and allows me to advance the hypothesis that they expressed their ideas, beliefs and religion materially and spiritually, through cults and a series of ritual activities that in some cases left as testimony different types of archaeological remains.
>
> They built a whole conceptual universe that went beyond the natural phenomena themselves to explain and complement the different factors and elements of everyday life." (González Arriata 2004: 368–369)

The groups that developed such culture in the desert had an intimate relationship with the natural environment in which they lived, not only derived from the appropriation and use of resources. They explained the world, its environment, and its existence through the natural elements with which they lived daily, such as fauna, flora, water, rain, thunder, lightning, mountains, sky, etc. All natural phenomena had a place in the conceptual and intellectual world of the inhabitants of the desert, to a greater or lesser extent. The high degree of specialization to which they arrived and the extensive knowledge of their natural environment made this relationship indissoluble. They worshipped lightning, the sun, and deer and had rites of passage to consecrate themselves as hunters.

That is why the cult of the natural elements was an elemental part of the pre-Hispanic worldview; in that sense it seems to us very appropriate and applicable to this study as Johanna Broda defines the terms *nature observation* and *cosmovision*:

> "Only this approach allows us to situate the problem to be studied within a historical perspective, and thus analyze the scientific knowledge of a people in its socio-cultural context. In this perspective, it is possible to analyze not only the relationship between this knowledge and the observation of nature, but also its close link with the cosmovision, religion and ideology." (Broda 1991: 462)

> "By observation of nature we mean the systematic and repeated observation over time of natural phenomena in the environment that enables predictions to be made and social behaviour to be guided in accordance with this knowledge." (Broda 1991: 462)

> "By cosmovision, we understand the structured vision in which the ancient Mesoamericans combined in a coherent way their notions about the environment in which they lived, and about the cosmos in which they situated the life of man." (Broda 1991: 462)

It should be clarified that Broda refers to Mesoamerican contexts because they are the ones she has worked on the most and knows best. It seems to me that the concept is clearly applicable to the groups of hunter-gatherers and fishermen who inhabited the desert regions of northern Mexico, since it is a concept that goes beyond territorial limits and definitions.

The cosmovision of the hunter-gatherers is captured throughout the Coahuila territory, and this is how we can find rocky shelters, caves, and rocky fronts with cave paintings. There are different colors, perhaps the most abundant is red, but there are also in yellow, black, white, and some shades of brown. There are also hills where, in the crests and chasms, there are petrogrphs with a variety and diversity of forms; these ideas are also represented in the sites with existing petrografts in the desert.

2.6 The Archaeological Interpretation of the Cave Paintings

The interpretation of the rock art manifestations in general is a complex exercise and requires a high degree of systematization, analysis, and comparison of the figures, which has to do not only with their shape but with the whole archaeological context in which they are found, in such a way that all the aspects can become variable in the interpretation, such as the location of each of the pictographs and their associations with others within the same panel and the archaeological site, the colors, the location, characteristics of the archaeological site, and so on. The subjective nature of the pictographs means that interpretation also becomes a completely subjective exercise and depends on the approach of each researcher when carrying out his study, as summarized by Carlos Viramontes:

> "It must be remembered that motives are not just forms, but that each form contains within itself a meaning, even if this sometimes escapes precise identification." (Viramontes 2005: 87)

Several researchers have developed many methods for the analysis and interpretation of the figures in the rock art, giving a different approach to their investigations, but most of them agree that they are carried out in the plane of the sacred; the rock art representations have to do with the ritual life of the authors of the pictographs, and Carlos Viramontes explains it in the following way:

> "Although we are aware that the rock art has multiple motivations and derivations, we consider that one of the most relevant aspects is its ritual character. In this sense, the concentration of sites with rock art manifestations in certain specific places, such as the surroundings of the Zamorano Pinal, makes us propose that these places participated in the cosmovision of the groups of hunter-gatherers as sacred landscapes." (Viramontes 2005: 182)

The hunter-gatherers were capturing ideas, situations, and experiences of religious character in the pictographs; the figures or drawings, in the case of Coahuila, are of ideographic character, that is to say, in a merely subjective plane the figures captured in the rock represent ideas or thoughts with a meaning intimately related to the personal experience of the one who captures it, and for our case, it also applies to the investigator who interprets it. The pre-Hispanic people of the desert made few figurative representations such as animals or plants; in this part of the Chihuahuan Desert, there are more nonfigurative representations of a schematic type and of a geometric character such as lines, circles, and others.

2.7 Conclusions

The cave paintings or pictographs are a reliable testimony of the ancient inhabitants of the desert, and although they cannot be read as a text with a basic structure like modern writings, nor as a system of hieroglyphics where the figures or symbols have a precise meaning and can be structured like a text, the archaeological interpretation of these vestiges brings us closer to the thought and worldview of the people who painted the rocky walls of caves and shelters.

The fact of knowing the thought and culture of the pre-Hispanic people of the desert is one of the scientific objectives of the archaeology we developed in the INAH Coahuila Center in order to write and tell our generations how life was then. Another fundamental aspect in our work as scientists and as one of the elementary objectives of the INAH is the conservation and protection of the heritage of these vestiges of the past, in that sense to know the archaeological sites, to register them, and to interpret them is the spearhead for their protection; nobody protects what not know.

To be able to rescue the collective memory of the desert hunter-gatherers forces us to disseminate their characteristics as a culture but above all to persist in the memory of the new generations as a testimony of our past as a species and as American peoples in the face of the imposing pace of globalization that erases everything.

This archeological reading that we make is fundamental to understand our past, to recognize the origins of our identity, and to know the links that unite us with other cultures. But if understanding our roots is fundamental to know who we are and to understand our present, it is more important to value its transcendence in a multicultural world, to preserve its meaning and to defend it against the overwhelming attacks of the forces that seek cultural hegemony at the expense of the historical and cultural heritage of the peoples of America. In order to preserve and enrich our roots, reading in general and archaeological reading in particular are indispensable.

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Chapter 3
Life in Cuatro Ciénegas: A Historical Tour of the Coahuila Desert Between the Sixteenth and Ninetieth Centuries, Its People, and Their Relationship with the Environment

Carlos Manuel Valdés Dávila, Claudia Cristina Martínez García, and Ana Sofía Rodríguez Cepeda

3.1 Early Colonial Years

To understand the history of Cuatro Ciénegas, it is important to also understand what has happened around this exceptional place, and this is not possible without considering a large number of facts that originated this town. Now everyone considers this region as a special place, but people usually think about its natural richness, the flora, and the fauna. We believe that its history is also highly original, as you will see by going through the pages that follow. There are some questions that remain in the shadows and that will be revealed by linking the documented data with those from biology, ecology, chemistry, and other natural and human sciences.

Cuatro Ciénegas has been overlooked by historians, some of whom have taken refuge in generalities and isolated data, failing to understand its odd past, giving it an essential coherence to understand the present. Cuatro Ciénegas was considered by the Spanish conquerors and evangelizers as a strange region mainly because of its geographical location: the natural border that served as a gateway to the realm of the desert, since the early Spanish explorers came from an area abundant in water, the one that surrounds the Nadadores River. It is an unusual corridor that comes from Candela, passing through Monclova and which ends precisely in that huge group of lakes, lagoons, springs, marshes, ponds, and canals. Cuatro Ciénegas was an "aquatic world," from which one passes almost suddenly to the desert. But the opposite can also be considered: the desert is the gateway to a world that begins in

C. M. Valdés Dávila · C. C. Martínez García · A. S. Rodríguez Cepeda (✉)
Facultad de Ciencias Sociales e Investigación y Difusión del Patrimonio, Universidad Autónoma de Coahuila, Saltillo, Coahuila, Mexico
e-mail: sofiarodriguez@uadec.edu.mx

V. Souza et al. (eds.), *Conflicts Between Biodiversity Conservation and Humans*, Cuatro Ciénegas Basin: An Endangered Hyperdiverse Oasis,
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marshes, whose water, when running, transforms everything in its path until it irrigates Monclova, the capital of the Province of Nueva Extremadura de Coahuila.

It is a natural, but it is also social border. From the moment one confronts the old manuscripts, one comes across hundreds of desert societies related to the populations of the Nadadores River and, without a doubt, with those who occupied those enclaves, which the Jesuits named "Laguneros." In the documents we find abundant information about the indigenous nations (bands or parties) that temporarily occupied or roamed areas of the Bolsón de Mapimí.

When talking about their inhabitants, one must leave behind that the common idea of linking the desert to the words deserted, abandoned, or forlorn, since thousands of indigenous people (divided into many societies) lived in that desert before the arrival of Europeans and during the colonial era (Griffen 1969).

To understand this history, we must first clarify that the foundation of Cuatro Ciénegas was part of a political, economic, and religious struggle. When the Kingdom of Nueva Vizcaya was created, as its name indicates, a power group was installed that had a domain project that was in the hands of the Basque Country. Its governors were Basque for a long time, passing the command to each other. They incorporated the Society of Jesus into their economic empire, which played a fundamental role in their history. If Nueva Vizcaya incorporated what is now southern Coahuila (Saltillo, Parras, San Pedro), it was because they needed to occupy spaces in competition with other provinces.

We know that the first evangelizer of this area was a Franciscan, and the first European discoverer and founder was a captain: both came from Mazapil, Nueva Galicia. Friar Pedro de Espinareda arrived in 1567 and Captain Francisco Cano in 1568, legally founded a first town and, probably, a mission, since there were baptizing Indians.[1] The Basques were disregarded both among the population and by the missionary and were replaced. It has been considered that the Jesuits created the first lagoon communities, which is incorrect, but in addition to the named friar, there was a foundation that bore the name of "Parras–San Francisco" 28 or 30 years before the arrival of the Jesuit priest Gerónimo Ramírez in 1594. Then we can observe a design of strategic appropriation: to leave out Nueva Galicia and the Order of Friars Minor (Franciscans) and to appropriate their lands. However, although they eventually achieved their purpose, it was a complicated process.

Historiography traditionally accepts that the Jesuits founded the first missions in the area and began by visiting the two lagoons, Parras and Mayrán, which offered adequate resources for the survival of the Indian communities who were thinking of converting to Christianity: a land rich in natural elements of flora and fauna that would ensure the subsistence of their missions. At first the Jesuits came from Zacatecas to study the possibilities of the missions, then they arrived from the city

[1] Documents from the Archivo General de Indias de Sevilla (AGI). AGI, Patronato, Letter from Fray Pedro de Espinareda, 1567. AGI, Patronato, 22, 1, 1, Report of Captain Francisco Cano. AGI, Guadalajara, Cartas al rey, 51, 138, Letter from Doctor Alarcón, February 25, 1569. Fray Pedro de Espinareda was a Nahuatlato and was fluent in Cuachichil and Zacateco.

of Durango, capital of Nueva Vizcaya. They soon discovered that some Indians spoke Mexican, albeit "rudely," but they learned that there were those who had Zacateco as their own language, others Tepehuano, and some Cuachichil. Within their strategic calculations, they brought Jesuits who spoke those languages to the area, hence they brought Father Juan Agustín de Espinosa, who knew Zacateco and others who spoke other languages. The fundamental element of a relationship, the language, was thus covered.

A Jesuit wrote his annual letter to Father General Claudio Aquaviva in Rome (which was obligatory), to inform him that before his arrival, there were some baptized natives but that they only had vague knowledge of the truths of the faith. It was a critical reference to the evangelizing stage of the Franciscans. But once they were installed in the Parras and Mayrán lagoons, they immediately planned their expansion. Several Jesuits mentioned to their superiors that they wanted to find five more missions, one of which bore the name of "las cuatro ciénegas." And obviously they were not referring to four landforms but to an existing settlement.

Father Nicolás de Arnaya informed Father Provincial Francisco Váez that:

> On the way back, I came by the river of the Nassas, passing through many settlements, of the *quales* and others of the Laguna, the fathers plan to make four or five towns; and the one will be of how many people we want; because, in a few leagues, there are valleys inhabited by innumerable Indians: all very eager, both to reduce themselves to population and to receive baptism. (Zubillaga 1976, pp. 686–87).[2]

Other letters followed, in which they specify that they will establish a mission in each of the cardinal points and to which they already attributed names. Now Father Francisco de Arista writes to the provincial that in addition to the town of Las Parras, there are five others where the company can be employed:

> The fifth and last population of what was discovered is what they call the Quatro Ciénegas, about thirty leagues north of the other part of the Laguna. There, apart from the people from the valley itself, many of the people from the Herradura valley meet; and its mountain range starts from a valley they call Tlaxcala, and from 3 other rivers and mountains, with which a town of 2,000 residents can be formed (Zubillaga 1976, p. 688).

And we will have the auction of information and plans in a later letter, in which it was now the Province of Mexico that urged Father Aquaviva to allow the creation of that mission, which would be:

> The 5th population that, for now, seems the last in what is discovered in this region, without what Our Lord offers, is the one that they say here of the 4 Ciénegas, the most copious and populated of all, with an extraordinary crowd. It is about 30 leagues from this place, tucked to the north, at the back of the Laguna. The people of the valley and mountains itself attend ally ultra (…) a great crowd of Indians. Which being effected thus, with the divine grace and help that V.R. We will be emboldened, at the present time those who eagerly ask for the doctrine and evangelical fee, more than 2,000 neighbors, all of them people of good capacity and peaceful natives, and what is more to feel, destitute of all human favor in the business of their souls (Zubillaga 1981, p. 243).

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[2] Zubillaga rescued and paleographed thousands of annual letters sent by missionaries to Rome. The letter is from 1596.

When we read the letters that said what they wanted to communicate to their superiors, we can see with ease, that the first letter indicated “the one they called de las Quatro Ciénegas” and the last letter indicated “the one they say here de las 4 ciénegas”. That means that the place already existed and that they intended to expand that way because of the wonderful conditions that the place offered. Where would such a village have come from? Where did they extract data to imagine a mission of 2000 inhabitants? (see Fig. 3.1).

For what has to do with this story, it is necessary to say that there was a first foundation of Cuatro Ciénegas, in which both the Audiencia of Guadalajara and a Franciscan participated (i.e., neither the Nueva Vizcaya nor the Jesuits). We know the data because some friars dared to go to evangelize the Indians of New Mexico and the time passed without knowing anything about them. It is necessary to know that Fray Bernaldino Beltrán asked Durango, capital of Nueva Vizcaya, for help to go rescue his brothers. Antonio de Espejo, a rich man, risked his fortune for this company and hired 14 soldiers and got 115 horses and mules:

> …and thus, having understood the holy zeal of the religious saying, and my intent, Captain Joan de Onteveros, mayor by His Majesty in the towns that call the Cuatro Ciénegas, which are in the said Government of Nueva Vizcaya on the part of East, seventy leagues from the said mines of Santa Bálbola, at the request of the said Fray Bernaldino, gave his command and commission, so that I with some soldiers could enter the said New Land, to bring and help the said religious and people who in she stayed.[3]

Again, an imprecise reference appears: “the towns they call the Cuatro Ciénegas.” Note that it is spoken in the plural. More important is the existence of a mayor who extended a permit. Now we can glimpse that a place dependent on Nueva Vizcaya had been created. Someone denied the existence of that mayor, but there would have been no possibility that Antonio de Espejo, an official of rank, lied in Spain about the position of mayor, a position that was dispensed and controlled by the provincial governor, by the viceroy, and even by the Seville bureaucracy. From this report sent to the king we know that in 1581 there were towns in Cuatro Ciénegas and a mayor. Something that differs from the information proposed by Canales Santos (2000, p. 61) stating that Captain Alberto del Canto founded Saltillo, Monterrey, Monclova, Cerralvo, and Cuatro Ciénegas in 1577.[4]

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[3] “Report of the trip, which I, Antonio de Espejo, a citizen of Mexico City, a native of the city of Córdoba, made, with fourteen soldiers and a religious of the order of San Francisco to the provinces of New Mexico, whom I put by name, New Andalusia, in the contemplation of my homeland, at the end of the year 1582 one thousand and five hundred and eighty two.” In: *Colección de documentos inéditos relativos al descubrimiento, conquista y colonización de las posesiones españolas en América y Oceanía*, taken for the most part, from the Real Archivo de Indias, Madrid, Printing of Manuel B. Quirós, 1864.

[4] Canales Santos does not cite a document that supports the data. Del Canto founded Saltillo in 1572, Ojos de Santa Lucía and Minas de la Trinidad in 1577, but not Cuatro Ciénegas. It is possible that Canales follows Alessio Robles (2001, p. 33), who quotes Luis de Carvajal’s statement before the Holy Office in which he affirmed that he commissioned Espejo. He states that Carvajal could have founded Cuatro Ciénegas “before 1585” but mentions Onteveros who served as Mayor of Cuatro Ciénegas in 1581.

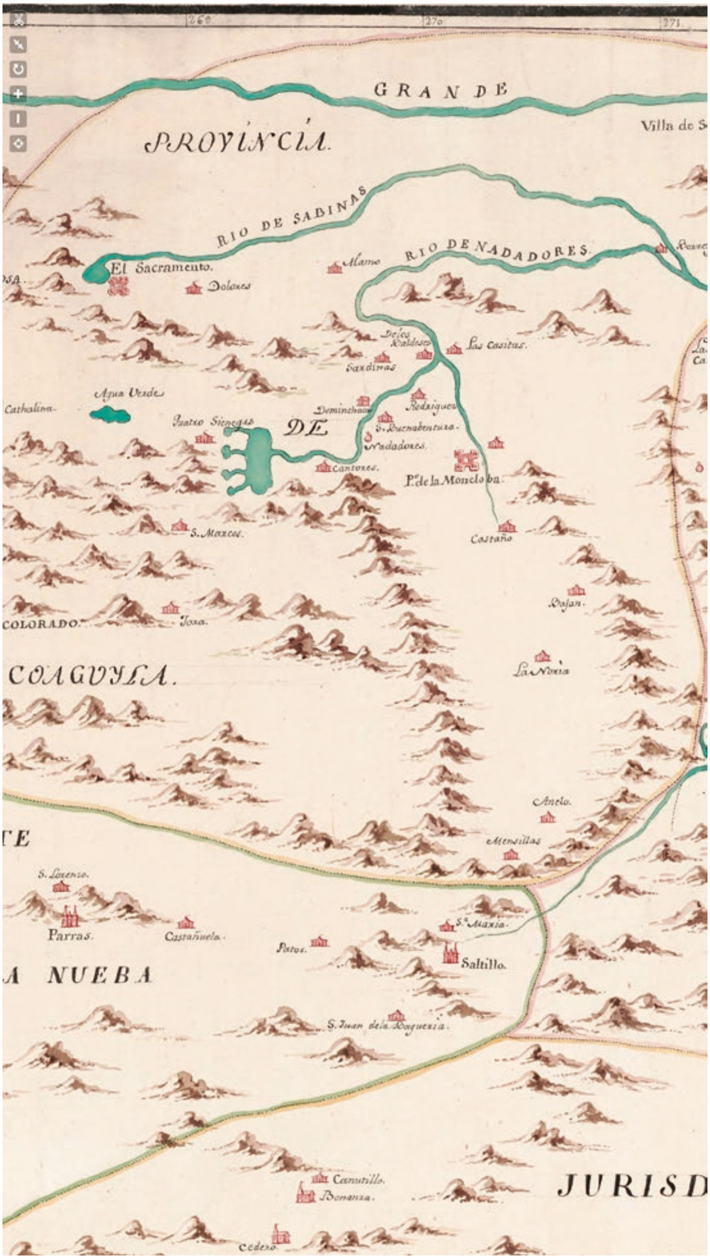

Fig. 3.1 Map of North America. José de Urrutia, 1728–1800. Nicolás de Lafora, approx. 1730–1769 (Library of Congress, Geography and Map Division, Louisiana: European Explorations and the Louisiana Purchase. Washington, DC. 20,540–4650)

However, something happened, because afterwards the place was not mentioned again. According to Canales Santos (2000), the mission stopped generating news in 1603. And, according to Rodolfo Escobedo, the bishop of Durango, Fray Gonzalo de Hermosillo, was not in Cuatro Ciénegas during his pastoral visit in 1610, no doubt because it no longer existed (Escobedo Díaz de León 2008). The statement is true, but it must be clarified that the Diocese of Durango did not yet exist: he was bishop of Guadalajara.

It is unavoidable to believe that an event of the utmost importance necessarily took place, so that this highly planned community suddenly ceased to exist. Perhaps we can deduce something that explains its abandonment. The two dates indicated in the previous paragraph, 1603 and 1610, are around an event that took place in 1606, in the area of the Nadadores River, in the community of Santa Rosa de Viterbo, where the friar Martin de Altamira was accompanied by four indigenous catechists from San Esteban de la Nueva Tlaxcala, who helped him preach the Gospel as many Tlaxcalans learned the languages of the nomads with some ease. Something happened that year, because there was an uprising of Quamocuan Indians that caused the murder of the priest, his four Tlaxcala collaborators, and some Indians from the region who had converted. One manuscript states that they ate those who had become Christians.[5] Clearly, the indigenous people were against those whom they considered to be invaders of everything that represented them, and Nadadores is too close to Cuatro Ciénegas for its population to not be affected by this act of violence. From the absence of news in 1603 to the murder of Altamira in 1606 and the nonexistence of the mission in 1610, there must be a cause-and-effect relationship. Besides the reference to cannibalism, the sacrifice of Fray Martin de Altamira has been mentioned by not a few "historians," introducing legends which they want to pass as facts. It is said that he was moved to Monterrey and buried on the slopes of Cerro de la Silla, where there is indeed a tomb. It is also stated that Captain Francisco de Urdiñola took his body to bury in Saltillo, something impossible since he went to punish the quamocuanes until a year later. And we must not forget that Urdiñola used the crime to his advantage: as punishment and under his care, he transferred the entire Quamocuan gang to his farm in San Francisco de los Patos, where they would serve as free labor. "Obviously, it was at this time that Urdiñola acquired land titles in Castaño, Boca de Tres Ríos and Cuatro Ciénegas" (Gerhardt 1996, p. 406).[6]

This is relevant information, because it was the beginning of the depopulation of the region both at the desert and at the rivers: the Spaniards will force Indian groups, such as chizos, bobosarigames, or salineros, to the Parral mines. They also moved to Parras, as entrusted, various desert societies, such as the hueyquezales and the cabezas, and the boboles and alazapas to Monterrey. By 1673, the governor of Nueva Vizcaya kidnapped all the women and children of an ethnic group as a form

[5] The quamocuanes were a band or party of the great Coahuileños ethnic group, who inhabited the Nadadores River and many other territories as far as southern Texas, northern Nuevo León, and much of Coahuila.

of control: this fact is what led to the creation of the missions of Coahuila by Father Juan Larios and his colleagues.

This long interruption in the data that we have so far about Cuatro Ciénegas and its influence suggests that its aboriginal inhabitants had to live years of restlessness, searching for solutions to their problems and exploring other spaces outside of those they had occupied for centuries. An example is the attack on the small mission of San Buenaventura, on the Nadadores River by desert Indians. They kidnapped two children, stole some objects, some beasts, oxen, farm implements, and, especially, the sacred vessels, priestly ornaments, a missal book as well as the appointment of the Indian governor of the town of Santa Rosa. Captain Retana would catch them with the loot in Chihuahua, 700 km from the place, with handwritten documents of the mission. Everything indicates that the Hispanic presence demolished indigenous societies in a short time (Valdés Dávila and Corona Páez 2002).

Sixty-seven years had to pass for the Spanish State to reestablish its control in the region using in part the abduction of women, since Fray Juan Larios was asked by the cabezas and salineros Indians to intercede with the governor to free their families. Larios walked from Monclova to Parral, passing through Cuatro Ciénegas, but failed before the governor, who refused to release them. Faced with failure, it occurred to him to ask the Audiencia of Guadalajara for permission to create four missions. The Audiencia supported him but went further: he created the Province of Nueva Extremadura de Coahuila, to which both Nueva Vizcaya and the Nuevo Reino de León opposed, since they had the Coagüila region almost as a reserve, where they could capture people who would serve as free labor, as can be appreciated form the following reference:

> In 1673 the Franciscan Juan Larios arrived with the intention of founding self-sufficient missionary communities in Coahuila. The residents of Saltillo, led by their mayor, Agustín de Echeverz y Subiza, forced him to return. Echeverz, who had inherited Francisco de Urdiñola's vast estates, rightly saw the missions as a threat to his [free] labor endowment (Gerhardt 1996, p. 406).

We will always lack data and details to understand the dynamics between people who encountered different types of fatalities, but we believe that both Indians and missionaries had to negotiate their own symbolic patrimonies, finding that they were needed and that together they managed to overcome certain problems. And after 70 years of misery on the part of the aborigines and of yearnings for the moral demands of the preachers, or the policies of the ecclesiastical authorities, there was a respite.

Somehow, the Franciscans had to accept the imposed rules. Fray Juan Larios arrived with several priests from San Francisco along with a lay brother as the only human capital. The bishop imposed himself on the Diocese of Durango, which until then, without sufficient Christian personnel, he was the owner of an imaginary area. The Indian misfortune, without being aware of it, created the circumstances for a

[6] This appropriation and exploitation of the Indians also took place in Patos, Nieves, Bonanza, and other places.

strategic change. In effect, the alliance with a strange religion and its promoters started from convenience and experience.

Thus, the arrival of the friars to New Extremadura brought other forces whose reason was beneficial to the nomads, which can be verified by the immediate arrival of the bishop to establish his royal offices, expanding his enormous diocese, marking limits, borders, and obedience. In his first pastoral visit to a place far from his headquarters, Bishop Manuel Fernández de Santa Cruz traveled from Guadalajara to Coahuila in 1676 and he did not forget to inform the Viceroy Bishop Fray Payo de Rivera that:

> To the Catujanes I pointed out for their population the site of the Baluartes, about sixteen leagues distant from the Coahuila post, and distributed the lands and waters necessary for its conservation. To the salineros and cabezas in the place called de las Cuatro Ciénegas, at the same distance from Coahuila[7] (see Fig. 3.2).

It is important to note that the word *coahuila* suffered many vicissitudes, because in the manuscripts it was used according to what the Spanish believed to hear. There are at least 18 spellings. But in the previous paragraph that name is the one that was initially given to what would be the capital: Monclova. This would bear the nickname San Francisco de Cuagüila, hence the bishop took the place as a term that indicated a reference. Cuatro Ciénegas was the same distance from Monclova as Candela. The first toward the west and the other toward the east. Even if the existence of this Candela-Cuatro Ciénegas corridor had already been pointed out

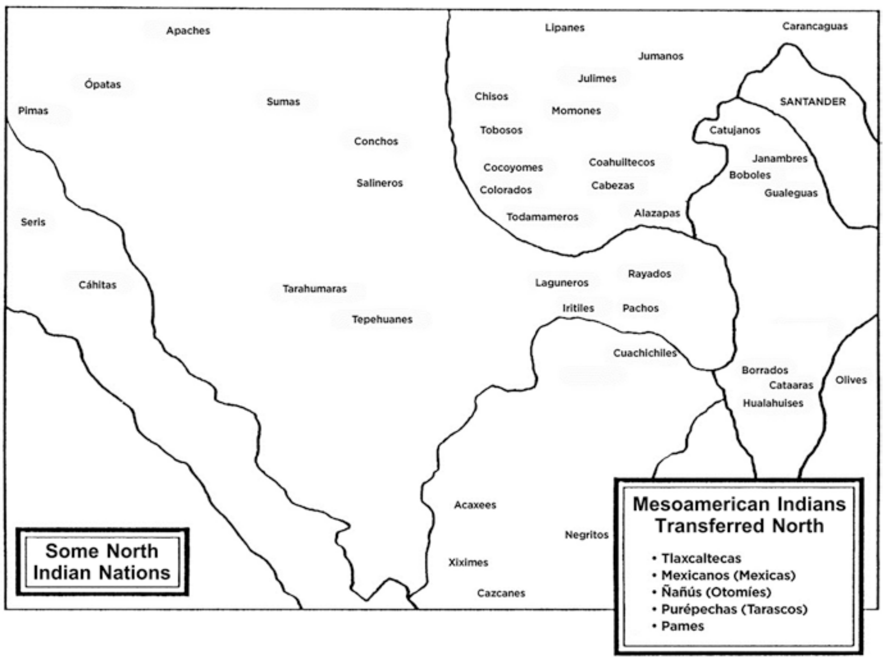

Fig. 3.2 Map prepared by Carlos Manuel Valdés

previously, what could be the reason behind considering this corridor? Perhaps it is not only the water, since between Monclova and Candela there is a good desert section, although there is a small river in that mission. The answer could be that nomads, that is, the indigenous people, were the ones who had those borders. This seems to be verifiable by the thousands of contacts between Indian gangs and in the alliances that they established between them to fight the Spanish. From the Bolsón de Mapimí, with its entrance gate that was Ciénegas, to Candela, confederations motivated by impiety would take place.

It does not seem out of place to warn that there was also external political force, not only for the Indians but also for the Spaniards (i.e., missionaries, bishop, Audiencia…) and this was that of the queen. Since 1675, when just the first foundational entry was made, the Queen of Spain wrote a letter encouraging these new conversions. And it is worth noting that other queens (consorts or queen mothers) will defend "my beloved Chichimeca subjects" and will forcefully lash out abuses, including those of the provincial governors. Something that is found in manuscripts almost always generated by the interventions of some bishops.

Four missions were founded, one "in the year 1674, by Fray Manuel de la Cruz, in a place called Cuatro Ciénegas with indios cabezas, contotores and bauzarigames, but he could not stay there for many years, because of the hostilities of the barbarians" (Alessio Robles 1938). These hostilities should be considered normal, since the raids of the slavers, i.e., the kidnapping of Indians by the Spaniards of Nueva Vizcaya and the Nuevo Reino de León, continued without rest. The indigenous people did nothing but fight for their ancestral territories and for their lives. There is important information, such as *respect* for the law: since the slavery of the Indians was prohibited since the reign of queen Isabel the Catholic, and was ratified by Carlos I and his son Felipe II, everyone knew that enslaving them was a serious crime. A Spaniard let the authorities know that men (adults) were respected but that the law did not mention women or boys, so they kidnapped these categories without the slightest fear of legal process.

Faced with the Indian onslaught, Bishop Manuel Fernández de Santa Cruz himself, who had already been transferred to Puebla, recommended the implantation of military prisons:

> "in the new conversions of Coahuila and the Cuatro Ciénegas, and in the latter it would be advisable to take special care in restraining its natives who are the Salineros, a very bellicose nation and who have committed many deaths and robberies, taking the mules and horses of this Kingdom, and by putting a presidio in the said Cuatro Ciénegas, the peace of this Kingdom and of a large part of Vizcaya will be assured and the population of all the real mines that His Illustrious Mines reports in the antecedents, with which His Majesty would have very grown fifths."[8]

The bishop himself will pressure the viceroy to derive the support for farm and food implements that are granted to the cuachichiles of Mazapil and Saltillo, to the

[7] Archivo General de Indias (AGI), Cartas al rey del virrey Payo Enríquez de Ribera, México, 50, N 6.

creation of those presidios. Either way, the truth soon came to light: in Mazapil there was only one cuachichil and in Saltillo six, so some bureaucrat was taking advantage of those resources.

Had the Christianization of the Indians of the Bolsón de Mapimí and the Cuatro Ciénegas failed? Everything indicates that it did not. Brother Fray Manuel de la Cruz must have been very loved, since he would soon receive priestly ordination in Guadalajara, so that from now on, in addition to baptizing and marrying, which is permitted to a layman, he could officiate mass and confess. How do we know that it was successful? We have now found out because the reports of sacraments received by the indigenous people of that mission were found. The name of Fray Juan de León appears as a doctrinaire of the mission, since the Order of San Francisco did not favor the isolation of a friar, but rather assigned at least two preachers to each mission, but the presence of Fray Manuel was not clarified.

According to a list of all the indigenous people who received sacraments, signed by the custodian father, Fray Francisco Peñasco in 1681, and ratified by Miguel de San Miguel, protector of the Indians of the Pueblo de la Virgen de los Dolores, we know the results of those efforts. The mission had 532 Indians, while the town numbered just over a thousand inhabitants. Between the years 1676 and 1680, 249 were baptized and 35 were given a Christian burial, which indicates that there was no epidemic such as those that devastated villages and missions from time to time. We must add an interesting fact, which the Spanish San Miguel highlights. There were:

> two prosecutors, Pedro, and Domingo, from the Babosarigames nation, who are very devoted to divine worship. They have settled their people in the form of the babosarigames, salineros, cabezas, contotores, conianes, babaimamares, and daimamares, deer feet, totonacas, colorados, cacalotes and tobosos nations that make a number of more than a thousand Indians.[9]

This report was signed by two authorities, one religious and one civil, and is very important, because despite the lying information transmitted to the viceroy and the king, they give concrete, precise, dated data, with the name of each of the people who received a sacrament. In particular, we know for the report that the mission had the capacity to shelter Indians from various nations. Let us remember that some of them were constantly accused of being barbarians, thieves, and murderers, including the tobosos, the salineros, and the cabezas.[10]

It is necessary to stress that the idea transmitted in several books and articles about the abandonment of Cuatro Ciénegas must be changed: it did not happen in those years or in the following years, as will be seen. If there was a detailed account of the sacraments imparted, it is proof that religious people and agents of the Spanish monarchy were there. The protector and his relatives are warned of these. The friars are named Fray Juan Macias, Fray Francisco Navarro, and Fray Juan de León, but it is clarified that Father Manuel de Santa Cruz previously attended the mission.

The copy of the sacramental books was delivered signed dated 1681, while mayor Joan de Onteveros was the head of the Cuatro Ciénegas commune in 1581,

[8] AGI, Cartas al Rey, México, 50, N 6, 6 de marzo de 1677.

that is to say that 1000 years had passed. It is not clear whether it can be called a village, mission, Indian town, or presidio or to recognize that it was holding the name of each of these institutions through which the Spanish state was present. At least in 1681 we know that two corporations survived that were always linked: mission and town. Everything indicates that the town had already disappeared and that a presidio had not been built, until then.

A year later, one of the bishops who condemned the mistreatment of the Indians of northeastern New Spain, to whose combat he dedicated 8 or 9 years, would arrive on a pastoral visit: Juan de Santiago León and Garabito. As bishop of Guadalajara, he oversaw one of the largest dioceses in the world. He demanded a lot from the priests and the religious, from which he had many problems, but his main fight led him head-on against the slave owners and the encomenderos. It was up to him to install secularization, which consisted in the fact that a mission, once it had been successful and whose Christians persevered in the faith, had to become a parish. As a mission disappeared and became a parish, it came under the power of the bishop. Evidently, the Franciscans were furious. How, after so many years of sacrifice, were the diocesan priests now going to supply them? And knowing that the bishop was approaching Monclova, after touring the missions of Tamaulipas and Nuevo León, they organized the resistance to that transformation. The friars of Coahuila announced to the Indians that they would abandon the missions, which created a great problem among thousands of indigenous people from no less than 20 nations, both from the desert and from the entire Nadadores basin, to which Cuatro Ciénegas belonged.

The indigenous people knew that the missions were the best refuge to protect themselves from their persecutors. They saw the most feared threat coming upon them, because without friars they would be easy prey by slavers and other businessmen. They learned that the bishop would travel from Monterrey to Monclova, passing through Saltillo, and leaders from 18 nations rushed to this town to demand that he would not allow the missionaries to abandon them.

They walked or jogged 200 km to be there before him. When he arrived, they were already waiting for him and asked for an audience, which the bishop granted immediately and spoke with them, the translator involved:

> The said chichimeco Indians said (…) to His Excellency they came to give him an account and news (…) of how all the religious missionaries of the four missions that are in the said province of Coahuila, had been summoned and were already together and congregated in the town and mission of San Francisco de Coahuila (…) to get out and abandon the said missions.[11]

They had assimilated the ecclesiastical rules and knew that a bishop was the highest authority. It should be noted that 11 of them were gentiles and only 7 christians, which means that without being all members of the church, they knew, from

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[9] AGI, México, 52, N. 29, Cartas del Virrey Marqués de la Laguna. Information made in the mission of San Buenaventura de las Cuatro Ciénegas.

[10] A list of Christian Indians is inserted in a separate box.

experience, that missions were a protection and, in a certain sense, a right. The bishop expressed intelligent determinations in support of the caciques, which are preserved in the Saltillo archive.[12] Then they undertook the trip to Monclova together, where they were met with the incredible surprise that the friars locked themselves in the convent, refusing to dialogue with the bishop. It was too difficult a negotiation, due to the radical position of the friars. In the end they both had to give in: the friars would stay, but they were given the appointment of parish priests. The triumph was due to the indigenous people, and it benefited them in the first place. San Buenaventura de las Cuatro Ciénegas, which was the one that was most exposed due to its geographical position between the desert and the oasis, also won, but its achievement was short-lived, and its Indians would soon be seen making peace in Saltillo, whose mayor found that "pacification" as an unforeseen gift. Those who delivered were a thousand indigenous people from various nations, including the cabezas, the hueyquezales, the cuechales, the coahuileños, and others.

Then, the mayor made a terrible decision by handing them all over to Mrs. Francisca de Valdez, a large landowner from Parras and a descendant of Urdiñola. For a short time, they endured the regime of oppression, and one fine night they secretly escaped and returned to the Franciscan missions, especially San Francisco and Santa Rosa. What had happened? We do not know, only that the yoke of forced labor weighed on them: they preferred the mission with its collective work obligations, the imposed Christian rites and obedience (Valdés Dávila and Carrillo Valdez 2019). The manuscript of Parral comments on it with offensive words:

> And the forementioned cacique Lázaro as a ladino Indian does it in order to disturb the domestics and live in their freedom and wickedness and this is their purpose and not to be baptized and live quietly, because if they had another pretext they would have been in the town of Parras in the hacienda of Doña Francisca de Valdez, whose charge was the chief Esteban de los Hueyquetzales, where he descended from peace and was baptized and was in doctrine, having to eat and dress and left everything to return to his natural and bad life.[13]

It is hardly credible that the Spanish authorities did not understand that people preferred to be free, even if they were fatigued to find their food in the desert and the mountains, than to have a safe house and food in seclusion. In the years immediately following, information on Cuatro Ciénegas as a mission is lost. There is another type: as a place of passage for travelers and the military or as the headquarters of ranches and farms. A casual action will reveal something similar in terms of strategy

[11] Biblioteca Nacional de México, Reserved Fund, Franciscan Archive, 1680. See the supplementary document of the Archivo Municipal de Saltillo, PM, e32, 1680, Information at the request of Father Fray Francisco Peñasco, Commissioner of the new conversions of Coahuila.

[12] Let us remember that Saltillo did not belong to Nueva Extremadura or to the diocese of Guadalajara, both instances where these nations were located. It was not the first time that the mayor of Saltillo played the role of intermediary for problems outside his jurisdiction. In this case it was Mayor Diego de Valdés.

[13] Archivo Histórico Municipal del Parral, Colonial Fund, A 21, 001.

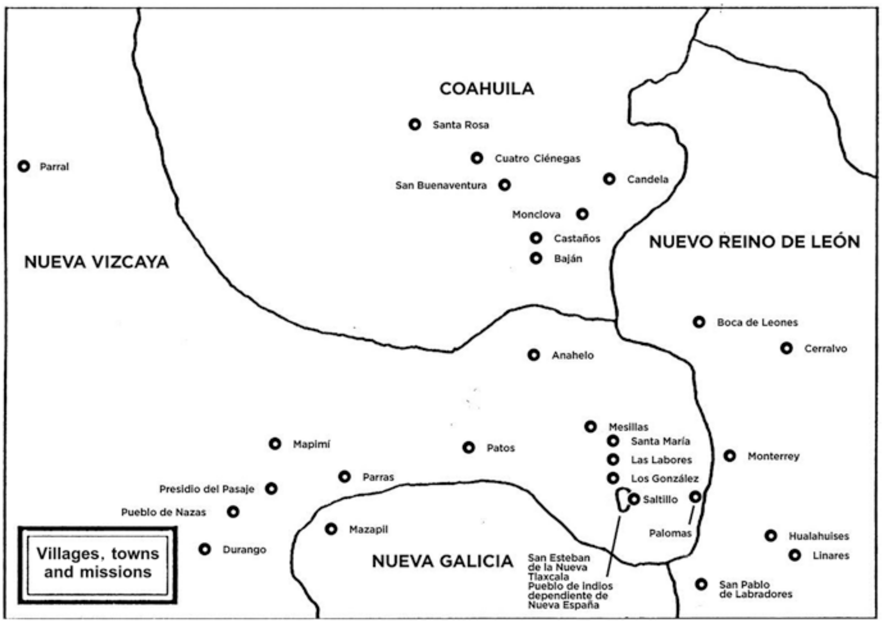

Fig. 3.3 Map prepared by Carlos Manuel Valdés. Villages, towns, and missions during the colonia

but in the field of armed struggle. In a battle, the Spanish captivated one of the leaders: Domingo, from the Bobosarigame nation. When questioning him:

> He confessed that he had been baptized in the mission of Cuatrociénegas, that he left his land with Captain Salvador, of the Colorado tribe, and with Captain Marcos, of the Odame nation with the intention of killing the Spaniards who traveled along the roads that they go from the Nuevo Reino de León, Saltillo and Parras to the reales de Zacatecas and Sombrerete; that they killed a Spaniard in the port of San Juan and stole Patos's horse.[14]

It is necessary to return to the aforementioned about the town of Nuestra Señora de los Dolores and remember that one of its two prosecutors was precisely Domingo Bobosarigame and that his two colleagues, Salvador Colorado and Marcos Odame, received baptism, one in 1676 and the other in 1677. And Indians like these, whom they named apostates, for having deserted the faith, abounded in colonial Coahuila.[15] Let us point out that the various leaders, Don Dieguillo Cuechal, Don Esteban Hueyquetzal, Cacique Lázaro, and many more, had their origin in the region that encompasses the desert and the rivers of the mission of Cuatro Ciénegas (see Fig. 3.3).

One last piece of information appears in 1692: the foundation carried out by Fray Martín Ponce in the Nadadores River of the mission of San Buenaventura de los

[14] The quote belongs to Portillo (1886b, pp. 183–218), and it refers to the trials ordered by Governor Alonso de León, pp. 183–218. It also appears in Alessio Robles (1938, p. 305).

[15] An apostate, as is known, was the one who abandoned the previously accepted religion. An apostate deserved the death penalty according to viceregal ordinances.

Colorados, which means that the mission of Cuatro Ciénegas had disappeared and that it replaced it without changing its name, only attributing it to a specific society, the colorados. Somehow, Bishop Manuel Fernández de Santa Cruz and Fray Juan Larios had suspected it from the beginning.

Several years will pass with little or no information, except marginal, as is the following case: Juan Vázquez, Marquis of Casa Fuerte, viceroy of New Spain, ordered the exploration of the Río Grande region, which was already besieged by groups of indigenous people who arrived from the north, especially Apaches. The governor of Nueva Vizcaya appointed José de Berroterán, who was captain of the San Francisco de Conchos presidio, to take care of the matter. And the first thing he did was a trip of inspection and knowledge of the territory that was entrusted to him. The interesting thing is that he mapped out several routes in which he indicated specific data for each presidio, mission, or village in a large part of Coahuila and Texas, thanks to which we can have data from the year 1729.

This novel concern had not been born from an occurrence of the viceroy, but from the changes that had been implemented since the year 1700 and increasingly became more present in New Spain. It all started with the decline of the Spanish empire and the impoverishment of Castile. The Habsburg dynasty had reigned since Carlos I, and now, two centuries later, the Spanish crisis led to the imposition of a Bourbon king of French origin, Felipe V. From this, a series of reforms emerged in terms of tax control, the control of the territories, and the reorganization of the Navy, which came to affect the entire province of Coahuila and, in addition, Cuatro Ciénegas.

From here on the original Indians will be mentioned less and less and others that were not native much more frequently: apaches, lipans, comanches, caíguas, and others. It is about them that the chroniclers will write and not those referred before. Not that they no longer existed, but their number had rapidly decreased, either because of the slave raids, or because of the epidemics of cholera and smallpox, or because they were transferred to the south of Coahuila, to the estates of Nuevo León, to the mines from Zacatecas, or even to the Antilles (Montemayor Hernández 1990; Venegas Delgado and Valdés 2013).

From the Berroterán report, we must emphasize that one of their concerns was to repress horse robberies, assaults, and deaths carried out by indigenous people in many places, often very distant from each other. Now the aborigines were horsemen who could move quickly, since they brought spare horses so as not to tire them. Hence, it seems that Berroterán was interested in trivial data if you look at its importance, but that once grouped they represent a true state of war:

> During his stay in the presidio and in the capital of Coahuila, Berroterán also held consultations and exchanged opinions with the governor and captains to be able to follow the trail of the Indians that he had lost in Cuatro Ciénegas; Although he did not obtain useful indications, he did obtain the loan of four Indians who were considered the most skilled spies (Rodríguez Sala 1999).

On several of its pages the names of the places of our interest appeared. Thus, for example, we know that in 1729 he was in Aguachila and "from that place Berroterán sent, again, in search of water and pastures, indigenous explorers on horseback, in the direction of the site named Cuatro Ciénegas" (Rodríguez Sala 1999 p. 49).

Berroterán needed to be aware of natural resources if he was to be successful in his assignment. He knew that all geography, in its smallest details, was known to the Indians and that, furthermore, they surpassed it because they knew how to use every plant that could serve as food.[16]

Based on his field explorations, always accompanied by indigenous people who guided him, Berroterán reaches somewhat defeatist conclusions. It was not one but several reports that he wrote, but that of 1748 seems to be, without a doubt, the clearest and richest in results. He explained that the Bolsón de Mapimí:

> It cannot be inhabited or populated by christian rational, because the one who could have communicated this good to them, if there were anything populable, it would be by its watering holes, and these are at distances from each other from twenty to twenty-five and thirty leagues, and so short that he can maintain a neighbor in each one of them, with the short set of one hundred and fifty head of large cattle and horses, and the more interned in the mountains, varying their situations in different directions (Navarro García 1965, p. 80).

Knowing that Berroterán had military experience as a horseman and in the field, those statements are incredible. When it says that the Bolsón was not populated, it means that no sustainable population can be established, which contrasts with the experiences of its first inhabitants, the aborigines, who were always mentioned by thousands. However, people of the desert had managed to reproduce biologically and culturally for millennia. The very dissimilar system of conceiving the environment is evident between those who are heirs of Western culture and those who learned in its long duration to master the resources offered by the desert.

Let us take an example of your perceptions about a resource, water. José de Berroterán let it be known that:

> Only in Acatita la Grande and the Charquerias from rain could a company of fifty soldiers be maintained at the time of these. The population of the bosom was the area from the Sierra de San Marcos de las Cuatro Ciénagas, to the Río Grande, to the east, at its intervals to those of Nadadores and Santa Rosa. And from here to the west everything was desert and no mountains had a name (Navarro García 1965, p. 80).

It is evident that Berroterán is only learning the results of two centuries of unequal struggle and murder. For these Spaniard settlers, the Indians were not the subject of history but beings at the service of those who dominated them. The paradigm changes the whole model, so people like Berroterán cannot understand that places that are inhospitable for them could have been populated by thousands of human beings who, otherwise, were tall, strong, and tireless. Berroterán knows what exists, without knowing what preceded it:

> In 1744, the named Labor of Our Lady of Sorrows is the property conferred on Pedro Ignacio Valdivielso Espinal, fourth Marquis of Aguayo, thus this place is cited in an inventory of the belongings assigned to him; in another later inventory it is called San Juan de las Cuatro Ciénegas. (Peña Chávez 2013, p. 287)

[16] It is known that in the Chihuahuan Desert there are hundreds of edible plants (Valdés Dávila 1995).

With the reforms of the Bourbon kings, new relations between the monarch and his subjects began. The almost personalized epistolary treatment of Felipe II, his viceroys, and the bishops were put aside. Now the state appears for what it is: an entity that without doing so in an obvious way oppresses all those who are under its control, a control that appears in the form of a defined organization that is implanted in a territory, between human beings who inhabit it and that they are objects of an all-embracing power that is perceptible only by its effects – legislation, bureaucracy, a single and compulsory religion, a social division based on racial definitions.[17]

One of the institutions that an emperor, a monarch, or any dictator imposes from time to time is that of recourse to registration: How many are the subjects, what do they do, what characteristics do they have? Thus, the Bourbon kings imposed a large census that took place in the year 1777. Detailed results were obtained and preserved for most of the large and small populations. Some have not been found, but in the case of Cuatro Ciénegas, we have several registers of very different origin: there are some missions, a few farms, a presidio, and parishes. What matters in this study is that they reveal curious and interesting facts: registers are found in the magnificent Historical Archive of the Parish of Santiago in Monclova, including the number of those raised in haciendas and *rancherias* who fulfilled the sacraments. It is amazing that they documented recourse to the sacrament of confession, writing the names of each penitent. It is known who went to confession at the Hacienda de Sardinas, and it is clarified who took communion the next day, that is, who did or did not sin that night. Does not this show an excessive control system not only of the bodies, which were dominated through daily work, but also of their souls to the most subtle, the intimate?

We found a "Register of the workers of the Hacienda de Nuestra Señora de los Dolores de Quatro Siénegas, confession and conversion and toddlers that as perceived by their games, there are the number of 79 people of confession, communion and toddlers," in which it is observed not only the recourse to the fulfillment of the commandments of the Church but (and also) the description of the race or caste of each adult: mulatto, Spanish, Indian, *lobo*, *albarazado*. The sacrament of penance serves the maintenance of the circumstances of power.

There are registers of subsequent years: 1757, 1758 (two), 1761, and others, but not always from the same hacienda or parish, which enriches the knowledge of the populations regarding their composition, inter-ethnic relations, or the number of children a family has.

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[17] A monarchy (from the Greek monos: one; arqué: power). The Bourbon kings decided what was good, what was bad, what and when each one must do something, defining obedience and institutional submission.

Hacienda de Cuatro Siénegas, 1781

María de Torres, a free mulatto, widow, has a daughter and two toddler children.

Eugenio de Hortiz, a free mulatto, married to Gertrudis de Mata, a free mulatto: he has 3 toddler children.

Mexandro Valenzuela, married to María Francisca Segura, a free mulatto: he has a toddler daughter.

Estevan de Lerma, free mulatto, married to Juana Francisca de la Cruz, free mulatto.

Blas María Ruiz, free mulatto, married to María Jossefa de la Cruz, free mulatto.

Vicente de Luna, free mulatto, married to María Petra Álvarez, has 2 free mulattoes and 2 (?) Single.

Note: the census includes Monclova town register, hacienda de la Estancia, hacienda del Señor San Jossef, Las Adjuntas ranch, San Vicente ranch, hacienda de Santa Gertrudis, San Buenaventura village, hacienda de San Diego de Sardinas, hacienda del Señor San José de las Encinas, hacienda de San Ignacio del Tapado, and hacienda de Cuatro Ciénegas. The total number of parishioners that make up the Ciénegas parish appears, and we note the *quality* of its inhabitants: 1410 Spaniards, 435 mestizos, 1249 mulatto, and 214 Indians, giving a total of 3308.

The concept of *quality* was applied to people to define their belonging to a racial or caste sector. Even the peninsular Spaniards were attributed a higher *quality* than that of the Spanish born in America.

Valdés Dávila CM, Martínez Loera S, et al. (2018/2019). Catálogo del Archivo Histórico Parroquial de Santiago, Vols. I–IV.

The Bourbon Reforms did not stop at a people count: the kings forced the inhabitants of America to pay taxes. The Census had to be complemented with a field audit that reflected reality. It means that all populations should be visited to make a count of the resources they had, not only the villages but each of their neighbors, which implied the use that was given to the land, water, products, and the trade of the same. For a large part of the North, an envoy of great experience was chosen. It is about Fray Juan Agustín de Morfi, son of Irish and Asturian, who joined the Franciscan order in Mexico and left many writings. His stay in Coahuila dates from 1777.

From Cuatro Ciénegas, he highlighted the most important resource: "The Nadadores river carries nine cubic rods of water in this part, it goes through hills higher than the rest of the plain that facilitates irrigation at low costs. He was born on the hacienda de Cuatrociénegas" (Morfi 1980). In his traveler notes, Morfi wrote down other things that should reveal to the viceroy the problems of each of the peoples and their causes. He recorded that:

> A report was received from Captain Montero, stationed at Cuatro Ciénegas, in which he reported that six soldiers and a corporal from his company and detachment of Sardinas, who were escorting a pack of mules loaded with flour, met thirty apaches; that they attacked and killed two, taking the mules (Morfi 1980, p. 397).

In one sentence, he captured data that could be read from various senses: there is a hacienda, Sardinas, which produces corn, wheat, and cotton, which has several mills, hence the theft of the Indians is a problem that affects social peace when the same time as the commerce, the muleteer, the life of the workers.

Morfi was a keen observer, so much so that he raised issues that many others had never noticed. He said something interesting about Texas that could be applied to the Bolsón de Mapimí and Cuatro Ciénegas: "Nothing proves the imponderable abundance and fertility of these lands more effectively than the multitude of nations that inhabit them. The interior of the country, the coast and even the islands are full of people" (Curiel 2003).

From when the foundation of a mission was simply considered to be in the year 1597, it was already mentioned that in "las Cuatro Ciénegas" there were a multitude of Indians, as if to form a community of 2000, which coincides with Morfi's idea that if there were so many Indians, it was because there were many resources to feed themselves. The terrible question we ask ourselves today is: why did these thousands of human beings become extinct in 300 years of Spanish and Mexican governments?

In these years, a stage begins in which two strategies will be developed: the fight against the North American Indians, whom everyone will call "the barbarians," and the fight for spaces. It was a century of savagery, from one side to the other. The military will take an exceptional place in the construction of economic power since they hold the political and the monopoly of legitimate physical violence. It is not difficult to reveal that the families that were consolidated in that century that goes from 1791 to 1890 achieved it thanks to their double game. A registered case says that:

> In Coahuila there was news of the entry of large groups of lipanes, lipiyanes and mezcaleros. The governor reported on the activities of Captain Panocha and Poca Ropa, who seemed faithful. San Fernando de Austria and Cuatro Ciénegas suffered undoubted damage and therefore Teodoro de Croix decided to send half of the third company flying from Chihuahua to Coahuila. (Navarro García 1965, p. 346)

But it was not just about the two towns that are named there but about the entire province. Hence the army was deployed throughout the territory; 250 soldiers were installed, of which two positions of 50 men were assigned: from Saltillo to Monclova 100, fixed in Monclova 30, in Nadadores 30, in Sardinas 40, and in Cuatro Ciénagas 50 (Navarro García 1965, p. 355). How did the change come about? How did it go from the combat or submission of the nomads to the attack on the apaches, lipans, and others? The change was brutal. They were experienced soldiers, such as Don Ramón de Castro, from a noble family from Castilla La Vieja, who was appointed commander of the eastern provinces with the task of suppressing the Indian attacks:

> He entered Coahuila through Monclova and went to Cuatro Ciénegas to recognize the ports and canyons of Santa Rosalía, Jara, San Marcos, Ciénagas, El Marqués and Menchaca, where the *mezcaleros* from Bolsón entered Saltillo, Nuevo León, Monclova, and finally through Sardines, Santa Gertrudis and San Buenaventura he arrived in the Santa Rosa Valley, ill, but having acquired the knowledge he believed necessary (Navarro García 1965, p. 483).

From that entry, he considered definitive that "the most populous part of the bosom was the area from the Sierra de San Marcos de las Cuatro Ciénagas, to the Río Grande, to the east, in its intervals to those of Nadadores and Santa Rosa. And from here to the west, everything was deserted, and no mountains had a nomination" (Navarro García 1965, p. 80). He found what Berroterán had discovered and reported to his superiors 67 years ago. And again, the difference between the original indigenous people and the Europeans and mestizos appears against a specific environment.

The Bourbon administration would soon institutionalize their dominance by creating fixed populations that would acquire interests, compelling them to defend their families, their possessions, and their horse, sheep, and cattle. The idea was to create villas in which each owner had a family heritage and that each community identified with a territory and a past. Hence, the institutions necessary to create identities, such as schools, were soon generated. But first they had to create the human nucleus.

In 1797, the governor of Coahuila, Antonio Cordero y Bustamante, visited Cuatro Ciénegas, "which found it inhabited, for which he believed it necessary for such a settlement to be legally formalized" (Peña Chávez 2013, p. 287). Another document reports the opposite, that Cuatro Ciénegas looked abandoned and only the vineyard was in good condition. Either way, the governor made the decision to formalize the existence of that population as a town and head of the municipality. He made a report and spread propaganda inviting families from Coahuila to go live in Cuatro Ciénegas, although he let it be known that he would carefully review the qualities of the candidates (Canales Santos 2000, p. 105). A chronicler at the time recorded the details about this new foundation: "this town was founded in the year 1800, by orders and instructions of the Governor of the Internal Provinces D. Pedro de Nava, addressed to the Governor of the Province of Coahuila D. Antonio Cordero" (Portillo 1886a, p. 485). The mention refers to an authority that had a broader vision and saw the problems of Coahuila as much as those of Chihuahua, Nuevo León, or Texas. Pedro de Nava considered Cuatro Ciénegas as the enclave that could unite parts of the internal provinces.

When creating the municipality, authorities had to be appointed: President Jesús Carranza, first councilor Lázaro Maldonado, second councilor Alvino Morales, third councilor Cayetano Arambírez, and fourth councilor José María Salinas Arreola. It was found that there were three physicians, two schools for boys and two for girls, an inn, a priest, a temple, and ten springs. At first, 11 heads of household were registered, which would increase to 17. The temple of San José de las Cuatro Ciénegas was built, giving the earthly father of Christ the invocation.

Very soon the bureaucrats and the military would cease to have the prerogative of information. Periodical publications (newspapers, weeklies, monthly magazines) began to arrive, attracting the attention of neighbors. News came of events in Europe, even Constantinople or Russia: the gossip of royalty was read but also the problems themselves. Some of the front page columns are noted:

> *El Monitor Republicano*, February 27, 1852: "The newspaper *El Ensayo Republicano* that appears in Saltillo, Coahuila, reports on the defense plan against the barbarians that is being prepared by the commissioners of the states. The collegiate states are expected to give prompt approval."
>
> *El Monitor Republicano*, March 1, 1852, San Buenaventura, Coahuila. "The residents of this place presented the government with five hairs and a live Indian, after a meeting between the neighbors and the barbarian Indians."
>
> *El Monitor Republicano*, July 10, 1852, Villa de Ciénegas, Monclova, El Pozo. "There are two pieces of news that come from the newspaper *Ensayo Republicano*, in which there are reports of murders committed by the Indians; one in the person of Mr. Jesús Rodríguez and the other in a family. The president of the city council, D. J.M. del Valle issued orders to all the rancherias for a force of 25 residents to persecute the Indians."
>
> *El Universal*, July 10, 1852, Saltillo, Villa de Ciénegas, Monclova. "From *Ensayo Republicano* of Saltillo a piece of news is published that describes the way in which Mr. Jesús Rodríguez was assassinated by a group of barbarian Indians."
>
> Rojas Rabiela T, Ramos JL et al. (1987) El indio en la prensa nacional mexicana del siglo XIX: catálogo de noticias. Vols. 1–3, CIESAS, Mexico.
>
> *El Coahuilense*, March 16, 1868. Antonio Garza gave a verbal report that the barbarian Indians had raised 40-odd mule beasts from El Pozo, two leagues distant from the town of Cuatro Ciénegas, which belonged to Jesús Carranza. A party of ten men left, but they did not catch up with the Indians.
>
> *El Coahuilense*, March 20, 1868. The presidency of the Sacramento City Council to the Secretary of the Government of the State of Coahuila, reveals the way in which the barbarian Indians have robbed and attacked various people in different parts of the town.[18]

[18] The newspaper library of the Archivo Municipal de Saltillo is under the care of Ernesto Terry Carrillo.

The "barbarians" of the north, on the one hand, and the two foreign invasions, on the other, severely affected Cuatro Ciénegas. The sufferings were enormous, but not exclusive to this town: the Cieneguenses suffered just like the residents of San Fernando de Austria, Santa Rosa (Múzquiz), or Peyotes. Lacking support from the center of the country, the villages organized to stop the attacks from the northern nomads, defending their families. There were many parents who traveled to Texas or Kansas in search of their children or women kidnapped by the American Indians and openly sold in a "Casa de Trato"; a father paid 50 pesos and a horse for his own son. The people of Coahuila had to organize armed resistance, and they were very efficient. Neither the Mexican government nor the US military did anything to control systematic robbery and kidnappings.

It is important to rescue the opinion of an American who arrived in Coahuila with the invading troops in 1846, the surveyor George W. Hughes, who was stationed in Monclova and was forced to travel to Cuatro Ciénegas. He praises the people of Ciénegas: "the town of Ciénegas has, according to the latest census, 1,428 inhabitants (…) Its inhabitants are distinguished by being industrious, sober and deeply religious people. In politics, unlike the people of Monclova, they are mostly federalists and enemies of the current government of Mexico. His hospitality is proverbial" (Villarreal Lozano 2007, p. 30).[19]

Perhaps for the reasons that Hughes gave about their complaints against the central government, the powerful families of Coahuila, among them the Carranza, Madero, Garza, Galán, Salinas, and others, supported the annexation of Coahuila to the state of Nuevo León proposed and established by the dictator Santiago Vidaurri. Voluminous correspondence between Vidaurri and Jesús Carranza is preserved, including a letter in which Vidaurri, wanting to solve the Apache-Comanche problem, proposed to destroy Cuatro Ciénegas pools. He sent Carranza some cans of poison with the order to pour it into the desert watering holes, to see "if with the fear of dying just by drinking water, we can banish those beasts with human figures."[20] Don Jesús Carranza did not obey the orders, since he himself was a rancher and hunter and knew that in addition to harming the Indians, he would harm the inhabitants of his town, as well as other animals without a human figure.

Clashes also arose between municipal and ecclesiastical authorities. The influence of Juarista politics was felt, and the Reform Laws of 1857 were radically adopted from Cuatro Ciénegas to Monclova. Cemeteries were taken away from parishes, families were forced to take newborns to the Civil Registry before baptizing them, a mayor prohibited the ringing of bells, arguing that some citizens might not be believers, which would upset them; in short, things were conducted to subtleties

[19] Cited and translated by Javier Villarreal Lozano.

[20] The letter is in the Archivo Histórico del Estado de Nuevo León. The Vidaurri signature and the recipient is Jesús Carranza. The historian José Luis García Valero communicated it to us.

and mediocrities. For its part, the church tried to survive these attacks, although with no few difficulties. Very soon the neighbors had forgotten that when the Independence of Mexico was sworn in Ciénegas, the one who took the oath to all its inhabitants was the priest.

As a conclusion, we can say that events described above are without doubt important and enlightening making justice to the fame of Cuatro Ciénegas for its natural rarity and global importance. Topics and characters dealt with deserve more biographical, social, cultural, and anthropological studies. But what has been discovered so far is a window that reveals a long, complicated, and splendid past (see Figs. 3.4 and 3.5).

Fig. 3.4 Field day at Molino del Rey. Cuatro Ciénegas, June 21, 1899. Donated by Eloísa Zarza de Cantú (Archivo Municipal de Saltillo, Fototeca, F, c 1.1, p 2, f 2)

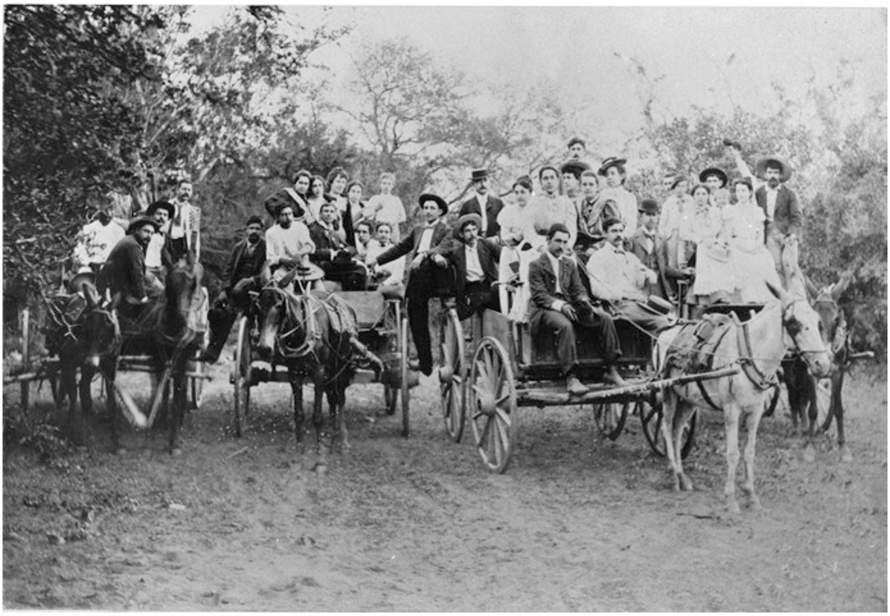

Fig. 3.5 Walkers during a picnic in Molino del Rey. Cuatro Ciénegas, June 21, 1899. Donated by Eloísa Zarza de Cantú (Archivo Municipal de Saltillo, Fototeca, F, c 13.1, p 6, f 6)

Information made in the Mission of San Buenaventura de las Cuatro Ciénegas

In the town of San Buenaventura de las Cuatro Ciénegas, jurisdiction of the province of Coahuila, on the 14th day of the month of January, 1600 and 81 years, Captain Miguel de San Miguel, protective captain of said town by His Majesty, in pursuance of what was requested by the custodial father Fray Francisco Peñasco, which consists of the request of four of the current, I came to said position, and said Custodian father through Father Fray Juan de León, doctrinal of the mission, presented the books of her congregation of baptisms, marriages, and burials, of which to certify which items that are settled in them and are as follows:

In the year of 1600 and 76 this mission was founded and on April 20 of that year the following were baptized and put the holy oils on: Diego, Lucas, Bernardino, Marcos, María, Jacinto, Bernabé, Josepha, Marcos, Isabel, Diego, Ana, Isabel, Teodora, Lázaro, Marcos, Cecilia, Santiago, Juan, Francisco, Manuel, Esteban, Antonio, María, Teodora, Cristina, Verónica, Marcos, Juan, Cristóbal, Pedro, Antonia, Francisco, Catalina, Isabel, Juana, Luisa, Ventura, Lorenzo, Andrés, Esteban, Fabián and Santiago.

[And so on, many other names of baptized, married and buried for several years are named].

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Chapter 4
Water as a Socializing Element: Hydraulic Culture in New Spain Between the Sixteenth and the Eighteenth Centuries

Miguel Ángel Sorroche Cuerva

4.1 Introduction

When in the first third of the eighteenth century the Marqués de Aguayo established the settlement of San Antonio de Béxar in Texas, and with it the Franciscan missions meant to indoctrinate and evangelize indigenous groups, he was accompanied by families from the Canary Islands where they were going to apply their knowledge of land cultivation with irrigation. The islands had been a necessary middle ground in the process of expansion of a tradition, which was a consequence of the adaptation of medieval Muslim techniques to an insular context. This is a specific case that we are going to analyse later on and that serves as a closure of the chronologic arch with which we are going to work in this text encompassing the sixteenth, seventeenth and eighteenth centuries.

Controlling water, from its collection, storage and distribution, has historically been one of the greatest achievements of humankind in order to settle in a place. Furthermore, if the territory was of a desert-like nature, this accomplishment turned into a feat. The bond that has been created between Europe and America since the fifteenth century and in the case of the territories that constituted New Spain since the sixteenth century enabled the pouring of experiences that were added to the ancestral pre-Hispanic practices.

The result was a set of traditions, places and instruments necessary to manipulate the liquid element, which has left a cultural mark that nowadays is part of the

Translated by Verónica Paula Recchioni, contract substitute professor in the Department of the Didactics of Language and Literature.

M. Á. Sorroche Cuerva (✉)
Department of Art History, University of Granada, Granada, Spain
e-mail: masc@ugr.es

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contribution of a country like Mexico to humankind. All of this is the evidence of how the process of settlement and land control carried out by the Europeans was supported by the control of the hydraulic resource based on the necessary utilization of the ancient pre-Hispanic practices and the introduction of techniques and rules of conduct that are deeply rooted in Islamic traditions, which had been defined throughout eight centuries in the Iberian Peninsula and after that they had been adapted to the insular context of the Canary Islands. Their introduction in the American world put in contact experiences that were hundreds of years old and that merged. This complex heritage has become one of the most interesting chapters of the Mexican culture, which represents an exchange that goes beyond its material nature and permeates the immaterial. Today, types of behaviour and knowledge are part of a tradition that needs identification and conservation.

In the concrete case of the desert, water is of paramount importance, given that they are two antagonistic spheres designated as heritage. With respect to documentary evidence, they are the setting and the protagonists of some declarations concerning world heritage where their union has created noteworthy cultural manifestations. The way in which human beings have historically related to the desert, facing and "taming" it, by giving it back its lost fertility thanks to water, is representative of their capacity to overcome challenges.

We consider that this dualism, the indomitable spirit of the place and its capacity to create life, can serve as a way of reflecting about the social dimension of deserts. As a habitable place, it demands that the groups of humans that live in it have strong bonds. Furthermore, it forces them to have a perfect organization that makes the best possible use of scarce resources like water. But also, the meagre presence of water turns it into an object of dispute leading to conflicts over the access to it, affecting the stability of those communities and above all the severe damage of the places they inhabit.

The case of Cuatro Ciénegas can well serve as an excuse to understand the fragile relationship among water, land and humans. The bonds that have been created among these three components along history are really fragile when the public and private domains clash over its use. Inhabited since the pre-Hispanic period, human communities have left an indelible mark on the territory. Cuatro Ciénegas unique pools, as ecosystems with endemic forms of life, face the dilemma of surviving due to the overexploitation of the aquifers that nourish them. Apart from their endemic species, the acknowledgement of their uniqueness may make their conservation possible given the raising awareness of the local communities. A clear example is the formative programme in their schools, which has had one of the most remarkable outcomes in terms of social involvement in heritage conservation.

4.2 Water and Social Dimension

Water is capable of bringing together human beings at the social level and in different degrees. A look over the territories that have incorporated its use shows that those lands have an interwoven social organization, with close bonds, which are subject to the demands that impose manipulating the liquid to a great extent. Land which is being irrigated in any way is a social space, and that affects all the mechanisms that control the effective use of water, including work relationships. The importance of its control, which involves building the necessary infrastructures to obtain, store and distribute it, also implies the order and the way of having access and using it, turning it into the vital structuring element that demands a strict individual behaviour. Thus, in the context of irrigated lands, communities cannot settle far away from the farmland, since, for instance, they are subject to strict irrigation shifts, cleaning and maintenance of the ditches, etc.

Regardless of the approach we take, the ancestry of the two contexts involved in Mexico, the pre-Hispanic Mesoamerican and the Castilian from New Spain, demanded a clear social organization. In the first case, the concept of the common good governs every action. Besides, in the Castilian case, there is the added value of being the heirs of the Muslim tradition which managed to cultivate monsoon species in territories with hot summers but poor rain, changing in this way the diet on both sides of the Atlantic (Watson 1998). Pre-Hispanic cultures had developed a continuous and autonomous process, only with some regional variations, which proves the long tradition over water control and community organization. This social structure implies a different level of consideration: from the pre-State and State domain, ruled by the basic principle of public benefit in the distribution of infrastructures, to the individual domain, characterized by the community labour necessary to carry out the completion of these works (Rojas et al. 2009).

Apart from its pragmatism, as we have highlighted, water holds an important symbolism. Religion and aesthetics go beyond their meaning, from an almost practical stand to a philosophic and religious status, values which are present not only in pre-Hispanic America but also in medieval and modern Europe. As such, we can find water in the myths of origin and narratives of many of the local peoples that lived in America before the arrival of Europeans. Being agricultural societies, their prayers and pleas were directed towards one of the most important and ancient gods, Tláloc, who is still worshiped on the hills nearby the city of Texcoco (Clavijero 1970). However, water also contributed to the creation of recreational spaces, like the lakes that were part of the property of Moctezuma. From Europe, water management ideas arrived along with a religion and christening, a foundation stone of their massive evangelization.

Finally, we cannot overlook the fact that it also implied a language use that enabled the people in charge of its construction or maintenance to have a precise idea of what was being done. A vocabulary, currently non-material heritage not yet acknowledged, which has its origins in the convergence of the pre-Hispanic and European traditions. Practices, in this case of Islamic origin, whose recollection is surprisingly alive in terms such as *dula* or in organizational practices like those of the irrigation communities from Baja California, who are still solving the problems derived from their use accepting that they are part of the Jesuit legacy (Sorroche 2011).

4.3 Pre-Hispanic Background

The Mesoamerican civilization, which developed with the support of agriculture, had the deity linked to water praised on the top of its pantheon. Societies which progressively defined themselves as farmers and warriors had this liquid element present in their mental, social and cultural structure. In the mythical texts, it is in the centre of the primitive waters where the island that symbolizes the centre of the world as a sacred mountain is located. Similarly, there is a basic concept for their territorial and social organization, which is the *altepetl*, where water and mountain are referred to in its very name (Fig. 4.1) (Bernal and García 2006).

The Mesoamerican context has left us endless examples that let us understand the social demand and the ability to make use of water, which prove that this can only be done in a well-structured community. As stated by Teresa Rojas Rabiela: "This development must be understood as the combination of the prevailing techniques and socio-economic and political forms of organization in the historic period we are analysing in here, so that certain problems like those related to work tools in Mesoamerica, all of them manual, made out of wood, stone and, in some occasions, metal (hard copper), must be interpreted in the specific context of the society where they were being used, with the concomitant workforce politically organised by the State. We are mainly making reference to the systems directed towards applying

Fig. 4.1 Migration of Mexica people from a mythical mountain in the water. Boturini Codex. S. XVI

work to a great diversity of collective tasks, including public and hydraulic works, of course" (Rojas 2009, p. 19). A journey along the 3000 years of history prior to the arrival of Europeans in America illustrates the fundamental role that Europe had in such specific aspects like stabilizing settlements and exploiting farmland (Rojas 2009).

Apart from the material factor, water appears to be a key element within the pre-Hispanic tradition found in codices and traditions that have been passed on from generation to generation to the present day. Key component of a structure that places water as the primitive liquid as we have seen above, in all the cases the necessary social organization that its use demands illustrates the ability to build artificial structures. In this way, really diverse environments have been inhabited, like the watery habitat of Veracruz by the Olmecas, the lakes in Tenochtitlan with the creation of chinampas by the Mexicas, who managed to change the lacustrine territory by building different structures such as aqueducts and *albarradas* or dikes, and we cannot overlook the case of the Hohokam society already in the deserted north, who were always close to their irrigated lands.

This social dimension takes us to another topic, to value the role of the State or the institutions in the creation of these infratructures, as Ángel Palerm has already pointed out when he raised awareness about the fact that irrigation was successful in spaces that had a major people concentration (Palerm 1972, 1973). The cohesive nature of the political operational structure is essential to understand the organizational capacity of periods like the Olmeca, without which it would be impossible to understand the volume of work done during the Pre-Classical Period. During this period there is already evidence of the presence of dams and irrigation canals, infrastructures that demand an internal organization which was inherent to the society and without which the great engineering works, like the construction of artificial islands and pyramids, as in the case of San Lorenzo or La Venta, would not have been possible. Also, the production of monumental sculptures requires an established order and the acknowledgement of social hierarchy that is internal to the group (Soustelle 1984).

During the Classic Period, it has been proved by archaeologists that the organization of the States was able to move great amounts of labour to carry out engineering works. In this way, great water reservoirs had been created, which proved their unquestionable capacity and which reached an utter perfection in their infrastructure works in this period. The canalization of the banks of the San Juan river as it passes by the city of Teotihuacán in a moment of urban expansion, together with an imbricate irrigation system (Manzanilla 2009), the great water reservoirs of Mayan cities like Tikal (Scarborough and Grazioso 2015) or more specific cases, like the cistern that exists in the central square of Monte Albán, illustrate a civil service of the classic State that we should bear in mind.

In the case of the Post-Classical Period, the lacustrine environment of a city like Tenochtitlán and the successful adaptation of the Mexica group demand looking backwards and questioning its origin and its connection to other humid contexts. Also, the organizational capacity to understand the creation of the *chinampa* as a unit in the urban definition of the city and, on the other hand, the very provision of

Fig. 4.2 Chinampas in Xochimilco. Mexico City

services for survival in that place show a perfect adaptation to an aqueous environment. Some of the most salient constructions are diverse aqueducts, such as those of Chapultepec and Acuecuexco in Coyoacán, which brought water to Tenochtitlán, and that of Tocotzinco (Acolhuacan), which is known as “Baños de Nezahualcóyotl” and is the best preserved up to date. The *albarradas* were also outstanding, as dikes or combining their use as roads, necessary for the containment of the waters of a lake, which not only were of a different nature, salt and fresh, but were affected by the rainy season due to the contribution of the basins that supply the lake and that they had to control. The Albarradón of Nezahualcóyotl illustrates what is mentioned above as it is a construction work that managed not only to control the regular floods of the lake but also to separate freshwater from saltwater, benefiting from what each of them offered, irrigation and food.

4.4 European Contributions: The Sixteenth Century

Well into the Colonial Period, water did not only play an important role in the territorial control of the new spaces, but it was also a key element to guarantee the functioning of cities and to begin the exploitation of large land extensions; to this purpose, its private and public use was regulated. As we have pointed out in the case of the pre-Hispanic period, throughout the colonial period water and the building of infrastructures to control it demanded an important social organization and the intervention of indigenous labour at the beginning.

From the beginning, the water demand by the newcomers was the key to understand the process of the occupation of land. In Castile, the culture of water was already perfectly defined as the heir of medieval Muslim and Christian traditions (Arroyo 1998). Therefore, the objectives were clear: to provide water for agriculture and mining, with the incorporation of new technological innovations, and to supply the population. The transfer of the Castilian legislation as the only resource due to the initial unfamiliarity with the pre-Hispanic regulations turned water into eminent and direct property of the Kings (Birrichaga 2009). The idea that it was a common good let all the inhabitants in a city have free access to it by means of public sources; however, there were various cases in which its private use was regulated: "the private uses of water had been granted to different bodies (indigenous peoples, religious orders and civil institutions) or to individuals by means of royal grants, that is, it was a use sanctioned by a *merced* granted by the King or on his behalf, which guaranteed the right to use a water current or spring; in the event of disputes, these documents were required in order to determine who had the right over the property" (Birrichaga 2004).

The importance of water led to the creation of rules and regulations to optimize its use. Thus, we find the water distribution of 1560, which regulated its use confirming the granted rights by royal concessions or *mercedes*, by which the colonial distributions served as legal justification for the solution of conflicts over the rights of indigenous peoples and Spanish settlers on the use of the waters (Birrichaga 2009, p. 44), and the Ordinances by Philip II of 1573 for the foundation of towns, which indicated the way to distribute water and crop land. The most common pattern was the equitable distribution among the town founders. In spite of this, the inconsistencies in these rules and regulations made it hard to apply the law in the North of New Spain (Birrichaga 2009, p. 44). Not until the end of the eighteenth century, with the foundation of Pitic in 1789, were ordinances that considered water distribution to towns founded subsequently put forward (Fig. 4.3).

With respect to agriculture, the medieval legacy was enduring in that it was a fundamental element to continue the expansion of a set of cultivated plants towards the west of Mexico, species that had previously acclimated to the Iberian Peninsula since the ninth century. These cultivars expanded from Spain to the Canary Islands, where they adapted to a new place, so that from there they took a penultimate step, first on the Caribbean islands and afterwards on the continent, becoming the base of European agriculture in America and later becoming part of the American diet as a common element of Ibero-American culture, including plants like the sugar cane, rice, peaches, oranges, lemons, figs, olives, pomegranates and many more. These plants could serve as food for the new population that was settling in the new territories, and together with them, the necessary means of survival, while the plants and people were adapting to the local environment (Solano 1990): the necessary knowledge and technology for their cultivation travelled with them. This situation has always raised the question as to whether Moorish population also travelled in spite of the royal prohibitions. Given the high level of specialization that was required to

Fig. 4.3 Town of Coxcatlán, or of San Juan Evangelista, and its subjects, of the Diocese of Tlaxcala. AGI, MP-MEXICO, 19

put those systems forward and the lack of knowledge of Castilians about the management and control of the water that existed throughout all al-Andalus, this possibility has always been left open.

Today, this heritage makes up one of the most interesting chapters of Mexican culture, since it witnessed an exchange that goes beyond its material nature, by means of infrastructure, like aqueducts, mills or ditches, and transcends the immaterial sphere, leaving modes of conduct, knowledge and terms as part of a tradition that needs identification and conservation.

However, the changes that took place in the fields of technology and legal organization disrupted the pre-Hispanic dynamics, finally replacing the existing collective equilibrium of social reciprocity, by another one of rights acquired over land property and water use of great significance, which has not prevented us from finding some of these traditions in the present day.

The occupation of the territories that would make up New Spain demanded that Castilians built a whole series of infrastructures that guaranteed the stability of the process of concentration of indigenous population in towns. By the sixteenth century, the descriptions made by the travellers along the road that linked the port of Veracruz to Mexico City described cultivated land with species that arrived from

Europe, crossed by ditches, and this can be proved by the development of the industry in Puebla de los Angeles, where channels and ditches were drawn from the city rivers, like the San Francisco river, so that tanneries, *obrajes*, brick makers and pottery workshops could work (Loreto 2009, p. 57). We should not forget the exploitation of the already existing resources. In the same vein and due to the land extensions and distances to travel, the elements that took part in that process were given great prominence as in the case of religious orders (Espinosa 1998) and the training and knowledge in engineering and architecture that some of their members had. By the last quarter of the sixteenth century, all of the territory that had been occupied by the Europeans had gone through a clear transformation with respect to its exploitation.

This allowed for the acceptance of traditions and systems, as in the case of the pre-Hispanic *albarradas* of which the *albarradón* of Ecatepec is a clear example. This infrastructure, of which there are still remains, incorporated the concept of "dike road" that had been perfected in the context of the lake of Texcoco. But apart from this, others were improved, which were not left unnoticed in the pre-Hispanic period, but which would have diverse formal characteristics and dimensions, as in the case of the aqueducts, when the arch was added, fountains or dams. This is illustrated by the aqueduct built by Padre Tembleque, or all the fountains with which the city of Mexico was supplied, like Caja de Agua, or Laguna de Yuriria, which was put forward by the Agustinian priest, Diego de Chávez, who founded the convent in 1544.

All the cases showed the changes that were taking place, both technologically and socially: "What happened in the field of hydraulics since the arrival of the Spanish to Mesoamerica was much more than just a 'technical change' in which some artefacts and materials (of wood and stone) were replaced by others (metallic), and in which totally unknown machines and species like waterwheels, mills or working animals were introduced. These innovations meant a true 'technological revolution' in the sense that they brought about a new cultural and socio-political system which gave a different meaning to those 'things' and caused new phenomena. This does not deny that metallic tools made it possible to dig wells and water reservoirs (*jagüeyes*, cisterns, wells, underground aqueducts) more deeply, that the waterwheel, the lever, the lathe and the pulley made it easier to pull out the water and lift it, that the animals, alone or combined with wheels (carts, wheelbarrows) made land transport more efficient and 'freed' the *tamemes*/human carriers, and that the arch in aqueducts and bridges made it possible to take the water to longer distances and connect roads more efficiently" (Rojas 2009).

Nevertheless, the changes also started to take place in the fields of social relationships and property, which modified the existing models. Customary law was replaced by the rights legally granted by means of allocation given to newcomers; thus the spoken word was replaced by the written word: "…the substantial changes, those that radically changed reality in technical terms, took place in the socio-political, economic and cultural spheres. In the same vein, in the legal field, one of the biggest changes took place with respect to the rights over water; in the socio-organizational sphere, in the *coatequitl* […] or collective and compulsory work system carried out in the pre-Hispanic period by ordinary people in order to build and maintain hydraulic works and public works in general. The ones and the others caused endless legal and ordinary conflicts among the Europeans and the indigenous populations. The owners of mills, *trapiches,* sugar mills and fulling mills that had been granted royal *mercedes* acquired the property of the land and the right to use the water to move their machinery or irrigate their fields. Sooner or later, this disrupted the functioning of Mesoamerican hydraulic systems from the technical point of view, but not only that, it also changed the meaning of the whole socio-political organization that made them work (construction, maintenance), nourished by the sense of collective use and social reciprocity" (Rojas 2009).

4.5 The Seventeenth Century

The seventeenth century is characterized by the continuity of what had been started in the previous century. What is more significant is the attempt to control new territories that were being integrated after the expeditions supported by the viceroys. They had to reinforce what they had already gained before the threat of European powers that were trying to settle on those spaces which were not directly controlled by the Spanish Crown. In any case this was a complex century, in which the crisis that affected Spain travelled to America, where there was a progressive power loss after the death of Philip II in 1598, which Philip III, Philip IV and Charles II could only slow down.

As in the sixteenth century, the chronicles written both by the religious and the military are an essential source of knowledge of how the conflicts over natural resources between European settlers and indigenous populations intensified. Nearly all the aspects of New Spain were detailed. For example, in this century, the *Demarcación y Descripción de el Obispado de Michoacán y Fundación de su Iglesia Cathedral…* by Francisco Arnaldo Issasy serves as an example in which populations are being described in great detail concerning their ecclesiastical architecture, including in some of them references to fountains and water distribution (cited by Ettinger 1999).

The disputes to control the volume of water of *aguajes* became frequent, bringing to light the problems related to the access to a resource that in some northern areas was starting to be scarce. Expeditions, especially to the north, were intended to find routes and consolidate a presence that was becoming increasingly threatened by the more peripheral spaces of the coast of California or the Mississippi basin. They were made up by soldiers, missionaries and civilians, and their routes were plotted on the basis of the information and experiences of the indigenous people that went with them and that turned *ojos de agua* and *aguajes* [refers to springs and small dams] into fundamental elements in their routes and later into the foundation of settlements, be them villages, missions, mines, etc. In the seventeenth century those settling processes became consolidated, since some missions were turned into churches becoming real towns, where their urban outline was being developed at the same time as in the cities. This was a new period, and this is also illustrated to some extent by the fact that the dynamics are no longer led by the Spanish but by people from New Spain.

The panoramic view that New Spain offers in the seventeenth century shows that the new creole society had already settled and where the necessary infrastructures for production were one of the many features of the scenery. By 1622, in the coast of Veracruz, the descriptions made by travellers and passers-by show us that this hot land hosted some settlements inhabited by indigenous people among its towns. It also had a coastal area called “the plains of Almería”, where the cattle ranches and *haciendas* founded by the Spanish had been settled along sugar mills, lands cultivated with corn, tobacco and other seeds spread across the whole territory.

If in the previous century the process of getting into contact had taken place between the arrival, occupation and perception of the new reality that had to be dominated, during the 1600s the changes were more radical. This was not only due to what has been mentioned but also for the institutionalization of a new way of land exploitation, the hacienda, which had started being implemented in the continent in the mid-sixteenth century. Without a doubt, the changes that had taken place in the management of water, which until the previous century were clearly controlled by indigenous institutions and had gradually been set aside or transformed in their essence, had been accelerated due to technical innovations. Illustrated in the new machinery put to the service for land exploitation, this had a clear impact on the changes in the use of soil, even in the reduction of the extension of irrigation lands, which decreased in favour of extensive lands for the cultivation of cereals or the introduction of livestock, a non-existent component before the Europeans’ arrival. Overall, in this century the acclimation of species that had arrived in America in the previous century is evinced, and it is interesting to notice how fruit trees, as citrus, bananas, pears, apples, plums and walnuts, are numerous in the descriptions of the territories of New Spain that are made in this period.

As mentioned earlier, the presence of those *haciendas* was added to the increasing number of mills, *trapiches* and fulling mills, illustrating the changes that started to take place since the sixteenth century. The scenery was sprinkled not only by these new components but also by some changes on the surface of grazing lands which competed with those of irrigation. Such a duality even made that the towns which were further from the outskirts of urban contexts were the ones which later perceived the change in the use of land or the water access from springs. In some way, the great protagonist, *la hacienda*, was positioning itself as the great organizing centre of the farming space, reassuring a hegemony that would last even until the twentieth century (Fig. 4.4).

But it was also a moment in which disputes between the Spanish and the indigenous people became frequent. These confrontations even led to the destruction of ditches and dams. The medieval right of *mercedes* and the indigenous customary law clashed with respect to water use and the need to irrigate the lands that the indigenous people had. In the case of Querétaro, by the beginning of the seventeenth century the situation worsened due to the fact that the Spanish took over the best properties, which demanded a greater amount of water.

Fig. 4.4 Dam and ditch in the mission of San Francisco Javier Biaundó. Baja California. Mexico

The situation in this city illustrates the moments of tension and decline of traditions. On the one hand, due to the fact that the urban population was a mixture of indigenous people, mulattos and Spanish, the use of water from ditches that crossed the towns was complex, but above all, due to the controversies that arose due to the limitations the viceroys established over the use of water and irrigation, because water belonged to the indigenous people since the foundation of the towns. By the middle of the seventeenth century, the problem was already present, and as it can be seen in a document from the year 1640: "…and on behalf of all the other settlers in the neighbourhood of the Mexicans from Santa Cruz of this town as our right, we claim that in order to support ourselves and our wives and children, provide them with the basics and pay the royal tribute we have in our houses and out of them some sort of lands with fruit trees and tillage land where we sow maize, wheat and other seeds that need irrigation that belongs to us as naturals to the River of this town since we have used it since its foundation and now it is being disturbed by *mayordomos* and landlords and other people that perform the works they called Jurica and of Santa María and others that are on that other part of the River breaking the dam to take it against our will" (Loyola 1999, p. 119).

4.6 Epilogue of the Eighteenth Century: The Control of Northern Desert Areas

By the eighteenth century, the territories of New Spain have reached their utmost extent to the North. The remoteness of the decision centres somehow led to the dependence on the autonomy attained by the control over water and the exploitation of the agriculture and livestock lands. Against that general background, the examples that can be found are those of overcoming the environment, becoming more and more desert-like, and those of indigenous groups that besieged the Spanish outposts. A vast territory coveted by European Powers and, later on, by Russia and the USA.

We will take as reference one of the examples that can serve as a framework for understanding the socializing role of water in these confines and on which we have been working for years. Previously, a hybrid legislation filled a legal gap of more than 200 years, dating from Viceroy Antonio de Mendoza's *Ordenanza sobre medidas de tierras y aguas* of 1536, and two documents of the second half of the eighteenth century, *The Royal Decree in which H.M gives instructions on how to solve mercedes and sales of Crown properties and wasteland in charge of Excmos. Viceroys and Presidents of the Royal Audiences* of 1754 and the *General Regulation of Water Measurement*, published in 1761, which comes into force in 1783.

4.6.1 The Case of Baja California

The history of the occupation process of the strip that currently comprises the Mexican peninsula of Baja California developed from the 1530s, with Hernán Cortés's first attempts and the South Sea expeditions, and the mid-nineteenth century, with the settlement of the last Missions in San Francisco Bay context (León Portilla 1985). Between those two dates, numerous chapters in which intrepid expedition members played a leading role enabled the configuration of an ever-closer image of the reality that was being pursued, imitating on the coastline what was happening inland (Rodríguez et al. 1995; Rodríguez 2002). Sebastián Vizcaíno noticed the strategic importance of the region, as described by Clavijero (Clavijero 1970, p. 77). At the end of the seventeenth century, Isidro de Atondo y Antillón and Father Kino's expeditions laid the foundations for a period that had been initiated by the Jesuits and would determine the subsequent events.

In view of the characteristics of the territorial articulation, different stages can be distinguished in this historical context. A first stage lasted until 1697, when the Baja California peninsula involved merely a peripheral occupation of the area. In this period the initial difficulties of the process became evident, due to the harsh geography and extreme weather conditions. This is also the moment when the image of its geography is shaped, a geography that will have considerable importance in the definition of the peninsular reality of Baja California and would affect the supply proposals from the coast on the opposite side of the Gulf of California, both by sea and land.

The second stage was marked by the foundation of the Jesuit missions and which we will roughly delimit from the foundation dates of the first mission in 1697 and the expulsion of the Jesuits from the New Spain territory in February 1768. A new missionary model characterized by the remoteness of the decision centres was defined, and has been studied thoroughly by historian Ignacio del Rio (Rio 2003). During this stage, the mission became the territorial occupation cell, a tool in a process in which the civil and military element had a delimited space but not with the determination of the religious one. In this case, the choice and location of the missionary centres were determined by the inland peninsular expeditions, taking into account the information provided by the indigenous groups, in which the reference to water points and the existence of lands that could be cultivated were vital (Baegert 1989). However, the level of difficulty was such that it took a long time to define a process with guarantees of permanence and that would lead to a process of structuring in *cabeceras* and *visitas*, the same way the central area of New Spain was organized in the sixteenth century (Espinosa 1998). In the first stages of the occupation process, the news in relation to the changes in location of the missionary settlements mainly because of the lack of resources to supply the populations like water is frequent.

The third stage begins with the expulsion of the Jesuits and the arrival of the Franciscans and Dominicans. The decision of the Spanish Crown to consolidate its control over this coastline once and for all meant that the new foundations were arranged on the coast, reassuring the role of border and hence with a double function, religious and political, which actually they never lost. This stage was led by the Dominicans and determined by the need to manage the abandoned missions and complete the articulation of a vast territory comprising the last Jesuit foundation, Nuestra Señora de los Ángeles, and the first Franciscan mission already on the present US territory, San Diego de Alcalá. By agreement with the Franciscans, the Dominicans will be granted the Jesuits Missions in Baja California and will be asked to complete the central stretch of the itinerary that should conform the Camino Real of the Missions (the Royal Road), from the nucleus constituted by the Franciscan foundation of San Fernando de Velicatá area, well known by the indigenous peoples (Nieser 1998; Meigs III 1994). In this case, the environmental conditions marked a division between the Dominicans' peninsular foundations and the Franciscans' in present US California.

The truth is, as stated before, the methodology applied by the Jesuits in Baja California thrives on the one defined by the Franciscans in the sixteenth century in other contexts of New Spain. Supported by the knowledge to act principle, but without the Jesuits' self-sufficiency, Franciscans differentiated from the Jesuits in that they looked for remote places where to carry out their utopian plans and for which they needed the least interference possible (Espinosa 2011, pp. 79–112). Together with this, from 1697 on, the collection of letters between the different fathers that took part in this episode reveals the strategic political and religious character of the penetration process.

An analysis of the Californian geography enables us to understand that the access to water was different, depending on the region. Thus, while there is abundance and stability of sources and courses in American California, the scarcity of water is predominant to the south. In this context, the identification of a water spot was crucial from the outset in which efforts were made to establish stable settlements at the southern end of the region, being essential for human supply and the irrigation of land through a system of storage and distribution. An example to understand this matter is the context of the territory controlled by the Dominican Mission of Santa Catarina in Baja California, in which the *cabecera* and *rancherías* nearby are located next to a water point. This dynamic, essential to guarantee the success of the missions, was already applied before the missionaries' arrival. The existence of indigenous place names allusive to water elements is a clear proof of that and is registered in Father Nicolás Tamaral's report in relation to the state of the Purísima Mission, for example, Santa Catarina's mission's name, *Jactobjol*, means "place where water falls over stones" (Río 2000).

In the process of arrival and occupation of the Californian territory by the Jesuits, Franciscans and Dominicans described in different sources, the need to locate fertile arable lands, pasture for livestock and, mainly, stable water sources to guarantee supply for the population and land irrigation is evident. Although the constituent elements are practically the same, the constructive guidelines are diverse, prioritizing the construction of some elements over others, depending on the field we are referring to (Rodríguez et al. 2003).

The hydraulic infrastructure on which they relied, and which some of the Baja Californian missions still have, although its components show some homogeneity, presented variations in relation to the materials, the nature of the water source they thrive on (e.g. stable *aguajes* or streams with sporadic currents whose water is retained in dams), distance from the cultivated lands and the orography itself, which in a way affect, among others, the construction systems, the number of components and their distribution (Ruiz and Sorroche 2014).

From the three orders, the Jesuits' missions offered better quality and a more complex repertoire, with proportions only rivalled by the Franciscans in the North, although the number we got of these latter systems is smaller. The same does not hold true for the Dominicans, which had more humble characteristics of the constituent elements, construction and irrigation, as perceived both in their dimensions and in the materials with which they were made. In any case, it is one of their most salient heritage items, not only because its presence can still be perceived due to its dimensions but also because the hydraulic infrastructures are still working in some of them, constituting the base of a historical memory supported by some traditional systems of land exploitation.

From the group of infrastructures, we can differentiate between dams and dikes (we use both terms, as they have appeared indistinctively in the consulted sources as in the field work done; they make reference to the structure used to retain water and derive it into a canal), *albercas* or cisterns, ditches, between which we can differentiate dirt and manufactured ones, and finally other elements such as *partidores.* In relation to dams and dikes, they possibly represent the most spectacular group the missions rely on. They appear in those in which the sporadic aspect of the water source, generally temporary river flows from which they have to be supplied in the best way, demands to be slowed down before being distributed. They also appear in those places with a stable water source which needs to be collected before being distributed. They are located in the proximities of the mission as well as in what we can call their population nucleus, always with the common denominator of being higher than the lands to be irrigated and at an adequate distance to determine the overall irrigation surface. The relevance that entails the alteration of any of these elements was revealed in Texas in the twentieth century (Glick 2010).

Dams and dikes are made of masonry with mortar, illustrating the constructors' clear knowledge of hydraulics. This is made evident in their design, as well as their location, endowing them with the sufficient consistency to withstand the passing of time and the harsh environmental conditions, which were the main reasons of destruction as occurred in the reconstruction of the Jesuit Missions in 1770. Together with this, their complexity varies. Possibly, the Santa Catarina Mission will stand out as an example. Organized in two points separated from the valley where they were located, three dikes stood, two in a first backwater, on the highest area, and a third one in a lower position and near the population nucleus. Made out of different materials, the first ones are considered the oldest ones and represent an example of the need to rationalize the water, once it was demonstrated that the calculation done to measure the irrigation did not cover the expectations to both supply the population and the irrigation of lands (Meigs III 1994).

From the group of missions, the ones which still preserve their infrastructures are the missions of Todos Santos, San Luis Gonzaga, La Purísima, San Francisco Javier Biaundó, Santa Rosalía Mulegé, San Ignacio Kadakaamang and Nuestra Señora del Rosario de Arriba, and from the rest of the infrastructures only the news of their existence remain (Meigs III 1994). In addition, there are numerous remains of the presence of contentions and distribution dikes, which we have little testimony of to have a slight idea of their dimensions and locations (Fig. 4.5) (Meigs III 1994, p. 136).

The news we got of the Jesuit missions allows us to know the state of the infrastructure during the Jesuit period as well as after their expulsion. The chronicles written by the Jesuits after their exile let us rebuild some areas of the Jesuits' irrigated land. Also, the reports commissioned to the Franciscans together with the letters that other members of the Franciscan Order interchanged, such as the ones Father Palóu wrote in 1772 within the inventory process of the missional possessions, complement the first group of sources. In the case of the Dominicans, some expeditions at the beginning of the twentieth century serve as the most appropriate reference to understand their state up to that date. Nieser (1998) and Meigs III (1994) works serve as reference.

Regarding the Franciscans, most sources describe the missions in Alta California in a basic way, and the available data is vague, so it is unsurprising that in the case of the missions founded by Father Serra, the information is exiguous; see, for instance, Clavijero (1970).

Fig. 4.5 Water sources at the Hacienda de San Juan de Sabinas. Coahuila. Mexico

In relation to San Francisco Javier Mission, the components of its hydraulic structure were described (Palóu 1994). The Purísima Concepción de Cadegó Mission in 1772 had an important area that could only be exploited if there was a dam that controlled the water of its stream (Palóu 1994, p. 219). In the case of the former, Father Ugarte's foundation process stands out as he situated the settlement based on the location of a stable water point found with the help of Yaqui Indians brought from the surrounding coast (Barco 1988, p. 257). As for the Purísima, a process of relocation due to the characteristics of the first settlement took place, as described by Father Barco (Barco 1988, p. 260).

In mission of Guadalupe, as in mission San Francisco Javier, the reports from 1772 describe the options to back down the water and lead it to the farmland (Palóu 1994, p. 220). This system not only applied in the *cabeceras* in built-in points that could offer optimal characteristics for farming, for example, the already mentioned San José de Gracia, which depended on this mission (Palóu 1994, p. 221).

The damage caused by heavy rains and resulting floods, for example, in 1770, affected all missions. These include some of the most important infrastructures that still remain in Baja California, such as Santa Rosalia Mulegé dam. This is one of the most spectacular environmental complexes because of its characteristics and dimensions: a huge palm grove generated from the control of water of the wetland, giving rise to the current oasis. When the dam was destroyed in 1770, the Franciscans reconstructed it (Palóu 1994, p. 222).

Another mission that has left an outstanding group of hydraulic structures is San Ignacio Kadakaamang, already reported in 1772 (Palóu 1994, p. 224). The dam that slowed down the water flow is one of the most salient elements, and from its sides a group of ditches branched out to irrigate the whole extension of land, in part occupied by the palm grove and at the back of the church.

Finally, the only Franciscan foundation in Baja California, San Fernando de Velicatá, had a dam that helped slow down the water flow necessary for irrigation, as described by Palóu: "It is founded in a small valley in whose centre a stream runs with sufficient flow to irrigate the land in its meadow, and was easily obtained with an earth and stone dam built in that stream, with which the water was slowed down" (Palóu 1994, p. 230).

Regarding the Dominican missions, Nuestra Señora del Rosario de Arriba mission stands out, still preserving the remains of its dam in the proximities of the nucleus of the first of the two missions that would spread in a big valley that conforms, from east to west, one of the main penetration routes from the coast into the interior.

When the flow of the water source is permanent, the options to collect it vary, from the creation of a cistern for storage, as in the case of San Borja and some *ranchos* near the missions, such as the Dominican Santo Tomás, where we find permanent *aguajes* that were initially stored before being distributed, to the option of direct canals, taking advantage of the quantity and permanence, for example, the case of San José de Comondú or Santo Tomás which, due to their characteristics, will be mentioned in the section of ditches. The San Borja cistern is one of the most common cases that can be found in the missions, but the largest in size, that along with the dams, showcases the huge work and organization capacity that was available for their construction.

The surviving infrastructure examples enable us to extrapolate a model that varies in its dimensions. Overall, they are square or rectangular base receptacles, placed in the water source or along the ditches, which in some cases still retain the remains of the *almagre*, with which the interior of their front was covered. Their capacity varies in relation to the water supplied by the source or *aguaje*, the number of people to supply and the land surface to be irrigated. In some cases, they are of modest dimensions but enough for irrigation. Those of monumental proportions illustrate the importance of water and of the cultivated land; in either case, the ditches start from the source.

Water deposits spread in the cultivated land and along the ditches represent a variant. An example of this is mission San Francisco Javier, in charge of collecting the water for irrigation as the last stage before going back to the riverbed, as stated in the Franciscan reports of 1772. In this sense, there exist many similar references in relation to Jesuit missions. In the case of the Guadalupe mission, lime sinks were used as complement of the hydraulic system to irrigate small orchards (Palóu 1994, p. 220).

San Francisco de Velicatá complex stands out within this group of water deposits of large dimensions. Approximately located a kilometre from the nucleus of the mission, the storage cistern is placed higher than the crop lands. From it, the water canal carries the water to the proximities of the central building (Barco 1988, p. 340). The distance between the water deposit and the mission shows the ability to adapt the supply conditions to the evangelization, providing the centres with the necessary resources despite the long distance. The remains of El Descanso mission in the state of Baja California up to the present day are remarkable. This Dominican mission was dependent on the San Miguel mission, which the former replaced at a specific moment due to a reduction in the number of indigenous people of the latter. The distinctive feature of El Descanso lies in that it is the only one in which the orchard that supplies the mission is located 5 km into the valley from the coast, near the *ojo de agua* that supplies it, doubling the distance between the main nucleus and the crop lands from other missions in Baja California. The weather conditions account for this unification, in a context in which mists predominate throughout most part of the year, hindering crops. The remains of the irrigation system up to the present consist of a water deposit and a ditch, by which water was distributed, and were supplied from a spring that had been deviated (Meigs III 1994, p. 198).

Within this group of missions, two examples are worth pointing out due to the exceptional ruins that remain today. On the one hand, a pair of small *albercas* situated in Santo Domingo mission, and embedded in the irrigation system from where they took water, were destined to otter skin tanning, which they traded with Russian and English people in the region (Meigs III 1994, p. 137). Hidden next to the terracería nearby, they represent the only example recorded to that aim. On the other hand, the remains of a water deposit constructed like a well made of brick that stands in San Buenaventura mission is the only example reported with these characteristics.

The ditches situated around these missions represent the most complex framework for its dimensions and the direct implication of their location, distribution and exploitation of land. Built with different techniques, such as directly dug into the ground, carved out of rock or made in masonry filled with mortar and covered, in some sections, with flagstones, they are the genuine arteries through which the water reaches every single plot. Locatable in every mission, the ditches exemplify in every case the perfect knowledge of the necessary engineering mechanisms to bridge the distances and fix uneven ground with the aim of making land arable for missional supply. They branch from the dikes in which the water is slowed down, from the cisterns where water is stored or directly from the *aguajes* or sources. As for the first ones, they have been diverted from the mainstream to outline the path through which the water reaches the crop lands from a higher level. In some cases, when the land has a significant level difference, aqueducts are used to keep the route.

In the case of the aguajes, water is directed straight to the ditch, simply diverted with stones. One of the best examples is the layout of the San José de Comondú ditch. Their route is determined by the uneven surface and the distance to bridge, so it is necessary to run along the perimeter of the cultivated land, taking advantage of the gravity to move a quantity of water that must be regulated to avoid the force to be excessive and generate erosion in the channelling system or in the crop plots.

The different sources that have been mentioned cite them as zanjas. Always related to the *aguaje* they nurture from or the dam that regulates the current of water, and in most cases they are the main element described to reference the initial community works destined to provide supply to the missions.

As regards the Jesuit missions, all of them offer an important set of ditches that still fulfil their function. Not all of them have been recorded in the sources, but field work would enable the reconstruction of some of the historical extensions of the crop lands organized by the religious. Cases like La Purísima, San Francisco Javier or San Ignacio, for example, whose land boundaries can still be identified through resources developed by the new technologies, such as aerial photography, show the dimensions of these systems. From some of them, there exists the building document of the first infrastructure, such as Santa Gertrudis mission, whose process was described by Father Barco, and where the scarcity of water led to the canalization of an *aguaje* that guaranteed the supply, narrating the process of gradual improvement of the infrastructure (Barco 1988, p. 285). From the reports by the Franciscans in 1772, Palóu states that San José de Comondú mission had an *ojo de agua* from which water was extracted through a *zanja* (Palóu 1994, p. 218). The typology of ditches that can be identified vary from the channelling dug in earth to the ones arranged in vertical stone walls that were directly carved in the rock. The complexes of Todos los Santos, Santiago de las Coras, San Francisco Javier San Ignacio or San Luis Gonzaga stand out. In the case of San José del Cabo, the urban pressure has practically wiped out its vestiges.

4.7 Conclusions

Access and use of water have always been a limiting factor in the process of occupation of a territory. The convergence of New World and Old World traditions in the Americas since the sixteenth century can be considered in a series of stages that the traditional chronology arranges in a logical succession of centuries.

By the sixteenth century the European arrival to unknown lands is illustrated by the very ignorance of their extensions, and the cirumstances led to the exploitation of the resources already available. The time gap between the acclimation of the techniques and vegetables brought from Europe and that had already got to the Canary and Caribbean archipelago required the indigenous experience in the continent. There is no doubt that the implementation required the resources already known, and for this reason even medieval legal principles were transferred to begin the dynamics of occupation.

The transformation was evident in the seventeenth century, when the interests of colonists and indigenous people clashed over the access to the use of a resource, whose private and public use have seen the replacement of the pre-Hispanic principles by the Europeans' "newly acquired" rights. The constant disputes illustrate this.

The eighteenth century consolidated the expansion that started in the previous century. The principles of rationalization implemented by the Bourbons in the management of the territories they governed, typical of the Enlightenment affected their reorganization and land exploitation. The construction of infrastructures for that purpose, in which hydraulic ones became essential, enabled the installation and occupation of spaces far from the decision centres and that looked for autonomy in a hostile environment.

This text only reveals the tortuous path that water control has traversed in Mexico since the times of the New Spain and how the clashes over its use and the main role of the occupation of spaces have been constant. The moral is that both circumstances led to opposing outcomes that can be applied to Cuatro Ciénegas. If in the first case, the confrontations limited the access to an essential asset of part of the population in Mexico, causing disputes, its rational exploitation facilitated the conquest of lands were the settlers found resources to stock up. A balance between them both might well be a bet on the management of this privileged territory in the North of Mexico.

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Chapter 5
Environmental Conservation, Water, and Wetland Governance in Mexico

Teresa Souza Bosh

5.1 Evolution of Environmental Law

Mexico's environmental legal framework stems from a patchwork of legal provisions accumulated over time, with each provision reflecting the environmental governance perspective of its time. Provisions thus often reflect conflicting ideologies. To better understand environmental law in Mexico, we must study the evolution of environmental law in conjunction with the evolution and influence of international environmental treaties.

5.1.1 Allocation and Management of Natural Resources

The first environmental laws covered the allocation and management of natural resources. As a result, environmental laws were enacted to protect property rights and to ensure the future availability of natural resources. *L'ordonnance des eaux et forêts* (Law of Water and Forests)—one of the first environmental laws in the world—was issued in 1669 by King Louis XIV to ensure there were sufficient timber supplies for the construction of warships (Sand 2015). Similarly, many legal provisions governing natural resources in Mexico were enacted to allocate and manage natural resources. As we will explore throughout this chapter, this is particularly true for water and wetlands. The first provisions regulating wetlands were enacted to promote the draining of wetlands to allow for their fruitful occupation and transformation into settlements and agricultural fields, rather than to protect them.

T. Souza Bosh (✉)
Consultoria Legal Ambiental, Ciudad de Mexico, Mexico

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Similarly, the first provisions regulating water were enacted to promote irrigation for agriculture.

5.1.2 Preservation of Animals, Plants, and Natural Heritage Sites

At the end of nineteenth century, fishermen and hunters started to establish conservation societies following fears of species extinction due to overhunting and overfishing (Prendergast 2003). Examples include the Sierra Club, founded in the United States in 1892 by John Muir; the Boone and Crockett Club, founded in the United States in 1887 by Theodore Roosevelt; or the Society for the Preservation of the Wild Fauna of the Empire, founded in London in 1903 by Edward North Buxton (Gissibl et al. 2012). The pressure of these international conservation societies led to the Convention for the Preservation of Wild Animals, Birds and Fish in Africa, signed in London in 1900 by the European colonial powers (Prendergast 2003). The Convention established a list of endangered animals and promoted the creation of natural reserves (Prendergast 2003).

In Mexico, the Sociedad Mexicana de Historia Natural (Mexican Society of Natural History) was established in 1868 and was followed by the *Sociedad Mexicana de Geografía y Estadística* (Mexican Society of Geography and Statistics) and the *Sociedad de Amigos de los Árboles* (Society of Friends of the Trees) in 1890 (Rincón 2006). The work of Mexican conservation societies led to the enactment of the first forestry law, *Ley Forestal* (Forestry Law), in 1861, which required ten trees to be planted for every tree that was cut down, and was subsequently replaced by the *Reglamento para la Explotación de Bosques y Terrenos Baldíos y Nacionales* (Regulations for the use of Forests, Vacant and National Lands) in 1894 (Rincón 2006). In addition, lobbying by such societies led to the creation of Mexico's first national parks in 1876 and 1894 (*Desierto de los Leones* and *El Chico*, respectively) and the creation of the of *the Departamento de Bosques* (Forestry Department) in 1910 (Rincón 2006). Similarly, the *Comisión Geográfica Exploradora* (the Geographic Exploration Commission) was established in 1878 to collect and catalogue Mexico's flora and fauna for the creation of Mexico's National History Museum, founded in 1890 (Rincón 2006).

Around the world, societies were established to preserve countries' shared natural heritage. In Amsterdam, Brussels, Geneva, and Paris, societies such as the *Vereenignig tot Behoud van Natuurmonumenten* (Society for the Preservation of Natural Monuments), founded in 1905, and the *Société pour la Protection des Paysages de la France* (Society for the Protection of French Landscapes), founded in 1901, were established to preserve natural monuments (Gissibl et al. 2012). These were followed by the *Premier Congrès International pour la Protection des Paysages* (First International Conference on Landscape Protection) in Paris in 1909 and *Die Weltnaturschutzkonferenz* (the World Nature Protection Conference) in Bern in 1913 (Tucker et al. 2018).

The international commitment to preserve a global natural heritage culminated in the signing of The Ramsar Convention on Wetlands of International Importance, especially as Waterfowl Habitat in Ramsar in 1971 and the Paris Convention concerning the Protection of the World Cultural and Natural Heritage in 1972 (Sand 2015). The Ramsar Convention established a list of wetlands of international importance, with member states committed to create natural reserves and implement actions and policies to conserve wetlands and waterfowl. Likewise, the Paris Convention established a list of extraordinary natural and cultural sites which were deemed to identify our shared heritage and should be protected and preserved by committed member states.

5.1.3 The Mexican Revolution

The Mexican Revolution uniquely shaped laws regulating natural resources and environmental conservation in Mexico. Article 27 of the Mexican Constitution—drafted during the Mexican Revolution—crystallized the revolutionary ideals of land redistribution and national control over natural resources (Hart 1989). It established national ownership over all land, waters, and national resources located within the Mexican territory. Additionally, it gave communities rights over land and water and allowed for groundwater to be used freely (without the need of any permit, authorization, or concession). These ideals were further implemented in 1934 by President Lázaro Cárdenas through the nationalization of oil and the creation of *ejidos*, a legal area of communal land owned by farmers (Boyer and Wakild 2012). Cummings and Nercessiantz (1994) describe this land redistribution as the "centerpiece of the Mexican revolution," further stating that the development of irrigation infrastructure made the land reform implementation possible. Paradoxically, Lázaro Cárdenas was responsible for both the loss of forestland and the creation of most of Mexico's forest reserves and national parks. During land redistribution, Cárdenas declared vast stretches of forests *ejidos*, causing forests to be replaced by farmland (Rincón 2006). Nonetheless, due to the conservation work of Miguel Ángel de Quevedo (known as the Tree Apostol), Cárdenas was also the president who created the most forest reserves and national parks (36 forest reserves and 39 national parks) (Rincón 2006). Emily Wakid (Wakild 2012) argues that the creation of forest reserves and national parks was seen by Cárdenas as an instrument to promote nationalism.

In 1942, a new *Ley Forestal* (Forestry Law) was enacted to protect national parks. Subsequent reforms in 1950 established forestry reserves and protected catchment areas to ensure water was available for irrigation and hydroelectricity (Rincón 2006).

During this time, the government created and implemented water policies to irrigate *ejidos* for the development of agricultural production. As a result, many water governing institutions focused on the development and construction of irrigation infrastructure and were closely linked to the agricultural sector (Ramos Osorio 2006). This included the *Dirección de Aguas, Tierras y Colonización* (National Bureau of Water, Lands, and Colonization) in 1917, the *Comisión Nacional de Irrigación* (National Irrigation Commission) in 1926, the *Secretaría de Recursos*

Hidráulicos (Ministry of Hydraulic Resources) in 1947, and *the Secretaría de Agricultura y Recursos Hidráulicos* (Ministry of Agriculture and Hydraulic Resources) in 1976 (Juárez Villaseñor et al. 1986). Laws were established to promote and regulate the use of surface water for irrigation, such as the *Ley de Irrigación con Aguas Federales* (Law on Irrigation of Federal Waters) in 1926, the *Ley de Aguas de Propiedad Nacional* (Law of Waters of National Property) in 1934, and the *Ley de Riegos* (Irrigation Law) in 1947 (Juárez Villaseñor et al. 1986).

Originally, groundwater was not regulated, and article 27 of the constitution allowed groundwater to be used freely. However, following the constitutional amendments of 1934 and 1945, and the enactment of the *Ley Reglamentaria del párrafo quinto del artículo 27 Constitucional en materia de Aguas de Subsuelo* (Law Regulating the Fifth Paragraph of Article 27 of the Constitution) in 1948, groundwater use was regulated (Juárez Villaseñor et al. 1986). Groundwater use was further limited by the establishment of prohibition zones over almost 70% of the aquifers in Mexico through 144 decrees to create prohibition zones between 1948 and 1988 (Figueroa de Jesus 2005).

The *Ley Federal de Aguas Nacionales* (Federal Law on National Waters) was enacted in 1972. For the first time in Mexican history, this law regulated both surface and groundwater and sought to establish a national water planning system (Juárez Villaseñor et al. 1986). It created irrigation districts and required a concession or permit to use groundwater in prohibition zones (Juárez Villaseñor et al. 1986). Later, in 1986, the Federal Law on National Waters was reformed to protect aquifers from overextraction, promoting the efficient use of water and recover costs associated with the operation and maintenance of irrigation infrastructure (Juárez Villaseñor et al. 1986). In 1989, the *Comisión Nacional del Agua* (National Water Commission) was established as an autonomous entity under the jurisdiction of the Ministry of Agriculture (Juárez Villaseñor et al. 1986).

5.1.4 Environmental Protection

The United Nations Conference on the Human Environment celebrated in Stockholm in 1972 and the Stockholm Declaration reflected the shift in thinking from conservation to environmental protection (Sand 2015). The Stockholm Declaration recognized the human right to a healthy environment and the need for coordinated actions to protect the environment for present and future generations (Stockholm Declaration, Principles 1, 2, 3, 4, and 5). While states continued to have the sovereign right to exploit their own resources, the Stockholm Declaration mandated that they must ensure activities within their jurisdiction did not cause damage to the environment nor pollution (Stockholm Declaration, Principles 6, 7, and 20).

The Stockholm Declaration was followed by several international treaties for environmental protection and pollution and hazardous substance control. The most notable were the Convention on International Trade in Endangered Species of Wild

Fauna and Flora in 1973, the Convention on the Conservation of Migratory Species of Wild Animals in 1979, the Vienna Convention for the Protection of the Ozone Layer in 1985, the Montreal Protocol in 1987, and the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal in 1989.

Mexico's first environmental law published in 1971, the *Ley Federal para Prevenir y Controlar la Contaminación (*Federal Law to Prevent and Control Environmental Pollution), reflected this international ethical movement toward environmental conservation (López Sela and Ferro Negrete 2006). It sought to protect Mexicans' health by conserving and restoring the environment and its natural resources. While its focus was indeed on human health, this was the first time that the environment was considered a good that should be protected by the state. To this day, there remains a strong link between human health and environmental protection in Mexican legislation.

In 1982, the *Secretaría de Desarrollo Urbano y Ecología (*Ministry of Urban Development and Ecology) was created in Mexico, followed by the release of the *Ley Federal de Protección Ambiental (*Federal Law for Environmental Protection) (López Sela and Ferro Negrete 2006). This law integrated the environmental impact assessment procedure, regulated atmospheric pollution from factories and vehicles as well as from the incineration of waste and other materials, regulated water pollution from wastewater discharge, and regulated waste management and soil contamination caused by hazardous wastes (Federal Law for Environmental Protection, Articles 7, 17, 18, 23 and 34).

In 1987, Article 27 of the Constitution was reformed to established that the nation has the power to regulate the use of natural resources to ensure the welfare of all and "to preserve and restore the environment," thus establishing the obligation of the state to protect the environment (Brañes Ballesteros 2018). Additionally, Article 73 of the Constitution was reformed to establish the concurrent obligation of the federal, state, and municipal governments to protect the environment and their power to enact laws protecting the environment (Brañes Ballesteros 2018). In 1988 the Federal Law for Environmental Protection was substituted by the *Ley General de Equilibrio Ecológico y Protección Ambiental* (General Law on Environmental Balance and Environmental Protection (LGEEPA)), which regulated the concurrent powers and obligations of the federal, state, and municipal government to protect the environment (Brañes Ballesteros 2018).

In 1992 the Ministry of Urban Development and Ecology was replaced by the *Secretaría de Desarrollo Social (*Ministry of Social Development), which oversaw the *Instituto Nacional de Ecología* (National Institute of Ecology) and the *Procuraduría Federal de Protección al Ambiente (*Federal Environmental Protection Agency) (López Sela and Ferro Negrete 2006). This reflected the vision that environmental policy should serve both economic and social development (López Sela and Ferro Negrete 2006).

5.1.5 Sustainable Development

The Rio Conference on Environment and Development from 1992 and the resulting Rio Declaration of Environment and Development established the concept of sustainable development and the common but differentiated responsibilities of developed and developing nations in sustainable development (Rio Declaration of Environment and Development, Principles 3 and 7). The Rio Declaration also established fundamental principles of environmental law, such as public participation and access to public information, the precautionary approach, the polluter pays principle, and environmental impact assessments (Rio Declaration of Environment and Development, Principles 10, 15, 16 and 17).

While the Rio Declaration was a turning point for international environmental law, it still viewed environmental protection as a means to protect human welfare and development. The first principle states that "human beings are at the center of concerns for sustainable development" and that "they are entitled to a healthy and productive life in harmony with nature." Furthermore, the second principle reinstated the sovereign right of states to exploit their resources while ensuring that activities within their jurisdiction or control did not harm the environment. Finally, the Rio Declaration stated clearly that environmental protection should never get in the way of free trade (Rio Declaration of Environment and Development, Principle 12).

As a reflection of the adoption of the new environmentalism embodied by the Rio Convention, during the 1990s Mexico overhauled its environmental law and institutional framework, enacting the *Ley de Aguas Nacionales* (National Waters Law (LAN)) in 1992, creating the *Secretaría de Medio Ambiente, Recursos Naturales y Pesca* (Ministry of Environment, Natural Resources and Fishing) and moving the National Water Commission to the Ministry of Environment, Natural Resources and Fishing in 1994 and completely reforming the General Law on Environmental Balance and Environmental Protection in 1996. Further, in 1999, the Mexican Constitution was reformed to recognize the human right to an adequate and healthy environment. The following year, with the change of government, the Ministry of Environment, Natural Resources and Fishing became the *Secretaría de Medio Ambiente y Recursos Naturales* (Ministry of Environment and Natural Resources).

However, the reform of Mexico's environmental laws and institutions might have also been a result of the negotiations for Mexico's inclusion in the North American Free Trade Agreement (NAFTA). Many environmentalists feared that NAFTA would result in environmental dumping (the relocation of factories from one country to another with less strict environmental laws) (Gil Villegas 1994). As a result of the activism of environmental nongovernment organization, Bill Clinton opposed NAFTA during his presidential election and, once elected, lobbied for the inclusion of labor and environmental provisions and Mexico's commitment to improve its environmental laws and institutions (Gil Villegas 1994). Thus, the signing of NAFTA in 1992 was followed in 1993 by the signing of a parallel environmental agreement, the North American Agreement on Environmental Cooperation, to ensure environmental law compliance in the three member countries (Mexico in particular). Further, the Agreement on Environment Cooperation establishes the *submission on enforcement matters* process, which allows any person to file a complaint if that Canada, Mexico, or the United States is failing to effectively enforce its environmental law.

The United Nations Framework Convention on Climate Change, celebrated in New York in 1992, and the World Summit on Sustainable Development, celebrated in Johannesburg in 2002, marked a new commitment to halt humans' potentially detrimental impact on the environment. This revamped global commitment to the environment also took place in Mexico, as seen through the enactment of the *Ley General de Vida Silvestre* (General Law of Wildlife (LGVS)) in 2000, the *Ley General de Desarrollo Forestal Sustentable* (General Law on Sustainable Forest Development (LGDFS)) in 2001, the *Ley General para la Prevención y Gestión Integral de Residuos* (General Law for the Prevention and Integral Management of Waste (LGPGIR)) in 2003, the *Ley General de Organismos Geneticamente Modificados* (General Law for Genetically Modified Organisms) in 2005, the *Ley General de Pesca y Acucultura Sustentable* (General Law on Sustainable Fishing and Fisheries) in 2007, and the *Ley General de Cambio Climático* (General Law on Climate Change (LGCC)) in 2012. Finally, in 2012, Article 4 of the Mexican Constitution was reformed to establish that, in addition to the human right to a healthy environment, the state had a correlating obligation to guarantee the enjoyment of this right, establishing liability for damages to the environment. The reform additionally established the human right to clean water and sanitation.

5.2 Environmental Laws Governing Water in Mexico

The Mexican Constitution establishes the right to a healthy environment, the state's duty to guarantee that right, and the liability of those who cause environmental damage (Constitution Art. 4). Under the Constitution, the state has ownership over natural resources. Consequently, it has the power to regulate the use of natural resources, establish prohibition zones, and reserve natural resources to preserve or restore the environment (Constitution Art. 27). The state must also ensure national development is sustainable (Constitution Art. 25).

The *Ley de Aguas Nacionales* (National Waters Law, LAN) state that the conservation, preservation, protection, and restoration of water are an issue of national security. Further, national water programs must establish priority water uses, such as establishing environmental flows to recharge aquifers and wetlands, defining the quantity and quality of water required to conserve and restore wetlands (LAN Regulations Art. 23, Section VIII). The National Water Commission is charged with the administration of water and the preservation of aquifers, water bodies, and wetlands (LAN Art. 3, Section XXVIII; LAN Art. 4) and must preserve and restore the hydrological balance of aquifers and water basins, as well as the environmental balance of ecosystems that is central in preserving hydrological balances (LAN Art.

14, Sections VII and IX). Therefore, integral water management must successfully coordinate the management of water, land, agriculture, forests, fisheries, and the environment to maximize social and economic well-being without compromising the sustainability of vital ecosystems (LAN Art. 3, Section XXIX). In theory, this marked a shift in the national hydraulic policy, from irrigation development to integrated water management (Ramos Osorio 2006). However, the National Water Commission has remained focused on the development of hydraulic works (Ramos Osorio 2006). This is shown by the fact that the National Water Commission has consistently allocated most of its budget to the development, operation, and maintenance of public works (ASF 2013). Further, most of the information filed by the National Water Commission before the Federal Audit Authority relates to public works and not to water management (ASF 2013).

5.2.1 Water Conservation

As previously mentioned, the Mexican federal government has the authority to establish water prohibition and regulation zones and reserve water for priority uses when aquifers or water bodies[1] become overextracted (e.g., through overexploitation or during droughts). Relatedly, the federal government can establish regulation or prohibition zones to control the use of water (LAN Art. 38). Regulation zone decrees must establish the volume of water to be granted under a concession, water use limits, and any required conditions (LAN Art. 39). Prohibition zone decrees may regulate or ban the use and/or discharge of water (LAN Art. 40). Additionally, the federal government may reserve water supplies to ensure there is enough water for environmental flows, urban water supply, and hydroelectric energy (LAN Art. 41). In particular, the federal government can reserve water for the environmental flows needed to recharge aquifers and water bodies to ensure wetlands are conserved and/or restored (LAN Art. 78, Section IV).

On September 2, 2013, the government established a regulation zone over the Cuatro Ciénegas aquifer to restore the aquifer's hydrological balance[2] (Official Federal Gazette, September 2, 2013). The subsequent decree established that groundwater could not be freely used and required a concession to use groundwater within the aquifer. The amount of water conceded by the decree was 11.084782 million m^3 a year. Nonetheless, those who were previously granted concessions to use groundwater could continue operations as usual. Thus, the decree allowed for additional concessions to be granted but limited the annual volume of water to be used to 11 million m^3, without affecting the previous extraction volumes.

[1] The term water body refers to rivers, lakes, water currents, or any other body of surface water.

[2] *Decreto por el que se establece como zona reglamentada aquella que ocupa el acuífero denominado Cuatrociénegas, ubicado en el Estado de Coahuila*, published in the Official Federal Gazette on September 2, 2013.

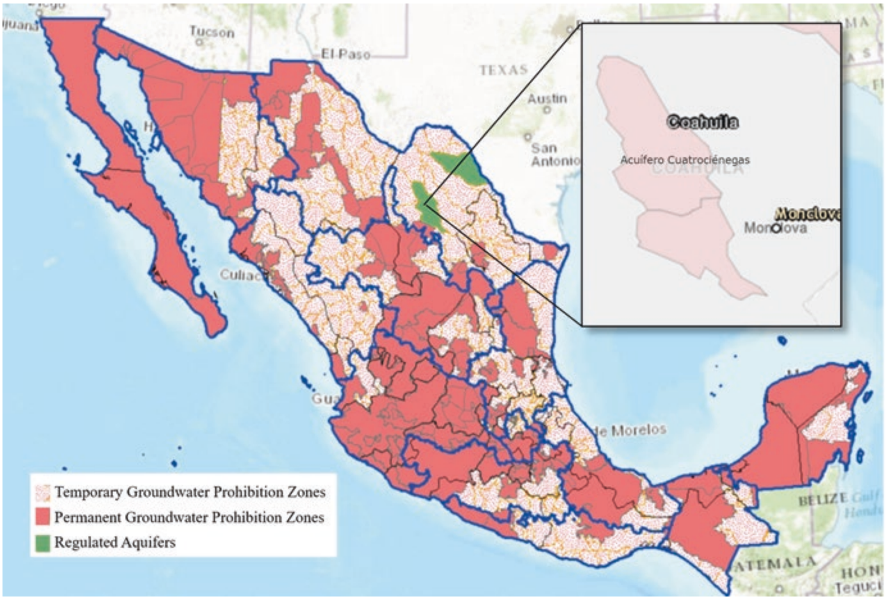

Fig. 5.1 Permanent and temporary groundwater prohibition zones. Permanent prohibition zones are shown solid red. Temporary prohibition zones in dotted red. Regulated aquifers are marked in solid green. Made from information provided by the National Water Commission in 2017

The creation of a reserve, prohibition zone, or regulation zone may regulate and limit the volume of water to be used and require a concession to use groundwater. However, these zones do not ban water use, revoke existing concessions, or forbid new concessions. Although there are 144 decrees establishing prohibition zones over nearly 70% of Mexico's aquifers and temporary prohibition zones over the remaining aquifers (Official Federal Gazette, April 5, 2013), the number of water concessions granted to use groundwater has continued to increase since 1999 (Figueroa de Jesus 2005). Figure 5.1 shows permanent prohibition zones in solid red, temporary prohibition zones in dotted red, and regulated aquifers, such as Cuatro Ciénegas, in solid green.

Similarly, the Mexican government has established 106 prohibition zones over surface water (CNA 2017).

On June 6, 2018, the government replaced some surface water prohibition zones with water reserves for energy, urban water supply, and the environment. Nonetheless, the number of water concessions granted to use surface water has continued to increase since 1999. Figure 5.2 highlights these surface water prohibition zones and reserves.

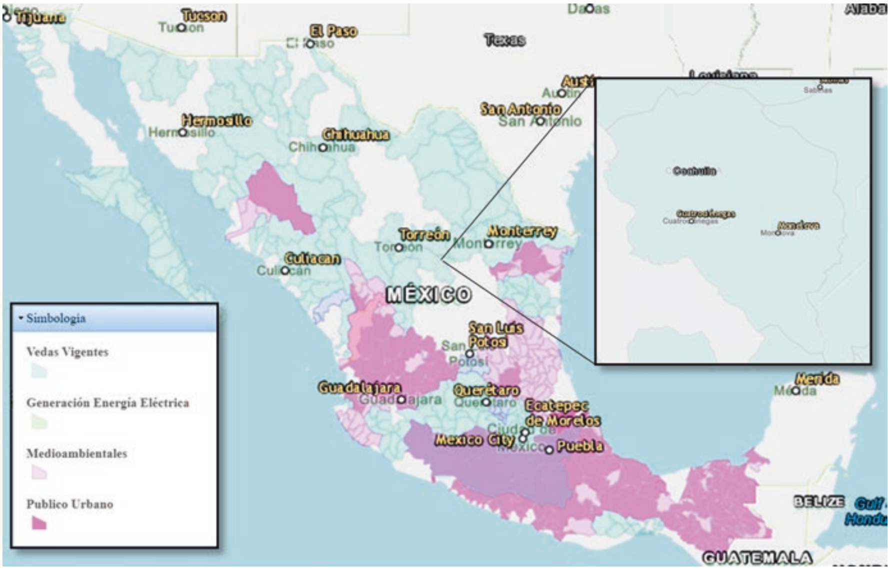

Fig. 5.2 Permanent surface water prohibition zones and surface water reserves. Permanent prohibition zones shown in blue, water reserved for energy in green, water reserved for the environment in light pink, and water reserved for urban water supply in magenta (CNA 2017)

5.2.2 Concessions

As previously stated, Article 27 of the Mexican Constitution established national ownership over natural resources, including all surface and groundwater. Therefore, a concession is required to use surface water (LAN Art. 20). However, surface water can be used without a concession if it is used for domestic consumption, provided such use does not significantly alter waterways, water quality, or water quantity (LAN Art. 17). Nevertheless, groundwater can be freely used by owners of property in which a well is located. However, if the well is located within a groundwater prohibition or regulation zone, a concession is required to use the groundwater (Constitution, Art. 27; LAN Arts. 18, 20, and 42). As most of Mexico is covered by groundwater prohibition and regulation zones, a concession is required to use groundwater in almost all cases.

Now, let us look a little bit more into how water concessions work. A concession grants rights to use a specific volume of water over a predetermined period. This period may vary from 5 to 30 years and can be extended for an equal period (LAN Art. 24). Concessions can be granted to individuals, legal entities, *ejidos*, user associations, or irrigation districts (LAN Arts. 50 and 53). *Ejidos*, user associations, and irrigation districts (the community-based recipients) can modify the amount of water distributed to each member in accordance with their respective regulations (LAN Art. 54). The National Water Commission may authorize concessionaries to modify the allowed use of water (e.g., from agricultural to industrial use) or the volume of water and may authorize concessionaries to transmit their rights to another recipient (LAN Arts. 25, 28, and 33). All concessions, including their modification, transfer, or revocation, are registered in the Public Registry of Water Rights (RPDA) (LAN Arts. 30, 31, and 32).

Concessions may be revoked if the user (1) does not pay the duties for water use and wastewater discharge; (2) obstructs an inspection by the National Water Commission; (3) transfers water rights to another user without prior approval; (4) does not measure and report the water being used; (5) does not use the granted volume of water for 2 consecutive years, unless they paid a bond to the National Water Commission for the unused amount, temporarily transferred the unused amount to the National Water Commission, or can prove that they invested in water saving technology; (6) does not properly treat wastewater in compliance with the federal pollution limits; and similarly (7) does not measure and report the quality of wastewater (LAN Arts. 26, 27, and 29 BIS 3; LAN Regulations Art. 47).

Unfortunately, the National Water Commission lacks the capacity to systematically carry out inspections. As a result, the LAN has not been properly enforced (CNA 2014). In 2012, merely 1% of water users were inspected, 29% concessionaries measured the water they used, and 4.8% of concessionaries paid duties for the water they used (ASF 2013). In general, we can state that only a handful of agricultural water users measure their consumption (ASF 2013). This is in part due to agricultural water users only having to pay duties once exceeding the allotted water use granted under their concession; therefore, they do not have an incentive to measure the water they use (Federal Law on Duties Arts. 224 and 223, Section C).

5.2.3 Water Allocation

Initially, the LAN granted existing water concessions to those who previously had been granted concessions under the Federal Law on National Waters. Those with existing concessions or authorizations had to file them before the National Water Commission to then allow their existing concessions to be replaced by new ones registered in the RPDA (LAN, Transitory Articles 4–7). However, by 1994, only 6400 million m^3 of water for consumptive use had been registered in the RPDA (CNA 2006). The government therefore issued decrees to reduce the requirements that were in place to prove the existence of water use rights in 1995, 1996, and 2002 (Official Federal Gazette, October 11, 1995; October 11, 1996; and February 4, 2002). This policy and the National Water Commission's tendency to prioritize agricultural and economic development over conservation have resulted in the overallocation of water granted in concessions and the overextraction of water from aquifers and water bodies (CNA 2014).

The National Water Commission has the right to refuse to grant a concession if the water in question (1) was used for national or regional hydraulic planning programs working toward ensuring adequate economic, social, or environmental welfare of human settlements; (2) could affect regulated, protected, or prohibition zones

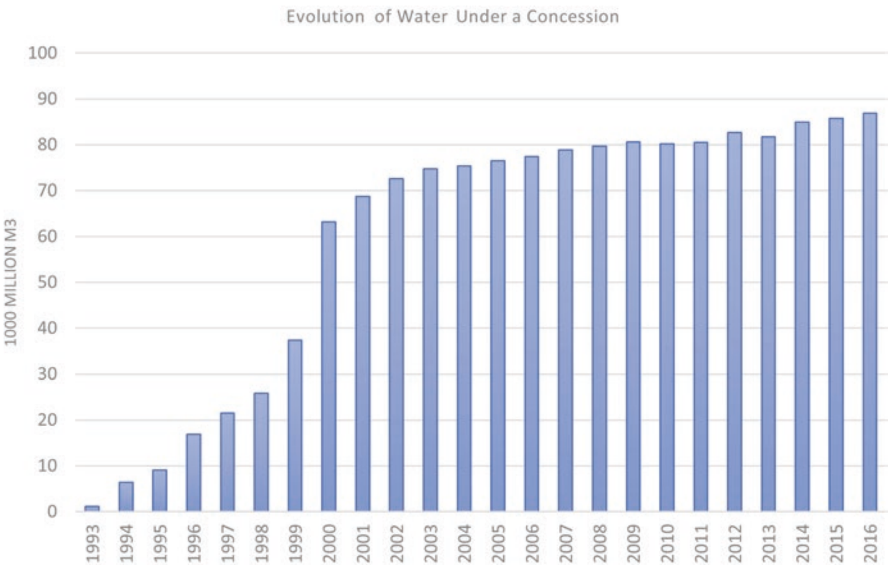

Fig. 5.3 Evolution of total annual volume of water under a concession. Made from public information published by the National Water Commission in 2017

established to preserve or restore ecosystems; or (3) impacted environmental flows (LAN Art. 29 BIS 5).

Today, water concessions have continued to grow despite severe hydraulic stress of aquifers and water basins and the enactment of prohibition zones, regulation zones, and water reserves over most of the aquifers and water basins in the country. In 2016, there were 529,609 concession titles registered in the RPDA for the use of 86,900 million annual m^3 of water (CNA 2017). Figure 5.3 shows the evolution of registered water concessions in the RPDA.

5.3 Environmental Laws Governing Wetlands in Mexico

There are few legal provisions specifically governing wetlands in Mexico. The LGEEPA regulates coastal ecosystems and coastal wetlands but has no provisions governing inland wetlands. Similarly, the sole Official Mexican Standard governing wetlands (NOM-022-SEMARNAT-2003) only establishes provisions for the preservation, restoration, and sustainable use of coastal wetlands in costal mangrove areas. Nevertheless, in this section we will examine the legal provisions that govern wetlands. The LGCC states that national climate change policy must prioritize the conservation of wetlands, mangroves, coral reefs, dunes, and coast areas (including lagoons) to work toward battling climate change vulnerability (LGCC Art. 26, Section XI). Specifically, federal, state, and municipal governments must implement steps to conserve and restore wetlands to protect environmental water flows, which will in turn recharge aquifers and water basins (LGCC Arts. 30 and 34).

The National Water Commission must identify, delimitate, and take inventory of all wetlands; promote the enactment of water reserves to preserve wetlands; and promote the enactment of Official Mexican Standards to preserve and restore wetlands, including the water that feeds into the wetland and the associated water ecosystems (LAN Art. 86 BIS 1). As previously stated, LAN regulations require national water programs to define the quantity and quality of water required to conserve and restore wetlands (LAN Regulations Art. 23, Section VIII). However, the LAN additionally requires that the National Water Commission carry out the necessary work to protect roads, settlements, and flood zones so that lands may be used "productively" (LAN Art. 83). Consequently, the National Water Commission may grant permits to dry wetlands for the use of land and/or the protection of settlements (LAN Art. 86 BIS 1, Section V).

5.3.1 Land Use Regulation

The LGEEPA states that national development plans must incorporate environmental policies (LGEEPA Art. 17). Thus, land use regulations (at the national, state, and municipal level) must consider the environmental impact of human settlements and activities on existing ecosystems (e.g., national parks) (LGEEPA Art. 19). Similarly, urban development planning must be sustainable by considering preexisting land use regulations and ensuring development is not degrading areas of high environmental value, such as environmental conservation areas (LGEEPA Art. 23). The *Ley General de Asentamientos Humanos, Ordenamiento Territorial y Desarrollo Urbano* (General Law on Human Settlements, Land Use Regulation, and Urban Development) (LGAH) outlines steps to design, manage, and regulate settlements and urban centers to ensure they are resilient and sustainable (LGAH Art. 2).

Similarly, according to the LGAH, the National Land Regulation and Urban Development Program should contain guidelines for sustainable development—considering regions' natural resources and productive activities—and aim to balance human settlements and the natural environment (LGAH Art. 26, Section V). As such, settlements should not exceed an ecosystem's carrying capacity, deplete water resources, or encroach on natural protected areas or forests (LGAH Art. 4, Sections VII and IX). Furthermore, no new settlements may be built in areas of high hydrometeorological risk, such as wetlands that have a high flood risk (LGEEPA Arts. 46, 48, and 67). Federal, state, and municipal governments must develop and circulate climate change risk atlases, and promote human settlement relocation in areas of high climate change vulnerability (LGCC Art. 30). Additionally, under the LGAH, the state may expropriate property to (1) protect a natural heritage site, (2) preserve and restore the environment, (3) identify risk areas, and (4) establish a protection or buffer zone (LGAH Art. 6, Sections VI, VII, and X).

5.3.2 *Conservation Areas*

The LGEEPA declares that actions undertaken to protect and preserve biodiversity (e.g., establishing conservation areas) are catalogued as public good action (LGEEPA Art. 2). Conservation areas are areas whose original environment has not been significantly altered by human ecosystems. In terms of the LGEEPA, they must be preserved to (1) conserve their fragile natural environment and ecosystem; (2) protect the hydrological cycle of their water basins; (3) protect the genetic diversity of their species, particularly of those species that are endangered, threatened, endemic, or otherwise rare; and (4) ensure the sustainable use of the natural resources, wildlife, and national territory (LGEEPA Arts. 44 and 45). More broadly, conservation areas can be established as (1) biosphere reserves, (2) national parks, (3) natural monuments, (4) natural resource protection areas, (5) flora and fauna protection areas, (6) sanctuaries, (7) state parks and reserves, (8) municipal conservation parks, and (9) private conservation parks (LGEEPA Art. 46). Figure 5.4 shows all of Mexico's conservation areas.

Conservation areas are divided into core areas and buffer zones to ease their administration and management, as described below.

1. Core areas. Here, one may carry out activities to preserve ecosystems as well as conduct scientific research and environmental education activities. Any use of these areas that alters the ecosystem is limited and may be prohibited.

   (a) Protected area. Areas that contain relevant or fragile ecosystems or critical habitats that require special care. In this case, only environmental monitoring and/or noninvasive scientific research activities are allowed.

Fig. 5.4 Conservation areas established in Mexico. Map taken from the Interactive Map of Conservation Areas published by the *Comisión Nacional de Áreas Naturales Protegidas* (National Commission of National Parks, CONANP) in the following site: http://sig.conanp.gob.mx/website/interactivo/anps/

(b) Restricted use area. Well-conserved areas. Restricted use areas allow for activities that do not modify the ecosystem, environmental education activities, low environmental impact tourism, noninvasive scientific research, environmental monitoring, and the construction of facilities to support research and/or monitoring.

2. Buffer zones. Where some activities may be carried out, as detailed below.

(a) Preservation area. Areas that are well conserved and contain relevant or fragile ecosystems. The following activities may be carried out in preservation areas: scientific research, environmental monitoring, environmental education activities, and productive activities with low environmental impact. These productive activities must not substantially modify an area's natural environment and must be supported by the local community. Activities are subject to supervision to ensure they are not harming the environment.
(b) Traditional use area. Areas where natural resources have continuously been used by indigenous or local communities that carry out small-scale, artisanal activities to satisfy basic needs (e.g., artisanal fishing). Other authorized activities include scientific research, environmental education, low impact tourism, and construction for required supporting infrastructure. This construction must use eco-techniques and traditional construction materials.
(c) Sustainable use of natural resources area. Here, natural resources may be used for sustainable activities such as the sustainable use of wildlife. Scientific research, environmental education activities, and low impact tourism may take place here.
(d) Sustainable use of ecosystems area. Individuals may carry out low-impact agricultural, fishing, and livestock activities so long as they comply with conservation initiatives in the area.
(e) Special use area. Areas containing valuable natural resources (e.g., precious metals). Individuals may mine these natural resources so long as doing so does not cause irreversible environmental damage, serious ecological imbalance, or substantially alter the landscape.
(f) Public use area. These areas present natural attraction for recreational or leisure activities. Facilities are constructed to support tourism, environmental education, scientific research, and/or environmental monitoring.
(g) Human settlement area. Here, settlements existed prior to the creation of the protected area.
(h) Restoration area. Areas where natural resources have been severely altered and must be restored (LGEEPA Art. 47 BIS).

Those who own land within a conservation area must abide by the regulations governing that park (LGEEPA Art. 44). Similarly, any permit, authorization, or concession given to explore or use natural resources within a conservation area is subject to park regulations (LGEEPA Art, 64).

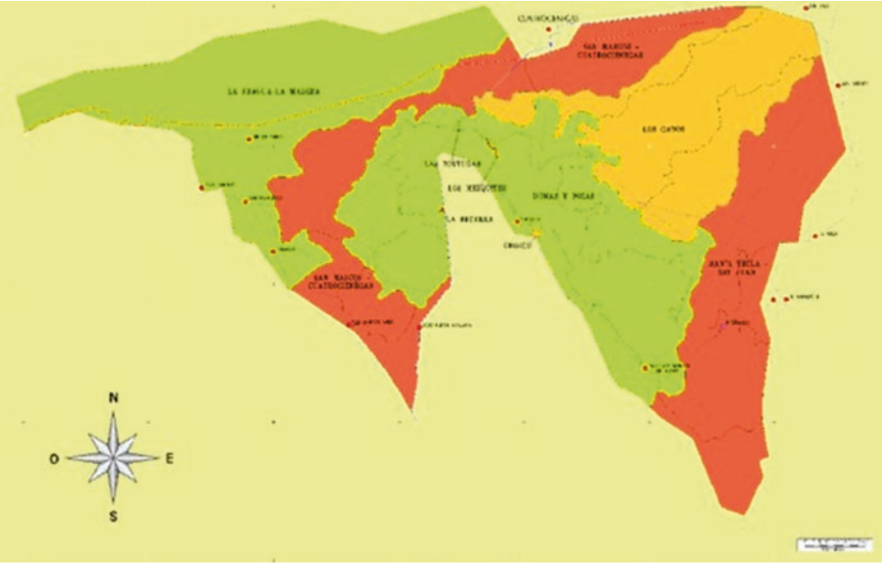

Fig. 5.5 Cuatro Cienegas area for the protection of flora and fauna zones. Map taken from the *Programa de Manejo del área de protección de flora y fauna Cuatrociénegas,* published in the Official Federal Gazette on March 24, 2000

The area of Cuatro Ciénegas was declared an area for the protection of flora and fauna on November 7, 1994.[3] The decree states that individuals who wish to carry out activities within Cuatro Ciénegas may have to pass an environmental impact assessment prior to beginning work and that all activities are subject to park regulations. Similarly, *ejidatarios* and other landowners with whose property is located within the protected area must actively work toward conserving Cuatro Ciénegas. No new human settlements may be created within the conservation area, and it is forbidden to modify the natural state of aquifers, water basins, or waterflows.

On March 24, 2000, the Cuatro Ciénegas Management Plan was created and established the following areas within Cuatro Ciénegas,[4] illustrated in Fig. 5.5:

1. Preservation area. This area covers wetlands and gypsum dunes, as well as areas already well conserved (e.g., Unidad La Fragua—La Madera, Unidad Tío Cándido, Unidad de Pozas, Unidad La Poza Azul, Unidad de Dunas, Unidad de Lomeríos Bajos 1). Here, it is forbidden to carry out any activities that could endanger protected flora and fauna or the flow of water. Scientific research, environmental monitoring, environmental education activities, and low-impact

[3] *Decreto por el que se declara como área natural protegida, con carácter de área de protección de flora y fauna, la región conocida como Cuatrociénegas, con una superficie de 84,347-47-00 hectáreas, municipio del mismo nombre, Coah.*, published in the Official Federal Gazette on November 7, 1994.

[4] *Programa de Manejo del área de protección de flora y fauna Cuatrociénegas,* published in the Official Federal Gazette on March 24, 2000.

recreational activities may take place. Existing grassland may continue to be used as pasture lands for cattle, and farmers may continue to grow crops in existing fields. Similarly, existing infrastructure may remain as is, but new infrastructure will be subject to environmental impact assessments.

2. Restricted use area. Areas that have been poorly conserved and should be restored. Examples include Unidad Orozco, Unidad de las Salinas, Unidad de los Gatos, and Unidad San Juan. Scientific research, environmental monitoring, environmental education activities, and low-impact recreational activities may take place. Existing grassland may continue to be used as pasture lands for cattle, and farmers may continue to grow crops in existing fields. Prior authorization is required for the use of new fields. Similarly, mining activities may continue to take place in existing mines that have a corresponding authorization. When establishing new mines, however, an environmental impact assessment is required. Here, new infrastructure may be built.
3. Controlled use area. Here, several activities are carried out, some of which may have significant environmental impacts. Examples include Unidad San Marcos, Unidad Santa Marta, Unidad La Becerra, Unidad Los Mezquites, Unidad de Lomeríos Bajos 2, Unidad Seis de Enero, Unidad Nueva Atalaya, Unidad San Pablo, Unidad Cuatro Ciénegas, and Unidad La Vega—El Venado. Scientific research, environmental monitoring, environmental education activities, and low-impact recreational activities may take place. Existing grassland may continue to be used as pasture lands for cattle, and farmers may continue to grow crops in existing fields. Prior authorization is required for the use of new fields. Mining activities may continue to take place in existing mines that have a corresponding authorization. When establishing new mines, however, an environmental impact assessment is required.[5] Here, new infrastructure (e.g., roads) may be built.

5.3.3 Natural Resources

As mentioned before, the Mexican Constitution grants the state ownership of all natural resources including lagoons, estuaries, lakes, rivers, and riverbanks (Constitution Art. 27). These natural resources are thus a public good that may be enjoyed by all. However, one needs a concession to use them (General Law on National Assets Art. 3, Section I, Subsections 6 and 7; Section VIII and IX; 8, 9, and 13).

1. Forests
   The General Law for Sustainable Forestry Development (LGDFS) states that forest ecosystems and water basins are a public good. Mexican law catalogues native vegetation that has not been altered as forests, including all plants that

[5] *Programa de Manejo del área de protección de flora y fauna Cuatrociénegas,* published in the Official Federal Gazette on March 24, 2000.

form tropical and template forests, arid zones, semi-arid zones, and wetlands (LGDFS Art. 7, Section LXXX). Additionally, all land that is outside the limits of population zones and that is not being used is catalogued as forest land (LGDFS Art. 7, Sections LXXI and LXXII).

The protection, conservation, and restoration of forests and water basins are prioritized over other activities and may be grounds for expropriation (LGDFS Art. 4, Sections I and II). The Ministry of Environment and Natural Resources has the authority to define riverbanks, lake banks, and catchment areas as protected forest areas (LGDFS Art. 125). Furthermore, under LGDFS, the Mexican government can establish prohibition areas to protect and restore endangered flora (LGDFS Art. 129). Similarly, the National Forestry Commission can establish subsidy programs to promote the conservation of forests and water basins (LGDFS Art. 122). Additionally, the National Forestry Commission can implement ecological restoration programs when forests are badly degraded or suffering a desertification process (LGDFS Art. 123). In these cases, forest landowners or the Commission will implement these programs at the owners' expense (LGDFS Art. 132).

The Ministry of Environment and Natural Resources may authorize "land use changes" within forest lands. However, this may only happen once both an environmental impact assessment and technical assessment take place to evaluate and mitigate the impact of the deforestation on the surrounding biodiversity and water catchment areas. These assessments must additionally provide plans to rescue and relocate affected flora and fauna (LGDFS Art. 93). Holders of land use change authorizations must submit periodic reports and pay a fee to the Mexican Forest Fund. The fund is used by the National Forest Commission to work toward restoring the affected ecosystems, preferably within the water basin where the project is authorized to take place (LGDFS Arts. 96 and 98).

2. Mangroves and Wildlife

The General Wildlife Law (LGVS) forbids the removal, filling, relocation, or any other activity that affects the ecological characteristics and services of mangroves (LGVS Art. 60 TER). It additionally forbids activities that could negatively impact the integrity of a mangrove—specifically if it impacts a mangrove's hydrological flow, ecosystem, natural productivity, nesting, reproduction, refuge area, and/or feeding area. Furthermore, it forbids any actions that may impact the interaction between mangroves, rivers, dunes, nearby maritime zones, and/or coral reefs. The Ministry of Environment and Natural Resources may establish refuge areas for wild species that inhabit wetlands (LGVS Arts. 65, 66, and 67).

5.3.4 Environmental Protection

1. Environmental Impact and Environmental Liability

According to the LGEEPA, all activities that take place in wetlands, coastal ecosystems, lagoons, rivers, lakes, and estuaries that are connected to the sea are subject to an environmental impact assessment and must obtain environmental impact authorization from the Ministry of Environment and Natural Resources to be carried out (LGEEPA Art. 28, Section X; LGEEPA Regulations on Environmental Impact Art. 5, Sections B and R).

The Federal Environmental Liability Law (LFRA) states that any individual or entity whose actions or omissions cause direct or indirect environmental damage[6]—without having obtained prior environmental impact authorization (e.g., a forest land use change authorization)—is liable for environmental reparation or compensation (LFRA Art. 2, Section III; Art. 7; Art. 10). Reparation is defined as returning habitats, ecosystems, and/or natural resources to the state they were in immediately preceding the actions that caused the damage, i.e., as if the destruction never took place (LFRA Art. 13). Compensation is defined as investing in actions to repair the environmental damage of the ecosystem or ecological region. Additionally, actions may be taken to repair another location ecologically and geographically linked to the damaged site for the benefit of the affected community (LFRA Art. 17). Those who intentionally and maliciously damage the environment will be subject to a financial penalty (LFRA Art. 11).

2. Environmental Crimes

Those who use, produce, store, dispose, or discharge of hazardous materials or wastes without (i) prior authorization and/or (ii) implementing the necessary safety and risk prevention measures to avoid damaging the environment, natural resources, ecosystems, flora, fauna, soil, or water can face 1–9 years in prison under the Federal Criminal Code. If such activities are carried out in a conservation area, the prison sentence can be increased up to 3 years (Federal Criminal Code Arts. 414 and 416). The discharge of hazardous materials or wastes may include discharging wastewater, chemical or biochemical liquids, or pollutants into the soil, subsoil, marine waters, catchments, aquifers, basins, rivers, lakes, or any other body of water (Federal Criminal Code Art. 416).

5.4 How to Better Protect Water and Wetlands

Although environmental laws and institutions in Mexico have transitioned from simply managing and allocating natural resources in the service of economic development to protecting the environment and ensuring the sustainable use of natural resources, many provisions and policies continue prioritizing development over the environment. Sadly, the National Water Commission has not fully embraced its mission of preserving and restoring the hydrological balance of aquifers, water basins, and wetlands through an integral water management that balances the needs of the different water users (rural and urban communities, industry, energy, and

[6] Defined as any loss, deterioration, or adverse and measurable modification of the chemical, physical, or biological conditions of habitats, ecosystems, or natural resources. This also includes impacting the environmental services they provide.

agriculture) and the environment. Currently, in Mexico there are no real mechanisms to ensure environmental water flows for the preservation and restoration of aquifers, water basins, and wetlands. Even the declarations of prohibition zones, regulation zones, and reserves do not revoke or limit existing water use rights granted through water concessions and, in most cases, have not prevented new concessions from being granted.

Although the National Water Commission recognizes water overextraction and over-concession as the greatest threats to water security (CNA 2014), the Commission has not only not taken any serious steps to reduce the volume of water granted in concession but has continued to issue decrees allowing those who did not renew their concessions in time to renew their concessions. To combat water overextraction and over-concession, the National Water Commission should: (1) adjust the volume of water granted in concession to reflect the amount of existing water considering water for environmental flows; (2) ensure that all water extractions are measured; (3) in accordance with the LAN, revoke the concession of those who do not pay duties for water use, do not measure and report the water being used, do not treat wastewater, report the quality of wastewater; (4) assign the majority of its budget to water management and to ensure compliance, and only a fraction to the construction of hydraulic works, and (5) prioritize the preservation and restaoration of aquifers, water basins, and wetlands.

Mexican Constitutional Article 4 establishes the human right to a healthy environment and the correlating obligation of the state to guarantee this right. Further, Constitutional Articles 27 and 25 establish the state's role as steward of our natural resources and its obligation to ensure the sustainable development of the country. In accordance with this constitutional mandate, the LGEEPA establishes that national development plans and land use regulations must incorporate environmental policies. Further, the LGEEPA establishes that ecosystems of high environmental value should be protected as conservation areas. In the same sense, the LGVS provides that protected areas may be established in wetlands to protect wildlife, and the LGDFS provides that protected areas may be established in wetlands and water basins to protect the recharge of aquifers.

In Constitutional Article 27, the LGEEPA, LAN, LGVS, and LGDFS all establish the possibility of enacting measures to prevent or stop environmental damage, including the establishment of bans on hunting, logging, or water use. In particular, the LAN provides that the National Water Commission may establish probation and regulation zones as well as reserve volumes of water for environmental flows to protect or restore wetlands, aquifers, and water basins. In the same sense, the LGVS bans any activity that may alter the hydrological balance and water flow to mangroves. Constitutional Article 4 establishes the liability of those who cause environmental damage. Environmental administrative, civil, and criminal liability are regulated by the LGEEPA, LFRA, and the Federal Criminal Code. However, it is clear that the Mexican Environmental Protection Agency and the National Water Commission do not have the sufficient resources and inspectors to enforce environmental laws and to prosecute all those who cause environmental damage.

Further, the protection, conservation, and restoration of wetlands are hindered by the lack of a comprehensive definition and legal framework that protects all wetlands. Such definition should include all wetlands protected under the Ramsar Convention to ensure our compliance of our obligations under the international treaty. Given that, currently, we lack a comprehensive definition and legal framework that protects all wetlands and existing provisions are scattered among different and laws, and in many cases, only coastal wetlands and mangroves are protected. Although the National Commission of National Parks is the authority designated to ensure compliance of the Ramsar Convention, and as such is charged with implementing all guidelines, decisions and resolutions derived from such convention, the National Water Commission is the authority in charge of the inventory, management, and preservation of wetlands.

Thus, a legal framework, clearly distributing powers among the different federal government entities, as well as among the federal, state, and municipal levels is urgently needed for Mexico. Such regulations should also establish mechanisms for the protection of the ecosystem, the establishment of environmental flows for the conservation of all wetlands, require environmental impact assessment of any work or activity carried out in wetlands, and establish a legal and institutional framework for the protection, conservation, and restoration of all wetlands designated under the Ramsar Convention.

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Chapter 6
Cuatro Ciénegas: An Aquifer at Risk of Overexploitation

Oscar Adrián Leal Nares, Gabriela Rendón Herrera, and Mauricio de la Maza Benignos

6.1 Introduction

Groundwater is essential for the country's socioeconomic development, as it represents 39% of the volume licensed for consumptive uses. Over two million irrigated hectares depend on ground sources, which comprise one third of the irrigation surface area at the national level. In addition, aquifers satisfy most industrial water demands and are the primary source of supply for the rural population (CONAGUA 2018).

As we could read in Chap. 5 of this book, Mexico's 1917 Constitution establishes that water is the property of the nation, but groundwater can be withdrawn without any allocation deed, which means that anyone can extract groundwater without a permit or concession. Such a situation has already caused an overexploitation of aquifers. However, in this same statute, the Federal Executive branch of government is empowered to establish ordinances regulating groundwater extraction through regulations and closures or by the suspension of free extraction. This situation prevailed until the middle of the last century, when the Federal Executive established regulations on the extraction of water in 55% of the country's territory, leaving the rest with a free extraction status (CONAGUA 2020).

In the remaining 45% of the Mexican territory, water users opposed administrative and legal efforts to regulate the free extraction of groundwater, arguing that the development of economic activities would be limited. Farmers in northern Mexico took advantage of this situation and began to acquire large extensions of land, as

O. A. Leal Nares (✉) · M. de la Maza Benignos
Pronatura Noreste AC, Monterrey, Mexico
e-mail: oleal@pronaturane.org

G. Rendón Herrera
Permanent Forum of Binational Waters, College Station, TX, USA

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well as increasing the extraction of groundwater, exceeding the natural recharge capacity of the aquifers (CONAGUA 2020). This caused an overexploitation of at least 15% of Mexico's aquifers, leading to the drying up of springs, the disappearance of wetlands, a decrease in the base flow of rivers, water pollution, and saline intrusion, in addition to large economic losses due to decreased well and land settlement yields (CONAGUA 2018).

On April 5, 2013, the Federal Executive signed eight agreements that provisionally suspended free extraction in the entire country. This aimed to regulate water use in the basins and aquifers affected by shortages and overexploitation and promote sustainability without limiting economic and human development (DOF 2013a).

The suspension of the free extraction of groundwater and the elaboration of the legal systems of groundwater (closed season, regulation, or reserve) required justification studies. These studies were based on technical, social, economic, and environmental considerations, including the sustainable use of renewable water resources by modifying water extraction by users, instead of the free and unlimited extraction at the expense of a finite reserve.

Given that, Article 18, Section III of the Law on National Waters stipulates that to establish a system for regulating groundwater use, a study must be conducted to justify it. In 2013, studies were conducted to justify the suspension of free extraction in 159 aquifers, most of which are located in the north of the country, due to natural water shortages and the urgent need to establish a system that regulates withdrawals (DOF 2013a).

Among the overexploited aquifers is the wetland of Cuatro Ciénegas. This valley is located in an arid region where mean annual rainfall is less than 200 mm, and evaporation reaches 2042 mm per year (Leal 2016). Although rain is scarce, water from aquifers feeds many water pools (>500) that originate from a great diversity of aquatic ecosystems composed of rivers, lagoons, floodplains, wetlands, and emergent wetlands (Wolaver 2008).

In this hyper-diverse oasis for millions of years, the stability of aquatic ecosystems has generated environmental conditions for extremely diverse biological communities, favoring isolation conditions for the evolution of endemism. This is more evident for the oldest inhabitants of the planet, microbes than conform microbial mats and stromatolites (Souza et al. 2018). However, in the twentieth century, agricultural channels were built, leading to alterations in soil humidity, changes in drainage patterns, and, in some cases, the loss of wetlands (Contreras-Balderas 1984). As you can read in Chap. 11 of this book, over 80% of the surface water is extracted through the Santa Tecla and Saca Salada canal systems. This water is mainly used for agricultural production, and only 10% of the volume is destined for the conservation of wetlands through a concession granted to Pronatura Noreste, A.C., for ecological use in 2014 (Leal 2016).

As a result of this series of malpractices, almost 90% of the original wetland in Cuatro Ciénegas has been lost (Souza et al. 2018, Chapter 11). A study conducted with satellite images over the last 25 years has estimated that the surface wetland area during this period decreased by over 10.5% mainly in areas close to the

Mezquites and Garabatal rivers (Leal et al. 2019). In the absence of guidelines on the use of the Cuatro Ciénegas aquifer, the extraction volume has exceeded the aquifer's recharge capacity, causing the collapse of the wetland.

In September 2013, the water authority established aquifer 0528 Cuatro Ciénegas as a regulated zone to protect the hydrological balance and improve, conserve, and restore the aquifer (DOF 2013b). However, CONAGUA (Comisión Nacional del Agua) did not issue any guidelines and provisions for the development, use, or exploitation of the waters nor any guidelines related to reviewing and updating the lists of users to guarantee the aquifer's water sustainability. This work aims to identify the status of the registry of users of the Cuatro Ciénegas aquifer to help generate the technical and legal strategies required to avoid the over-concession of the aquifer.

6.2 Materials and Methods

To fully model the aquifer 0528 Cuatro Ciénegas, we obtained the concessions contained in the databases of the Public Registry of Water Rights (REPDA) with a cutoff date of June 2018, which can be accessed from the CONAGUA portal (app.conagua.gob.mx/Repda.aspx). The records were obtained for the Cuatro Ciénegas aquifer and adjacent aquifers: Castaños, Cuatro Ciénegas–Ocampo, El Hundido, and Monclova (CONAGUA 2018).

The records were systematized in geographic databases using the ArcGis® program, where each concession was projected on a geographic plane following the coordinates registered. We integrated the shapes of the concessions and land use into a geographic information system, including the layers of aquifers, ejido nuclei of the National Agrarian Registry (Registro Agrario Nacional, RAN), and urban and rural localities, to compare the information and identify inconsistencies (Fig. 6.1).

The criteria for selecting the records for the analysis were geographical and administrative; we used the titles registered for the Cuatro Ciénegas aquifer and those contained within the aquifer limits in line with their geographic coordinates, even if the allocation deed belonged to another aquifer.

To assess inconsistencies in the information and trends in the granting of the concessions, we compared the volume of groundwater availability at the Cuatro Ciénegas aquifer published in the *Official Journal of the Federation* (DOF, Diario Oficial de la Federación) and the databases reported in the Public Registry of Water Rights.

The legal base was the decree for the establishment of a regulated zone in the area occupied by the Cuatro Ciénegas aquifer, published in the *Official Journal of the Federation* on September 2, 2013 (DOF 2013b). This recognized the presence of the Cuatro Ciénegas flora and fauna protection area within the aquifer, whose springs and gushing flows have fed the water bodies and wetlands where ecosystems of great importance and scientific interest have evolved. In the absence of water, some of the great diversity of ecosystems and endemic species was at risk of

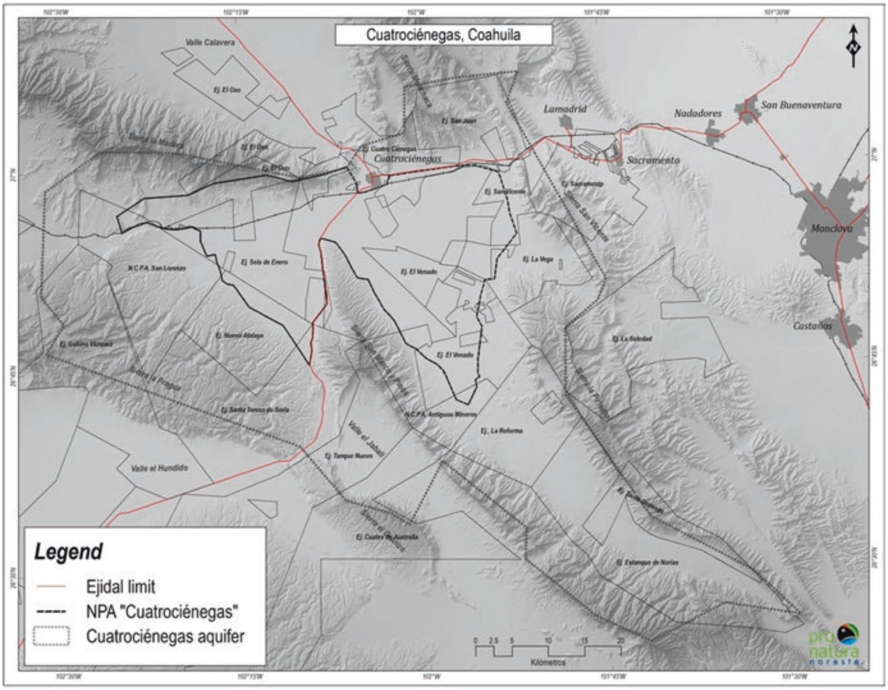

Fig. 6.1 Delimitation of the aquifer 0528 Cuatro Ciénegas, Coahuila, Mexico

becoming extinct. Consequently, it was considered necessary to regulate the extraction of national waters to prevent the disappearance of ecosystems and avoid risks to the population's water supply and to the development of the region, which depends largely on groundwater sources. From the most relevant aspects of the decree establishing the Cuatro Ciénegas aquifer as a regulated zone, the following are quoted verbatim:

> **CONSIDERING Sixteenth:** *That by virtue of the existence of availability capable of being granted 11.084782 million cubic meters per year, and derived from the analysis of the technical studies indicated in the preceding paragraphs, it follows that the aquifer that is the subject of this instrument requires careful management that reconciles environmental protection with the development of human activities within a strategy of integrated management of natural resources, Therefore, although the technical studies recommended a ban on the Cuatrociénegas aquifer, code 0528, the* National Water Commission *decided to establish a regulated zone that would guarantee adequate control of extractions and hydrological sustainability in the area.*
>
> **ARTICLE ONE:** *The reestablishment of the* hydrological balance *is declared of public utility, as well as the protection, improvement, conservation, and restoration of the Cuatrociénegas aquifer, code 0528, in the State of Coahuila, for which reason a regulated zone is established in the mentioned aquifer for the control of the extraction and the exploitation, use or development of the waters of the subsoil.*
>
> **ARTICLE FOUR:** *The bases and provisions to be adopted by the* National Water Commission*, regarding the form and conditions under which the use, development, and*

exploitation of national underground waters, which are the subject of this Decree, shall be carried out, are as follows.

I. *National subsoil waters may only be used, exploited, or developed within the regulated area when there is a concession or assignment title previously issued by the Water Authority, in terms of the provisions of the Law on National Waters and its Regulations as follows*

   (a) *The concessions or assignments granted shall be recognized provided that the title is in force and no grounds for suspension, extinction, or revocation of the title have been incurred; and*
   (b) *A concession or allocation shall be granted to users who have registered volumes of water subject to this Decree or those who use, benefit from, or exploit the aforementioned waters, up to the volume they prove.*

II. *The natural or legal persons who are in the case of paragraph (b) of the previous section, may continue with the use of such waters, provided that within a period not exceeding 60 calendar days after the entry into force of this Decree, apply to the Water Authority for recognition of the volume they have used within the previous calendar year, upon accreditation of the same.*
III. *Users who fail to file the applications indicated in the previous paragraph shall be subject to the provisions of section IV of this Article.*
IV. *The new concessions and assignments shall be granted in terms of the Law on National Waters, in view of water availability and in accordance with the order of presentation, once the recognition and granting referred to in paragraphs (a) and (b) of section I of this Article has been made.*
V. *The recognition and granting referred to in this Article may not under any circumstances exceed the overall availability of water under this Decree.*
VI. *As from the commencement of the validity of this Decree, the works for the* extraction *of groundwater existing in the regulated area may not change the use for which they are intended, nor increase their extraction costs and volumes, nor may the construction characteristics or the capacity of the pumping equipment authorized or used before the establishment of the regulated area be modified without the prior authorization of the Water Authority.*

ARTICLE SIX: *Within the regulated area, the construction of works for the* extraction *of groundwater that affect existing waters or ecosystems shall not be permitted, and the activities developed shall be subject to the provisions of the Management Program for the Cuatrociénegas Flora and Fauna Protection Area.*

ARTICLE SEVEN: *The granting of water allocations in sites located within the Protected Natural Area shall be subject to the availability of water in the aquifer, compliance with the requirements established in the National Water Law, and the restrictions established in the Management Program for the Cuatrociénegas Flora and Fauna Protection Area.*

6.3 Results

According to the reports in the REPDA databases, the initial volume granted in aquifer 0528 Cuatro Ciénegas was set in 1997, with an allocated volume of 1,002,000 m^3 annually. Nowadays, the amount exceeds 6.1 million m^3 per year (Fig. 6.2).

The analysis included 156 groundwater records reported in the REPDA databases for the year 2018 according to the selection criteria (administrative and geographical). Only 72 records of the total number were correctly registered with the

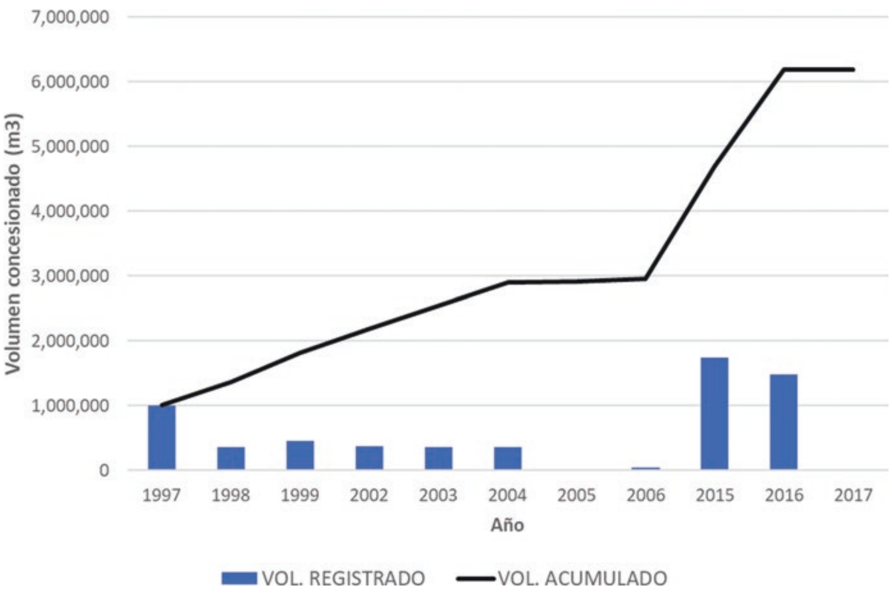

Fig. 6.2 The trend in allocated volume for aquifer 0528 Cuatro Ciénegas, Coahuila, Mexico

Cuatro Ciénegas aquifer (Fig. 6.3). The remaining 84 users were located at the Cuatro Ciénegas aquifer but were registered to a different aquifer. This analysis was conducted for the dates 2008, 2015, and 2018 to observe trends in the granting of concession titles (Table 6.1).

Our database analysis revealed that most of the records were erroneously assigned to the Cuatro Ciénegas–Ocampo aquifer (75 allocations), which is the neighboring valley to the north.

Of all the allocation deeds with discrepancies, 15 were registered in favor of the ejidos. To detect the source of the errors, we crossed the 15 allocation deeds of the ejidos with the shapefile of the ejido nuclei of the RAN and the name of the registered aquifer. In all 15 allocations, the deed holder (ejido) in the shapefile matched the RAN's layer of ejido nuclei, meaning the geographic location was correct; therefore, errors were imputed to the CONAGUA when registering the allocation deeds.

The analysis indicated that the differences in the volumes granted because of registration errors have increased as the CONAGUA issued new water concessions. Because of errors in allocation deeds, the water available from the Cuatro Ciénegas aquifer has lowered by 5,950,000 m^3 per year. Thus, the volume extracted from the aquifer is higher than that reported by CONAGUA (Table 6.2).

In the decree published in the DOF on September 2, 2013, which established the Cuatro Ciénegas aquifer as a regulated area, the water available was 11,084,000 m^3 per year (DOF 2013b). This document also established that the aquifer required careful management that reconciled environmental protection and human activities with the integrated management of natural resources. However, the DOF issued on

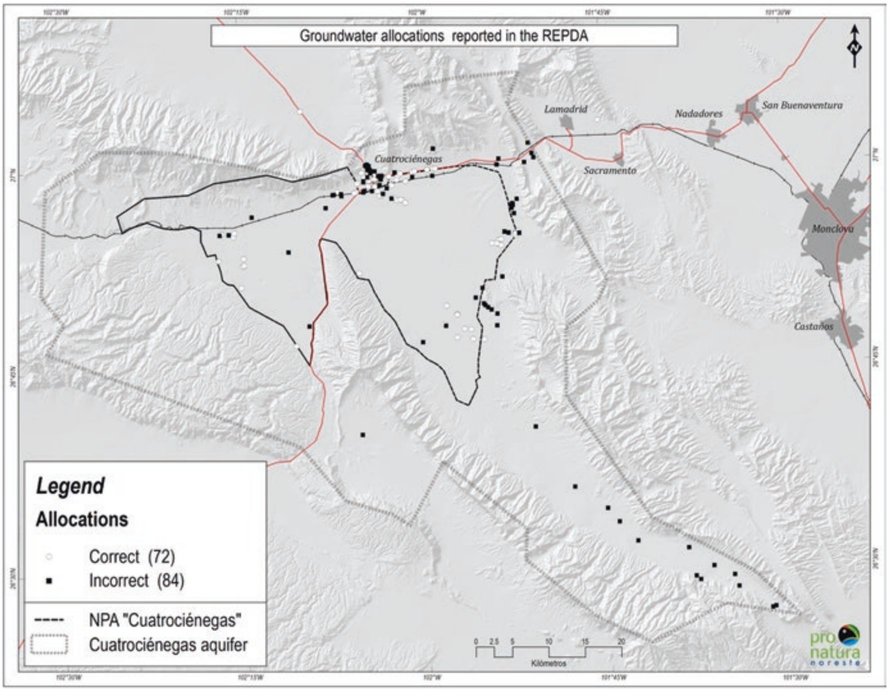

Fig. 6.3 Location and status of groundwater exploitation for aquifer 0528 Cuatro Ciénegas, Coahuila, Mexico

Table 6.1 Discrepancies identified in the granting of allocation deeds located in the Cuatro Ciénegas aquifer

Registered aquifer/year	2008	2015	2018
Castaños	4	4	4
Cuatro Ciénegas–Ocampo	73	76	75
Cuatro Ciénegas–Ocampo–San Miguel	2	0	2
El Hundido	1	1	1
Monclova	2	2	2
Misplaced records	82	83	84
Records correctly assigned to the Cuatro Ciénegas aquifer	21	25	72
Total records	103	108	156

January 4, 2018, reported a deficit in the water availability of −7,590,000 m^3 per year (DOF 2018).

Our results only considered the data reported by CONAGUA, without recognizing errors in the records, which can aggravate this situation because the deficit would increase to −13,540,000 m^3 when considering the difference of 5,950,000 m^3 (see Table 6.2). According to the total extraction volume (VCAS, Table 6.2),

Table 6.2 Differences found between REPDA official information, the *Official Journal of the Federation* (DOF), and the rectified data. The identifier is the acronym used in the official databases

Descriptor	Identifier	DOF	REPDA	Rectified data	Difference
2008					
Deeds			21	103	82
Well logs			25	113	88
Volume granted	VCAS	3.035	2.95	7.38	
Water availability	DMA	10.89	6.54	4.35	
2015					
Deeds			25	108	83
Well logs			29	117	88
Volume granted	VCAS	2.95	2.95	7.61	
Water availability	DMA	9.84		5.19	4.65
2018					
Deeds			72	156	84
Well logs			84	173	89
Volume granted	VCAS	4.7	6.18	10.65	
Extraction volume in free extraction suspended areas	SEE	11.509		11.509	
Volume of water to be titrated	VAPTYR	4.18		4.18	
Total extraction volume	SEE (VCAS + VEALA + VAPTYR)	20.39		26.34	
Water availability	DMA	−7.59		−13.54	5.95

Volumes expressed in million cubic meters per year

26,340,000 m^3 per year would be extracted from the aquifer, exceeding the capacity to maintain the wetlands' ecosystem functions (DOF 2018).

The 156 allocation deeds for groundwater withdrawal considered 173 well logs, including those with registration errors. Of these, 95% (10,150,000 m^3) were for agricultural purposes.

6.4 Allocations in the Natural Protected Area (NPA)

The natural protected area (NPA) of Cuatro Ciénegas includes 63 allocation deeds for obtaining underground water within its polygonal area. These allocations sum a total 5,600,000 million m^3 (including records with errors). After regulating the aquifer in 2013, the water authority registered 31 allocation deeds for agricultural use in the NPA comprising 2,690,000 m^3 per year. Therefore, the water authority granted the permits without any guidelines on issuing new allocations.

The results of our analysis indicate the urgent need to promote legal mechanisms to prevent the unregulated extraction of water in Cuatro Ciénegas and to avoid the overexploitation and depletion of the aquifer that sustains the population of Cuatro Ciénegas and the NPA wetland.

6.5 Discussion

The REPDA contains information on national surface and groundwater concessions that are the basis for determining the water available from river basins and aquifers. These data are the basis of national water management.

In the north of the country, where arid and desert environments predominate, the aquifers are a crucial source of water not only for human consumption but also for the development of activities such as agriculture, livestock, and industry. Therefore, it is essential to have reliable, up-to-date information on the uses and static levels of aquifers.

According to our analysis of the data on aquifer 0528 Cuatro Ciénegas, more than half of the allocation deeds circumscribed to this aquifer contain errors. This situation is attributable to the registration of the allocation deeds by CONAGUA. According to the data obtained, these errors underestimate the volume of extraction by 5,950,000 million m^3 per year, which implies a risk of overexploitation.

Because of the value of water resources for sustainability of ecosystems, the water authority issued sustainable management guidelines in the "ecological management of the Cuatro Ciénegas region" published in the Official Journal of the Federation on August 12, 1997 (DOF 1997). The document stated that it was necessary to limit water extraction to 16,000,000 m^3 per year to avoid a deficit in the aquifer affecting aquatic ecosystems. The volume estimated that year was the maximum extraction potential of the valley and its surrounding areas.

According to the DOF on January 4, 2018, the aquifer reached a deficit of −7,590,000 million m^3; however, if we consider the amounts of groundwater granted erroneously, then the volume was −13,540,000 m^3, which threatens aquatic ecosystems and their biodiversity (DOF 2018).

In light of these results and of Article 27, paragraph five of the Federal Constitution, which establishes the express and obligatory regulatory power of the Executive, stating that "… when the public interest demands it or other uses are affected; the Federal Executive may regulate its extraction and use and even establish prohibited zones, as it does for other waters of national property …", an indirect injunction (amparo indirecto) was filed against CONAGUA, to prevent the issuance of allocations for the use or extraction of national waters in the protected zone of the Cuatro Ciénegas Valley. The injunction considered that the right to a healthy environment for development and well-being and the right to equitable and sustainable access to water resources had been violated.

In March 2019, the federal judge issued a ruling granting a definitive suspension due to the omission by the Federal Executive to establish guidelines on the development, use, or exploitation of national waters referred to in Article 4 of the decree establishing the Cuatro Ciénegas valley as a regulated zone. In this resolution, the General Director, the General Director of Water Administration, the Manager of Regulation and Water Banks, and the Manager of User Services, all of them from CONAGUA with its headquarters in Mexico City, as well as the general director and the director of Water Administration, both from the Commission's Rio Bravo Basin Organization, with headquarters in Monterrey, Nuevo León, were obligated not to issue new allocations and/or assignments for the development, use, or exploitation of national waters in the protected zone of the Cuatro Ciénegas valley.

Soon, the Supreme Court of Justice of the nation will determine whether, by not issuing the guidelines and provisions for the regulated zone of the Cuatro Ciénegas aquifer, the CONAGUA has incurred a normative omission of an obligatory exercise that is constitutionally mandated, because the public interest is affected. Therefore, the water authority is obliged to fully and effectively exercise its powers to reverse its overexploitation and reestablish the balance of the vital ecosystems linked to water in the Cuatro Ciénegas aquifer to ensure its environmental sustainability.

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Chapter 7
Demise of Churince

Evan W. Carson

7.1 Introduction

Churince is a curious source of inspiration for conservation and restoration of desert spring ecosystems. There is not much left, only a vestige of the headspring. This once vibrant desert spring system was dewatered as a consequence of unsustainable exploitation of water resources. Decades of water diversion and groundwater extraction ultimately staunched the spring flows that sustained Churince, which until recently (ca. 2004) was replete with aquatic habitats and associated biota. These habitats spanned from a headspring and its riverine outflow, to marshes, shallow margins, and ephemeral pools, through an intermediate laguna and instream pools, and then on to a vast, terminal laguna (Minckley 1969). Gypsum precipitated from this laguna supplied an expansive dune system (Figs. 7.1, 7.2, 7.3, 7.11, 7.12, 7.13, and 7.14; Minckley and Cole 1968).

So why find inspiration in Churince? The likelihood of its revival is exceedingly low. But Churince was not 'yet another' desert spring lost. Churince was a microcosm of the Cuatro Ciénegas Basin (CCB). Inspiration comes from Churince's outsized reflection of the magnificent variety within the CCB and thus a picture of what can still be protected. This protection, however, demands more prudent use of the water resources upon which the broader ecosystem and people of this parched land depend. Loss of Churince is, of course, sufficient motivation to conserve desert spring ecosystems that remain intact and to restore ones that can be revived.

E. W. Carson (✉)
San Francisco Bay-Delta Fish and Wildlife Office, US Fish and Wildlife Service, Sacramento, CA, USA

Biology Department and Museum of Southwestern Biology, University of New Mexico, Albuquerque, NM, USA
e-mail: evan_carson@fws.gov

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Candidates abound. Within the CCB, efforts are underway to revive the once majestic Rio Garabatal and for restoration of Rio Mezquites at the origin of the canal Saca Salada, a diversion that has been draining 90% of the surrounding wetland since 1970 (extracting 1800 L/s). These are ambitious efforts with great potential and even greater importance for the valley. Churince provides a vivid illustration of what is at stake.

In the pages that follow, take a walk down Churince (Figs. 7.4, 7.5, 7.6, 7.7, 7.8, 7.9, 7.10, 7.11, 7.12, 7.13, and 7.14). Catch a glimpse of what this singular desert aquatic ecosystem was like before, and how it lies after, drying. If you are left wanting and wondering, this chapter has served its purpose.

7.2 Cuatro Ciénegas Basin

Fig. 7.1 The Cuatro Ciénegas Basin is divided into central-southeastern (*right*) and western (*left*) lobes by the Sierra de San Marcos (*center*). The Churince system is located within the large white area (*left center*), a salt pan and gypsum dune system. Note the alfalfa fields (green circles) in the adjacent Valle del Hundido (*bottom*) and Valle de Calaveras (*top*). The fields are irrigated with extracted (pumped) groundwater. Photo credit: Google Earth, ca. 2018. For scale, each round green circle is 70 ha

7.3 Rio Churince System

Fig. 7.2 The Cuatro Ciénegas Basin is shown as it appeared in 1984 (*upper panel*) and in 2018 (*lower panel*). The Churince system (*bottom left*) is located at the southwestern base of the Sierra de San Marcos (*center*). The Rio Churince terminates in Laguna Grande, which is shown when full (blue green) in 1984 (*upper panel, left*) and dry in 2018 (*lower panel, left*); Las Playitas, the terminal laguna of the vastly larger Rio Mesquites system, is the prominent blue-green lake in the central basin (*right*). In Churince, note the extensive gypsum dune system represented by the white expanse (*bottom left of each panel*) in these satellite images. Note the similarity of dunes in Churince to dune systems of the central-southeastern basin. Photo credit: Google Earth, ca. 1984, 2018

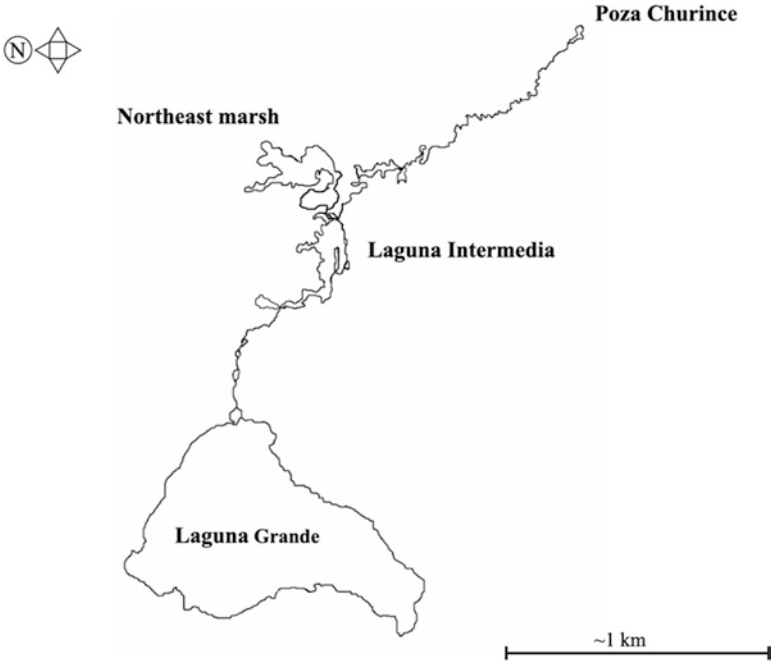

Fig. 7.3 Stylized map of the Rio Churince system. From the headspring at Poza Churince (*upper right*) to the terminal Laguna Grande (*bottom left*), there were marked physicochemical gradients from stable to severe and highly fluctuating. Similarly sharp gradients also occurred over very short distances, such as between the Rio Churince (*line trending from upper right to lower left*) and connected habitats at its margins. Rio Churince flowed into Laguna Intermedia (*center*), which also was fed by a smaller inflow from the northeast marsh (*center left*). The margins of Laguna Intermedia contained shallow habitats, some ephemeral, which were directly or periodically connected to the Laguna. The mainstem of Rio Churince reemerged and briefly widened below Laguna Intermedia. This stream reach was bounded by shallow habitats and soon narrowed sharply into a rivulet, except where interrupted by a series of large instream pools. Rio Churince reached its terminus at Laguna Grande, a once expansive evaporative barrial lake, beyond which an extensive dune system formed over eons from wind-driven transport of gypsum precipitated from the Laguna (Minckley and Cole 1968; Minckley 1969; Carson et al. 2008, 2012)

7.4 A Walk Down Churince

Fig. 7.4 Poza Churince. At first glance, the headspring appears unscathed in September 2010 (*upper left*) and August 2011 (*upper right*). By that time, however, much of the Rio Churince system was dewatered. An upper reach is shown as it appeared in 2002 (*lower left*), well before drying, and in August 2011 (*lower right*), when reduced spring flow resulted in stagnation and algal overgrowth. Poza Churince and upper reaches of Rio Churince supported not only the most ecologically diverse and speciose assemblage of endemic and native fishes (about 13, depending on whom you ask) of the system but also the vast majority of fish species found in the Cuatro Ciénegas Basin. Poza Churince, the type locality of the endemic springsnail *Mexipyrgus churinceanus*, also harbored large populations of other endemic springsnails, including *Mexithauma quadripaludium* and *Nymphophilus minckleyi*, as did upper reaches of the system. As spring flows declined, physicochemistry of the headspring and Rio Churince changed in tandem, with upper reaches taking on profiles historically more typical of some downstream reaches. These changes were followed rapidly by apparent extirpation of the native tetra *Astyanax mexicanus* and severe population declines—and possibly sudden loss—of many endemic springsnails. Extirpation of *Cyprinodon bifasciatus* appears to have followed soon after (Carson, pers. obs.)

Fig. 7.5 Farther downstream in the upper Rio Churince. Note the flumes used in a reciprocal transplant of endemic pupfish conducted winter 2003 (*upper left*; Carson et al. 2008). The same reach was stagnant and overgrown with algae in August 2011 *(upper right*). Many of the fishes and other organisms that thrived in the headspring also thrived in this reach of Rio Churince. Many were among the least tolerant of physicochemical stress and disappeared or declined rapidly as the system dried. An adjacent peripheral habitat (*lower left*), mere meters off-channel, was dominated by *C. atrorus*; note the corresponding half of experimental flumes (*lower left*). The same site was stagnant with algal overgrowth in August 2011 (*lower right*)

Fig. 7.6 Laguna Intermedia, shown when full in September 2010 (*upper left*) and in 2007 (*lower left*) and when dry in October 2011 (*upper and lower right*). Large schools of *Cyprinella xanthicara* roamed the Laguna, as did *Cyprinodon bifasciatus* and *C. bifasciatus*-like hybrids. *Cyprinodon atrorus* and *C. atrorus*-like hybrids, *Gambusia marshi*, and *G. longispinis* occupied the margins. Note exposed stromatolite field shown in its expanse (*upper right*) and topography (*lower right*)

Fig. 7.7 Habitats peripheral to Laguna Intermedia. The northeast marsh (undated; *upper left*), was a typical habitat of *Cyprinodon atrorus*, *Gambusia marshi*, and the secretive *G. longispinis*. This marsh flowed into Laguna Intermedia, which is shown drying in August 2011 (*upper right*). *Cyprinodon bifasciatus* and a low frequency of pupfish hybrids, predominantly advanced back-crosses to *C. bifasciatus*, were abundant in the Laguna. As the system dried down, *C. atrorus* and *C. atrorus*-like hybrids occupied remnant waters (Carson, unpublished). With Laguna Intermedia receding (*upper right*), shallow habitats at its periphery (*lower right*; 2001) and immediately downstream (*lower left*; undated) desiccated rapidly. Lower right photo credit: J. Elser

Fig. 7.8 Directly downstream of Laguna Intermedia, middle reaches of the Rio Churince broadened briefly, as shown in 2001 (*upper* and *lower left*). A stromatolite (*upper right*; undated) that was found instream within the middle to lower Rio Churince. A downstream view of hybrid zone Site CHU11 of Carson et al. (2012) is shown as observed in October 2002 (*lower left*). Immediately downstream, a dissolution channel (*lower right*) diverted a portion of streamflow directly underground. Presumably, this channel formed as the aquifer declined, years or perhaps decades before spring flows failed (Minckley, pers. comm.). The opening of the channel is indicated by the dark areas along the dry streambank, as seen in October 2011 (*lower right*). For at least a decade after emergence of this subterranean channel, surface flow continued to feed lower courses of Rio Churince down to Laguna Grande (Carson, pers. obs.)

Fig. 7.9 Middle and lower Rio Churince. Middle reaches are shown flowing in September 2010 (*upper left*) and dry May 2011 (*upper right*). Hybrids between *Cyprinodon atrorus* and *C. bifasciatus* abounded in these reaches (Carson et al. 2012). Few other fishes occupied these more environmentally severe and fluctuating habitats, though *Cyprinella xanthicara*, *Gambusia marshi*, and *G. longispinis* were common. *Dionda episcopa* and *Lepomis megalotis* also were encountered regularly in this reach, as were softshell turtles (*Apalone*), the endemic Coahuilan box turtle *Terrapene coahuila*, and other herpetofauna, as well as numerous invertebrates, notably the springsnail *Nymphophilus minckleyi*. The lower Rio Churince is shown flowing in September 2010 (*lower left*) and dried in May 2011 (*lower right*). Note the turtle tracks that led from the drying lower reaches toward the wetted reaches that remained upstream

Fig. 7.10 Lower Rio Churince and one of its instream pools in 2001 (*upper left*). The same site is shown dry in October 2011 (*upper right and lower right*). A closer view of the pool is shown as it was drying in May 2011 (*lower left*). Instream pools of the lower courses contained large aggregations of hybrid pupfish (Carson et al. 2012), as well as *Gambusia marshi*, schools of *Cyprinella xanthicara*, and native and endemic turtles, to name but a few organisms that tolerated or thrived in these physicochemically variable habitats

Fig. 7.11 Mouth of Rio Churince. Immediately upstream of the mouth of Rio Churince was the lowermost pool, shown full in September 2010 (*upper left*) and dry in May 2011 (*upper right*). Fauna were similar to those of previously mentioned instream pools. The mouth of the Rio Churince is shown flowing into Laguna Grande in October 2002 (*lower left*) and then dry in May 2011 (*lower right*). Note the gypsum dune system, shown as a narrow, white strip in the background of the lower panels (*left and right*)

Fig. 7.12 Laguna Grande was an expansive but shallow lake (winter 2007; *upper and lower left* panels) that for eons was the source of gypsum that nourished an extensive dune system. The dunes are seen here as a narrow, white strip in the background (*two left* and the *upper right* panels). Laguna Grande exhibited severe and fluctuating ecological conditions, yet some organisms thrived here, including the fishes *Cyprinodon atrorus* and *Gambusia marshi*, as well as a staggering diversity of bacteria and other single-cell biota that formed mats and stromatolites in this harsh habitat. Drying of Laguna Grande occurred episodically, and perhaps gradually, from at least the early 2000s. Here it is shown drying in September 2010 (*upper right*) and in summer 2001 (*lower right*)

7.5 Epilogue

The Churince system harbored astonishing aquatic biodiversity within a small footprint. To have walked Churince from headspring to terminal laguna—a scant 2.5 km—was, in effect, to have taken a short tour of the CCB. So the demise of Churince was not 'merely' the loss of a compact wonderland of biodiversity. It was a profound loss of an accessible educational asset, an open classroom where visitors could take in and engage with the panoply of biological, geological, and hydrological treasures that make Cuatro Ciénegas a desert basin without equal.

Churince is fading away, as have innumerable other desert spring ecosystems. Many were—and are being—lost as a result of unsustainable exploitation of scarce water resources, others vanished under prehistoric aridification. The difference from the latter is that the loss of Churince was predicted (Minckley, pers. comm.) and avoidable. Nonetheless, the demise of Churince is instructive, in part because

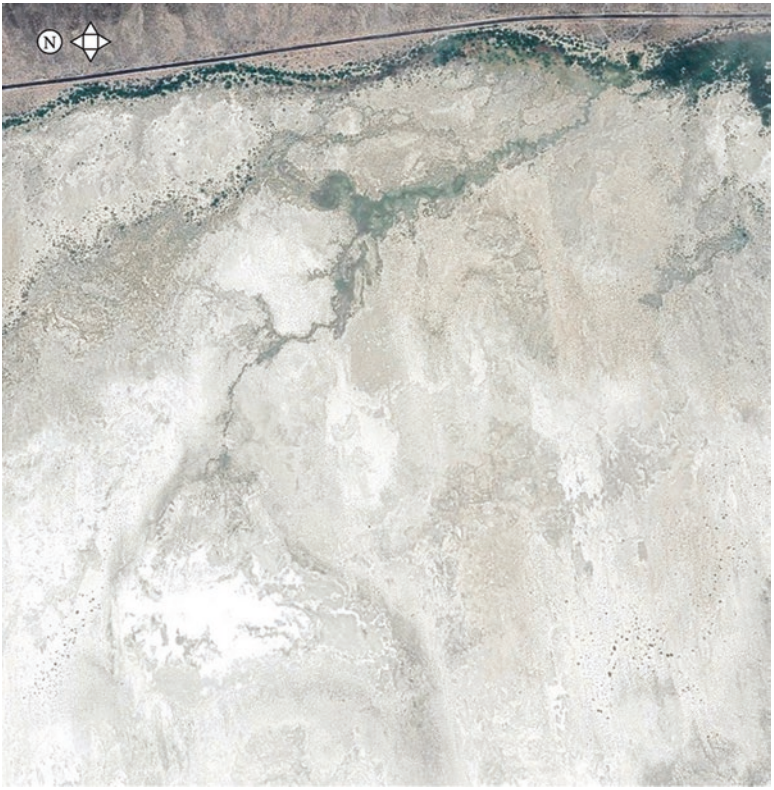

Fig. 7.13 Satellite image of the Rio Churince system, post-drying (ca. 2019). A vague outline of the system is evident (*cf.* Fig. 7.3), with the headspring at Poza Churince (*top right*), beds of Rio Churince (line trending from *upper right* to *lower left*) and the northeastern marsh (*left center*), and basins of Laguna Intermedia (*center*) and Laguna Grande (*bottom left*). Without renourishment of gypsum from Laguna Grande, the dune system (*bottom*), already mined extensively, is on a slow pace to oblivion. Perhaps it is worth noting that Churince remains a dynamic system, albeit in a different respect. Much can be learned about the ecological and evolutionary processes that attend and follow the demise of desert spring ecosystems. Photo credit: Google Earth, ca. 2019

impending loss was evident long before water vanished from the surface (see Chap. 8 in this book). This knowledge, *this example*, can inform conservation of systems that remain vibrant, or could be returned to form, before they too become 'dead springs flowing.' When thinking about risks to Cuatro Ciénegas more broadly, Churince is clarifying: the scale of loss is only a matter of degree. A walk down Churince, therefore, is not simply a record of a desert spring that once was but rather also illustrates the pressing need to protect intact desert aquatic ecosystems and to reignite the vibrancy of ones that can be restored.

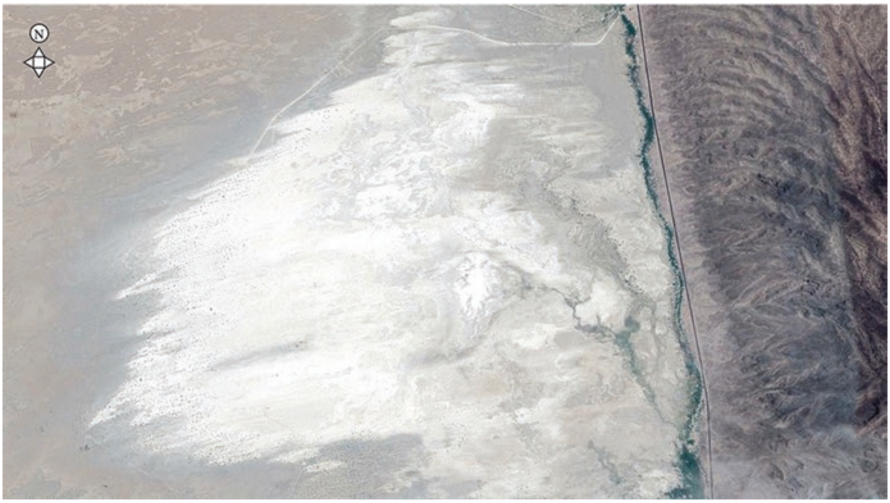

Fig. 7.14 The remnant Churince system, from headspring (*lower right*) to dunes (*left to top center*). The bed of Rio Churince is indicated by the muted-green meandering course (*lower right* to *right center*) that fades as it approaches the dry basin of Laguna Grande (*right center*). Photo credit: Google Earth 2019

Acknowledgments I thank WL Minckley for introducing me to, and helping me develop a deeper understanding of, the Cuatro Ciénegas Basin and the organisms that illuminate its uniqueness. This book chapter records an outcome that he knew all too well. Documenting the vibrancy and expiration of Churince is a bittersweet reminder of Minck's enthusiastic encouragement to focus my doctoral research on natural hybridization between the endemic pupfishes *Cyprinodon atrorus* and *C. bifasciatus*. I am grateful to Valeria Souza, in part for her support and equally enthusiastic encouragement, but mainly for her unrelenting determination to give Cuatro Ciénegas a voice, one that's certain to be heard if not always heeded. The findings and conclusions in this article are those of the author and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

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Chapter 8
Plants as a Canary in the Mine: A Wetland Response to Ecosystem Failure

Irene Pisanty, Mariana Rodríguez-Sánchez, Cynthia Peralta-García, Gabriel Cervantes-Campero, Valeria Souza, and María C. Mandujano

8.1 Introduction

8.1.1 Canaries in the Mine, Canaries on the Surface

Canaries have been used by miners to detect the presence of toxic gases while working underground. This practice, initiated in the early twentieth century (1911), came to an end when automatized measurements became available. For decades, canaries were an early alert system of high carbon monoxide concentrations, to which canaries are more sensitive than humans, so they would become ill or die before humans felt the effects of the gas, alerting miners to exit the mine on time. The practice was widespread, and the expression became part of the everyday metaphoric language, referring to early alerts in general. This is a simple example of how nature expresses itself and talks to those who are willing to hear.

Though the expression refers to underground environments, surface "land canaries" are abundant but, unfortunately, they are usually not taken as seriously as were the canaries in the mines. Signals of ecosystem changes, for example, have been empirically and scientifically identified and documented for a very long time already. However, there are far too many examples where the signals have been acknowledged but utterly ignored by the numerous stakeholders involved in

I. Pisanty (✉) · M. Rodríguez-Sánchez · C. Peralta-García · G. Cervantes-Campero
Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico
e-mail: ipisanty@ciencias.unam.mx

V. Souza · M. C. Mandujano
Departamento de Ecología de la Biodiversidad, Instituto de Ecología, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico

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decision-making, from a very local to a worldwide level (Gedan et al. 2009; Jayawickreme et al. 2011; Zepeda et al. 2012).

"Canaries outside the mine" include physical and biological components at different levels of complexity (biosphere, ecosystems, communities, populations, and individuals) and can be from brutal to very subtle. All living organisms react to different levels of environmental changes according to both long-term adaptations and short-term phenotypic plasticity (Nicotra et al. 2010; Guo et al. 2017). Plant canaries can tweet from small, almost silent morphological, physiological or ecological variations to boasting species extinctions, habitat fragmentations or ecosystem losses. Examples include the timing of flower production, which can vary slightly from year to year according to temperature or water availability, the disappearence of pollinatoris, and the extinction of water-dependant species due to drying out desert springs, (Strayer 2006; Parker et al. 2020).

Due to their wide range of responses to environmental changes, plants are among the most reliable above-ground canaries (Chapin III et al. 1993b). They register variations in a large spatial-temporal range and can tell us about long- and short-term events that can even become evolutionary forces, for behind every evolutionary change there is an ecological process with long-term effects (Chapin III et al. 1993a; Chitwood and Sinha 2016). Ecological variations do not always translate into big evolutionary leaps, but they are always related to small or large environmental changes or to stochastic significant processes (Becklin et al. 2016).

8.2 Deserts, Water and Canaries

8.2.1 Desert Springs

Desert springs, which generate surface water bodies, are extremely important in arid lands, as they create environments that contrast with the prevailing dry conditions, which can be real fairy-tale oasis. Water bodies like springs, wetlands, creeks, rivers, lakes and artisan pools (*pozas*) generate patches of riparian, aquatic and subaquatic vegetation (Fig. 8.1). These water bodies also influence adjacent zones. Riparian areas are usually richer in species, for they are a transition between aquatic and terrestrial ecosystems, and as perennial fresh water sources, they sustain wildlife (Nilsson and Svedmark 2002; Hendrickson et al. 2008; Parker et al. 2020).

Riparian plant species live in the interphase between water and land and are distributed along the borders of superficial water bodies, creating discrete patches of vegetation that indicate water availability. Riparian species are hydrophytes, i.e. species with a high demand of water, which tolerate shifts from floods to relative droughts (Capon et al. 2013; Capon and Dow 2007). They can tolerate anoxic conditions due to floods, as well as different aerial conditions, including the harsh ones that characterize xeric environments. In the latter, survival, growth and reproduction depend on how they adapt to and how keen they are coping both with stochastic and periodical seasonal changes (Naiman and Décamps 1997; Leck and Brock 2000; Cronk and Fennessy 2001; Nilsson and Svedmark 2002).

Fig. 8.1 Desert springs in Cuatro Ciénegas, Coahuila, Mexico. (**a**) Poza Churince, Churince system (50.90 m), (**b**) Los Hundidos system (600 m)

Fig. 8.1 (Continued)

Riparian species in arid and semiarid zones have to deal with contrasting selective forces, as they need to cope both with excess of underground water and above-ground lack of it. They also face extreme temperatures that can range from several degrees below zero to more than 45 °C, and different types of soils that imply different concentrations of salts and textures. In short, they have to deal simultaneously with both semi-aquatic and xeric conditions. Responses to this wide range of conditions are equally large (Naiman and Décamps 1997; Capon 2003; Bush 2006; Merlo et al. 2011; Huang et al. 2013; Cervantes-Campero et al. 2020; Rodríguez-Sánchez et al. 2020).

8.2.2 Water Systems in Cuatro Ciénegas

The Cuatro Ciénegas Basin (CCB), located at 26° 45′ 0″ and 27° 0′ 00" N 101° 48′ 49″ and 102°17′ 53" W, in the heart of the Chihuahuan Desert, is a unique place in many senses. As a result of its very complex geological history and of its latitude, it harbours an important set of different ecosystems and vegetation types (Minckley 1969; INE 1999; Wolaver et al. 2013; Souza and Eguiarte 2018; Ezcurra et al. 2020; Scheinvar et al. 2020). However, it is water that distinguishes this desert valley, where wetlands harbours many endemic species of aquatic animals, plants, fungi and prokaryotes in its Lagoons, rivers, and hundres of *pozas*. The presence of five hydrological systems (Churince, Garabatal-Becerra-Río Mesquites, Tío Cándido-Los Hundidos, Santa Tecla and El Anteojo) characterized the CCB. The Churince system was the most differentiated of them due not only to its gypsum-dominated soil but also because it is a little bit higher than the other systems (IMTA 2006). Churince used to have a terminal lagoon, an intermedia lagoon, a river and a spring. Not so long ago, superficial water bodies could be detected at a distance, because characteristic discrete patches of riparian vegetation announced them. These systems created unique aquatic and semiaquatic environments of great ecological importance, including the fact that they have been the habitat for stromatolites and microbial mats formed by complex microbiological communities (Souza et al. 2006, 2012; Corman and Elser 2018; De Anda et al. 2018a; Souza and Eguiarte 2018), and of several animal and plant endemic species or those species adapted to this unique conditions (Minckley 1969; Cole 1984; Pinkava 1984; INE 1999; Hendrickson et al. 2008; Villarreal-Quintanilla et al. 2017).

These water bodies are vital for human activities, like cattle raising and agriculture. We guess that right now you are thinking: Agriculture in the middle of the desert? Well, yes, and even if it sounds unbelievably wrong, alfalfa, which is one of the most water-demanding cultivars in the world, is the main cultivated species in the area. Now you must be thinking: Are they mad? No, they are not. Soils in arid lands are rich in salts, and their concentration prevents many other cultivated species from growing even when water which, by the way, is also salty, is available. Alfalfa stands the high soil salinity, which is a dominant characteristic in CCB (INE 1999). As there seemed to be plenty of water in the CCB area, impoverished *ejidatarios* accepted to grow alfalfa and sell it to passing trucks that give them 2 pesos (0.10 USA dollars) per kilogram, given its low quality. However, the cultivation of alfalfa has generated a major disturbance in the hydrological system of the valley.

Water has been overexploited in the Cuatro Ciénegas region for a very long time. The first important hydraulic change took place in the 1890s, when a canal was built to carry water from the valley to another river (Río Salado de los Nadadores), thus providing additional water many kilometres downward CCB (Hendrickson et al. 2008). Since then, other canals have been built, through which large volumes of water have been displaced at a huge environmental cost for the CCB, including the decline of the water table.

Different parts of the CCB complex hydrological system have been drying out progressively and sometimes dramatically fast. Maybe you wonder if no one ever thought that this would happen or maybe no one even noticed. Conflicts around water, land use and property, and conservation efforts are not scarce and, as could be expected, they influence decision-making and are increasing permanently. Please keep this in mind when reading the next pages.

The Churince system is an important part of the complex hydrological structure of the CCB. However, during the first two decades of this century, it has been deeply disturbed by the overexploitation of groundwater, and except for Poza Churince, mostly all of the surface water of this system is now gone, probably forever (Souza et al. 2006; Rodríguez et al. 2007; Cerritos et al. 2011; Pisanty and Rodríguez-Sánchez 2017; De Anda et al. 2018b; Souza and Eguiarte 2018; Pisanty et al. 2020). Its desiccation is already having effects not only on the water bodies, where dry lake beds have substituted the lagoons and most parts of the river, but also in the surrounding areas, like the borders and the highly saline plain in the south bank of the river (Pisanty et al. 2020).

You can easily imagine how serious the loss of these hydrological systems could be and then think that local stakeholders would avoid it at any cost. Well, the first thing is true, but the second proved not to be so. This desiccation process—a real tragedy—has been documented elsewhere, so we will go back to our canaries, for learning from their early advice might make us able to prevent further disturbances and help to avoid yet another one with the concomitant major socio-ecosystemic disruption and all its hard ecological, social, and personal repercussions.

8.2.3 Being Riparian in a Changing Arid Environment

Riparian plants in CCB include species from different families that have different growth habits and life cycles. Most of them are perennials, as is common in deserts with dry winters (Ezcurra et al. 2020). The most common riparian species include *Flaveria chlorifolia* (Asteraceae), *Samolus ebracteatus* var. *coahuilensis* (Primulaceae) and *Schoenus nigricans* (Cyperaceae) (Villarreal-Quintanilla et al. 2017; Pisanty et al. 2013, 2020).

As their original habitat disappeared because of the desiccation of the Churince system, several of the riparian species were able to colonize new habitats created by the disturbance affecting this hydrological system. As part of these new habitats, sinkholes were formed when the loss of strength of the water flux from the spring in Poza Churince began. This caused a sublevel flow of water in the plain close to the south bank of the Churince river (actually more a creek than a river), since water cannot reach the river mouth and the lagoon. This sublevel flow caused the loss of soil cohesion and the dispersal of soil particles, thus forming sinkholes, which, in lower quantites, are not uncommon in karstic and semi-karstic substrates. As surface water disappeared, so did the riparian habitats, and the plants inhabiting them died. However, many of these plants disperse easily, and they started colonizing the sinkholes (Fig. 8.2), which emulated their original habitat since they were humid and could even had water in them, at least for some time (Pisanty et al. 2013, 2020).

Fig. 8.2 Sinkholes with colonizing riparian species in the south bank of the Churince river, Cuatro Ciénegas, Coahuila, Mexico

Fig. 8.3 *Distichlis spicata* growing on the plain on the south bank of the Churince river

Some species, like *Samolus ebracteatus* var. *coahuilensis*, were also able to establish on the surrounding plain, where only *Distichlis spicata* (Poaceae) (Fig. 8.3), a salt-loving grass, would grow before this catastrophic mess. However, as water continued to be lost, the sublevel flow came to an end, and less and less water reached the sinkholes. Finally, basically all the sinkholes of the Churince system stopped having water in 2012, with only a few intermittent occasions, and by the end of 2017 there was no water in any of the more than 240 sinkholes that were formed through the desiccation period (Pisanty et al. 2020). As a matter of fact, numerous sinkholes are already closed covered with dry sand, with only a few riparian plants still growing where they had established. All this happened in a relatively short period of time, starting roughly in 2003.

Well, you might be saying, more than 15 years is not such a short time, but it is a terribly short one if you think of how long these hydrological systems and the aquatic, subaquatic and riparian habitats had been there before cows mooed and before alfalfa was even domesticated for cultivation. It took a short time to make superficial water, which had been there for millions of years, simply disappear. Shocking, isn't it? Having an accelerated formation of sinkholes is really bad news, the sad song of a canary that was not heard, but having dry sinkholes that will eventually close and disappear is even worse, for it means no water is left.

Unfortunately, canaries were there, and if their agony had been realized and accepted by decision-makers and other stakeholders, none of this would have happened, or at least it could have been stopped once it had started. Why our conservation efforts, and those of many other researchers and conservationists, were ignored in this process deserves a profound analysis that goes beyond the scope of this chapter.

How can we prevent this from happening again in other water bodies in the CCB and other desert hydrological systems? Many things are needed, and knowledge is indeed one of them. Albeit it not being enough on its own, science is badly needed in these cases, so we will start by introducing you to three of the above-ground canaries we have identified without forgetting that the formation of sinkholes is also a robust early warning system by itself.

8.3 Plant Canary # 1: *Samolus ebracteatus* var. *coahuilensis*

Samolus ebracteatus var. *coahuilensis* (Fig. 8.4) is a prostrate or erect plant from the primrose family (Primulaceae), and it is a very common species around water bodies throughout the CCB valley (Henrickson 1983; SEINet 2018). However, during the peak of sinkhole formation, it colonized the plain in the south bank of the Churince river, forming small clumps, as well as the newly formed sinkholes. In the seasonal census (2008–2017) of the sinkholes we mentioned above, this species tweeted a lot, initially occupying 85% of the sinkholes, with some seasonal variations.

Sinkholes were colonized very successfully by this plant, which was always among the first three species to establish in these newly opened habitats. When sinkholes were shallow and wide, *S. ebracteatus* var. *coahuilensis* thrived, producing many short branches and attaining a considerable plant cover; when they were narrow and deep, it also did well, for this plant shifted its growth from vertical and horizontal to only vertical, responding to shade with a long morph looking to get some light, although its plant cover was lower and the number of branches diminished considerably (Cervantes-Campero et al. 2020). In one way or another, it remained a frequent and dominant species in the sinkholes. As other species colonized the latter, sometimes *S. ebracteatus* var. *coahuilensis* would lose cover, probably through interspecific competition, but it continued being present (Pisanty et al. 2020).

Starting 2011, fewer and fewer sinkholes had water in them, and by January 2012 not a single sinkhole had water. As this process moved forward, conditions in the sinkholes were no longer so good for this canary, and it started tweeting less and sighing with more urgency, until the inevitable started happening, and this species clearly showed that something was going terribly wrong. By the end of 2017, *S. ebracteatus* var. *coahuilensis* was in less than 50% of the sinkholes and represented only 2% of the total plant cover (Pisanty et al. 2020), and plants in the plain became smaller and scarcer.

Additionally, many sinkholes closed during the desiccation process, due to the strong wind and sandstorms that are common in this valley, with the consequent loss of possible safe sites for this species. In January 2012, for example, in only 2 days 29% of the 148 sinkholes that were open in that date were covered by sand, and many of them did not re-open, for when there is no water to disperse its particles, soil accumulates permanently and eventually covers the depressions completely. Some of the riparian plants can remain for some time on top of what once was a sinkhole, indicating there is still some water availability, but if conditions remain as

Fig. 8.4 *Samolus ebracteatus* var. *coahuilensis* in the Churince system, Cuatro Ciénegas, Coahuila, Mexico. (**a**) On the plain, (**b**) colonizing a sinkhole

they are now, eventually they will die. *Samolus ebracteatus* var. *coahuilensis* is one of the first species to suffer under these conditions, as its morphological plasticity (Cervantes-Campero et al. 2020), frequency and cover indicate (Pisanty et al. 2020). First come, first served… and among the first to go.

Although the seeds of this species have a quick germination response as soon as water becomes available (Peralta-García et al. 2016, 2020), and the seeds can remain viable at least for a year, they do not seem to be well represented in the seed bank now (A. Santiago and I. Pisanty, pers. obs.).

Samolus ebracteatus var. *coahuilensis* tweeted again, starting in 2015. This plant started establishing on the riverbed (Torres Orozco-Román 2017; Pisanty et al. 2020), where there were no plants when water was flowing in the river. What was a terrestrial plant doing in the middle of a river? Well, it is because it was not a river anymore. There was no water flowing, and the aquatic habitat was gone. This was the only substrate that still held some water underneath. With seeds easily dispersed by wind and a rapid response to water, this canary easily started colonizing this newly opened habitat but was loud about the dramatic loss of water, again.

Inbox 1

Canary dialogues 1: *Samolus ebracteatus* var. *coahuilensis*

First warning: Changes in distribution, including decreasing abundance and eventual disappearance from riparian habitats. Colonization of new environments, like a more humid (due to sublevel flow) flatland, the desiccated lake and riverbeds and the disturbance-induced sinkholes.

Time is ticking: Less abundance in the new habitats, signs of population decrease and loss of fitness.

Too late! Disappearance of the zones it occupied before and after the desiccation of the water bodies, establishment of less water-demanding species in them. The species becomes locally extinct.

8.4 Plant Canary # 2: *Flaveria chlorifolia*

This erect plant from the daisy family (Asteraceae; Fig. 8.5) is common in the CCB for several reasons: it needs more water than xeric species, so it grows along the water bodies that used to be common, and it is a gypsovague, meaning that it can tolerate a

b

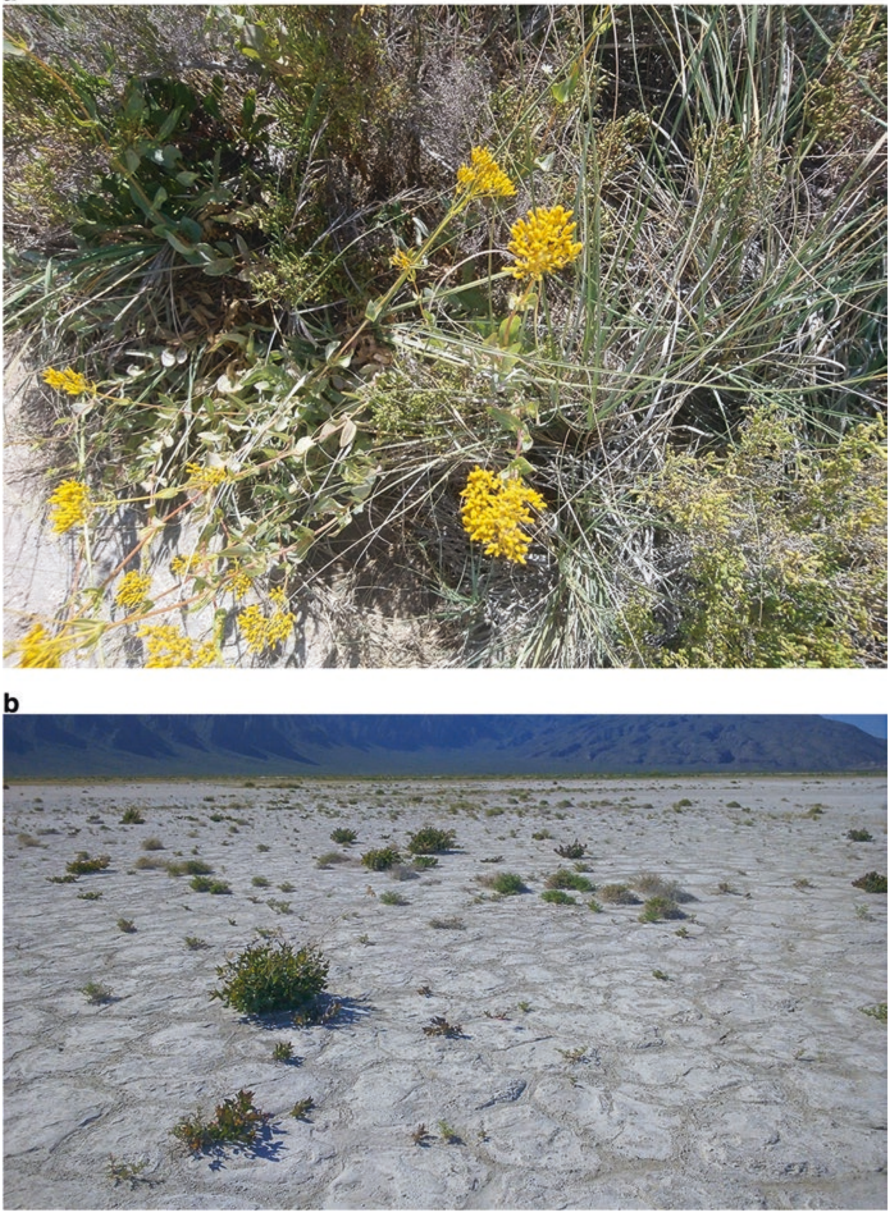

Fig. 8.5 *Flaveria chlorifolia* in the Churince system, Cuatro Ciénegas, Coahuila, Mexico. (**a**) *Flaveria chlorifolia* in a sinkhole, (**b**) colonizing the dry lake bed of the Churince lagoon, (**c**) in the border of the Churince river, forming a scrub

c

Fig. 8.5 (Continued)

high concentrations of gypsum ($CaSO_4 \cdot 2H_20$), which is a sulphate that frequently limits the establishment and growth of many species (Palacio et al. 2007, 2014; Escudero et al. 1999, 2000, 2015; Moore et al. 2014). While *F. chlorifolia* does not need gypsum to grow (Flores-Olvera et al. 2016; Peralta-García et al. 2016; Rodríguez-Sánchez 2018; Pisanty et al. 2020; Rodríguez-Sánchez et al. 2020), as true gypsophytes do (Meyer 1986; Escudero et al. 2015), but it can stand gypsum well. This trait makes it competitive in face of other species that cannot tolerate this salt. Even among other gypsovagues, *F. chlorifolia* is a frequent and successful colonizer of desert riparian habitats and of the new habitats the disturbance in the Churince system has created.

Flaveria chlorifolia was usually among the first three species to colonize sinkholes in the Churince and was found in 60% of them in the summer of 2008, reaching a maximum in August 2009 (68%) (Pisanty et al. 2013, 2020). The frequency of

F. chlorifolia has a clear seasonal pattern, decreasing in the cold season and increasing in summer. Nevertheless, in a longer term it showed much less variation and remained relatively constant, unlike that of the other canaries we identified (Pisanty et al. 2020). Plant cover of this species changes drastically during the cold season, for all leaves are shed, but, contrasting with *S. ebracteatus* var. *coahuilensis*, this species does not lose so much cover during the micro-successional process implied in the colonization of sinkholes.

Besides establishing in the cosy sinkholes, and sporadically on the plain, this species does what other riparian plants that characterized the borders of the water bodies in the CCB do not do: it profits of the underground water it can find in the cracks of the large, gypsum-rich lacustrine bed. Right, you got it: This species was the first to start colonizing the dry, inhospitable bed of the Churince lagoon, after several years of nothing growing there (Fig. 8.5b). Up to now, *F. chlorifolia* has been the most—actually almost the only—successful colonizer of the new and dry Churince area, an extreme habitat, but its demography proves colonizing this place is not an easy task (Rodríguez-Sánchez 2018). Scarce water, a very low content of nutrients and a thick gypsum crust add to the regular harsh arid conditions that make survival rates low, despite the many strategies the plant shows (Rodríguez-Sánchez et al. 2020). The latter include a perennial life cycle, based on the survival of meristems placed between the stem and the roots, which are frequently buried by sand. Leaves can be produced underground and have characteristic purple colour that turns into green as the young leaves emerge and are exposed to the intense sunlight.

Flaveria chlorifolia also establishes, sporadically, probably following temporal pits, but it has spectacular establishment on the dry plain and growth flushes around the borders of the water borders, impressively changing the typical landscape dominated by very short plants. In 2015, this species dominated the landscape around the river borders, with unusually large plants, more than a metre high, profusely branched and intensely producing flowers (Fig. 8.5c). Although it seemed they would dominate the riparian landscape soon, all of these uncommon individuals died after a couple of years.

A few years later, as the river desiccated further towards the spring, this process happened again, and many *F. chlorifolia* individuals settled around the river borders, where water was disappearing. Again, the landscape changed in part of the Churince system, with *F. chlorifolia* boastingly showing off its efficient colonization skills and use of the abundant sublevel water by intensively reproducing.

Unfortunately, our canary soon started sighing. Again, this sensitive canary was announcing the same tragedy: the loss of water. All these individuals died after a short period, while seedlings tried to establish in the newly desiccated part of the riverbed. *Flaveria chlorifolia* is not only an audacious and successful colonizer, but it can also be a hardy survivor once it establishes, as it can opportunistically occupy microsites in different environments and then endure selective pressures that can quickly eliminate other species, for example, gypsum concentration.

When this yellow-flowered canary gets sick and sighs, it is announcing lack of water in a desperate way since, due to its gypsovague character, it can grow under harsher soil conditions that include considerable concentrations of salt and gypsum, than the other two species of plant canaries we are looking at in this chapter. It is not notifying dangerous salt and gypsum concentrations, it is yelling that it is thirsty.

Inbox 2


Canary dialogues # 2: *Flaveria chlorifolia* **(Asteraceae)**

First warning: Changes in distribution, including loss of density, frequency and dominance in original riparian habitats and occupation of sinkholes, riverbed and, notoriously, the gypsum-rich dry lakebed. In the latter, it is among the first and few species that are able to establish in this difficult substrate. Short-term establishment of numerous individuals with a high growth rate where sublevel and deep water accumulations take place indicates an underground flow.

Time is ticking: No *F. chlorifolia* in the original riparian habitats, less individuals and loss of plant cover in sinkholes. Negative growth rates in the dry lakebed. Disappearance of the shrub-like clumps established near the river in the short-term establishment mentioned above.

Too late! Less water-demanding species displace this canary, more quickly in the sinkholes, the flatland and the dry riverbed than in the dry lakebed, due to the high tolerance to gypsum. It will soon disappear locally.

8.5 Plant Canary # 3: *Schoenus nigricans*

Schoenus nigricans (Fig. 8.6) is also a highly water-demanding riparian species. This is a grass-like plant from the sedge family (Cyperaceae). It plays a game of its own and is, thus, a very loud-mouthed canary. *Schoenus nigricans* has a very high affinity with water, as do many other members of its family (Bryson and Carter 2008; Simpson et al. 2011; Diego-Pérez and González-Elizondo 2013). It grows along river and lake borders and is an important element of the riparian landscape in the CCB.

Fig. 8.6 *Schoenus nigricans* in the Churince system, Cuatro Ciénegas, Coahuila, Mexico (**a**) at the border of *Poza Azul* in its natural riparian habitat, (**b**) growing in a sinkhole on the south bank of the Churince river

Schoenus nigricans grows both vertically (in height) and laterally, as it produces many tillers connected through very short internodes, thus forming clumps that can be quite large (Fig. 8.6). It reproduces through an annual period, producing many characteristic flowers and numerous seeds per fruit (50–120) that can be dispersed by wind or water.

This species has a contrasting germination response when compared with the above-mentioned *S. ebractatus* var. *coahuilensis* and *F. chlorifolia,* for seeds germinate very occasionally in natural conditions, and only in wet sites, with a low germination rate (velocity) in controlled conditions (Peralta-García et al. 2020). Contrasting with the other two species we have mentioned, it does not germinate in rich-nutrient soils under experimental conditions, even if its seedlings love all the nutrients and grow successfully on this type of substrate. Seeds might have a conditional dormancy (Martínez-Sánchez et al. 2006; Peralta-García et al. 2020) that can prevent germination under conditions of low water availability.

Schoenus nigricans was among the first canaries notifying that something was wrong, for it soon resented the lack of water in the original riparian habitats and disappeared from them, successfully moving to the sinkholes, where both lonely single stems and large, dense clumps could be found, thus indicating the availability of water. Being one of the three most common colonizers in the sinkholes, *S. nigricans* always grew in them or on their borders, but never far from them, i.e. this species would not colonize the flatland, neither frequently, as *S. ebracteatus* var. *coahuilensis* did, nor much more sporadically as *F. chlorifolia*.

The frequency of *S. nigricans* in the sinkholes increased with time while water was available, but it diminished very soon as the whole area desiccated. However, due to the fact that in the older and larger sinkholes it had already formed large clumps, plant cover remained relatively constant, for green and dry stems, which are slender, remain mingled. Additionally, dry and green stems mingle and coexist, which can lead to an overestimation of their cover. Of course, if living stems are present, some water must still be available.

Schoenus nigricans is a major canary due to its strict association with water availability and to the time seeds take to sense the environment seedlings would grow in if they germinate (Baskin and Baskin 1971, 2014; Rojas-Aréchiga and Vázquez-Yanes 2000; Martínez-Villegas et al. 2012). Since it forms big clumps, changes in the riparian habitat they occupy are usually soon visible through the landscape modification along the water bodies. When new habitats are formed due to disturbance, this species is reluctant to act as a colonizer unless a good supply of water is guaranteed. This canary will become restless and sick very soon, leaving no doubt that something is not as it should be. Early warnings can be so useful when properly attended!

Inbox 3

Canary dialogues# 3: *Schoenus nigricans* **(Cyperaceae)**

Early warning: Strips of *S. nigricans* start losing density, and patches disappear along the riparian area. As sinkholes form, isolated stems appear and eventually form thick clumps, especially in the large ones. Seedlings appear in the dry riverbed.

Time is ticking: Clumps of *S. nigricans* show an increasing number of dry stems, mingled with green ones. Small clumps or isolated stems become less and less abundant. If, due to conservation efforts and a better management, water returns while underground stems are still alive, new stems will be formed. If there is a seed a bank or seeds from other sites in the CCB are dispersed, germination and new recruitments can take place, despite the characteristically difficult germination of this species.

Too late! Only dry clumps of *S. nigricans* remain. Local disappearance of the species will take place.

8.6 Conclusions and Perspectives

The canaries in the mine were clearly alarmed, they tweeted in despair, we as scientist together with other stakeholders and were listening. However, even if we tried to amplify their despair with our voices, the inertia of the government, the lack of understanding of the powerful and the unwillingness to act at all levels left the canaries agonizing or dead and the people facing the consequences of the aquifer depletion. Initially*, Samolus ebracteatus* var. *coahuilensis*, *F. chlorifolia* and *S. nigricans*, together with other less frequent and dominant species, lost their original riparian habitat in the Churince system from CCB but found alternate ones that, in some way, emulate it, like the sinkholes. They also found a habitat to colonize on the riverbed and in those parts of the plain where water was flowing through abnormally numerous minuscule canals. The succesful colonization of these new habitats was stopped by the progressive loss of water in them.

Very little is known about other species that could also act canaries, like the grass *Sporobolus airoides* (Poaceae). This species is a halophyte and needs water to be available, but it is not a riparian species. Nevertheless, it requires more water than strict xerophytes and found sinkholes suitable to establish in, especially on the borders, because of water availability (Pisanty et al. 2013, 2020). Today, it is very abundant and dominant in the plain, and is transforming it into a grassland of ca 50 cm high.

Further studies about these and other species will certainly highlight the conditions its growth indicates, but before that is known, we must keep in mind that quick changes in arid and semiarid places always indicate intense physical and/or biological changes. When the latter are anthropogenic (Pimm and Raven 2000), they are usually bad news, especially in this type of ecosystems (Unmack and Minckley 2008)

What comes next for the Churince and similar disturbed areas in CCB? Early warnings, like the formation of sinkholes and changes in abundance and distribution of our canary species have not been turned off, and many other have started tweeting hard and clear. The complete modifications of local environments and the local extinction of riparian species are the most probable scenarios.

And then? We need to identify canaries, not only from the Churince system but from all the systems in CCB and similar ecosystems, and then to observe and listen to them, for early warning can—and must—be a major conservation tool and, thus, a tool for the viability of local and regional human societies and their permanence. Every population that goes extinct contributes to the risk of permanently losing whole species especially when small populations of endemic and microendemic species are involved (Lande 1993; Lande et al. 2003; Mathies et al. 2014).

Indeed, tangible and intangible ecosystem services are at stake, and preserving them in such a unique place is in the interest of all stakeholders. It is in our own interest as humans. Desert springs are severely threatened by human activities. Time is ticking.

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Chapter 9
Can Bacterial Populations Go Extinct? Evolutionary Biology and Bacterial Studies in Cuatro Ciénegas Shed Light on the Extinction Process

Manuel II García-Ulloa, Valeria Souza, Gabriela Olmedo-Alvarez, and Luis E. Eguiarte

9.1 The Biology of Extinction

Extinction is the irreversible response of species that are unable to cope with rapid environmental change (Arumugam et al. 2020). Although habitat destruction has been suggested to be the main cause of species extinction, global warming is also expected to be one of the leading causes of species extinction in the near future (Pimm and Raven 2000). Also, as the growing human population demands more resources and occupies more space, habitat destruction increases. It has been suggested that as the environment changes, species become maladapted and risk local extirpation or extinction unless they rapidly adapt or migrate (Arumugam et al. 2020). The concurrent extinctions lower ecosystem functioning and affect community stability (Pimm and Raven 2000). Moreover, patchy environments with uneven distribution of low-abundance organisms are particularly vulnerable to environmental disturbances (Pimm et al. 1995).

Strategies for conservation require much more research. Many models have been formulated under the framework of metapopulations introduced by Levins (1969). Metapopulation ideas play an increasingly important role in landscape ecology and conservation biology. Metapopulation models in this context can be applied for modelling of heterogeneous environments (e.g., viable and destroyed areas), where what counts is local extinction, dispersal among sites, and colonization. With

M. I. García-Ulloa · V. Souza (✉) · L. E. Eguiarte
Departamento de Ecología Evolutiva, Instituto de Ecología, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico
e-mail: souza@unam.mx

G. Olmedo-Alvarez
Laboratorio de Bacteriología Molecular, Departamento de Ingeniería Genética, CINVESTAV – Unidad Irapuato, Irapuato, Mexico

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this approach, species are assumed to occupy a number of patches or sites (Yokoi et al. 2019), and it is the number of occupied patches that is tracked, instead of the number of individuals within the patches (Logue et al. 2011). Habitat destruction is included as a reduction in the total number of patches available for species to colonize.

Except for local extinction and colonization, local population dynamics are usually ignored, and it is the number or proportion of metapopulation patches occupied—instead of the numbers of individuals within patches—that is tracked. Habitat destruction is included as a reduction in the total number of patches available for species to colonize.

Even without the extensive evidence and modeling on the number of species lost every year, we believe that microorganisms run many of the same extinction risks as "visible" organisms.

9.2 Species Extinction Is Forever, and Bacteria Are Not Immune to It!

In bacteria, extinction may be harder to prove than in a rhino, but conceptually, they face many of the same risks. Considering that bacteria can do almost anything almost anywhere, many researchers find it difficult to conceive scenarios where they could go extinct. For these reasons, almost all the literature assumes that bacteria resist everything, as they occupy all habitats. But the confusion stems from the fact that everyone thinks of "bacteria" as a single omnipresent species and do not understand that the colonization of different environments by different bacterial taxa is the result of millions of evolutionary years. The permafrost, the forest, or the human intestine bacteria are by no means the same. Every community is vulnerable to changes in its own environments.

We should therefore emphasize that we know little about bacterial resilience other than from a few model mesophilic bacteria and a few that are exceptional in their resistance to UV but sensitive to changes in pH (Rousk et al. 2010). Actually, most bacterial groups cannot even survive more than a few degrees departure from their optimal growth temperature (Hurtado-Bautista et al. 2021).

Bacteria do have traits that make specific taxa highly resilient. Metabolic versatility, phenotypic plasticity and persistence (Rotem et al. 2010), and resistance mechanisms such as endospores (Gest and Mandelstam 1987; Nicholson et al. 2000) and biofilms (Karatan and Watnick 2009), alongside with an ease of dispersion, have rendered them the most diverse and abundant group of organisms on Earth (Horner-Devine et al. 2004), successfully colonizing virtually every environment, from the deep-sea hydrothermal vents (Harmsen et al. 1997) to the oligotrophic hard waters of Cuatro Ciénegas (Bonilla-Rosso et al. 2012). However, beyond the immediately observable traits of bacteria, the underlying characteristic that allows for and further potentiates all of the above is their evolvability and its role in rapid adaptation to environmental stress (Foster 2005; Galhardo et al. 2007; Baquero 2009; Wein and Dagan 2019).

Contrastingly to other organisms, bacterial populations can be very large and possess the ability to react to stressful or disturbed environments, increasing their odds of survival in short periods of time by fine-tuning their mutation and recombination rates, thus allowing selection to take place more rapidly (Cebula and LeClerc 1997; Travis and Travis 2002; Foster 2005; Vos 2009; Wielgoss et al. 2016).

On the one hand, the upregulation of their mutation rates produces de novo variation (Denamur and Matic 2006; Jayaraman 2011). Increases in mutation rates of as much as 100-fold have been seen in aging colonies of *Escherichia coli* (Bjedov et al. 2003), and hypermutator strains have risen and fixated in Lenski's long-term evolution experiment under a single constant environmental pressure (Lenski et al. 1998; Couce et al. 2017). Emergence of hypermutable strains has also been reported in *Haemophilus influenzae* (Román et al. 2004), *Staphylococcus aureus* (Daurel et al. 2007), the acidophilic *Oenococcus* genus (Marcobal et al. 2008), and *Pseudomonas aeruginosa* (Oliver et al. 2000). Moreover, hypermutator strains of *P. aeruginosa* subjected to antibiotics evolve resistance more rapidly and retain it for more time than wild-type strains, even in the subsequent absence of the environmental pressure, highlighting the adaptive benefits of hypermutability under challenging conditions (Perron et al. 2010). On the other hand, recombination serves to bypass the gradual refinement that a gene requires to provide a selective advantage. Through the incorporation of exogenous DNA via horizontal gene transfer (HGT), new alleles or entirely new genes with new functions enter the gene pool, becoming potential targets of selection (Pál et al. 2005). Recombination occurs in all known bacteria, but at different rates, depending on the lineage (Vos and Didelot 2009) and the environmental circumstances and stressors a population is subjected to, with a tendency to increase when environmental conditions become adverse (Levin and Cornejo 2009; Aminov 2011). Furthermore, when the environment becomes harsh enough, the SOS response occurs, and recombination, sometimes alongside mutation rate, is further increased (Maslowska et al. 2019).

9.3 Periodic Selection in Bacterial Populations and Local Adaptation

Extant bacterial populations are the result of speciation process but also of extinction events (Louca et al. 2018). Bacterial lineage replacement is well understood at the intra-population scale. With some exceptions, under normal conditions recombination in bacteria is generally low (Cohan 2005). In such cases, periodic selection acts as the main mechanism of bacterial evolution, gaining particular relevance in constant, low phosphorous environments such as Cuatro Ciénegas, where recombination is highly constrained (Souza et al. 2008).

Periodic selection consists on the succession of a population (a bacterial lineage, if there is little or no recombination) when a new advantageous variant is acquired by mutation or recombination. If the new variant provides an advantage considerable enough in its current niche, it eventually sweeps through the entire population, outcompeting its ancestor strain until it is eliminated from the population (Cohan 2001, 2005).

Multiple instances of periodic selection have been observed in laboratory experiments (Atwood et al. 1951; Papadopoulos et al. 1999; Notley-McRobb and Ferenci 2000; Baym et al. 2016), clinical studies (Barrett et al. 2005; Caballero et al. 2015), and natural setups (Bendall et al. 2016). However, the capacity of accelerating evolution through the increase of mutation and recombination rates together with large populations that encompass many ecotypes, as is the case for most bacterial populations, makes bacterial extinction unlikely at the population level in constant environments or at least suggests that extinction rates must be very low (Rainey et al. 2000; Horner-Devine et al. 2004; Fraser et al. 2009).

9.4 Seasonal and Catastrophic Environmental Changes Affect Bacterial Populations

Environmental change happens regularly, even in the most pristine environments, through seasonal changes. Although sometimes very pronounced, those changes tend to be cyclical, and bacterial communities evolve with them given the recurrent environmental pressures (Bardgett et al. 1999; Giovannoni and Vergin 2012; Rodríguez-Verdugo et al. 2012; Alonso-Sáez et al. 2015). In Cuatro Ciénegas, for example, a typical yearly cycle can be roughly divided into cold-dry and hot-humid seasons, and seasonality has been observed to influence the *Pseudomonas* community composition (Rodríguez-Verdugo et al. 2012).

However, new, abrupt, and sometimes drastic changes can yield more permanent consequences. These include natural catastrophes, such as hurricanes, droughts, and freezes. Of special relevance now, there can be drastic anthropogenic perturbation, mainly in the form of climate change, pollution, and resource overexploitation.

However, at different magnitudes, sudden change translates into stress for bacterial populations. When an abrupt environmental perturbation is severe enough to lower the mean fitness of a population below 1, a state of negative growth ensues, and a race to escape extinction begins (Ramsayer et al. 2013). Nevertheless, if a population is able to withstand the new environmental conditions long enough and it possesses or acquires the necessary advantageous variation, an evolutionary rescue event is likely to take place (Bell 2017).

9.5 Evolutionary Rescue in Bacteria Can Help to Avoid Local Extinction

Evolutionary rescue is a process through which populations in rapid decline due to an abrupt environmental perturbation recover their positive growth by adaptive mechanisms (Carlson et al. 2014; Bell 2017). This rapid fluctuation in population size produces a hallmark U-shaped demographic curve, depicting the initial population decline and its subsequent recovery (Gomulkiewicz and Holt 1995; Ramsayer et al. 2013). The likelihood of an evolutionary rescue event to take place depends on many factors, including the severity of the perturbation, initial population size and genetic diversity, mutation and recombination rates, and benefits and costs of adaptive mutations (Gomulkiewicz and Holt 1995; Willi et al. 2006; Kawecki 2008; Willi and Hoffmann 2009; Ramsayer et al. 2013).

Up to date, evolutionary rescue had only been studied in laboratory experiments (Gomulkiewicz and Holt 1995; Orr and Unckless 2008, 2014; Uecker and Hermisson 2016; Vogwill et al. 2016; Van Den Elzen et al. 2017; Anciaux et al. 2018, 2019; Carja and Plotkin 2019) and through mathematical models (Bell and Gonzalez 2009; Agashe et al. 2011; Ramsayer et al. 2013). However, it has recently been observed for the first time in a natural setup in the Churince system of Cuatro Ciénegas, along its medium- to long-term consequences in a *Pseudomonas otitidis* native aquatic lineage.

9.6 Case 1. *Pseudomonas otitidis* from Laguna Intermedia, Cuatro Ciénegas

9.6.1 Natural Setup, Unnatural Stress

The Churince system is the best studied hydrological system of Cuatro Ciénegas, Mexico (Souza et al. 2018a). The whole system was, until recently, composed of four sequentially interconnected bodies of water in a span of 3 km: Laguna Grande, Laguna Intermedia, and the Poza Churince and Poza Bonita springs. Nutrient stoichiometry was unusually unbalanced in the entire system, with PO_4 as low as 0.1μM, often below detection, and N:P > 200:1 for total nutrients (Escalante et al. 2008; Ponce-Soto et al. 2015). These stoichiometric conditions have isolated this wetland from more modern microbial communities, preserving a highly diverse indigenous microbiota (Desnues et al. 2008; Moreno-Letelier et al. 2012; Gómez-Lunar et al. 2016; Souza et al. 2018b; Taboada et al. 2018) composed of unique bacterial lineages of which a large fraction descended from marine ancestors (Souza et al. 2006; Alcaraz et al. 2008).

Sadly, water overexploitation progressively drained the Churince water system, and only the Poza Churince spring remains since 2017 (García-Ulloa et al. 2019, 2020). Laguna Grande dried-up very fast in 2006 (Rodríguez-Verdugo et al. 2012).

In contrast, the decline of Laguna Intermedia was gradual. It went from a constant to a fluctuating environment, experiencing four partial but increasingly severe desiccation events in October 2011, November 2013, October 2015, and October 2016, finally drying up completely in October 2017 (García-Ulloa et al. 2019, 2020). By the third desiccation event, mean salinity had risen six times from its normal value, and the lagoon became fragmented into smaller ponds with each subsequent event. The differences in mean environmental measurements and variance between the normal and disturbed states of Laguna Intermedia can be seen in Fig. 9.1.

Metagenomic studies performed seasonally from 2012 to 2014 in Laguna Intermedia showed a decrease in biodiversity under disturbed conditions, along with an increase of negative interactions, mostly competition, among its microbial members (De Anda et al. 2018). Likewise, changes in water stoichiometry due to the oscillations in water volume and nutrient concentrations likely played a role in community composition. The new influx of nutrients from bacterial remnants and osmolites likely altered the dynamics, as seen in studies of soil under hydration-desiccation cycles (Šťovíček et al. 2017).

An in situ nutrient enrichment experiment was carried out in Churince using different proportions of N:P, showing that a lower N:P ratio favored the proliferation of generalist bacteria and algae at the expense of the typically rare endemic lineages (Ponce-Soto et al. 2015; Lee et al. 2015, 2017; Elser et al. 2018). This was the case of Pseudomonads, which appeared to benefit from the initial environmental disturbance (Ponce-Soto et al. 2015; García-Ulloa et al. 2019).

9.6.2 **Pseudomonas** *of Churince: 2003–2015*

Pseudomonas was a common and highly diverse genus in Churince (Rodríguez-Verdugo et al. 2012). Since the first molecular ecology studies of the system, *Pseudomonas* had been isolated from the water column of every lagoon and spring with every sampling performed and also observed to be present through metagenomic studies of Laguna Intermedia (Fig. 9.2). As a result, they are one of the best studied bacterial groups of the site.

In a study of free-living aquatic *Pseudomonas* from Churince, Rodríguez-Verdugo et al. (2012) observed a seasonal pattern in which the endemic *Pseudomonas cuatrocienegasensis* (Escalante et al. 2009) was only present in the winter, while an environmental lineage of *P. otitidis* was exclusive to the summer. Through Bayesian analysis, Avitia et al. (2014) found that three *Pseudomonas* lineages (including the before-mentioned *P. otitidis*, referred as P2_C in their paper) were demographically expanding until the date of sampling in 2003.

Additionally, studies from Ponce-Soto et al. (2015) and García-Ulloa et al. (2019) in the Churince system suggested a positive impact of the desiccation events on the genus *Pseudomonas*: Ponce-Soto et al. (2015) found the proliferation of *Pseudomonas* and other generalists in response to an enrichment experiment, and García-Ulloa et al. (2019) reported two novel *P. aeruginosa* subclades isolated from

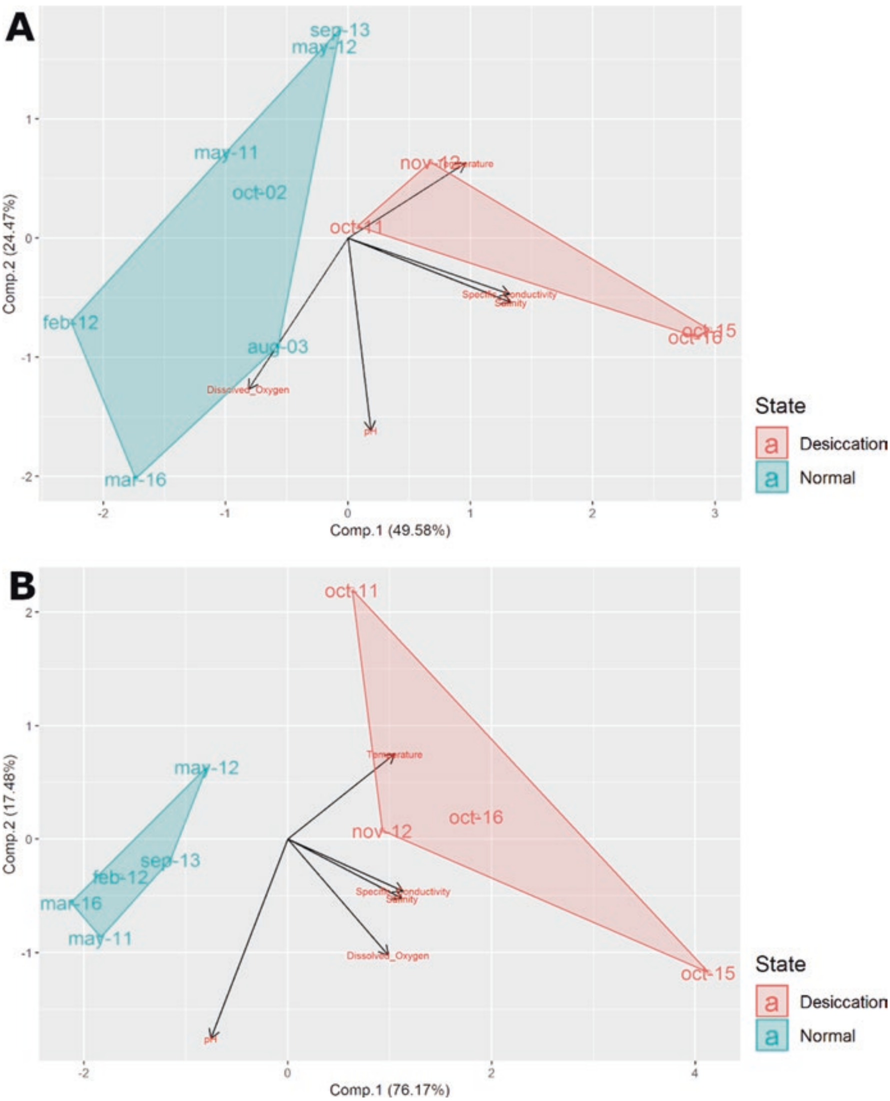

Fig. 9.1 Principal component analysis (PCA) of mean environmental measurements (**a**) and their variance (**b**) of Laguna Intermedia from the Churince system, Cuatro Ciénegas, Mexico. Black arrows with red labels represent the loadings. Samplings from October 2002 and August 2003 had no variance and thus had to be excluded from the variance PCA (**b**). Data from Escalante et al. (2008), Ponce-Soto et al. (2015), and García-Ulloa et al. (2020)

Laguna Intermedia only during the first and third desiccation events in 2011 and 2015.

In October 2015, during the third desiccation event, the same summer *P. otitidis* lineage that had been isolated from Laguna Intermedia during the 2003 sampling

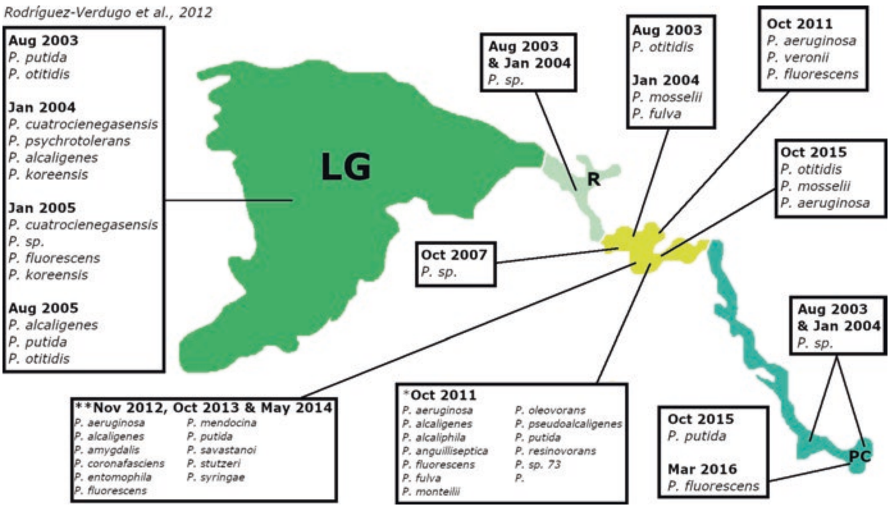

Fig. 9.2 All *Pseudomonas* samplings in the Churince system in Cuatro Ciénegas, Mexico, since 2003. *PC* Poza Churince; *PB* Poza Bonita; *LI* Laguna Intermedia; *R* rivulet connecting LI and LG; *LG* Laguna Grande. All identified *Pseudomonas* were isolated by culture, except for * = 16S tags and ** = shotgun metagenomes

and used in the Avitia et al. (2014) study was recovered again. This lineage used to inhabit the normal state of Churince and went through three desiccation events in a span of 12 years, thus providing the opportunity to assess the impact of desiccation at a genomic resolution in an in situ natural evolution experiment.

9.6.3 *The Demographic Roller Coaster of* Pseudomonas otitidis

Pseudomonas otitidis and other generalist lineages from Laguna Intermedia were undergoing gradual population expansions under the natural conditions of the system (Avitia et al. 2014). However, the desiccation events of the system altered their demographic and evolutionary trajectories (Ponce-Soto et al. 2015; De Anda et al. 2018; García-Ulloa et al. 2019, 2020).

Coalescence simulations based on the site-frequency spectrum of *P. otitidis* from 2015, considering the three desiccation events before 2016, showed a U-shaped demographic curve, as the theory of evolutionary rescue predicts (García-Ulloa et al. 2020). Both the inferred population decline during the first desiccation event in 2011 and the recovery in the next one at 2012 were very sharp. The bottleneck of 2011 left *P. otitidis* with an estimated effective population size 1000 times lower than the one calculated at the previous peak in 2003 by Avitia et al. (2014). The inferred population increase was even more drastic, as *P. otitidis* reached a

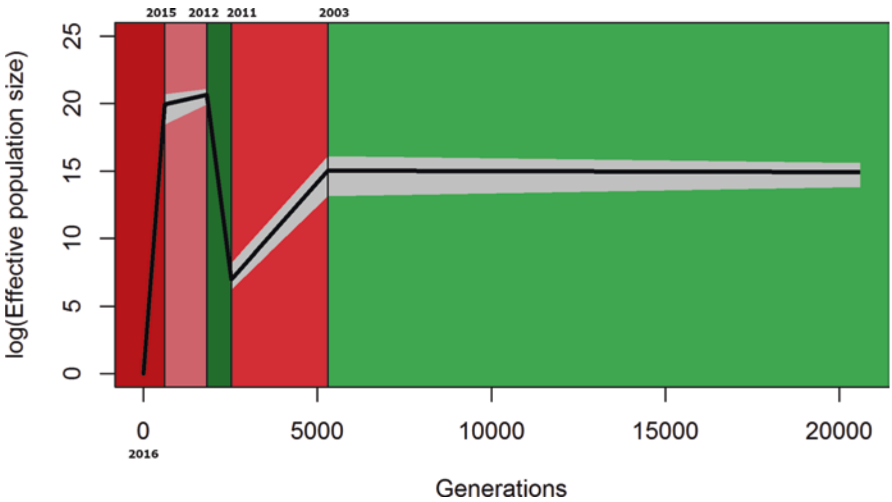

Fig. 9.3 Demographic history of *Pseudomonas otitidis* in Laguna Intermedia at the Churince system, Cuatro Ciénegas. The black line is the mean value, and the shaded area is the 95% confidence interval. Green and red backgrounds represent expansion and contraction, respectively. Magnitude of change is depicted by intensity of the background color. Desiccation events occurred in 2011, 2012, 2015, and 2016. The period from 20,000 generations to the year 2003 was calculated by Avitia et al. (2014) with a multi-locus Bayesian analysis; initial expansion started at 40,000 generations but was truncated to 20,000 for easier visualization. Population fluctuations from 2003 to 2015 were calculated by García-Ulloa et al. (2020), evaluating 27 demographic models derived from the whole-genome site-frequency spectrum. No pseudomonad was recovered since October 2016. Laguna Intermedia completely dried up in 2017

population size never observed before the desiccation event of 2012 (García-Ulloa et al. 2020) (Fig. 9.3).

Overall genetic diversity decreased after the population size fluctuations. By the final sampling of 2015, the core and accessory genomes had increased by 17.3% (559 genes) and 32.8% (486 genes), respectively, with respect to the 2003 sampling. Similarly, both mean nucleotide diversity of the core genome (3682 genes) and its variance also significantly decreased by 22% and 54%, respectively (García-Ulloa et al. 2020). This most likely happened as a result of the 2011 bottleneck and the subsequent population expansion and could have been potentiated by strong positive selection. Moreover, the small subset of the population that could survive and the radically larger effective population size compared to the one at the normal state of Laguna Intermedia points to a strong selective advantage, further supporting an evolutionary rescue event (García-Ulloa et al. 2020).

9.6.4 Adaptations and Evolutionary Rescue Observed in P. otitidis *After Environmental Changes in Churince*

For considering the occurrence of an evolutionary rescue event, there must be an adaptive component (Carlson et al. 2014). A pan-genome analysis provided evidence of the adaptations to the new environment by the genes that were gained and lost in the exclusive accessory genome and specific functions that acquired importance in the disturbed Laguna Intermedia (García-Ulloa et al. 2020). In contrast, McDonald-Kreitman tests (McDonald and Kreitman 1991) of the core genes in the genomes of *P. otitidis* showed no significant results. This negative result was possibly a consequence of the limited strain sample size (n2003 = 5; n2015 = 7) or because there was little time for a non-synonymous variant to fixate (García-Ulloa et al. 2020).

Gained genes include functions related to metabolism of organic nitrogen compounds and small molecules, modification of macromolecules, phosphorylation, and recombination (García-Ulloa et al. 2020). Indeed, both phosphorylation and recombination play a role in environmental stress response (Stock et al. 1989; Sutton et al. 2000; Lipa and Janczarek 2020). An increase in the small-molecule metabolism enables metabolic pathways useful in environments with a high availability of nutrients (Cases et al. 2003) or conditions of high competition (Torsvik et al. 2002), both of which happened in the disturbed Laguna Intermedia (Ponce-Soto et al. 2015; De Anda et al. 2018).

Changes in nutrient concentrations and availability due to water fluctuations and resulting massive microbial mortality (Šťovíček et al. 2017), likely selected for individuals that could use molecules previously unavailable or scarce in the oligotrophic state of the system. Additionally, the increase by 42.8% of genes with transport functions, particularly of organic substrates, further supports this hypothesis.

Pseudomonas otitidis lost genes involved in DNA and cellular metabolic process, biosynthesis of cellular macromolecules and nucleobase-containing compounds, and regulation of cellular process (García-Ulloa et al. 2020). Gene loss in bacteria is known to be an adaptive mechanism that removes the metabolic burden of genes no longer required for survival in a particular environmental context (Hottes et al. 2013). Loss of biosynthetic genes correlates with the gain of small-molecule metabolism genes, and both suggest a higher availability of metabolites in the environment (Morris et al. 2012). Also, alternate metabolic pathways that emerge in new environments benefit from the loss of regulatory genes (Albalat and Cañestro 2016).

Interestingly, the recombination rate also increased, pointing to its importance in the adaptive response of *P. otitidis* undergoing evolutionary rescue, as previously proposed by Uecker and Hermisson (2016).

In summary, as nutrients increased and were more available, *P. otitidis* apparently evolved to be able to pick a portion of them more efficiently from the environment, instead of having to synthesize them by itself, which may have been a more costly but necessary strategy in the previous oligotrophic state of the Laguna Intermedia from the Churince system.

9.6.5 All for Nothing? The Apparent Local Extinction of **Pseudomonas** *from Churince*

Despite subsequent routinely samplings, no pseudomonad was found after the 2015 desiccation event. In fact, 2016 was the first time ever that no pseudomonad was isolated from the system. Instead, numerous colonies of an environmental *Vibrio cholerae*, never seen before in Churince, were isolated with the same Pseudomonas Isolation Agar medium used for previous *Pseudomonas* samplings. This finding suggested a shift in the local bacterial community, which appears to have played a role in *P. otitidis* extinction.

We are currently studying the ecological niches of *P. otitidis* and *V. cholerae* in terms of metabolic spectrum and the ecological interactions between different environmental conditions to assess the role of competition in the observed outcome. However, given that *P. otitidis* of Laguna Intermedia was a free-living generalist bacterium, why would a community shift carry such drastic negative consequences on this lineage?

Evolutionary rescue implies an increase of an advantageous genetic variant (or a small subset of variants) in response to strong environmental stress, which usually involves the elimination of additional genetic variation that may provide resistance to further stressors (Carlson et al. 2014). This acts as a double-edged sword; on the short-term, the population can overcome the new stress, but on the medium to long term, standing genetic variation may not be enough to resist additional stressors or adapt to further changes. In other words, evolutionary rescue can produce specialization very rapidly. On 2016, *P. otitidis* may have reached a point of no return, on which smaller or previously non-harmful changes had a stronger impact on its fitness and, alongside an increasingly fluctuating environment, likely lead to its local extinction.

9.7 Case 2. *Bacillus coahuilensis* from Laguna Grande

9.7.1 The Long Search for **B. coahuilensis** *Strains*

Bacillus coahuilensis was first collected in August 2003, when thermoresistant strains were sampled in ten different sites of surface water samples along the Churince system (Cerritos et al. 2011). Of 417 thermoresistant isolates, three corresponded to what was later described as *B. coahuilensis* (one from site m4 (strain

Table 9.1 History of the isolation of *B. coahuilensis* strains

Sampling date	*B. coahuilensis* strains	Number of *Bacillus* isolates	Sampling site	Sample treatment	Reference
2003	m2–6, m2–9, m4–4	400	Laguna Grande, Churince	HT	Cerritos et al. (2008)
2003	P1.43	100	Pond, Churince	HT	Cerritos et al. (2008)
2007	None	450	From the Spring to the exit at Laguna Intermedia Churince	HT	Tapia-Torres et al. (2016); Rodríguez-Torres et al. (2017)
2011	CH_OCT_2011_15 CH_OCT_2011_10 CH_OCT_2011_9	89	Laguna Intermedia LI8, Churince	DP HT DP	Unpublished
2012	None	108	From the Spring to the exit at Laguna Intermedia Churince	HT and DP	Unpublished
2012	CH_Microcosm_51	57	Laguna Intermedia Churince	HT	Unpublished
2014	None	80	Core from Laguna Intermedia, site 7, Churince	HT and DP	Unpublished
2018	None	236	Archean Domes Pozas Azules	HT and DP	Unpublished

Heat treatment (HT) 80 °C 30 min or direct plating (DP) on Marine Medium agar

m4-4) and two from site m2 (strains m2–6 and m2–9) in Laguna Grande) (Cerritos et al. 2008) (Table 9.1).

In 2007, 450 more isolates were collected and later characterized as belonging to the *Bacillus* genus, including the cosmopolitan *B. subtilis sensu lato*, *B. cereus sensu lato*, as well as different groups of marine-related *Bacillus*, such as *B. horikoshii*, *B. vietnamensis*, and *B. aquimaris*. We did not recover, however, any *B. coahuilensis* strain (Pérez-Gutiérrez et al. 2013).

Four years later, in 2011, three new *B. coahuilensis* strains were sampled from a site downstream Laguna Intermedia (Table 9.1). One more isolate was collected on 2012 while carrying out a microcosm experiment (Table 9.1).

In an additional collection from Pozas Azules, another isolate of *B. coahuilensis* was obtained (Table 9.1). From this point on, numerous samplings and about 2000 *Bacillus* isolates have been obtained and identified by their 16S rRNA gene sequence. Many new *Bacillus* species were uncovered (Souza et al. 2018b). We invariably found isolates that belong to the same *Bacillus* taxonomic groups: *B. subtilis sensu lato*, *B. cereus sensu lato*, *B. horikoshii*, and a few aquatic *Bacillus* species, even in Pozas Azules (Tapia-Torres et al. 2016; Rodríguez-Torres et al. 2017). One first conclusion from this series of samplings is that *B. coahuilensis*, compared to most other *Bacillus* species from Cuatro Ciénegas, constitutes a rare species.

Bacillus coahuilensis did not appear in the soil sampling from Pozas Azules nor the Archean Domes samplings, supporting the idea that it is not a cosmopolitan *Bacillus* and has a rather narrow niche.

9.7.2 The Genomic Adaptation of B. coahuilensis

The genome of the *B. coahuilensis* m4–4 strain provided information on genes that seemed to reflect the adaptation of an ancient marine bacterium to a novel environment, providing support to a "marine isolation origin hypothesis" that is consistent with the geologic history of Cuatro Ciénegas (Alcaraz et al. 2008). With 3.35 megabases, this was the smallest genome of a *Bacillus* species so far assembled and provided insights into the origin, evolution, and adaptations of *B. coahuilensis* to the Cuatro Ciénegas environment. Their genomic adaptations include the acquisition through horizontal gene transfer of genes involved in efficient phosphorous utilization and highlight environmental tolerance (Alcaraz et al. 2008).

We also sequenced two other *B. coahuilensis* isolates (Gómez-Lunar et al. 2016), finding several auxotrophies that revealed them to be specialists dependent on the community for survival. To the previous conclusion of *B. coahuilensis* having a small population size, we can add that it may have a low physiological tolerance and thus be highly sensitive to environmental changes and, thus, vulnerable to extinction.

9.7.3 Interactions Among Bacillus *Strains from Cuatro Ciénegas*

Antagonism assays were conducted between 78 thermoresistant isolates, of which 72 were *Bacillus* spp. although *B. coahuilensis* was not part of this experiments. We obtained a detailed description of a network with hierarchical structure that exhibited properties that resembled a food chain, where the different *Bacillus* taxonomic groups occupied specific positions in the network. Interestingly, aquatic *Bacillus* species always occupy the lowest position, being in all cases the most vulnerable to killing by antagonist *Bacillus* (Pérez-Gutiérrez et al. 2013). As a marine *Bacillus*, *B. coahuilensisis* also susceptible to antagonism (unpublished data), and thus, its numbers can also decline through biotic interactions.

Further modelling of interactions based on antagonism information using a computational cell automaton approach showed that stability occurred only in a structured environment, but perturbations that allowed free encounters led the aquatic *Bacillus* to extinction (Zapién-Campos et al. 2015).

9.8 Concluding Remarks

Both *B. coahuilensis* and evolutionary rescued *P. otitidis* seem to possess species traits that correlate with being more vulnerable to extinction:

1. Rarity, either as a result of a very small geographic range or having a low population density on a larger range (Courchamp et al. 2006; Fontaine et al. 2007).
2. Lacking the capacity to survive environmental changes or not evolving the necessary adaptations to endure them (Colles et al. 2009; Day et al. 2016); this includes becoming less flexible (more specialized) in a changing environment, as seen in *P. otitidis* (García-Ulloa et al. 2020).
3. Being easily antagonized by closely related species and unable to withstand the competition (Hurtado-Bautista et al. 2021).

Alteration of the Churince system seems to have exceeded the physiological tolerances of both *B. coahuilensis* and *P. otitidis* to changes in pH, salinity, and in community structure that probably increases competition.

The model of extinction of Pimm et al. (1995) as a “cookie cutter on a not well mixed dough” seems to apply well to Cuatro Ciénegas, where organisms are not evenly distributed and are highly vulnerable to being “cut out” if their environment is destroyed, as seen in the Churince system.

The microbiota of Cuatro Ciénegas is highly vulnerable, and as water bodies progressively dry, the different patches that contain unique endemic life can be easily disturbed, causing the extinction of many of the highly specialized and low abundance taxa that are key for the dynamics of the community (Sánchez-Pérez et al. 2020).

This patchy local extinction is already happening in Cuatro Ciénegas with fishes and turtles (Gaytan et al. 2020), and now this study of *P. otitidis* and *B. coahuilensis* is a glimpse that we believe is also happening with many still non-described or poorly known bacteria species and lineages in the valley.

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Chapter 10
Children Can Save the World: CBTa 22, Rural High School as a Social Experiment for a Sustainable Future

Hector Fernando Arocha-Garza and Andrés Espinosa Montes

10.1 The Beginnings for the Conservation of This Marvelous Place

The story and the way for the conservation of Cuatro Ciénegas Valley began in 1999 when Valeria Souza and Luis Eguiarte were invited by Wendell L. Minckley to participate in the investigations that were taking place in the area. At that moment new species of turtles and fish were already described, but, nevertheless, the expertise of these enthusiastic Mexican scientists was not the organisms that were seen by the naked eye, because they were dedicated to the study of microscopic organisms. At this moment, when they arrived to the ponds and saw for the first time their beautiful turquoise waters and how innumerable endemic species lived there, and the marine snails laying at the bottom of the ponds, Valeria Souza mentioned—"My heart leaped for joy"—in her own words, and they both accepted the big challenge. Since then, they have been studying the microbial populations of Cuatro Ciénegas. As the years passed, it was their love for the place that has kept the secrets of the origin of life increasing constantly.

The important discoveries of this amazing place were also constantly increasing so many other collaborators and friends were joining to this adventure, and several years later, Valeria Souza, Luis Eguiarte, and Gabriela Olmedo with many other scientists realized that doing research and sharing the information were not enough for the adoption of an ecological consciousness for the valley's preservation. Thus, they decided to focus their efforts to gain awareness of the environmental

H. F. Arocha-Garza (✉)
Genesis 4C, Cuatro Ciénegas de Carranza, Coahuila, México
e-mail: harocha@genesis4c.mx

A. Espinosa Montes
Plan Cuatro Ciénegas 2040, Cuatro Ciénegas de Carranza, Coahuila, México

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conservation of the new generations. Since 2004, Valeria and Luis started introducing the high school students to basic environmental concepts through courses and workshops, they were invited by some teachers, and their goal was to increase their interest for science and the conservation of the Cuatro Ciénegas wetlands. The high school is the Centro Bachillerato Tecnológico Agropecuario 22 (CBTa 22). This is the only high school on the county, and, as it names explains in Spanish, its idea is not only to teach basic curriculum to teenagers but also to give them a degree as technicians in agriculture and animal husbandry. Therefore, it is a keystone place to show environmental management and sustainable water use in the desert. Later, in 2007 they got funding to expand this awareness to kindergartens and elementary students with the help of Fundación LALA and the leadership of Liliana Riva Palacio with ConcentrArte, a nonprofit association, which began promoting workshops aimed at raising awareness among young children on the environment (Fig. 10.1). Gabriela Olmedo joined this education effort with great enthusiasm since 2007.

Since most of the students of the CBTa's are from rural families, and their parents are the owners of the land, this group of scientists was extremely interested in promoting environmental education at CBTa's 22. It is paramount to teach them about the importance of taking care of water, restoring the soils, and using less chemicals in agriculture. Besides that, the scientists showed to the students the importance of stromatolites, the oldest evidence of life; they explained to them environmental microbiology techniques to check the health of the aquatic community using glass slides and how to use the microscope to analyze microbial diversity.

Fig. 10.1 ConcentrArte conducting educational programs with the Cuatro Ciénegas' community

They also taught the Cuatro Ciénegas' community how to establish mesocosms to better comprehend the effects of global change in these amazingly diverse microbes. Years passed and all these efforts started giving results, and not only the students became interested, so finally most of the population developed a collective community awareness. Finally, the Cuatro Ciénegas population understood the importance of this place. One of the objectives was becoming a reality; the inhabitants of Cuatro Ciénegas were transformed into the valley's keepers.

It was in spring 2012 that the unbelievable actually happened, with the help of the Universidad Nacional Autónoma de México (UNAM), Centro de Investigación y de Estudios Avanzados del IPN (CINVESTAV), Fundación Carlos Slim, and Fundación LALA: a molecular biology laboratory was built for the first time in a public high school in México (Fig. 10.2), opening research opportunities to the local students, guided by professional teachers and scientists. Many alumni have passed through the laboratory validating that this is a successful project, and it has been an inspiration for many to take the pathway in science studies. By clearly understanding the uniqueness of this oasis, local graduates have found the tools for making the best and most informed decisions to manage the conservation of Cuatro Ciénegas Basin.

Fig. 10.2 CBTa 22 students having, for the first time, the opportunity for doing scientific research, acquiring awareness of the importance of the ecosystem and becoming the change makers for conservation of the natural protected area

10.2 Plan Cuatro Ciénegas 2040: The Dream

Dreams are important because they inspire and give hope and purpose, but to have a real impact in the world, dreaming is not enough. We must combine dreaming with actions. Back in 2016, a group of people from Cuatro Ciénegas had an ambitious dream, to improve the living conditions of every single family from the town, giving them the best opportunities for quality education and family care. They had the dream of transforming the community into fully realized persons, especially its new generations.

To make this dream a reality, they realized the importance of having a plan, so in 2016 the Plan Cuatro Ciénegas 2040 was inaugurated as a long-term plan composed of concrete action steps to achieve the education opportunities for the local children. With a Home Visiting Model, Plan 2040 offered a planned sequence of critical topics to transform learning outcomes at just the right time for each family (Fig. 10.3).

Plan 2040, in collaboration with Rochat University and Genesis 4C, Cuatro Ciénegas' families were provided a systematic approach with in-depth information on a broad range of topics for the conservation of the zone's biodiversity.

Because early childhood is the time for rapid and extensive development, this plan provides opportunities for prevention and intervention since the early beginning of life. A key factor for decision-making and investments in ecosystem care promotion is building capacities of parents and communities in their children's education. Advances in neuroscience, molecular biology, and genomics give us a better understanding of how healthy development in the early years provides the building blocks for educational achievement and responsible citizenship for the next generation (Center on the Developing Child Harvard University 2010). It is incredibly important to support children and families during this critical stage to ensure the sustainability of the Cuatro Ciénegas ecosystems.

Can children save the world? The large effects seen at Cuatro Ciénegas high-quality programs and intervention are not due to magic; they are based on high-quality schooling programs especially at the local high school CBTa 22 where the molecular biology laboratory available resources have generated the capacities for a substantial environmental program where sustainable agriculture and understanding of the uniqueness of this oasis along with its stewardship are at the center of this effort.

During more than 3 years of the process of making these dreams come true, Plan 2040 learned some key lessons. The first and most important one is that the best way to preserve this community heritage, specially the amazing biodiversity of Cuatro Ciénegas, is increasing ways to inform about the ecosystem's richness. Environmental education is defined as "a learning process in which individuals gain awareness of the environment, acquire knowledge, skills, values, and experiences, which will subsequently enable them to act—individually and collectively—to solve environmental problems" (UNESCO 1978). The foundations of the conservation of Cuatro Ciénegas are built by incorporating environmental education into the community from early childhood within the school curricula and the families' education

Fig. 10.3 Plan Cuatro Ciénegas 2040 supporting the community through an accompaniment program with the help of volunteers doing home-based educational visits and early stimulation classes

programs. This needs to start early by introducing awareness of how environmental conservation is a must for a society involved in creating a brighter future for its children. Beginning in these early years is transformational because this is the most important stage in a child learning to form attitudes that will remain in their personality and in how they act toward the world around them. There are many potential benefits from children interacting firsthand with nature, for exploring positive learning experiences and for increasing awareness and knowledge of the local biodiversity. This is the best link to connect knowledge with real influencing behaviors that contribute to environment conservation.

Community involvement is critical. Commitment and responsibility for the promotion of education and development of the children and young people, such as the enforcement of legalization and regulations for the preservation of the places and species, are essential. "Just as children develop in an environment of relationships, families function within a physical and social environment that is influenced by the conditions and capacities of the communities in which they live" (Center on the Developing Child Harvard University 2010). Creative new strategies for community-wide intervention represent a vital contribution to the town's ecosystem and for the preservation of the environment.

Social initiatives that promote the evolving values suggest a restructuring of community behavior in which responsible use and recycling of water resources helps to develop a rational ecosystem preservation. To be able to reach each of the inhabitants and visitors of Cuatro Ciénegas, it is crucial to have a fully committed space for generating and sharing the knowledge of this unique place.

10.3 Unifying Efforts: Genesis 4C, a Museum-Laboratory

Years of effort and big changes happened; scientists, entrepreneurs, teachers, foundations, and many citizens worked from different sides to promote environmental education and the conservation of the natural protected areas of Cuatro Ciénegas. It was in January 2020 that all this efforts brought to life the idea of Genesis 4C, an extended project of Plan Cuatro Ciénegas 2040, a museum with a laboratory dedicated to bioprospecting with the mission of "being the most advanced education and biotechnology research international center dedicated to the diversity of the endemic species of Cuatro Ciénegas Valley, with the target of an integral vision of human ecology and to give support to Plan Cuatro Ciénegas 2040." With this project local inhabitants and visitors will have the opportunity to live an educational experience learning the origins of the universe, Earth's formation, the origins of life, and the contributions to science that have been generated in Cuatro Ciénegas during more than 50 years of research. They will also be able to visit a laboratory where local scientists and students will work in the development of biotechnological products using the isolated microorganisms of the area applicable in agriculture, industry, and health following the Nagoya Protocol (2010) to achieve a sustainable future, and the revenues will be used to help the community's most important needs.

Genesis 4C will be the union point, the bond that was missing to finally preserve one of the most important biodiversity hotspots of the planet (Souza et al. 2018), offering the inhabitants of this small town the tools needed to understand and to generate awareness of the place that keeps the secrets of the diversification of life.

A better understanding guides us to preservation. Now we are convinced that together we will achieve it!

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Chapter 11
Conservation of the Most Diverse Oasis of the World and the Future of Our Path in the Deserts: Lessons from Cuatro Ciénegas to the World

Valeria Souza, Gabriela Olmedo-Alvarez, and Luis E. Eguiarte

11.1 The Past

As this book has shown, water in the desert and other arid and semiarid environments is both a gift and a curse. In an oasis, water is a gift of life, and its mere name conjures fantastic stories, places of gathering for thirsty wildlife (both local and migratory) and tired travellers, as well as the home of civilizations that vanished when the water disappeared. However, it is also a curse, given human ambition to conquer and use all the resources, water included, to exploit what we deem as a free recourse—even when it is scarce—to grow and develop what does not belong to the arid landscape.

We, modern people, forget that water was sacred for all ancient civilizations. This is no mystery: water is literally life. As Alberto Búrquez explained in Chap. 1 of this book, there has been an ancient fascination with the deserts, their landscape, and their beauty. In the second chapter, archaeologist Yuri de la Rosa told us about how ancient hunter and gatherers that populated the Chihuahuan desert revered the oasis of Cuatro Ciénegas, painting stories of water and stars in the caves around the valley. In Chaps. 3 and 4 we can see how these ancient dwellers of the desert were ferocious fighters and how the equally ferocious colonial Spaniards found them so hard to conquer. Nevertheless, by the end of the colonial period, there was already

V. Souza (✉) · L. E. Eguiarte
Departamento de Ecología Evolutiva, Instituto de Ecología, Universidad Nacional Autónoma de México (UNAM), México City, Mexico
e-mail: souza@unam.mx

G. Olmedo-Alvarez
Laboratorio de Bacteriología Molecular y Ecología Microbiana, Departamento de Ingeniería Genética, CINVESTAV – Unidad Irapuato, Irapuato, Mexico

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a small Spanish settlement in the Cuatro Ciénegas Basin (CCB). The water started to be managed to use it for the orchards and the town.

During the convoluted Mexican nineteenth century, Cuatro Ciénegas settlements, particularly the town with this same name, grew and developed, thanks to the ample water availability. Later it was home to intellectuals, military, and also entrepreneurs during the Mexican Revolution. Some of them played critical roles, including president Venustiano Carranza, who was born there in 1859.

According to Chap. 6 in this book (Leal et al. 2021), the environmental problems of Cuatro Ciénegas started with the early attempts to drain the basin through two canals that exported the water toward the east of CCB (Fig. 11.1). The first canal is called canal "Saca Salada" and was built primitively in 1902 with the explicit purpose of draining the wetland and allowing agricultural development. Saca Salada canal was much "improved" in the 1970s by making it wider and deeper. It is estimated that this canal now drains ca. 90% of the superficial water (1500 L/s) for ca. 80 km, toward the city of Monclova along with another canal, Santa Tecla (Fig. 11.1). Santa Tecla drains the water out of the CCB since ca. 1966, even if it has a smaller capacity (250 L/s). It has a length of ca. 53 km, crossing most of the east side of the basin and joining Saca Salada canal in its exit from the CCB.

Another canal was built around 1966, to conduct the water from the main spring, La Becerra, toward the Ejido de Cuatro Ciénegas (Fig. 11.1). Canal La Becerra has

Fig. 11.1 The different canals that have drained Cuatro Ciénegas

a capacity of 600 L/s, and its construction rapidly drained the wetland of El Garabatal (Minckley 1992).

Before the construction of these draining canals, wheat, vineyards, and pecan trees were productive options along with goats, cows, and horses in the valley. We strongly recommend the reading of *All the Pretty Horses* by Cormac McCarthy (1992) to have a feeling for this savage land before the canals where built. Minckley's (1992) paper depicts interesting pictures taken before the canals in the 1960s, and the wetland looked almost intact, including a river coming down from the valley of Ocampo-Calaveras, Río del Cañon, that no longer exist (Fig. 11.1). This river propelled the mills that produced flour for the local people. Less than 2000 people lived in the Cuatro Ciénegas village in those years, and the locals enjoyed the "pozas" (natural pools of spring water) for recreation and fished the large populations of endemic fish.

Thirty years later, Minckley in 1992 reported a totally different town, "with no more vineyards, no more wheat and flour production, dying pecan trees and drying wetlands. The main road from Monclova to Torreon crosses the basin, and now dry stromatolites are common. As the canals and the deep wells drained the wetland and interrupted the recharge of the aquifer, while alfalfa fields are everywhere within CCB and in the neighboring valleys." Here Minckley (1992) tells us the tragedy of the dead microbial communities (stromatolites) as a passing reference; however, these microbial communities are relicts of ancient oceans that survived at CCB all the known extinctions but, sadly, are not surviving the Anthropocene and the aquifer overexploitation (Souza and Eguiarte 2018). We have to remember that alfalfa (*M. sativa*) is a forage plant, native to Asia, introduced to America during the Spanish conquest to feed cattle and is one of the thirstiest cultivars, and in the desert up to 10,000 L of water is needed to irrigate just a square meter of alfalfa, for a mere kilogram of produce. The water utilization efficiency for harvested yield of alfalfa hay with 10–15% moisture is 1–2.0 kg/m^3 after the first year (FAO, http://www.fao.org/land-water/databases-and-software/crop-information/alfalfa/en/), and its moisture content as fresh green matter is about 80% (Saeed and El-Nadi 1997).

Therefore, given this tragedy of the commons (Hardin 1968), what does the law on water management says about conservation and regulation in México? In few words, the answer is nothing or very little, as explained in Chap. 5 by Teresa Souza. The section of the Mexican federal government in charge of water administration and use regulation, the National Water Commission (CONAGUA), seems to be prone to build dams and canals. It has an uncanny talent for selling water rights but not on checking on them. CONAGUA, particularly, did not even acknowledge some international treaties in the past, despite these having been signed and ratified by México, such as the Wetlands of International Importance, better known as RAMSAR (https://www.ramsar.org), where CCB wetlands are included as having high importance for conservation and water management.

This was a tragedy that kept on getting worse in CCB, despite the fact that it was declared protected area in 1994 (CONANP 2020, https://www.gob.mx/conanp), just after Minckley's plead to preserve this amazingly diverse oasis became public in México. What Minckley did not know but suspected, was CONAGUA's legendary corruption and that the lack of regulation of water usage in the desert was not going to change easily. So the endemic aquatic species became protected under the umbrella of Area de Protección de Flora y Fauna (APFF) de Cuatro Cienegas (Diario Oficial 07/11/1994; http://www.dof.gob.mx/nota_detalle.php?codigo=4759233&fecha=07/11/1994). Paradoxically, at least to us though not to the federal politicians and bureaucrats of that era, the drainage of the wetland was not stopped.

In the 1990s, the pozas, rivers, and lagoons in CCB started to reduce their water levels, some of them getting to be critically low, endangering the micro-endemic aquatic life they nurture in their distinctively crystalline waters. In desperation, Minckley, who was a professor at the Arizona State University (ASU), turned to a brand new program of astrobiology of NASA, the Astrobiology Institute (NAI) founded in 1998, which made a call to apply for grants for teams to study different models of early Earth, as well as planetology, in particular to explore the question: Is there life beyond our planet?

Minckley, a fish expert that had worked in the natural history of CCB from 1958, had the intuition that the conditions of ancient Earth had been preserved at their azure blue pozas rich in microbial mats and in particular stromatolites (ancestral complex microbial communities abundant in the Proterozoic) (Minckley 1969). Given these pozas are also very poor in nutrients, he suggested that the ancient Mars planet had similar conditions and minerals than CCB. Minckley convinced Jim Elser to work together on an astrobiology grant to study this special oasis in Northern México. Jim, a limnologist, and also an expert in phosphorous (P), was then a young professor from ASU. NAI grant first review was mixed, the site looked promising, but they needed evolutionary microbiologists in their team, and they also needed Mexican scientist, since CCB was in México and required for its study sampling permits. Minckley was delighted, as he wanted to involve Mexican scientists in order to "pass the task" of conservation of this Mexican paradise to the nationals. That is how NASA found us, Luis Eguiarte and Valeria Souza. We travelled for the first time in 1999 to the site and became in love with its beauty and all the potential mysteries of life in these extremely oligotrophic pools (very low P) (Souza et al. 2018a).

Twenty years later we found that Minckley's "hunch" of the existence of a hydrothermal vent from the Panthalassa Ocean of the Jurassic period trapped in this oasis, which explained its marine like conditions, was not farfetched. Minckley got almost everything right, except the dates, as apparently, this oasis that stored the history of bacterial life in this planet is even older (Souza et al. 2018b). We believe now that that the Sierra de San Marcos y Pinos (Figs. 11.1 and 11.2), which forms at the center of CCB an arrow-shaped magnificent uplift from the Cretaceous period, stored in its depths ancient microbes, along with ancient ocean conditions. In our hypothesis, the water cycle between the wetland and the deep aquifer is propelled by a magmatic anomaly (Wolaver et al. 2013) that moves water and life from a deep mineral biogeochemical cycle to a "sun-powered cycle," as the water moves toward the sun-drenched pozas, and microbes organize themselves in microbial mats (Fig. 11.3) and stromatolites.

Fig. 11.2 Cuatro Ciénegas Basin and the Sierra de San Marcos y Pinos from the height of the Sierra la Madera (photo David Jaramillo)

Fig. 11.3 A microbial mat from the hypersaline site "Archean domes" at the ranch Pozas Azules. All of life's functions are in between Valeria Souza's fingertips. (Photo Miguel de la Cueva)

In these complex microbial communities, life assembled, since the beginning, all the gears of the biogeochemical cycles in a compact cohesive way (Souza and Eguiarte 2018). The bottom black layer is the most ancient; it is anoxic and chemolithotroph. In this layer we have the methanogens that fix CO_2 from the atmosphere, making methane and small sugars that fermenting heterotrophs consume. The next layer is also anoxic and depends on sulfur, while the third constitutes the layer of ancient anoxic photosynthesis, where the purple sulfur and non-sulfur bacteria assemble the photosystem II, while the green sulfur and non-sulfur bacteria assemble the photosystem I (Madiga and Jung 2009). These bacteria, however, were already connected to cyanobacteria (Baumgartner et al. 2006). Cyanobacteria live in the uppermost layer and have both photosystem I and II in tandem, as well as more powerful pigments that allow them to capture the more energetic photons and break the surrounding water and in the process liberating oxygen. It is this process that changed Earth's atmosphere and oceans from anoxic orange to oxygen-rich blue (Govindjee and Shevela 2011). We are here as humans reflecting on the history of life on Earth, thanks to the concerted work of these humble microbial communities for billions of years.

Stromatolites and microbial mats are the first fossilized evidence of life on Earth (Souza and Eguiarte 2018). They dominated the ancient oceans till the extremely low phosphorous conditions of those oceans changed with the second snowball Earth event (Souza and Eguiarte 2018). The glacier activity in the Cryogenian period, because of its extreme cold conditions, eroded the continental shelf, liberating large quantities of phosphate that allowed metazoan evolution (Filippelli 2008; Planavsky et al. 2010; Brocks et al. 2017). In this new world rich in phosphorous, the slow-growth communities did not stand a chance. However, they survived in sites where the conditions were extreme enough to prevent growth of algae and herbivores and where there was a deep source of sulfur. CCB is still one such sites, and when the diversity of these oasis' communities is compared to other sites with stromatolites, we observe that microbial and viral communities in CCB are much more diverse and unique (Souza et al. 2018b; Taboada et al. 2018). The preservation of CCB stromatolites through stopping the aquifer overexploitation of the Anthropocene is therefore paramount.

The hydrological system of El Churince (Fig. 11.1) succumbed as a result of the aquifer overexploitation for the irrigation of alfalfa crops. In Chap. 7 of this book, Evan Carson tells us the sad story, including the loss in fish species and other aquatic animals after the dry out of the Churince system due to the aquifer overexploitation. A major disturbance that also impacted plants and, no doubt, microorganisms. Hopefully, the ancient microbes are still there, out of reach for us, hidden in the sierra depths and have followed the water. What is more disturbing is that the disappearance of Churince was a tragedy long foreseen, as indicated above. This overexploitation of water is not new; it has been occurring since the 1960s both by canals that drain the superficial water and through deep wells that drain the deep layers, as described in Chap. 6 by Oscar Leal. These deep wells increased in numbers in the late 1990s both in the valley of Ocampo, north of CCB, and in 2002 in the valley of Hundido, south of CCB (Fig. 11.1). The water of these three valleys is connected by tectonic faults that move the deep water (Souza et al. 2006). Therefore, the increase in the exploitation of the water in these three valleys sharply decreased the level of the water table.

In recent years, we obtained an enormous amount of data on the Churince system. With a very large team of researchers, we have been following the path of the superficial water and the biodiversity that it sustained, making the Churince system the best studied site in México (this book series by Springer is a testimony). Between 2002 and 2006, we lost the main lagoon of the Churince system (Souza et al. 2008), a large evaporating lagoon that used to measure 2 km in diameter (Fig. 11.4a and b),

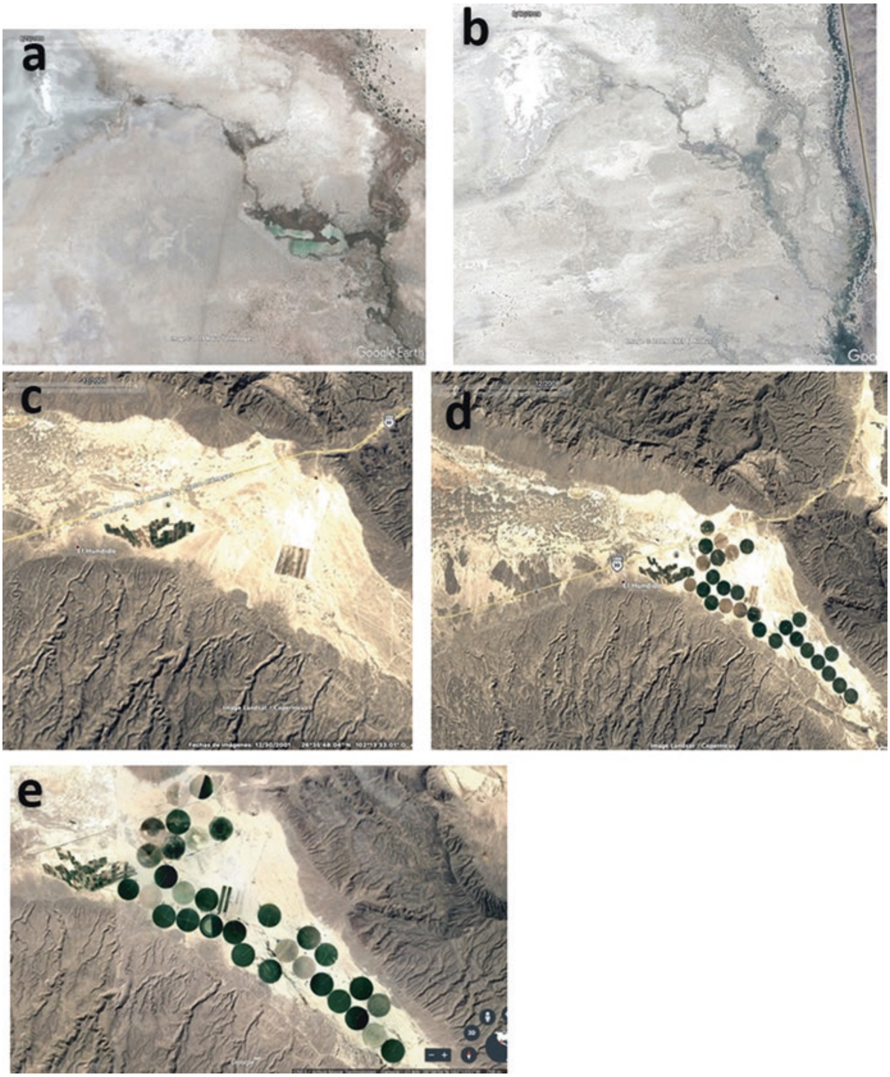

Fig. 11.4 (**a**) View of the Churince water system in 2009 and (**b**) 2019. (**c**) View of the of the alfalfa fields at Los Hundidos agricultural development, in 2001, (**d**) Los Hundidos in 2008, and (**e**) Los Hundidos in 2019. Google Earth images

and then the slightly deeper Intermedia lagoon (Fig. 11.1) started to lose its water, reaching a dramatic moment in the summer of 2011, when the levels got so low that there was a massive death of fishes, covering the sediment with a grim layer of corpses that glowed green due to the bacterial growth on top of them. The system got a respite by the end of 2012, when the canal La Becerra was closed to prevent further decay, and the system started to recover in summer 2013 (De Anda et al. 2018). Sadly, it was a just a mirage, as the canal got reopened by the ranchers in early 2014, and the system died completely by 2016 (Fig. 11.4b). At the same time, the number of alfalfa "rondines" (as the central pivot irrigation systems are locally called) in the nearby Hundido valley increased from almost nothing to a large density of alfalfa plots (Fig. 11.4c–e). It is fascinating that the riparian plants had predicted the decay of the system, before we could see it, as Irene Pisanty and colleagues describe in Chap. 8.

11.2 The Present

We have been working at understanding CCB's extraordinary biodiversity for the last 20 years (see other books from this collection by Springer), and 18 of those years trying to preserve the wetland from dying. It has been a long battle against powerful companies and persons, federal and state governments, and lame local action by the county authorities, but mostly it has been a battle against ignorance, fear, and poverty.

In order to try to win such a battle, we decided to fight it along with the owners of the future, the children from CCB. Since 2004 we have engaged with the local high school to share our knowledge with students and teachers, design experiments, and take the kids outdoors to see the wetland (as most of them had never visited the pozas). In 2011, with the support of WWF-Fundación Slim and Fundación LALA (the latter, a dairy giants that were our previous opposers, now our allies in conservation), we built a molecular biology laboratory in the CBTA22 high school. We aimed to empower the students with firsthand knowledge of the biological treasure they had in CCB and the sense of discovery that DNA can give you when finding new species and doing experiments to learn about the great biological capabilities and biotechnological potential of these invisible creatures.

Besides teaching and collaborating with teenagers and their teachers, we have been working with children from kindergarten to sixth grade. In a fantastic program of consciousness through art led by Liliana Riva Palacio and ConcentrArte, a group of artists and teachers has been working since 2007 with all the children, every year, supported by Fundación LALA. With this project, they transform everything they touch and has been transformative for the CCB society (Lobo 2009; https://www.wwf.org.mx/?208550/presentan-libro-cuatro-cienegas-la-mirada-de-sus-ninos/).

Nowadays, the students from the CBTA 22 high school travel to our labs in México City and Guanajuato to learn biotechnology. They now have a sense of duty to the ecosystem. Even more so, the CCB society is transforming because of these kids. It is impressive what knowledge, along with consciousness, can do to a small town. Actually, one of the many kids that were captivated early on by our science projects in the CBTA 22 high school was Héctor Arocha (see Chap. 10). Hector has now a Ph.D. in biotechnology, which he obtained studying the strains from Cuatro Ciénegas. Héctor, along with his family members and friends, has been leading a fantastic social program named Plan Cuatro Ciénegas 2040, determined to ensure health and education for every child and a sustainable future for CCB. Héctor is now in charge of Genesis 4C, showing the students of his former high school how to tap the genetic recourses of this unique oasis. They will be the example of the Nagoya treaty for México: the first case where the owners of the land also own the knowledge to understand and develop the potential of this extraordinary biodiversity.

However, as Oscar Leal and collaborators reminds us in Chap. 6, the overexploitation of the aquifer is extreme, and we need to do something very soon. Parts of the canal Santa Tecla are already closed, and the wetland is recharging; also, parts of canal La Becerra have been diverted to recharge the aquifer, slowly but surely. The best news of all was that by the end of 2020, the canal Saca Salada was diverted to many small lagoon systems that started to restore the river Rio Mesquites (Fig. 11.1). However, those efforts were destroyed 5th of May, 2021 by a mob of angry ranchers from outside the basin. Before that, the president of México, Andrés Manuel López Obrador promised to the country to protect the CCB wetland. Let's hope it is not too late for the wetland animals whose populations have been depleted. We suspect it won't be too late for the resilient and hyper-diverse microbiota.

11.3 The Future?

While our crystal ball is still cloudy, our hope is that CCB becomes a lesson, a survival lesson for México and the world. We are exhausting our natural resources everywhere and badly managing the most important asset of the entire world: water.

Water is the essence of life; it is, simply, what determines the possibility of life. Earth is a blue planet, the only blue planet that we know in the universe, a planet apparently full of water and oxygen. However, even if 71% of the planet is covered in water, 96.5% of it is salty ocean water. Most of the drinking water is either deep in the underground, or forming ice in glaciers and ice caps, or already more or less polluted, leaving just 0.007% available for human use. From this tiny portion of clean water, 80% is used for agriculture (Albinia 2020).

In many cases, the water used for agriculture can be reduced and optimized, in particular in the desert and arid lands. Most people in the world will soon live in water-scarce sites; therefore, it is paramount to learn how to live and produce with less water. For México, the example can be CCB.

Many things have to happen in CCB to become such an example. The CCB canals have to be finally closed, so the wetland starts to recharge. Ranchers, as part of the local society, have to learn how to feed their cattle with less water-demanding crops and implement better agricultural practices. Children and students will teach their parents that each pond and stream, each water body, is a treasure trove, relevant for the future of human society, agriculture, industry, medicine, and ecosystem functions. Both because the water is by itself priceless and also because the invisible microbes in these waters contribute to the entire planet's functions and also hold in their biochemistry innumerable possibilities.

Many things must occur to arrive at this hopeful end, but it is like "the Lorax" children book by Dr. Seuss, "Unless someone like you cares a whole awful lot, nothing is going to get better. It's not."

We believe that this series of books edited by Springer is a testimony not only of the importance and fragility of this extraordinary oasis but also an ode of love by all the scientists that have painstakingly worked to describe as fast as possible a site that was on the verge of collapse. But most importantly, to work as hard as possible to transmit our passion to transform consciences and therefore change the future for a better one. We want a valley where the rivers run and the wetland is wet, a place where children, turtles, fishes, and stromatolites can share the wetland, a world where the future for all creatures is important, because we do care a whole awful lot.

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