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Water Availability and Management in Mexico

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Preface

Water problems in Mexico have been investigated by many native scientists, several of them with a long career devoted to studies on various water topics with the aim to give proposals for decision-making politicians. Few have managed to be heard. However, in recent years, water has been the subject of exceptional attention because proposals of new laws and rules would lead to the privatization of water. This situation has provoked controversy and protests by different social sectors.

Water research is considered a priority issue in the National Council of Science and Technology (CONACYT), and there has been increasing projects aimed to solve water challenges, such as water use and reuse; water management; demand and supply scenarios; ecosystems services and risks; and water uses and governance. This book is an outgrowth of this priority.

The CONACYT Network for Water Quality and Availability (AQUANET) has promoted the edition of the present book with the partnership of other Networks' members, integrating contributions from various institutions, researchers, and organizations. Each chapter has been double-blindly peer-reviewed to guarantee scientific rigor.

AQUANET improves multidisciplinary collaboration toward: (a) Water-Quality; (b) Health and Water Nexus; (c) Remediation Technologies; (d) Water-Energy-Food Nexus; (e) Water Availability Scenarios and Climate Change; (f) Governance and Hydrological Policies; and (e) Sustainable Agricultural Practices.

The book *Water Availability and Management in Mexico* is structured in four parts. First, an introductory Chap. 1 offers a brief scenario about the current state of water in Mexico, allowing the reader a concentrated informative summary.

Part I, "Water Availability," is comprised of four chapters. Chapter 2 discusses the division of hydrologic basins in Mexico with an emphasis on its history and legal definitions. Chapter 3 examines in detail the estimation of runoff and uncertainties including the impact of climate change. Chapter 4 analyzes the general panorama of groundwater hydrogeochemical parameters due to urban areas' demands. Chapter 5 discusses the controversial issue about the hydraulic fracturing of unconventional oil and gas in Mexico, considering the impacts on water resources. Without neglecting the importance of the effects of climate change and ecosystem degradation, this section underlines the need to include case studies, with behavior patterns that could be similar in other regions of the country.

Part II, "Water Quality," includes six chapters with typical cases about the pollution problems of surface and groundwater bodies. Two chapters analyze the rivers' issues. Chapter 6 diagnoses the quality stressors in Nexapa River and Chap. 7 describes the restoration of ecological services in the Candelaria River. The next two chapters focus on groundwater. Chapter 8 describes the relationship between vulnerability and groundwater quality in Tulancingo by an original approach, and Chap. 9 studies the hydrogeochemical parameters of the Puebla aquifer, affected by strong urban demands. Special attention is paid in Chap. 10, which is devoted to the unsustainable agricultural irrigation with wastewaters from Mexico City for more than a hundred years in Mezquital Valley. Chapter 11 diagnoses the quality of wetlands around Cajititlán Lake in order to apply for a RAMSAR site that could be reproduced in other cases. The contamination problems lead to health risks, and the cases show a lack of effective law and a need for enforcement and efficient regulations.

Part III, "Water Allocation," presents various features of water use. Chapter 12 analyzes water supply for agricultural irrigation in Puebla State. Chapter 13 poses the aquaculture water use in Hidalgo State. Chapter 14 considers the estimation of and uncertainties in water resources as a recommended methodology. Chapter 15 calculates the population and tourism consumption scenarios in Baja California Sur, and Chap. 16 describes the drinking water supply system in Nuevo Leon. Scarcity is aggravated by the demographic growth, agricultural irrigation, industrial development, and commercial/services sectors.

Part IV, "Water Management and Governance," discusses approaches related to politics, social, and management of water resources. Chapter 17 concretizes ecological services of National Parks, based on good management practices. Chapter 18 focuses on the problem of water sanitation in Zacatecas, which represents the whole reality of the country. Chapter 19 demonstrates the experience of mining water recycling through collaborative results with the academic and the industry. Chapter 20 reviews the urban resilience of Mexican areas, ending with a methodological approach that could be useful for other case studies. Chapter 21 proposes natural water treatment in vegetated dishes, based on successful experiences in Mazatlan. Chapter 22 describes water management supply organizations and development of different regions in San Luis Potosi. Finally, Chap. 23 proposes a water treatment strategy adapted to the orography of Cuernavaca City, where sewage is poured to canyons as springs.

Authors and editors hope that this book will be comprehensive and helpful for students and researchers, but mostly for decision makers. The examples and proposals would be applied in other developing countries, with similar problems caused by ancient practices and lack of governance.

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The original version of the book was revised: Volume number has been corrected. The correction to the book can be found at https://doi.org/10.1007/978-3-030-24962-5_24

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Chapter 1
Water at a Glance in Mexico

Elena María Otazo-Sánchez and Amado Enrique Navarro-Frómeta

Abstract Water resources in Mexico show different scenario depending on the region, from high scarcity in the north to abundance in the south. The central to northern parts of the country are semiarid and arid regions with water stress due to agriculture, industry, and domestic demands. Pollution is a common threat by the growing industry and population, with not enough treatment plants and specific places with noticeable contamination considered as environmental breakdowns affecting health and ecosystems since decades. The government is taking care of the impairment consequences by better programs, with new public policies and a revised national water law that arise controversies in social sectors.

Keywords Mexico · Hydrologic organization · Basins · Groundwater · Water data

1.1 Introduction

Mexico deals with severe problems in water availability and contamination, as well as increased drought and flooding. The most overexploited aquifers are situated near the biggest cities, or at the north, where most arid areas occur. Considering the water availability criteria, Mexico could be divided into three regions. The southeastern part is low populated with mighty rivers, rainy climates, and precipitation values over 2000 mm/year. The central region is the most inhabited and industrialized, with more than 50% total population of the country. The North is the largest area, characterized by substantial water shortage. Central and north regions are semiarid to desertic with precipitations below 500 mm/year.

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Table 1.1 México: some relevant data

	Data	Source
Surface	1,964,375 km^2	CONAGUA (2018a)
Desertic to semiarid (%)	58.7%	SEMARNAT (2016)
Population (last survey, 2010)	112,336,538 inhab	INEGI (2013)
Population (estimated, 2015)	119,938,473 inhab	INEGI (2015)
Population in extreme poverty	9,400,000 inhab	INEGI (2015)
Political division	31 states and Mexico City	INEGI (2015)
Metropolitan areas	59	INEGI (2015)
Urban population percentage	79.9%	World_Bank (2018)
Water availability 50s	18,035 m^3/inhab	INEGI (2015)
Water availability 2006	4573 m^3/inhab	CONAGUA (2006)
Water availability 2017	3656 m^3/inhab	CONAGUA (2018a)
Renewable water 2017	451,585 hm^3	CONAGUA (2018a)
Hydrologic-administrative regions	13	CONAGUA (2018a)
Hydrologic regions	37	CONAGUA (2018a)
Hydrologic basins	757	CONAGUA (2018a)
Hydrographic basins	1471	CONAGUA (2018a)
Aquifers	653	CONAGUA (2018a)

Recent publications reviewed the water challenges in Mexico by different approaches and vast analysis (Jiménez Cisneros et al. 2010; Ackermann et al. 2015; Pacheco-Vega 2014; SEMARNAT 2016; Vélez and Saez 2011). This chapter aims to give a brief sight of the current Mexican water problems to the reader.

Table 1.1 displays some data related to social and water condition in Mexico. The water availability has been lowering since the last century, and the urban population percentage rose from 50% in 1950, 57.4% in 1968 to 79.9% in 2017 (World_Bank 2018).

For consulting detailed data, the authors recommend the National Commission for Water official Web site with exhaustive information about basins, aquifers, water quality, hydric footprint, irrigation, and water allocation, which is currently updated (CONAGUA 2018b) and the Annual Water Statistical Reports. Also, the socioeconomic and political data are compiled in the Water Atlas of Mexico (SEMARNAT and CONAGUA 2016) and (Fondo para la Comunicación y la Educación Ambiental 2018).

1.2 Water Cycle in Mexico, 2017

The water cycle of the country is shown in Fig. 1.1. Despite the positive balance, with the availability of 451.58 km^3, the scarcity in the central and northern zones is

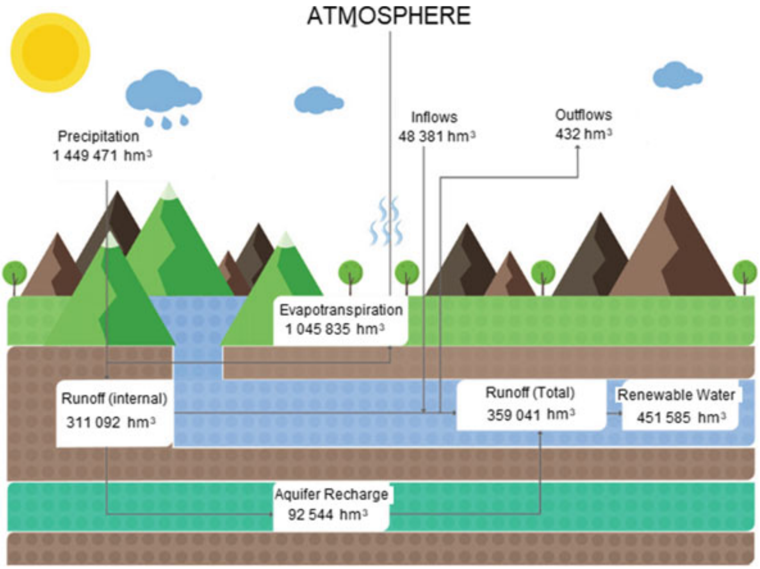

Fig. 1.1 Mean values of water cycle parameters in Mexico, 2017 (CONAGUA 2018a)

notorious. As it is well known, the water situation is local, and the country balance does not represent the problems. The water resource is shared in the north and south borders with the USA and Guatemala, respectively, which explains the importations and exportations of the balance. There have been agreements and discussions about the water use of Rio Colorado and Rio Grande basins with Texas and California, due to the scarcity of the area.

Each year, precipitation provides 1.45 billion of cubic meters whose 72.1% returns to the atmosphere by evapotranspiration, 21.5% runoff to rivers and 6.4% infiltrates naturally to aquifers recharge. The renewable clean water accounts 451,585 hm^3 (CONAGUA 2018a). Mexico is the 92nd country of the world concerning renewable water per inhabitant (3.656 m^3/inhab/year).

As it is well known, the water condition is local, and the country balance does not represent the real panorama. Some regions have as low as 144, 1019, and 1057 m^3/inhab reported for Mexico Valley, Rio Bravo, and Baja California in 2017 (CONAGUA 2018a).

1.3 The Hydrological-Administrative Regions

Since 2006, the National Commission of Water (CONAGUA) is the governmental institution designated to administrate, rule, and decide the management of water in Mexico which consequently divided the country into 13 hydrological-administrative

Fig. 1.2 Hydrological-administrative regions of Mexico (SEMARNAT and CONAGUA 2016)

regions (HAR). Each one manages and oversees the basins enclosed within through the Basin Councils, as the basic units for the administration of hydric resources.

Figure 1.2 shows the map with the location of the HARs. The HAR with plenty of water availability is represented in dark blue and the more stressed, in yellow. See the smallest region XIII in the center.

Table 1.2 displays relevant data of the HAR. The Region XIII is the most stressed because it is the highest inhabited and industrialized of Mexico; but also, it presents the smallest surface and the most affordable to the gross domestic product. In this HAR locates Mexico City, the 11th most significant urban area of the World, and the population density is high.

The largest HAR is the Río Bravo Basin, at the north with the lowest renewable water. The HAR XI presents the main renewable water value due to its high precipitation.

1.4 The Hydrological Regions

Figure 1.3 shows the map with 37 hydrological regions (HR) that compile the 731 Mexican basins, for simplifying reasons. They are defined as regional areas whose boundaries encompass similar characteristics in orography, morphology, and hydrology, and their limits do not match with the political division. A classic study of HR was reported (Cotler Ávalos 2010), and recently, the HR limits were updated by a government decree (CONAGUA 2016a).

Table 1.2 Hydrological-administrative regions of Mexico. Principal data (SEMARNAT and CONAGUA 2016)

#	HAR	Surface (km^2)	RW (hm^3/year)	P 2015 (millions inhab)	PD (hab/km^2)	RW 2015 (hm^3/inhab/year)	GDP (%)	Municipalities
I	Baja California	154,279	4958	4.45	28.8	1115	3.61	11
II	Northwest	196,326	8273	2.84	14.5	2912	2.86	78
III	North Pacific	152,007	25,596	4.51	29.7	5676	2.88	51
IV	Balsas	116,439	21,678	11.81	101.4	1836	6.14	420
V	South Pacific	82,775	30,565	5.06	61.1	6041	2.29	378
VI	Río Bravo Basin	390,440	12,352	12.3	31.5	1004	14.29	144
VII	Central North	187,621	7905	4.56	24.3	1733	4.19	78
VIII	Lerma-Santiago Pacific	192,722	35,080	24.17	125.4	1451	19.08	332
IX	North Gulf	127,064	28,124	5.28	41.6	5326	2.24	148
X	Central Gulf	102,354	95,022	10.57	103.2	8993	5.62	432
XI	South Border	99,094	144,459	7.66	77.3	18,852	4.93	137
XII	Yucatán Peninsula	139,897	29,324	4.6	32.9	6373	7.38	127
XIII	Mexican Valley	**18,229**	3442	23.19	**1272.2**	148	24.49	121
Total		1,959,248	446,777	121.01	61.8	3692	100	2457

RW Renewable water, *P* population, *PD* population density, *Pc* per capita, *GDP* gross domestic product

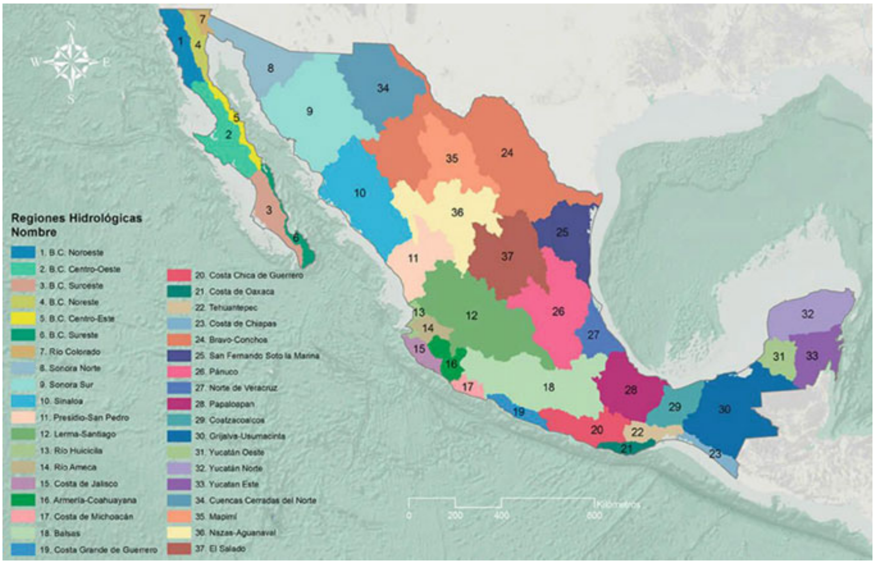

Fig. 1.3 Hydrological regions of Mexico (Para_Todo_México 2018)

The most significant runoff (103.378 hm^3/year) was reported for the HR30, which contains the most significant rivers of Mexico, the Grijalva, and Usumacinta. The most extensive is the HR24 along the Rio Bravo and Conchos, whose waters are subject of trans-boundary agreements with the USA due to the substantial agriculture demands from both countries.

The hydrological basins should not be confused with the hydrographic basins, whose boundaries are naturally limited by the precipitation runoff, defined by the elevations and comprises only surface waters. On the contrary, the hydrological basins integrate the aquifers below.

An extensive characterization of hydrographic basins was extensively described by Cotler Ávalos (2010) and this book Rentería-Guevara et al. (2019).

1.5 Groundwater

Groundwaters are essential for the socioeconomic development of Mexico, representing 38.7% of the total concessional volume for consumptive uses such as population, irrigation, and industry.

México has 653 aquifers, but 195 of them (30%) have no availability since all capacity is already allocated; 106 (16%) are overexploited, 31 (5%) are saline, and 15 (2%) present marine intrusion. Figure 1.4 shows the aquifer distribution in Mexico and its condition.

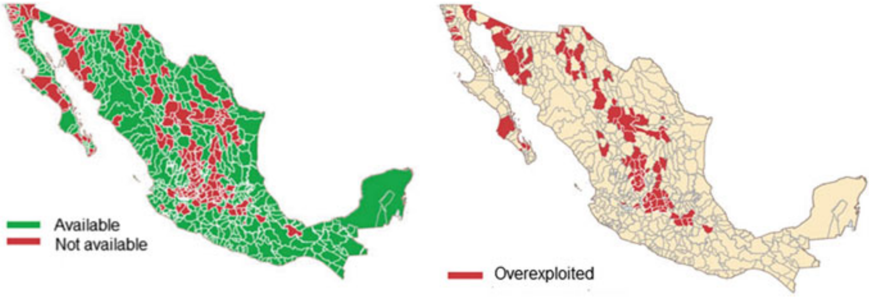

Fig. 1.4 Mexican aquifers. Over-exploited in red (CONAGUA 2018a)

The overexploited aquifers could lead to severe irreversible damage and should be prevented by injecting the treated wastewater and constructing pluvial drainages. The coastal aquifers at the Pacific shore present sea intrusion due to the intense agriculture irrigation, especially in the Baja California Peninsula (CONAGUA 2018a).

Mexico City aquifer is one of the most overexploited in the country, and it is still being harmed without any mitigation, causing the sinking of the city, in some places at the astonishing speed of 20–40 cm/year, reported for 20 years (Lesser lllades and Cortés Pérez 1998; Tortajada 2006).

Another harm of the Megacity nearness caused the overexploitation of the aquifer Cuautitlan–Pachuca, the main water supplier for economic activities, and population in the northern region of Mexico City. Its water level is increasing outflows and insufficient infiltration scenarios from 2007 (base year) to 2031. The negative impacts on the decline water levels predicted the most substantial effect due to overpumping caused by the population growth that would intensify the deficiency up to -236.29 hm^3/year (Galindo-Castillo et al. 2017).

An extensive review of the most harmed aquifers due to the overexploitation in urban areas is presented in this book (Ocampo Astudillo et al. 2019).

1.6 Surface Water

The principal rivers and ponds are shown in the map of Fig. 1.5. The high mountains and the central Mexican plateau throughout the country create two main slopes toward the Pacific and the Gulf of Mexico and few flows into lagoons.

The most important rivers are shown in Table 1.3, whose most significant flows are mainly present in the southern part of the country and slopes toward the Gulf of Mexico. Their waters are employed in hydroelectric dams and agriculture irrigation.

The largest river is the Rio Grande in the north, and the mightiest is Grijalva in the south, whose waters have been allocated to the biggest hydroelectric dams of the country.

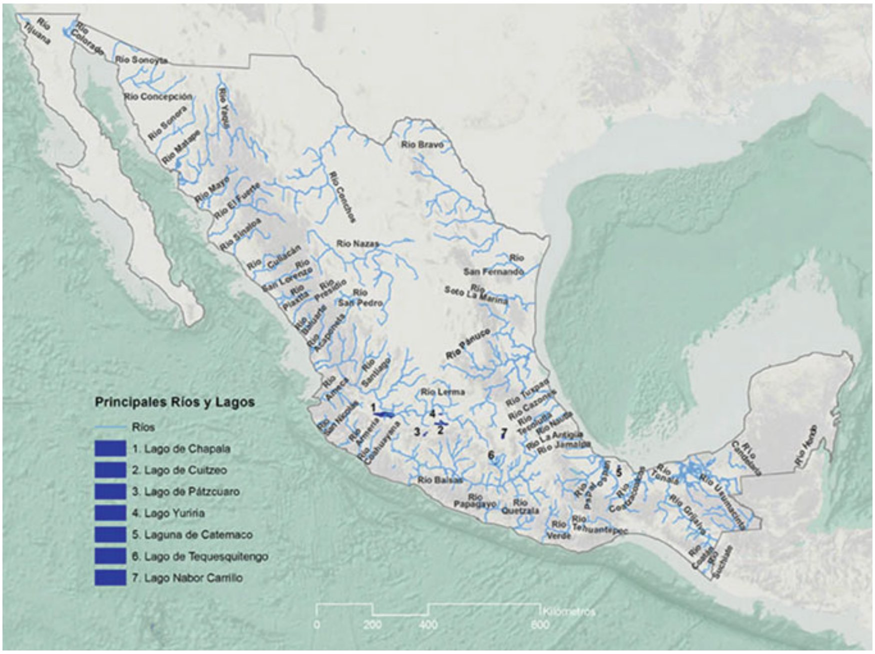

Fig. 1.5 Principal water bodies in Mexico (Para_Todo_México 2018)

Table 1.3 Most important Mexican rivers (CONAGUA 2018a)

River	Flow (hm^3/year)	Length	HAR/Slope
Grijalva Usumacinta	104,089.2	1521	XI/Gulf of Mexico
Papaloapan	42,018.3	354	X/Gulf of Mexico
Coatzacoalcos	28,717.4	325	X/Gulf of Mexico
Panuco	20,223.6	510	IX/Gulf of Mexico
Tecolutla	6126.8	375	X/Gulf of Mexico
Rio Bravo	5671.8	ND	VI/Gulf of Mexico

There are more than 5163 dams in Mexico, storing near 150,000 hm^3 water, and only 181 loads more than 103,000 hm^3. In 2014, the hydroelectric plants used 133,018 hm^3 water and generated 37.5 TWh, 14.9% of the national electric generation. The biggest Mexican hydroelectric dams are in Chiapas, which belong to the Grijalva River. The largest is the 2400-MW Manuel Moreno Torres, at the Chicoasen Dam in Chiapas, followed by La Angostura and Malpaso with 147 and 138 m high walls, respectively, and Peñitas. Other giant hydroelectric plants are located in Las Balsas Basin (HAR IV) at the Pacific slope (El Cajon, Aguamilpa, La Yesca, and Las Cruces in Nayarit state) and Lerma-Santiago (VIII) in the center. A detailed

Table 1.4 Consumptive uses of water in Mexico in 2017 (CONAGUA 2018a)

Use	Distribution (%)	Volume (hm^3)
Agriculture irrigation	76.0	66.799
Public	14.4	12.628
Industrial	4.9	4.267
Electricity (not hydro)	4.7	4.147
Total	100	87.842

review of the history and development of the hydroelectric generation in Mexico was published by (Ramos-Gutiérrez and Montenegro-Fragoso 2012).

The dams and lakes are the most important reservoirs of the country. Mexico has few ponds and lakes, and the biggest is the Chapala Lake, with 1116 km^2. Located in Jalisco state, it receives the contaminated waters of the Lerma-Santiago River, and rehabilitation programs are designed to restore the ecological condition of the lake (SEMARNAT and CONAGUA 2016).

1.7 Consumptive Uses of Water

In Mexico, water use is regulated by law. The granted water allocation is published in a Public Registry of Water Rights (REPDA) (CONAGUA 2018c) as well as protected regions defined by the government (CONAGUA 2018d). The rules are based on the National Water Law, reserved for population, irrigation, industry, environment, and electric generation (Honorable Congreso de la Union 2016).

Surface waters fulfill 61.3% of the total consumptive volume, and the rest comes from groundwaters. CONAGUA reports the consumptive volumes (84,930 hm^3/year) as shown in Table 1.4 and their distribution by sector, in 2017. Also, hidroelectrics produced 30.1 TWh with 133,938 hm^3 water (not consumptive).

Irrigation is the highest demanding sector for consumptive uses, principally with surface water (63%) which supplies 40 thousand irrigation units that compile 6,500,000 ha.

1.8 Water Quality

The population and industry growth in the last century lead to rising water demands, whose contaminated untreated discharges impacted ecosystems freely, due to the lack of legal controls of quality standards. That is why, water quality is a generalized impairment in Mexico, as the deficiency of good governance practices and attention to the sewage have last for years, producing regions that stand out for their environmental damage, still affecting public health and ecosystems. Only 62% of the water is acceptable for human consumption. Hydrological Regions VIII and XIII present the high values of BOD_5 (>120 mg/L) and COD (>200 mg/L), where almost half the population and industries of the country exist. By now, there are 5028 control sites for monitoring the surface and groundwaters, including discharges (CONAGUA 2018a).

The most impaired sites occur near Mexico Megacity, settled on the ancient Texcoco Lake, fully described recently (Tortajada 2015) which presents linear vertical subsidence rates over 30 cm/year driven by water extraction producing the aquifer overexploitation (Chaussard et al. 2014). Mexico City is the 11th world's larger built-up urban areas presenting severe water delivering and distribution, despite the 127 km aqueduct constructed from Cutzamala-Balsas Basin (1100 m depth) to fulfill high demands by 450 m^3/year (14.9 m^3/s) water imports. The impressive urban growth of Mexico City has encouraged an expensive water policy that has overexploited groundwater bodies within its boundaries since the local supply is insufficient. Frequently, this system collapses, with economic and social consequences (Morales-Novelo and Rodríguez-Tapia 2012).

The Megacity has also caused damages in its proximities, as it happened in the Mezquital Valley at the north. It is the deposit of the untreated wastewater coming from Mexico Megacity since the nineteenth century, by pumping the sewage to three main channels and tunnels up to the Salado and El Salto Rivers, tributaries of the Tula River, the main flow of the Valley. Many reports have been published about the long-term environmental impairment that led to soil degradation and pollution with the health risk of communities due to wastewater exposure (Contreras et al. 2017). Contradictory, this inconceivable unsustainable practice allowed the agriculture development in this semiarid valley, where three irrigation districts exist. In this year, a colossal treatment plant started functioning in Atotonilco de Tula, at the entrance of the mighty sewage Salad River, and the sustainable conditions of the valley should be achieved at 2030, and the downstream communities will also be protected (see Fig. 1.6).

Many municipal wastewaters treatment plants are not in operation, although the number has risen from 394 in 1992 to 2477 in 2015, with 2832 industrial wastewater treatment plants (CONAGUA 2016b).

Fig. 1.6 Mexico City wastewater treatment plant in Atotonilco de Tula, Hidalgo state

In the last years, public politics have increased the attention to the water remediation problems and the restoration of the most impaired water bodies and basins.

1.9 Political Arrangements: Laws and Prevention

Rolland and Cardenas (Rolland and Vega Cárdenas 2010) reported that water management in Mexico has developed through two stages: The 1972–1992 period marked by a centralized federal model and after 1992 by a decentralized model with privatization options.

The Water Allocation Law with Federal jurisdiction was launched in 1910. Before it, there was no attention to groundwater. The 115 article of the Constitution gives the responsibilities to the states and municipalities for the services but declares that the water is a property of the Nation and grants concessions to fulfill the sector and region demands.

Another important law was the Agrarian Code, launched in 1934, to regulate the irrigation water until 1972, repealed by the Water Federal Law (1972), and further substituted by the Water National Law (1992), reformed in 2004 but suffered a bid delay being published in 2008 (Rolland and Vega Cárdenas 2010). The new National Water Law was launched recently (Honorable Congreso de la Union 2016), but it will be subject of new revisions shortly to prevent privatization.

1.10 Final Remarks and Perspectives

Public politics have increased the attention to the water remediation problems and the restoration of the most impaired water bodies and basins. The future of water availability is being considered by the government. Nevertheless, the experimental measurements of water in rivers and aquifers should be done because there is a lack of reliable data, needed to design appropriate management programs.

Finally, and not less unimportant, the remediation of wastewaters and water bodies is essential to prevent infections and injury by chemicals, a present risk in many localities where the water treatment plants are closed or not controlled. The people education is essential to face such impairments and to participate in their rights demands.

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Part I
Water Availability

Chapter 2
Hydrological Basins in Mexico: Divisions and Legal Definition

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Abstract In Mexico, despite the existence of a legal definition of the hydrological basin and an official delimitation of hydrological basins, there are multiple hydrological delimitations. They generate confusion in those who require such information for research or hydrological analysis among other objectives. This chapter focuses on showing the essential features of various hydrological basin delineations that have been proposed for the Mexican territory, pointing out the inconsistencies of the current official delimitation concerning the hydrological basin legal definition in Mexico. The total number of basins in which Mexican territory has been divided is a simple indicator of the variety of criteria considered to perform hydrological delineation. In recent times, this number had varied from 142 to 1474 basins depending on the institution and time when delineations were performed. In the absence of a useful and consensual scientific hydrological delineation, current hydrological delimitations could be systematically identified with names, codes, purposes, and possibilities of use. This regulation could reduce confusion and facilitate the proper application of each hydrological division. Official river basin delimitation in Mexico

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is applied to calculate surface water availability and in turn to legally confer water rights. However, such delineation does not comply with Mexican legal definition of the hydrological basin. Since official and legal precepts must be consistent, a measure to harmonize this inconsistency is convenient. Changing precise delimitation is a primarily technical and administrative task with possible legal implications. In this sense, it appears more convenient to modify the legal definition to match official hydrological basin delimitation.

Keywords Basin · Delimitation · Surface · Water · Availability

2.1 Introduction

According to the World Meteorological Organization, a basin is an "Area having a common outlet for its surface runoff" (OMM 2012). In that sense, the number of hydrological basins in which the territory of a country can be divided is infinite. Nevertheless, a consensual hydrological basin delimitation is essential for formal water management in Mexico. This due to river basin is legally considered as the unit of management of water resources (SEGOB 2016). However, one of the main problems that scientists and decision makers face is the absence of a consensual hydrological basin delimitation to the interior of a country (Cotler 2007). As a consequence of this, in Mexico there are multiple delineations: This country has different hydrological divisions established under different criteria, which results in the existence of hydrological units whose limits differ between each other (Cotler 2007). The government, as well as academic institutions, has created several divisions for hydrological basins in Mexico (CONABIO 2008b).

This situation continues to date. Although there is an official delimitation of hydrological basins (CONAGUA 2016a), the national water authority itself had recognized the existence of multiple divisions of hydrological basins (CONAGUA 2012) that can be used for different purposes, even to the interior of its administrative scope. It generates confusion in those who require such information for academic purposes, research, professional objectives from various branches such as hydrological analysis, water right management, economy, among others; or just informational purposes on the hydrological conformation of Mexico.

The number of drainage basins in Mexico can be considered as a simple indicator of the diversity of hydrological delineations historically carried out and accordingly the variety of criteria adopted to perform them. For example, according to Geography Institute of the National Autonomous University of Mexico, the number of river basins in Mexico is 142 (CONABIO 2008b), while the National Commission of Water set 722 river basins for Mexican territory (CONAGUA 2010b).

Also, official documentation reports different total numbers of hydrological basins, without specifying their delimitation. It is the case of the 314 river basins cited in the National Hydraulic Plan 1996–2000 (CONAGUA 1996). Besides, many nonexistent ‘hydrological regions’ are mentioned, such as Rosamorada River Region and Bejuco River Region, which are not among the commonly accepted “37 hydrological regions,” which divide the Mexican territory (CONAGUA 2016a).

This chapter focuses on showing the essential features of the various hydrological boundaries that have existed in the Mexican territory, pointing out the inconsistencies of the current official delimitation concerning the hydrological basin legal definition in Mexico.

2.2 Methods

2.2.1 Software and Data Sources

Hydrological basin divisions were extracted from documents issued by federal agencies that, at a given time, oversaw the water administration in Mexico. The documents include periodical publications such as Hydraulic National Plans, later called National Water Programs, and Statistics of Water in Mexico; unique publications are also included among the information sources. The presence of maps is prominent in this chapter, some of which were obtained as raster images, while others were obtained from vectorized versions, whose attribute files provided additional information to describe the main features of the geographical division described. Hydrological basin divisions in Mexico are explained in chronological order from 1900 until May 2017.

The dataset used in this study came from two different sources: geographical information of the Mexican Government and international databases. Mexican information includes hydrology and hydrological basin boundaries. The basin map at the scale 1:50,000 was obtained from the National Institute of Statistics and Geography (INEGI 2017b). The official delimitation of hydrological basins in Mexico was based on the coordinates of its vertices published in the Official Journal of the Federation (CONAGUA 2016a). Also, vector files from different sources were used.

The maps generated from vector files were produced using QGIS 2.18.3 Las Palmas software. The coordinates of the vertices were processed with QGIS to generate polygons that defined the hydrological basins division. Quantum GIS (QGIS) is an open-source tool with a simple and friendly interface. The QGIS was executed from the Windows platform. This software incorporated geospatial data. The georeferencing of the basic cartography was carried out using the WGS84 (World Geodetic System 1984) reference system and projection UTM (Universal Transverse Mercator), area 13.

2.3 Hydrological Divisions in Mexico

2.3.1 Historical Review of Hydrological Basin Divisions in Mexico

The first reference found about the division of the Mexican territory in hydrological basins is quoted in the book Perspectives on the Hydrological Basins of Mexico (Cotler 2010), which mentions that in Mexico, the first delimitation of hydrological basins was established by Antonio García Cubas during the years before 1910. In Fig. 2.1, around 39 large basins can be identified by different colors. In this division, 36 streams with the name were also identified, but without a delimited basin. Besides, 74 minor unnamed streams do not have a delimited basin.

In 1946, the extinct Secretariat of Hydraulic Resources divided Mexico into 37 hydrological regions, which were constituted by one or more river basins. According to Cotler (2007), the limits of each of these regions were raised visually and outlined by hand. These hydrological divisions were spread through hydrological

Fig. 2.1 First hydrographic chart of Mexico by Garcia Cubas. *Source* Mapas Alidrisi (2017)

No. DE REGION	No.DE BOLETIN HIDROLOGICO
1,2,3,4,5,6 y 7	28
8	39
9	40
10	36
11	30
12 Parcial	50
12 Parcial	51
12 Parcial	52
13,14,15,16 y 17	41
18 Parcial	47
18 Parcial	48
18 Parcial	49
19,20,21 y 22	31
23	37
24 Parcial	29
24 Parcial	34
24 Parcial	53
25	54
26 Parcial	44
26 Parcial	45
26 Parcial	46
26 Parcial	32
26 Parcial	*
27	42
28 Parcial	43
28 Parcial	*
29	37
30,31,32 y 33	38
34	33
35	S/D
36	35
37	55

* Boletines editados por la Comisión de Aguas del Valle de México y Comisión del Papaloapan respectivamente

Fig. 2.2 Hydrological regions in the Mexican Republic from hydrological bulletins. *Source* Scanned from SARH (1976)

bulletins, where information about hydrometric stations, surface hydrology, populations, and state political divisions was also added. These bulletins continued being published until years later also by the extinct Secretariat of Agriculture and Hydraulic Resources. The National Water Commission has digitized versions of these bulletins that are available on its Web site, which also contains maps of the 37 hydrological regions (Fig. 2.2).

Based on hydrological basins defined in the hydrological bulletins with information until 1970, CONABIO (2001) identified 3115 hydrological sub-basins in Mexico. The corresponding map was extracted from the Secretariat of Hydraulic Resources hydrological bulletins at scale 1:1,000,000 and shows the hydrological sub-basins in Mexico (Fig. 2.3). Cartographic data were obtained from a digitalization process. Nevertheless, the number of identified sub-basins is incorrect as it is explained later in this chapter. The corresponding vector files are available on the Web portal of this organization in shape format, from which the map in Fig. 2.3 was generated.

Subsequently, a first effort was carried out to plan the development of the water resources in Mexico through the Hydraulic National Plan in 1975 (SRH 1975). In the regionalization section of this document, it is mentioned that the national territory was divided into 13 regions for planning purposes. These regions were formed with one or more grouped basins. Also, these regions were subdivided into 102 sub-regions with socioeconomic homogeneity, which constituted the minimum development modules.

Fig. 2.3 Hydrological sub-basins in Mexico according to hydrological bulletins. *Source* Authors elaborated based on shapefiles of CONABIO (2001)

The division into sub-regions coincided with the municipality political division. It facilitated the collection and handling of information obtained at the municipal level. The corresponding map is presented in Fig. 2.4.

The map also shows a grouping of regions in four areas: North, North Pacific and Centre, Centre, as well as Gulf and Southeast. Then, the 1975 Hydraulic National Plan does not present an actual division by basins, but a configuration of regional entities based on municipalities. As it is known, the political demarcation of the municipalities in Mexico does not obey to hydrographic boundaries.

In 1981, the Direction of Studies of the National Territory (DETENAL and nowadays INEGI that stands for National Institute of Statistics and Geography) published the surface water hydrology chart in Mexico at scale 1:1,000,000. This chart includes the delimitation of 37 hydrological regions, based on the basin division proposed by the SRH. However, a total number of hydrological basins for the country is not indicated (Cotler 2007).

With the establishment of INEGI in 1983 (2017a), a surface water hydrological chart was developed at scale 1:250,000. In this product, natural features (such as hydrography and topography) were taken as criteria for basin delimitation. A terrain contour chart was also developed at scale 1:50,000 without any hierarchy or organization concerning basins (Fig. 2.5). A total number of river basins are not specified in Cotler (2007).

Fig. 2.4 Zones, regions, and sub-regions of the Hydraulic National Plan 1975. *Source* Scanned from SRH (1975)

Fig. 2.5 Hydrographical division at the sub-basin level. *Source* Raster image from Cotler (2007)

Later, in the Hydraulic Program 1995–2000 (CONAGUA 1996), the Mexican territory was divided into 314 basins, 72 hydrological sub-regions, and 37 hydrological regions, but there is no listing, nor map of these basins. On the other hand, the dictionary of hydrological data of surface water of INEGI (2001) sets out identification codes for 150 basins and 1003 sub-basins in Mexico.

In July 2001, the National Water Program 2001–2006 (CONAGUA 2001) indicated that a total of 44 studies about surface water availability were intended to carry out but only 35 were available; however, the number of basins covering every study is omitted, as well as the total number of basins. In 2003, the National Institute of Ecology (INE-SEMARNAT) prepared a nationwide map of hydrological basins at scale 1:250,000 (INEGI 2007). The criteria used for this delimitation were based on topographic and hydrographic features only (Cotler 2007). Figure 2.6 shows the delimitation of hydrological basins in Mexico in 2003. In this document, the number of hydrological basins in Mexico is not indicated.

In publication "Statistics of the Water in Mexico" editions 2003–2006 (CONAGUA 2003b, 2004, 2005, 2006b), a defined number of hydrological basins in Mexico is not mentioned. The 2007 edition of this document pointed out that the Mexican territory is divided into 718 basins (CONAGUA 2007).

In 2007, because of the joint efforts of the three governmental institutions (INEGI, INE, CONAGUA), a map of hydrological basins in Mexico was obtained at scale 1:250, 000. A total of 1471 hydrological basins were obtained (Cotler 2007). Unfor-

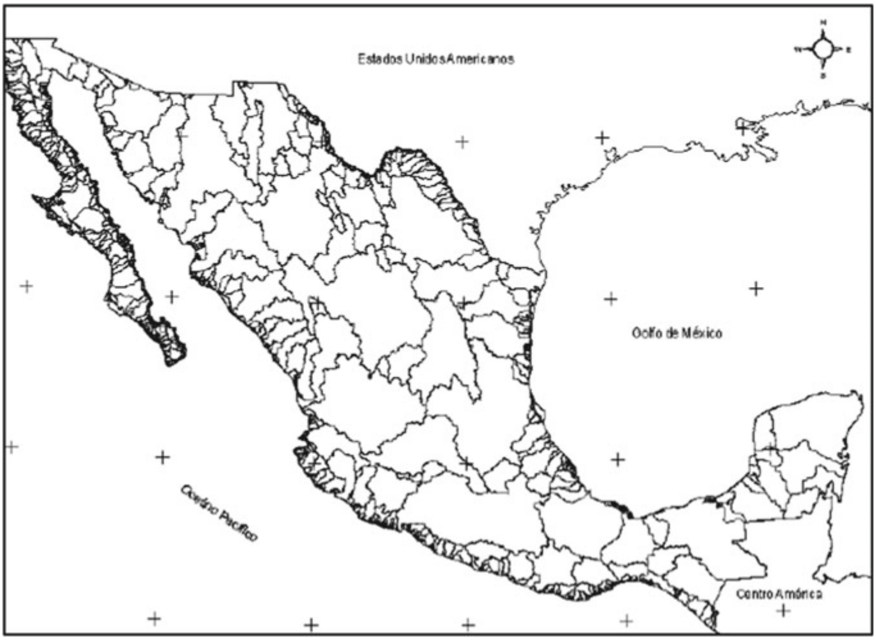

Fig. 2.6 Map of hydrographical basins in Mexico. *Source* Raster image from Cotler (2007)

tunately, the source of this map (Fig. 2.7) does not provide the shapefiles, and it does not indicate where to obtain them either.

In March 2001, CONABIO published on its digital Web site the vector shapefiles of the hydrographic basins in Mexico (CONABIO 2008a) according to National Water Commission (CNA). The file includes 1739 entities, from which 1579 are islands, and 160 are hydrological basins (Fig. 2.8). Technical information like identification, spatial and no-spatial attributes, and reference system of this map is available on the Web site of CONABIO (2008a).

CONABIO updated this information in 2008 with the support of the Institute of Geography of UNAM (IG) (CONABIO 2008b). Figure 2.9 shows the division of Mexico in 2008 by hydrological basins. The shapefile includes 234 items of which 92 are islands. Therefore, 142 are basins. Reference system, as well as spatial and no-spatial attributes, is specified in the Web site of CONABIO.

A color code identified 37 hydrological regions, and 79 hydrological sub-regions were identified with lines (Fig. 2.10). A table with their respective areas and perimeters is located at the Web site of CONAGUA (2008a).

National Water Program 2007–2012, CONAGUA (2008b), reported the existence of 718 basins. This number is related to the publication of water availability in aquifers and hydrological basins in Mexico, as part of a strategy to promote the integrated and sustainable management of water basins and aquifers. From this document, it

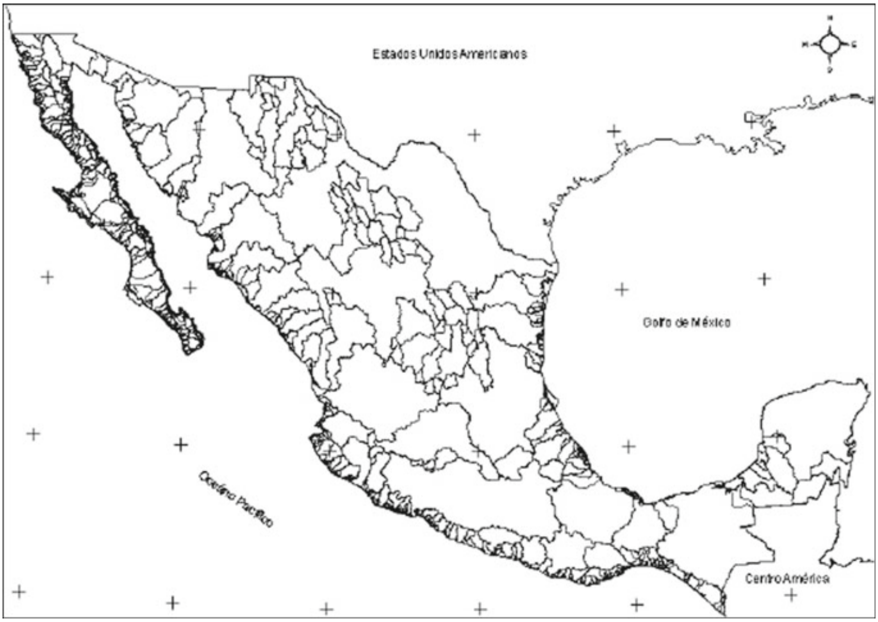

Fig. 2.7 Graphic representation of the hydrographical basins in Mexico from its original 1:250 000 (INEGI-INE-CONAGUA 2007). *Source* Raster image from Cotler (2007)

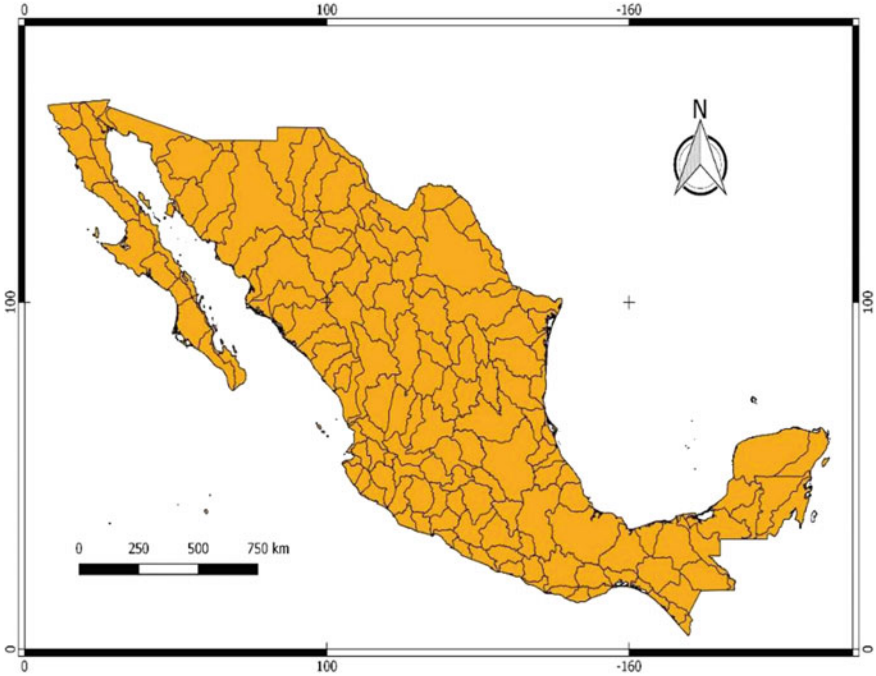

Fig. 2.8 Hydrological basins of Mexico according to CNA in 2001. *Source* CONABIO (2008a)

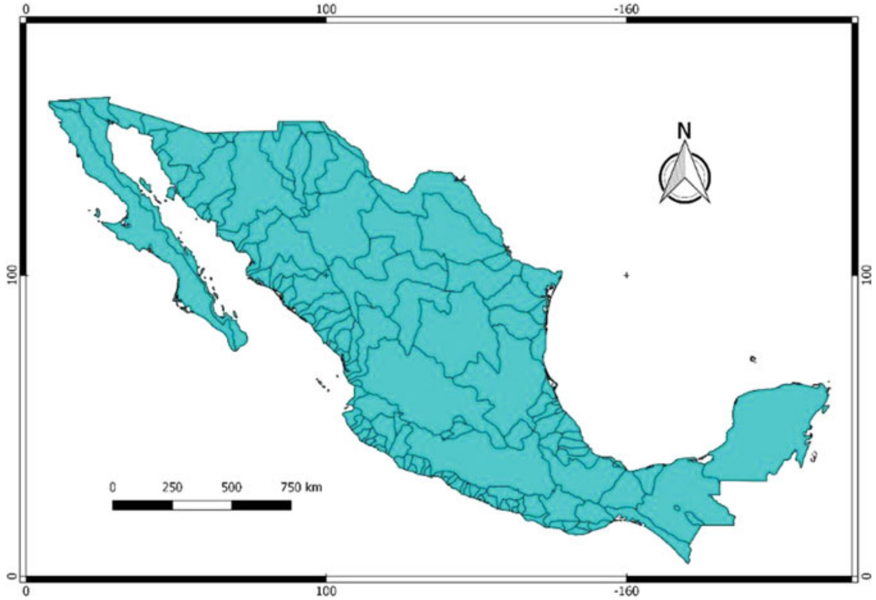

Fig. 2.9 Hydrographical basins that divide the Mexican territory in 2008 according to National Institute of Geography of UNAM. *Source* CONABIO (2008b)

Fig. 2.10 Hydrological sub-regions in Mexico according to the National Water Commission. *Source* Raster image from CONAGUA (2008a)

can be interpreted that this is the total number of basins in Mexico. Names and maps of hydrological basins are not provided.

As a complement of this division, CONABIO (2009) reports on its Web site the hydrological sub-regions in Mexico at scale 1:250,000 based on information of National Water Commission. Figure 2.11 shows a map generated using shapefiles. According to it, there are 78 hydrological sub-regions in Mexico. Identification, reference system, and spatial and no-spatial attributes are described in the Web site of CONABIO.

In Water Statistics in Mexico 2008 (CONAGUA 2009b) and Atlas of Water in Mexico 2009 (CONAGUA 2009a), the existence of 728 hydrological basins is mentioned. None of the two documents present map in this regard. In June 2007, CONABIO published online the shapefiles of hydrological basins in Mexico 2007 based on the information of INEGI, INE, and CONAGUA (Fig. 2.12). The corresponding files (CONABIO 2007) include 1474 hydrological basins, with no islands reported. CONABIO's Web site indicates information about the reference system, spatial and no-spatial attributes, and additional technical information.

In August 2010, INEGI (2010) released a drainage basin delineation of Mexican territory based on a 1:50,000-scale cartography. 976 sub-basins grouped in 158 river

Fig. 2.11 Hydrological sub-regions in Mexico at scale 1:250,000, based on CONAGUA division. *Source* CONABIO (2009)

Fig. 2.12 Hydrological basins of Mexico, 2007 according to INEGI, INE, and CONAGUA. *Source* CONABIO (2007)

Fig. 2.13 Hydrological basins according to hydrological network 1:50,000 of INEGI. *Source* Raster image from INEGI (2010)

basins were identified for the 37 hydrological regions (Fig. 2.13). INEGI (2010) provides a full description of the process of elaboration and technical characteristics of this delineation. It was based on a former division performed in a 1:250,000 scale which consisted in 983 sub-basins (INEGI 2010) although the "Dictionary of Hydrologic data of Surface Water" of INEGI (2001) sets out a list of 1003 codes for sub-basins.

INEGI's river drainage delimitation 1:50,000 scale is used in the Hydrographic Basin Flow Simulator (SIATL) which allows performing several hydrological analyses (INEGI 2017c). Hydrographic network in scale 1:50 000 can also be accessed through SIATL's Web site.

The book titled "The hydrological basins in Mexico: diagnosis and prioritization" (Cuevas et al. 2010) states that "as a result of the regionalization of basins, the total units dropped from 1471 to only 393." Figure 2.14 is the result of this regionalization. Although a total of 393 hydrological basins are specified, a list of 397 is provided because the Colorado River basin is divided into three sub-basins (117a, 117b, and 117c) and the islands of Cozumel and Del Carmen were included, which adds four more elements. Such islands are important as an economic criterion, but not as a hydrographic one.

In Water Statistics in Mexico Edition 2010, CONAGUA (2010b) reports water availability of 722 hydrological basins according to NOM-011-CONAGUA-2000 (SEMARNAT 2002). However, these basins do not represent the total number of basins in Mexico. Edition 2011 of the same publication (CONAGUA 2011b) indi-

Fig. 2.14 Hydrographic basins in Mexico obtained by grouping INEGI, INE, and CONAGUA hydrological delineation. *Source* Raster image from Cuevas et al. (2010)

cates that water authority identified 1471 basins in Mexico. The total number of basins identified agrees with the work carried out by the CONAGUA, INEGI, and the INECOL. These basins were grouped and subdivided into hydrological basins for surface water availability and publication purposes. In December 2009, water authority reported 722 hydrological basins in Mexico, but other 9 basins were added in December 2010.

Water statistics in Mexico Edition 2012 (CONAGUA 2012) refers to the formalization of 731 hydrological basins. This publication also argues that any other division reported in the literature is not appropriated for water resource management purposes. Editions 2013, 2014, and 2015 of the same publication also refer to the existence of 731 basins in Mexico (CONAGUA 2013d, 2014, 2015).

Geographic Information System of Water (SIGA) recognized that there are 1424 basins in Mexico, as it was identified by National Institute of Ecology and Climate Change (INECC), but the division of 731 basins (Fig. 2.15) is valid for water management purposes of CONAGUA (Monterrosa Reyes 2015). Topographic chart scale 1:250,000 was the base to elaborate this map with ArcGIS. An elevation model was generated with a resolution of 90 m per pixel.

Annual average availability of the surface water was published in March 2016. This information was given for the 731 hydrological basins, which comprise the 37 hydrological regions in Mexico (CONAGUA 2016a). However, in May of the same

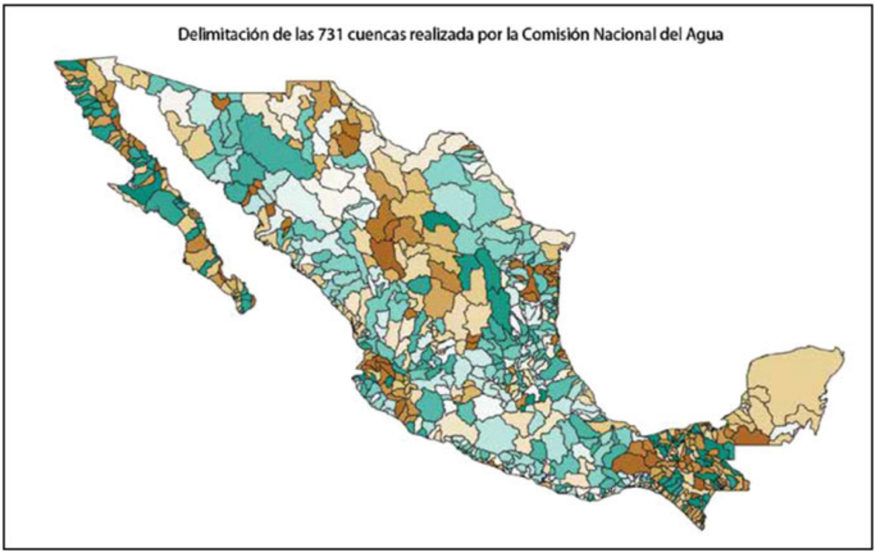

Fig. 2.15 Delimitation of official 731 hydrological basins in Mexico. *Source* Raster image from Monterrosa Reyes (2015)

year, an 800 pages publication was provided, where the water authority gives the boundary limits of 757 hydrological basins in Mexico (CONAGUA 2016a, b, c, d, e, f). "Water statistics in Mexico Edition 2016" (CONAGUA 2016g) mentions that there are 731 basins in Mexico which coincides with the number cited above.

2.3.2 Diversity of Basin Delimitations: Purposes and Criteria

The number of territorial entities of runoff in Mexico has had significant variations: from the 39 basins in the Garcia Cubas' map to the 3115 sub-basins suggested by CONABIO. The first was obtained at the beginning of the twentieth century with technical limitations and the second, with neglect, by the addition of elements identified as basins, sub-basins, hydrological basin, and including islands and portions of coastal bars in a single number. Excluding islands, coastal bars, and errors and adding up drainage entities (basins and sub-basins), the number of river basins is 1585. Basins and sub-basins can be added in a single number considering that according to the map of CONABIO both drainage entities exclude each other and because as defined in the International Glossary of Hydrology (OMM 2012) a river basin is "Area having a common outlet for its surface runoff." In this sense, the sub-basins constitute basins.

Excluding the two preceding drawbacks, the published number of basins in Mexico has varied considerably. The lowest number of the range of basins is 142 that CONABIO proposed based on the information from the Institute of Geography of UNAM followed by 150 basins that INEGI suggests in the Surface Water Hydrological Data Dictionary. The highest is 1474 basins published by CONABIO with information of CONAGUA and INEGI proceeded down by 1471 basins reported in publication "Delimitation of river basins in Mexico" at scale 1:250,000 (Cotler 2007).

Despite the variety of river basin delimitations, CONAGUA settled 757 official hydrological basins in 2016. It proves that river basin delimitations are not adequate when purposes are different even though the hydrological basin delimitations are the product of rigorous and documented efforts, as those reported by INEGI, INECOL, and even CONAGUA in 2007, which resulted in 1471 basins. It also applies to the effort carried out to reduce the number of basins from 1471 to 393 (Cuevas et al. 2010).

Delimitation in 1471 basins had as objective "*… to develop a common spatial vision of Mexico for all academic, governmental agencies and any user requiring to know the configuration of the hydrological basins of the country*" and "*… to establish joint and common criteria for the delimitation of the basins and the definition of its toponymy*" (Cotler 2007). Cuevas et al. (2010) had the purpose of "*… having a manageable number of hydrographic units and that its dimensions allow extrapolating municipal data.*"

On the other hand, the division in 757 basins seeks to "*provide greater certainty to users regarding the exact location of the place in which the holding, use or exploitation of the waters takes place, as well as improving the Administration and management of water resources …*" (CONAGUA 2016a). In other cases, the purposes of divisions must be deducted from its origin. For example, a division of 1585 hydrological basins from hydrological bulletins containing hydrometric information can be associated with delimitation from the drained areas to gauging stations.

2.3.3 Hydrological Basin Grouping Level

The National Waters Law (LAN) establishes hydrological basin grouping levels in Mexico: hydrological-administrative region, hydrological region, basin, sub-basin, and micro-basin. However, the official division of 757 basins published in the DOF does not include sub-basin or micro-basins, but includes the sub-region level, which is not considered in the LAN.

A hydrological region is a territory comprised of the grouping one or several hydrological basins with geographical proximity. Grouping several hydrological basins was carried out to perform data analysis, diagnostics, and action programs for water management purposes in Mexico. Also, water authority adapted its organizational structure to 13 hydrological—administrative regions, which are mostly integrated grouping the 37 hydrological regions.

Despite the diversity of hydrological basins divisions in Mexico, the division of 37 hydrological regions is almost constant over time; since it was established by federal goverment this division has been accepted, apparently unquestioningly. In contrast, the precise criteria under which the basins were grouped to form these regions do not appear in any consulted work. Cotler (2010) suggests that the delimitation of Mexico in 37 hydrological regions was carried out in 1946. Instead, in several issues of Federation Official Diary (CONAGUA 2003a, 2006a), the year of 1969 is mentioned as the time when such delimitation was accomplished. In 1976 (SARH 1976), a series of hydrological bulletins were organized by the 37 hydrological regions, mentioned 1969 as the starting year.

On the other hand, the terms "region" and "sub-region" are not used consistently in the official division. For example, the delimitation of 757 basins published in the DOF in 2016 mentions the Culiacan River Hydrological Region. This hydrological region is not included in the 37 hydrological regions commonly accepted. The same occurs for the Rosamorada River Hydrological Region, Sinaloa River Hydrological Region, Bejuco River Hydrological Region, among others. In some divisions, including one made by the water authority with a higher level of detail, the terms sub-basin and micro-basin are not used (CONABIO 2008a). In other delineations, the term sub-basin is used for delimiting areas, such as the division proposed by CONABIO (2001).

2.3.4 The Islands as Part of the Hydrological Basins Database

In CONABIO, sub-basin delimitation (CONABIO 2001) islands are wrongly counted as hydrological basins as it was pointed out before in this chapter. The definitions of both types of land surfaces do not show a logical similarity that enables such addition. An island is a natural extension of land surrounded by water smaller than a continent (Jędrusik 2011), while a basin, in its simplest sense, implies a territory with an outlet for its surface runoff (Barham 2001). Although an island could have a single output for its runoff surface, this situation cannot be generalized (Mink 1962). Besides, Mexican islands of significant size could have several drainage basins. These islands are excluded from Mexican basin inventory because of the lack of proper topography (INEGI 2010).

2.3.5 Formalization of Hydrological Basin Boundaries

Official delineation of hydrological basins is published in the Federation Official Diary. According to this publication, 757 basins in Mexico were established in May 2016. However, the official hydrological basin divisions have undergone several changes, as it was evidenced in CONAGUA (2012). The official delimitation originally included 731 basins. Then, it changed to 757. The division of 731 basins was formed through time with the serial publication of the official availability of surface water. However, the boundaries of these hydrological basins were not published officially. In May 2016, 757 basins were officially recognized by water authorities when 26 basins were added.

CONAGUA (2012) also indicates that the Federal Government supports the existence of different hydrological basin divisions, by the purpose for which it is intended to. It means that, on the one hand, the national water authority establishes an official delimitation of hydrological basins, and on the other hand, it accepts that multiple divisions by hydrological basins can coexist, even within their administrative branches.

2.3.6 Legal Definition of Hydrological Basin in Mexico

In Mexico, the hydrological basin constitutes the water resources management unit (CONAGUA 2016g). This natural territory takes an administrative connotation. The same happens in other countries, as in Chile where the delineation of hydrological basins is the official administrative delimitation of the General Direction of Waters, DGA (DGA Chile 2013). In this sense, and looking for congruence with the natural hydrological boundaries, the water authority in Mexico organizes its geographical presence through the creation of 13 hydrological-administrative regions based on grouping hydrological basins (CONAGUA 2010b). In practice, the boundaries of these regions are officially defined by adjusting hydrological basin boundaries to municipality boundaries (Espejel and Hernández 2005).

On the other hand, as mentioned previously in this chapter, in Mexico the delineation of hydrological basins has been formalized to determine surface water availability and to organize the legal distribution of water through concessions for the use and operation of water resources (CONAGUA 2016a). The legal definition of the hydrological basin in Mexico is (CONAGUA 2016g):

> … the territory unit, differentiated from other units, usually delimited by a hydrological basin or dividing line of the waters - that polygonal line formed by the points of highest elevation in this unit-, where water happens in different ways, and it is stored or flows to an exit point that can be sea or another internal body, using a hydrographic network of streams that converge in a primary one or the territory where the waters form an autonomous unit or differentiated from each other, even without leading to the sea. In the space delimited by a diverse topography, resources water, soil, flora, fauna, other related with these natural resources and the environment coexist. Basin together with aquifers, constitute the unit of

> management of water resources. The hydrological basin is in turn composed of sub-basins, and these are integrated by micro-basins.

This somewhat confusing definition leads to ambiguous interpretations which do not contributes to promote a consensual hydrological delineation, as in the case of assigning or denying water rights or concession. Concessions to use surface water are based on the availability of surface water. This availability is calculated based on the official division of hydrological basins. In turn, the official division of hydrological basins is set in the water use titles or deeds which are documents with legal validity (CONAGUA 2017). Hence, officially delimited hydrological basins must meet with the characteristics that the legal definition of hydrological basin establishes. However, this situation is not accomplished in numerous cases, for example, in river basins delimitated by hydrometric stations which is a widespread practice in Mexico.

2.3.7 Hydrometric Stations as Boundaries of Basins

The legal definition of basin indicates that a hydrological basin is a territory where water forms an autonomous unit or differentiated from others, even without leading to the sea. In the case of El Fuerte River basin whose hydrological delineation is official (CONAGUA 2016f), the division criterion is the presence of a dam and hydrometric stations, as shown in Fig. 2.16.

According to official delimitation, in this river, there are four hydrological basins. El Fuerte River basin 2 is separated from El Fuerte River basin 1 by the presence of Luis Donaldo Colosio Dam and from Alamos Creek basin and Choix River basin by hydrometric stations (not shown in Fig. 2.16) (CONAGUA 2010a).

As stated by Verdin and Verdin (1999), the presence of hydrometric stations does not mean the existence of differentiated autonomous units. The number of hydrometric stations identifies upstream areas but does not necessarily correspond to units for resource management. Locations of water flow measuring devices are usually established by logistical considerations such as ease of access on crossings of streams with roads or hydrometric operation needs installed at points of derivation. Similarly, a dam location is selected under criteria of geological and topographic convenience and not necessarily to separate autonomous units. It means that the four official hydrological basins mentioned above are not differentiated autonomous units as it is required by the Mexican legal definition of the hydrological basin. This situation occurs throughout the Mexican territory (CONAGUA 2013a, b, c, 2011a).

The reason for this is that official hydrological division is used to determine official surface water availability that must be calculated according to obligatory norm NOM-011-CONAGUA-2015 (SEMARNAT 2015). Water availability computation requires applying a water balance to a hydrological basin by using hydrometric information where it is available. Hence, to divide a hydrological basin by the presence of measuring devices is convenient even though it does not comply with the legal definition. To explain that, it is necessary to consider that in Mexico hydrometric

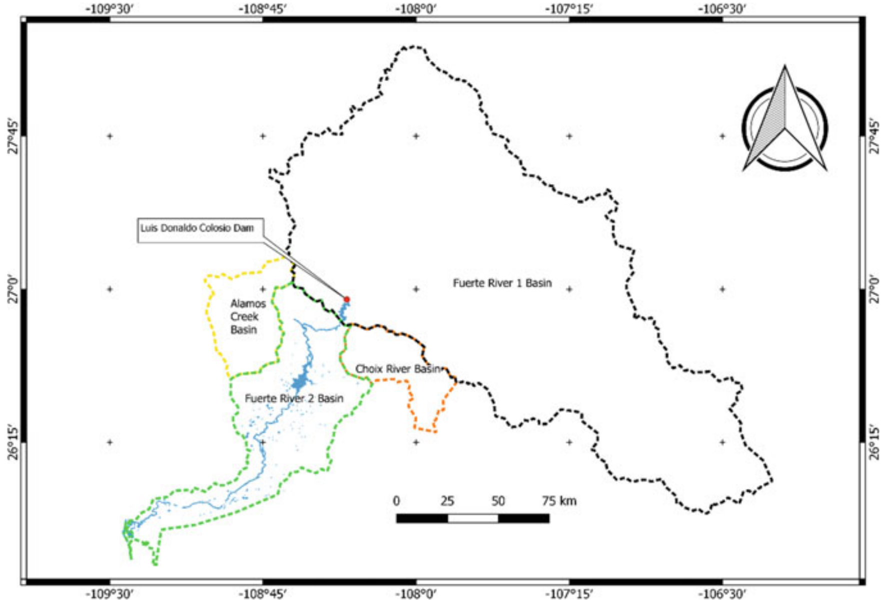

Fig. 2.16 Official delimitation of El Fuerte River basin. *Source* Own elaboration from the vertices published by CONAGUA (2016f)

information may be scarce in various areas. At the time of using the hydrometric stations, whether for hydrological forecasts or balance calculations, different problems are found: from the uneven distribution of the stations throughout the territory, different observation periods, gaps of hydrometric information, a drastic decrease in the number of stations, among others (Perevochtchikova and García-Jiménez 2006). This situation could explain the reason why officially delimitated hydrological basins take advantage of the presence of measurement devices to calculate the availability of surface water instead of observing the legal definition of the hydrological basin.

2.3.8 Legal Definition and Other Inconsistencies

According to Mexican legal definition of the hydrological basin, water "… *flows to an exit point that can be sea or another internal body, using a hydrographic network of streams that converge in a primary one* …" In other words, a hydrological basin must have a single point for its outflow. However, there are officially delimitated hydrological basins that do not comply with this requirement. For example, two basins named Altata Stream Group and Pabellones Stream Group are groups of small basins draining independently to the sea through different outlet points (Fig. 2.17).

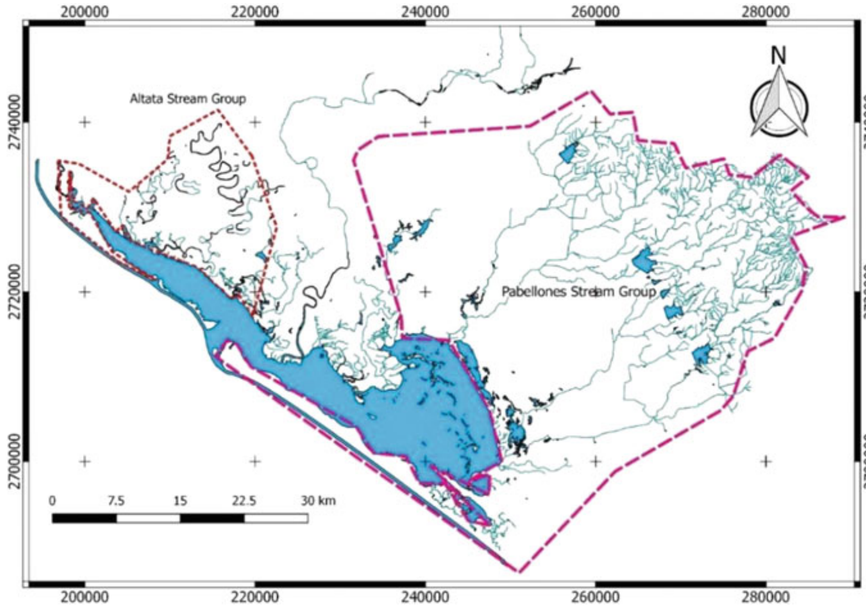

Fig. 2.17 Official hydrological basins Altata Stream Group and Pabellones Stream Group. *Source* Own elaboration using coordinate vertices published by CONAGUA (2016f)

In general, officially delimitated hydrological basins located in coastal plains do not comply with the condition of having a single outlet point because they group several small basins in a single drainage entity (CONAGUA 2016f).

In other cases, official delimitation of a hydrological basin includes significant surfaces corresponding to other hydrological basins and identifies them as a single basin. For example, Río Mocorito Hydrological basin has a hydrographic network separated from that of Culiacan River basin (Fig. 2.18) whose boundaries were published in 2016 in Federation Official Diary (FOD). However, officially, Culiacan River basin erroneously includes a portion of Mocorito River basin.

Human activities can affect natural watercourses. In areas with significant agricultural or urban development, natural channels may not explain the direction of runoff at each site to the interior of a basin delimited based on natural terrain (Souchere et al. 1998). The presence of irrigation and drainage channels, roads, and urban storm drainage, among other infrastructure projects, can modify the runoff patterns that naturally occur in the basin. Then, the influence of the agricultural or urban infrastructure must be considered to perform a surface water balance and a hydrological basin delineation.

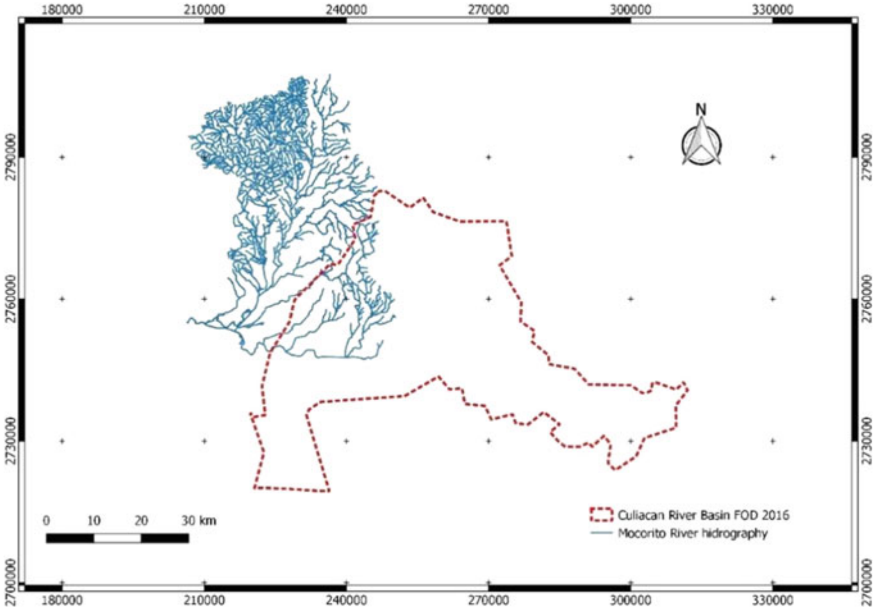

Fig. 2.18 Officially delimitated Culiacan River Basin and Mocorito River basin. *Source* Elaborated with coordinate vertices published by CONAGUA (2016a) and shape flies by INEGI (2017b)

2.3.9 Legal and Technical Implications

Official and legal precepts must be consistent. Therefore, officially delimitated hydrological basins in Mexico must comply with Mexican legal definition of the hydrological basin. Instead, as described above, they are inconsistent since such definition is not a criterion to delimitate official hydrological basins.

The divide of a hydrological basin is a physical limit to perform a water balance that enables to determine surface water availability, and in turn, to grant or deny water rights (SEMARNAT 2015). A water deed has to specify the hydrological basin where water is used (SEGOB 2016) and water rights are tied to hydrological delineation.

To eliminate such inconsistency, official basin delineation could be revised so that every drainage basin complies the characteristics established in the legal definition. In this case, revising geographical coordinates of thousands of vertices that delimit the 757 officially defined basins implies an intense technical work. Besides, deeds granted to the date should be checked to assure they correspond to a proper hydrological delimitation. It would require a significant administrative task at the country level. Therefore, the modification of the legal definition of the hydrological basin could be a better option since it would require less effort. A new legal definition could be based on international references such as the World Meteorological Organization (OMM 2012).

2.4 Conclusions

There are a variety of river basin delimitations in Mexico. The number of drainage entities in which Mexican territory has been divided is a simple indicator of the diversity of criteria that had been applied to perform hydrological delineation. This number has historically changed between 142 and 1474 basins. Although it is desirable a useful and consensual delimitation of hydrological basins in Mexico based on prominently scientific criteria, the truth is that Mexican water management requires practical tools for immediate implementation. In this sense, current hydrological delimitations should be systematically identified with names, codes, purposes, and possibilities of use. This regulation should be carried out with the aim to reduce confusion and facilitate the selection of a proper delimitation.

Nowadays, officially delimitated river basins have physical inconsistencies such as having more than one outlet or including surfaces that belong to other basins. Besides, human influence in natural flow patterns is ignored. To properly perform a water balance to determine surface water availability, the boundaries of each hydrological basin should be analyzed and revised if necessary. The concepts discussed in this chapter can be useful for these purposes.

Official river basin delimitation in Mexico does not comply with Mexican legal definition of the hydrological basin. Since official and legal precepts must be consistent, it is convenient to implement a measure. Changing official delimitation is a primarily technical and administrative task with possible legal implications. In this sense, it appears more convenient to modify the legal definition to match the official hydrological basin delimitation.

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Chapter 3
Runoff Simulation Under Future Climate Change and Uncertainty

Xiaoling Su, Jing Guo, Zheng Liang and Vijay P. Singh

Abstract Runoff is simulated using the Soil and Water Assessment Tool (SWAT) in the Shiyang River Basin and considering the precipitation and temperature obtained from five climate models in the Coupled Model Intercomparison Project Phase 5 (CMIP5), including MRI-CGCM3, CanESM2, CNRM-CM5, GFDL-CM3, and FGOALS-g2. Precipitation and temperature were downscaled as the input for SWAT, and the uncertainty in runoff simulation under climate models was evaluated based on the Bayesian information criterion (BIC) and expectation-maximization (EM) algorithms of Bayesian model average (BMA) method, also runoff variation in the future was predicted. Results showed that, for the downscaled precipitation, the accuracy index R^2 are mainly concentrated in 0.42–0.58. For the downscaled temperature, R^2 is greater than 0.5. The predicted runoff using BMA is better than that using the single climate model in most sub-basins. MRI-CGCM3 and GFDL-CM3 have larger contribution than other three models using BMA based on either BIC or EM algorithms. Compared to the period of 1990–1999, temperature of each climate model is obviously increasing during 2018–2100. While for precipitation, CNRM-CM5 and FGOALS-g2 showed an increasing trend in all sub-basins. But GFDL-CM3, CanESM2, and MRI-CGCM3 vary across sub-basins. The trend in runoff is consistent with precipitation. To sum up, precipitation, temperature, and runoff under most climate models will increase in the future. The results will provide a reference for the utilization and management of water resources in the future.

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The prediction of runoff under future environmental change is an important issue to define the impacts of climate change and human activities on runoff (Green et al. 2011). The Fifth Assessment Report of IPCC (Intergovernmental Panel on Climate Change) has pointed out that the global average surface temperature has increased significantly over the past 100 years (IPCC 2013). Global warming, on the one hand, increases the moisture content of the atmosphere (Meehl et al. 2005) and accelerates, on the other hand, the global water cycle (Allen and Ingram 2002; Ziegler et al. 2010). These effects not only change the temporal and spatial distribution of future precipitation but also increase the frequency and intensity of extreme precipitation (Dore 2005; Easterling et al. 2000). Scientists predict that surface temperature will continue to rise in the future. In response to climate change, global and regional scale climate change are receiving increasing attention, especially in areas that are relatively sensitive and vulnerable to climate change. Currently, global climate models (GCMs) are the most important tools which are used to simulate future climate variables, such as precipitation and maximum and minimum temperatures under different climate scenarios. The GCMs are based on mathematical equations that govern the laws of the changing physical climate system and use numerical methods to solve for the scenarios of future climate change. Climate models can be divided into global climate models and regional climate models based on spatial range. The climate models, used in climate change prediction, mainly include the complete sea–air coupled model, and more than 40 global climate models have been developed in countries around the world. Different GCMs will lead to different runoff forecast results.

When meteorological data from GCMs are used as input data for hydrological models, the uncertainty of the climate model, downscaling method, and emission scenario will directly affect the input data, thereby indirectly affecting the result of runoff simulation. At present, the uncertainty resulting from GCM structures is the dominant source of uncertainty in runoff projections. A reduction in uncertainty would require an improvement of our understanding of processes incorporated in the models and using finer resolution in GCMs and RCMs. In order to reduce the uncertainty in hydrological predictions under climate change in the future, first, the methods of dynamic downscaling or statistical downscaling (Knutson et al. 2013) were used to reduce the uncertainty due to climate models. Then, ensembles of different climate models for hydrological forecasting, such as simple average method, weighted averaging method, neural network method, and Bayesian model averaging (BMA), also were used to get the optimum estimation of runoff predictions (Demirel and Moradkhani 2015; Seong et al. 2017; Wang et al. 2017). The ensembles of synthesizing forecasting results of GCMs can provide more accurate meaningful multiple synthetic prediction results and get quantitative assessments about the uncertainty of forecasting results.

Different models have different advantages (Kharin and Zwiers 2002). Forecasting results from a single model are always limited. Better comprehensive forecasting results can be obtained by weighting the predicted values of different models (Doblas-Reyes et al. 2005; Tebaldi and Knutti 2007; Tippett and Barnston 2008). Some studies mainly include neural networks (Wang et al., 2013) and fuzzy systems (Raftery et al. 2005). The BMA method can be used to analyze the uncertainty of a comprehensive model and comprehensively considers the uncertainty of model inputs, parameters, and structure. BMA has been widely used in many fields for meeting the preceding requirements. Using the BMA method synthesizes runoff forecasting results from different GCMs to obtain the probability distribution of predicted values. The mean value of the distribution is seen as the synthetic predicted value of each model. The variance or confidence interval reflects the probable variation range of a predicted value. Thus, uncertainty of the forecast can be quantitatively evaluated.

This chapter discusses downscaling of precipitation and temperature data of five climate models in the Shiyang River Basin, and forecasting of future runoff from the study area, analysis of the variation trend and uncertainty of runoff prediction using five climate models based on the BMA.

3.1 Method

3.1.1 Study Area

The Shiyang River Basin, as shown in Fig. 3.1, is a typical arid inland basin located in the Gansu Province (China) and covers an area of 41,400 km^2 (Kang et al. 2009). The study area consists of six sub-basins located in the upper reaches of the Shiyang River Basin, including the Xida River Basin, Dongda River Basin, Xiying River Basin, Jinta River Basin, Zamu River Basin, and Huangyang River Basin. The average annual precipitation is 505 mm, and the average annual depth of runoff is approximately 209 mm. The basic meteorological data consist of precipitation, temperature, wind speed, solar radiation, and relative humidity obtained from meteorological stations of Wushaoling. Daily precipitation data were collected from 32 rain gauge stations for the period of 1989–2008. Runoff data from 1990 to 2013 were obtained from six hydrologic stations, which corresponding to the six river basins described above, respectively, were Xida River reservoir station, Shagousi station, Jiutiaoling station, Nanying reservoir station, Zamusi station, and Huangyang reservoir station, as shown in Fig. 3.1.

3.1.2 SWAT Model

The Soil and Water Assessment Tool (SWAT) is a watershed scale and physically based distributed hydrological model (Arnold et al. 2012; Neitsch et al. 2011) that was developed by the US Department of Agricultural Research Service (USDA-

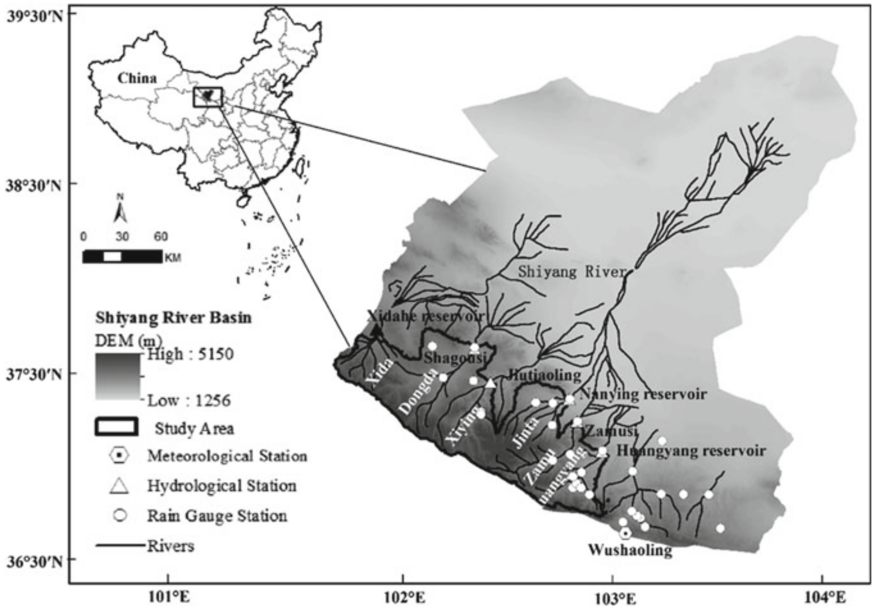


Fig. 3.1 Basic information of the Shiyang River Basin

ARS 1994). It can use the spatial data information provided by GIS and RS to simulate a variety of different hydrological processes in complex large watersheds, including the transport and conversion processes of water, sediment (e.g., sand), chemicals, and pesticides. In recent decades, the SWAT model has been widely used for hydrological simulation, nonpoint source pollution load estimation, and water resources management and has also been used to predict the impact of future climate on the evolution of water resources (Kumar and Merwade 2009; Kushwaha and Jain 2013; Narsimlu et al. 2013). In the SWAT model, a watershed is first divided into several sub-basins, each of which is composed of one to several hydrological response units (HRUs) that consist of homogeneous land use, topographical, and soil characteristics. Therefore, the parameters related to surface runoff, soil water, and groundwater are ranked according to their sensitivities to runoff.

The errors between simulated and measured runoff data may be introduced by the initial model structure and input data. The performance of the SWAT model can be evaluated based on the visual comparison and statistical criteria, such as deterministic coefficients (R^2), the Nash and Sutcliffe model efficiency coefficient [*NS*, Eq. (3.1)] (Nash and Sutcliffe 1970), root-mean-square error [*RMSE*, Eq. (3.2)] (Kushwaha and Jain 2013), and runoff volume relative error [*RE*, Eq. (3.3)], and the *NS* of calibration is classified according to the scheme ($0.75 < NS \leq 1.00$ very good; $0.65 < NS \leq 0.75$ good; $0.50 < NS \leq 0.65$ satisfactory;$NS \leq 0.50$ unsatisfactory) for the goodness of fit (Leitinger et al. 2015).

$$\text{NS} = 1 - \frac{\sum_{i=1}^{N} \left(Q_{m\_i} - Q_{s\_i}\right)^2}{\sum_{i=1}^{N} \left(Q_{m\_i} - \bar{Q}\right)^2}, \tag{3.1}$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(Q_{m\_i} - Q_{s\_i}\right)^2}, \tag{3.2}$$

$$\text{RE} = 1.0 - \frac{\sum_{n=1}^{N} Q_{s\_i}^{n}}{\sum_{n=1}^{N} Q_{m\_i}^{n}} \tag{3.3}$$

where Q_{m_i} and Q_{s_i} are the measured and simulated runoff of the ith month in the study period, respectively. $\bar{Q}$ is the average monthly runoff obtained from Q_{m_i}, and N is the total number of the months.

3.1.3 Climate Model Downscaling

Downscaling methods mainly include a statistical downscaling method, dynamic downscaling method, and dynamic-statistical downscaling method (Bates et al. 2008; Christensen et al. 2008; Lafon et al. 2013; Salathé 2003; Teutschbein and Seibert 2012). Among them, the statistical downscaling method is to establish the statistical relationship between the global scale climate model output data under the climate scenario and the regional climate elements through years of observation data and test the relationship with independent observation data, and finally apply this relationship. Large-scale climate information output by GCM, scenario prediction of future climate change in the region, and conversion of large-scale and low-resolution climate information are included into surface-scale or point-scale ground climate information, such as rainfall and temperature. Finally, as an input condition, the basin hydrological model then analyzes the impact of climate change on hydrology and water resources. It compensates for the lack of GCM to predict regional climate change scenarios. The statistical downscaling method is relatively simple and easy to utilize, and its accuracy is as much as the dynamic downscaling method. Its research area and specific implementation scheme have greater flexibility. Therefore, it has been widely used in regional climate simulation and prediction studies.

The CMhyd tool (Rathjens et al. 2016) is selected to downscale climate data from GCMs for the Shiyang River Basin. CMhyd downscales the data provided by GCMs based on bias correction and to provide simulated climate data that can be considered representative for the location of the rainfall gauges used in a hydrological model. The bias correction framework is shown in Fig. 3.2. The bias correction is calculated based on the bias correction between the observed climate variables and the historical simulated climate model variables. The bias correction is performed by using a transformation algorithm for adjusting climate model output. The fundamental idea is to identify biases between observed and simulated historical climate variables to parameterize a bias correction algorithm that is used to correct simulated historical

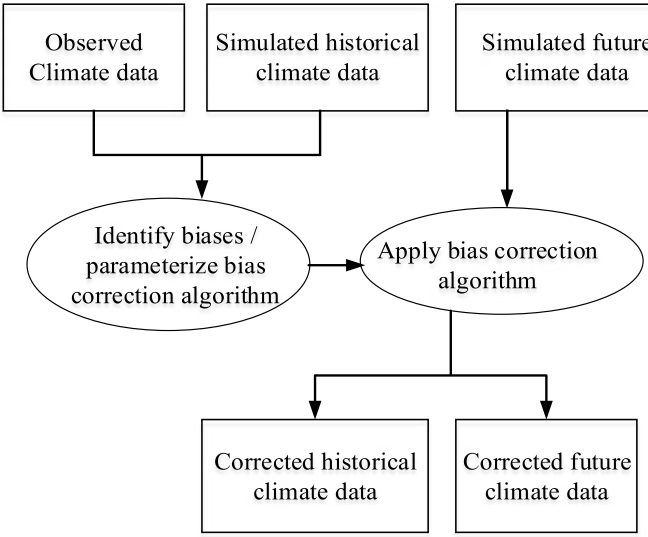


Fig. 3.2 Bias correction framework

climate data for each base site. Thus, the same bias correction algorithm is used to correct the forecasting variables of future climate scenarios exported by GCMS. However, it is not clear whether the conditions of future climate are consistent with the conditions of historical climate that are used for bias correction. In other words, the bias correction algorithm has a good performance during the evaluation of simulated historical climate variables does not guarantee a good performance under changed future conditions. Studies by Teutschbein and Seibert (2012) have shown that a method that performs well in climate data correction during the calibration period may have better performance of data correction in future climate change conditions than the methods that have performed poorly. In this study, the method is considered to be stable, for the correction algorithm and its parameters of current history climate condition are directly used for deviation of future climate.

3.1.4 Bayesian Model Averaging (BMA)

The global climate system models have a low resolution for precipitation simulation. Although many of these models can simulate large-scale regional precipitation trends in some regions, the simulation capability is poor at small scales (Steinschneider et al. 2012). Besides, due to the uncertainty of future emissions scenarios and downscaling methods, the estimation of future climate change is subject to great uncertainty. Therefore, how to reduce the uncertainty of global climate change and impact on water resources has become a difficult point (Fowler et al. 2007; Roosmalen et al.

2010). In recent years, multi-model integration methods have been widely used in the prediction of weather and climate and have achieved good prediction results.

Bayesian theory is often used to the study of climate change uncertainty. Raftery et al. (2005) developed the Bayesian model averaging method (BMA), based on Bayesian theory, to study the probabilistic prediction of surface temperature for 48 h. This method is a statistical post-processing method for predicting the probability density function. In recent years, this method has also been applied to hydrological comprehensive forecasting and hydrological model uncertainty analysis, such as groundwater model and rainfall–runoff model (Wilson et al. 2007). The mathematical method which obtains more reliable comprehensive forecasting value by weighted average forecast values of different models not only provides a more accurate model set forecast but can also calculate uncertainty within and between models through confidence interval estimation to quantitatively evaluate the uncertainty of model predictions (Ajami et al. 2006; Duan et al. 2007). Based on weighted estimates, two methods are used in this chapter, including Bayesian information criterion (BIC) and expectation–maximization algorithm (EM) which are introduced separately.

Bayesian Information Criterion BIC is a method for estimating weight approximately (Burnham and Anderson 2004). Many studies show that the Bayesian model averaging weight is more dependent on BIC when the number of samples is large enough. k is the number of model parameters. The definition of BIC in model M_i is:

$$\mathrm{BIC} = \log L(S|M_i, \theta_i) - \lambda \frac{k}{2} \log n \tag{3.4}$$

where λ is the penalty coefficient, n is the length of data series, and $L(D|M_i,\theta_i)$ is the likelihood function of sample data S given the model M_i.

$$L(S|M_i, \theta_i) = \prod_{m=1}^{n} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\left(\ln(y_m) - \ln\left(\hat{y}_m\right)\right)^2}{2\sigma^2}\right) \tag{3.5}$$

where θ_i is the model parameter, and y_m and $\hat{y}_m$ are the observed value of the mth data set and the estimation of the model, respectively. The posterior probability of model M_i is:

$$p(M_i|S) \approx \frac{\exp\left(\frac{\mathrm{BIC}_i}{2}\right) p(M_i)}{\sum_{l=1}^{k} \exp\left(\frac{\mathrm{BIC}_l}{2}\right) p(M_l)} \tag{3.6}$$

where $p(M_i)$ is the prior probability of model M_i, and $p(M_i) = 1/m$.

Expectation–Maximization Algorithm (EM) EM is an efficient method for calculating BMA based on the assumption that K model predictions are subject to a normal distribution (Raftery et al. 2005). Q is the forecast variable, $D = [X, Y]$ is the observed data (X is the input data, Y is the observed runoff data), and $f = [f_1, f_2 \ldots, f_K]$ is the ensemble of K model predictions. The forecast probability of BMA is:

$$p(Q|D) = \sum_{k=1}^{K} p(f_k|D) \cdot p_k(Q|f_k, D) \tag{3.7}$$

where $p(f_k|D)$ is the posterior probability of f_k which is the kth model forecast result under given observed data. It reflects the matching degree between f_k and observed flow. In other words, a single model forecast value can describe the probability of actual runoff process. In fact, $p(f_k|D)$ is the weight of BMA. The higher the accuracy of the model, the greater the weight. All weights are positive and add up to 1. $p_k(Q|f_k, D)$ is the conditional probability equation of forecast value Q under the condition that the model prediction f_k and data D given. If f_k obeys the mean value of f_k, the standard deviation is a normal distribution, and $p_k(Q|f_k D)$ can be expressed as $g(Q|f_k \sigma_k) \sim N(f_k \sigma_k)$.

The BMA averaging forecast value is the weighted average result of single model forecast values. If a single model forecast value and observed flow follow a normal distribution, the equation of BMA averaging forecast value is:

$$E(Q|f, D) = \sum_{k=1}^{K} p(f_k|D) \cdot g(Q|f_k, \sigma_k) = \sum_{k=1}^{K} w_k \cdot g(Q|f_k, \sigma_k) \tag{3.8}$$

and the BMA forecast variance can be calculated as:

$$\begin{aligned}\mathrm{Var}(Q|f, D) &= \sum_{k=1}^{K} p(f_k|D) \cdot \mathrm{Var}(Q|D, f_k) + \sum_{k=1}^{K} p(f_k|D) \cdot \sigma_k^2 \\ &= \sum_{k=1}^{K} w_k \left(f_k - \sum_{i=1}^{K} w_i f_i \right)^2 + \sum_{k=1}^{K} w_k \sigma_k^2\end{aligned} \tag{3.9}$$

Now, one will calculate the weight of BMA and model forecast deviation σ_k^2 through the EM algorithm. Heteroscedasticity in hydrological data is a common phenomenon (Sorooshian and Dracup 1980). Before applying the EM algorithm, the Box–Cox function is used to normalize the observed data and the model forecast flow data, thereby eliminating the heteroscedasticity of the data. Then, one uses the mapminmax function in MATLAB to normalize the converted data. Finally, the EM algorithm is used. The following principle and procedure of the EM algorithm are introduced.

First, $\theta = \{w_k, \sigma_k, k = 1, 2, \ldots, K\}$ is used to indicate the parameters of BMA. Then, the logarithmic form of the likelihood equation is:

$$l(\theta) = \log(p(Q|D)) = \log\left(\sum_{k=1}^{K} w_k \cdot g(Q|f_k, \sigma_k) \right) \tag{3.10}$$

where $g(Q|f_k\sigma_k)$ is the function value of the normal distribution function $N(f_{k,}\sigma_k)$ corresponding to the dependent variable Q. According to the equation, it is difficult to resolve the maximization likelihood equation through the analysis method. However, the EM algorithm can yield the maximum likelihood value by the reiteration of expectation and maximization until convergence. Then, the numerical solution of $\theta = \{w_k, \sigma_k, k = 1, 2, \ldots, K\}$ can be obtained. The specific procedure of calculating the BMA parameters by the EM algorithm contains the following steps:

(1) Initialization: Let Iter = 0. Then

$$w_k^{(0)} = 1/K, \sigma_k^{2^{(0)}} = \frac{\sum_{k=1}^{K}\sum_{t=1}^{T}\left(Q^t - f_k^t\right)^2}{K \cdot T} \tag{3.11}$$

where Iter is the number of iterations, T is the data length for calibration, and Y_t and f_k^t are the observed flow at time t and the predicted flow from the kth model, respectively.

(2) Calculate the initial likelihood value $l(\theta)$:

$$l(\theta)^{(0)} = \log\left(\sum_{k=1}^{K} w_k^{(0)} \cdot \sum_{t=1}^{T} g\left(Q^t|f_k^t, \sigma_k^{(0)}\right)\right) \tag{3.12}$$

(3) Calculate the occultation variance Z_k^t:
Let Iter = Iter + 1

$$Z_k^{t^{(\mathrm{Iter})}} = \frac{g\left(Q^t|f_k^t, \sigma_k^{(\mathrm{Iter}-1)}\right)}{\sum_{k=1}^{K} g\left(Q^t|f_k^t, \sigma_k^{(\mathrm{Iter}-1)}\right)} \tag{3.13}$$

(4) Calculate the weight w$_k$:

$$w_k^{(\mathrm{Iter})} = \frac{1}{T}\left(\sum_{t=1}^{T} z_k^{t^{(\mathrm{Iter})}}\right) \tag{3.14}$$

(5) Calculate the model forecast deviation σ_k^2:

$$\sigma_k^{2^{(\mathrm{Iter})}} = \frac{\sum_{t=1}^{T} Z_k^{t^{(\mathrm{Iter})}} \cdot \left(Q^t - f_k^t\right)^2}{\sum_{t=1}^{T} Z_k^{t^{(\mathrm{Iter})}}} \tag{3.15}$$

(6) Calculate the likelihood value $l(\theta)$:

$$l(\theta)^{(\mathrm{Iter})} = \log\left(\sum_{k=1}^{K} w_k^{(\mathrm{Iter})} \cdot \sum_{t=1}^{T} g\left(Q^t|f_k^t, \sigma_k^{(\mathrm{Iter})}\right)\right) \tag{3.16}$$

(7) Test the convergence: if $l(\theta)^{(\mathrm{Iter})} - l(\theta)^{(\mathrm{Iter}-1)}$ is less than or equal to the preset tolerance (le-10), it will stop, otherwise go back to the third step (3).

There are two ways to express the degree of uncertainty of hydrological projection estimation, standard error and confidence interval. The projection standard error is the standard bias between the estimated projection sample and true projection which is unknown. The variance and confidence interval of the projection can express the importance and the degree of uncertainty of the projection. Besides, confidence interval is of vital importance to determine the most suitable distribution line type in frequency analysis (Benson 1968).The BMA method can reduce the uncertainty of the model forecast, and quantitatively describe the uncertainty of the forecast and improve the effect of probability forecast (Min et al. 2007).

After obtaining BMA's weight w_k and model forecast deviation σ_k^2, the Monte Carlo combined sampling method can be used to produce the forecast uncertainty interval at any time about BMA. The steps involved (Hammersley and Handscomb 1975) are as follows:

(1) The weight ($[w_1, w_2, \ldots, w_k]$) of runoff is simulated according to each climate model, and an integer is randomly generated in the $[1{,}2 \ldots, k]$ to select a model k. Detailed steps are as follows:

- Assume a cumulative probability $w_k = 0$, and calculate $w_k = w_{k-1} + w_k (k = 1, 2, \ldots, K)$;
- Randomly generate a decimal u between 0 and 1;
- If $w_{k-1} < u < w_k$, it means that we choose the kth model.

2) Randomly generate flow by the probability distribution $N(f_k^{'}, \sigma_k^{'})$ at time t in the kth model.

(3) Repeat steps (1) and (2) M times, where M is the number of uncertainty interval sampling. $M = 1{,}000$.

BMA's 1,000 samples are obtained at any time through the above method and are sorted from small to large. BMA's 95% forecast uncertainty interval is the part between 2.5 and 97.5% quantities. It is worth noting that the 1,000 samples need to be converted by the mapminmax function and Box–Cox method.

Evaluation Index in BMA Three evaluation indices were used to evaluate the forecast uncertainty interval in BMA forecast results (Abbaspour 2014; Abbaspour et al., 2007).

(1) Coverage (CR): Coverage is the ratio of observed data to the forecast uncertainty interval. Higher coverage means better simulation results.

(2) Average bandwidth (B):

$$B = \frac{1}{T}\sum_{t=1}^{T}\left(q_u^t - q_l^t\right) \tag{3.17}$$

where q_u^t and q_l^t, respectively, represent the upper and lower bounds of forecast uncertainty interval at time t. B is one of the forecast uncertainty indices, too. For the specified confidence level, the average bandwidth of the forecast uncertainty interval should be narrow under the premise of ensuring a high coverage.

(3) Average deviation amplitude (DE): DE is an index measuring the degree of central line deviating from the observed flow hydrograph of forecast uncertainty interval.

$$\mathrm{DE} = \frac{1}{T}\sum_{t=1}^{T}\left|\frac{1}{2}\left(q_u^t + q_l^t\right) - Y^t\right| \tag{3.18}$$

where Y^t is the observed runoff at time t.

3.2 Results

3.2.1 Selection of Climate Model

To promote the development of climate models, 20 climate model working groups from around the world participated and developed the common climate simulation experiment, including the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012). All models in CMIP5 joined the process of the global carbon cycle and dynamic vegetation and improved the model horizontal resolution of the atmosphere and oceans and improved the atmospheric circulation dynamic framework, and introduced a new radiation project. These improvements have brought the simulation results closer to the historical real-world average climate conditions. CMIP5 uses a new generation of Representative Concentration Pathways (RCP), which is a new scenario that uses unit area radiative forcing to represent stable concentrations over the next 100 year, including RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Each of RCP was named by the expected radiative forcing, warming and impact of human activities in 2100. RCP4.5 is a medium-emission scenario with a radiation forcing of 4.5 W/m^2 by 2100 and a carbon dioxide concentration of 650 ppm (Ebi et al. 2014; Taylor et al. 2012). This emission scenario is the most likely scenario in the future and the model test data are also the most realistic, and future climate change is more representative. Therefore, daily precipitation and temperature data in historical and future RCP4.5 scenarios of the five climate models provided by CMIP5 were selected, and the basic information of the models is shown in Table 3.1.

Table 3.1 Basic information on models

No.	Model	Research institution	Resolution
1	MRI-CGCM3	Meteorological Research Institute	320 × 160
2	CanESM2	Canadian Centre for Climate Modelling and Analysis	128 × 64
3	CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avanceesen Calcul Scientifique	256 × 128
4	GFDL-CM3	Geophysical Fluid Dynamics Laboratory	144 × 90
5	FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University	128 × 60

3.2.2 Analysis of Downscaled Precipitation

The precipitation series from the climate model were downscaled, based on CMhyd, and divided into historical verification period (1990–2005) and future forecast period (2018–2100). The former period is used for calibration and verification of the downscaling model; the latter period is used to forecast the precipitation change in the future. The future forecast period can be divided into three stages: 2018–2039, 2040–2069, and 2070–2100 and named period I, II, and III, respectively. The variation trends of temperature and precipitation in the three periods in different climate models were analyzed, and runoff was predicted. Observed precipitation interpolation database is the baseline site of precipitation. For the selection of the baseline temperature site data, the daily maximum temperature and daily minimum temperature data series for 2008–2016 of the SWAT model from China atmospheric assimilation driving database (CMADS V1.1) (Meng et al., 2015) were selected, and a total of 17 baseline sites were selected in the study area. Linear regression correlation analysis was used to downscale the temperature in the model to each reference site.

The simulated monthly precipitation value of the statistical climate model GFDL-CM3 during the verification period of six tributaries in the Shiyang River Basin was counted, and the scatter plot and correlation analysis with the observed monthly precipitation values in the basin were analyzed, as shown in Fig. 3.3. The difference between the linear regression slope and 1 is called the linear system error. The simulation results can be seen visually. Results show that in the verification stage of a climate model GFDL-CM3, except for the Xiying River Basin and the Huangyang River Basin, the R^2 between the simulated and observed values of other watersheds reached 0.5 or more. It indicated that the simulated precipitation value can reflect the observed precipitation. At the same time, the accuracy of simulated precipitation in the verification stage of other climate models was analyzed, as shown in Fig. 3.4. Results show that although the climatic models have different precipitation simulation effects in different watersheds, they are better than the MRI-CGCM3 model as a whole, and the correlation between the simulated values and the observed values is more. Among them, the precipitation simulation effect of each climate model in Dongda River watershed is better than that in other watersheds, and for the simulation

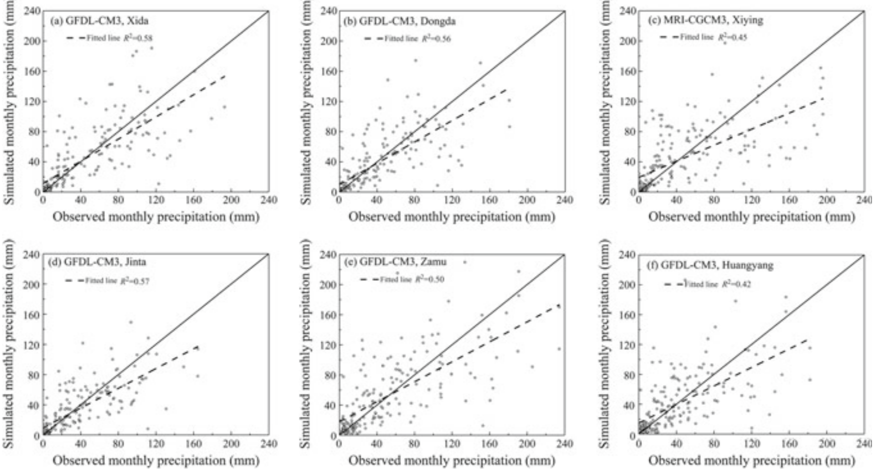


Fig. 3.3 Observed–simulated scatter plot of monthly precipitation in each tributary under the GFDL-CM3 climate model

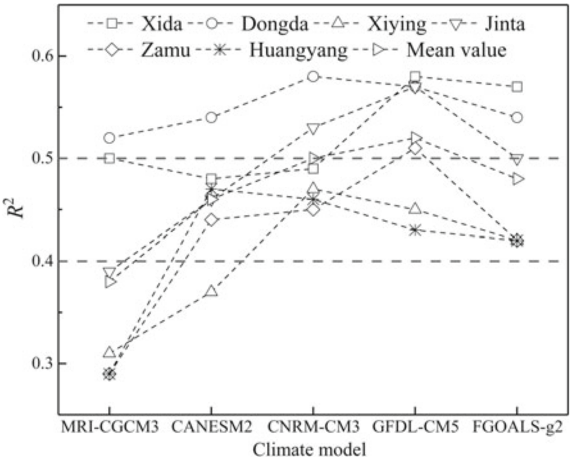


Fig. 3.4 R^2 of simulated and observed monthly precipitation in the six tributaries under climate model in 1990–2005

effect of different climate models in Shiyang River Basin, GFDL-CM3 is the best, only the model's average R^2 of the Shiyang River Basin exceeded 0.5, followed by CNRM and FGOALS, and the average R^2 is close to 0.5, while the MRI-CGCM3 was with the worst simulation effect. The R^2 of precipitation models in all watersheds was mainly concentrated between 0.42 and 0.58. Overall, the downscaling method used in this chapter will have different precipitation simulation values for different climate models and different basins in the verification period, but most of the models were within acceptable limits.

3.2.3 Analysis of Downscaled Temperature

The correlation analysis between the maximum simulation daily temperature, the minimum simulation daily temperature and the daily reference temperature are shown in Fig. 3.5, where climate models including MRI-CGCM3, CanESM2, CNRM-CM5, GFDL-CM3 and FGOALS-g2 at the base station #1 in the verification stage are con-

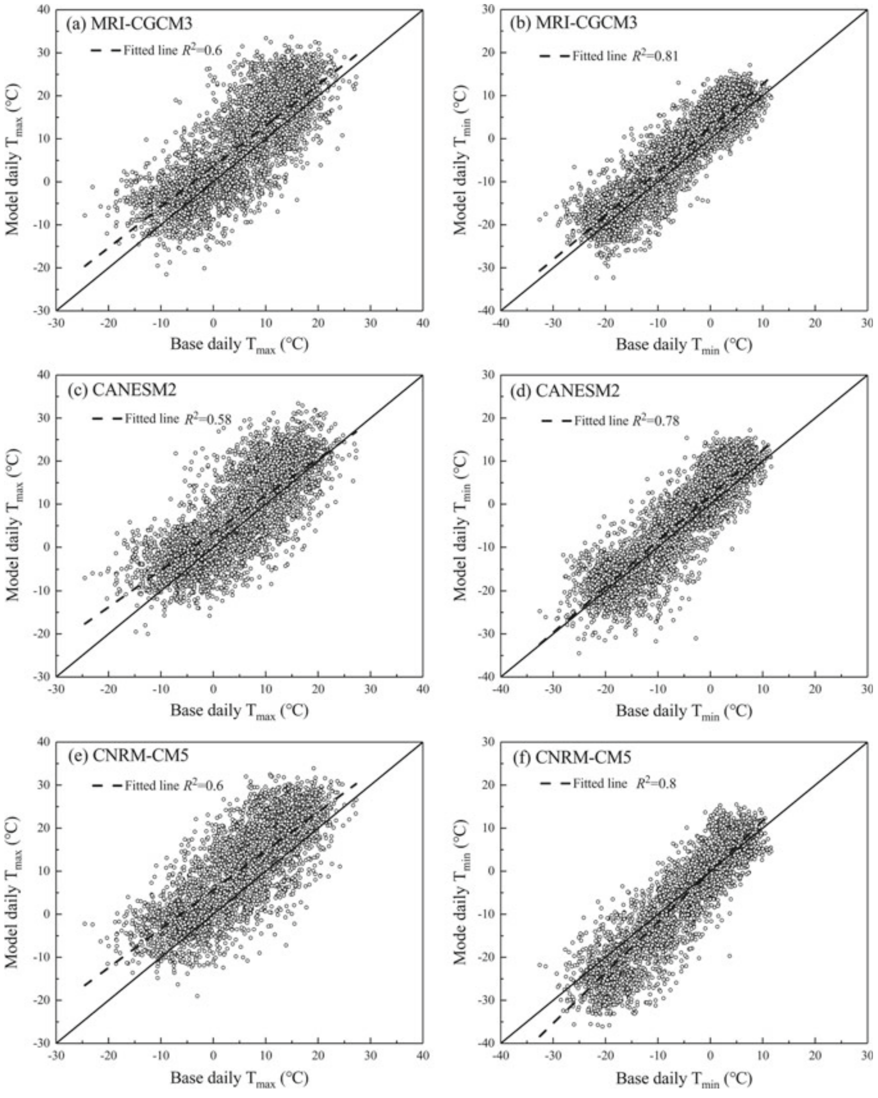


Fig. 3.5 Base-model scatter plot of daily maximum and minimum temperatures for different climate models at station 1

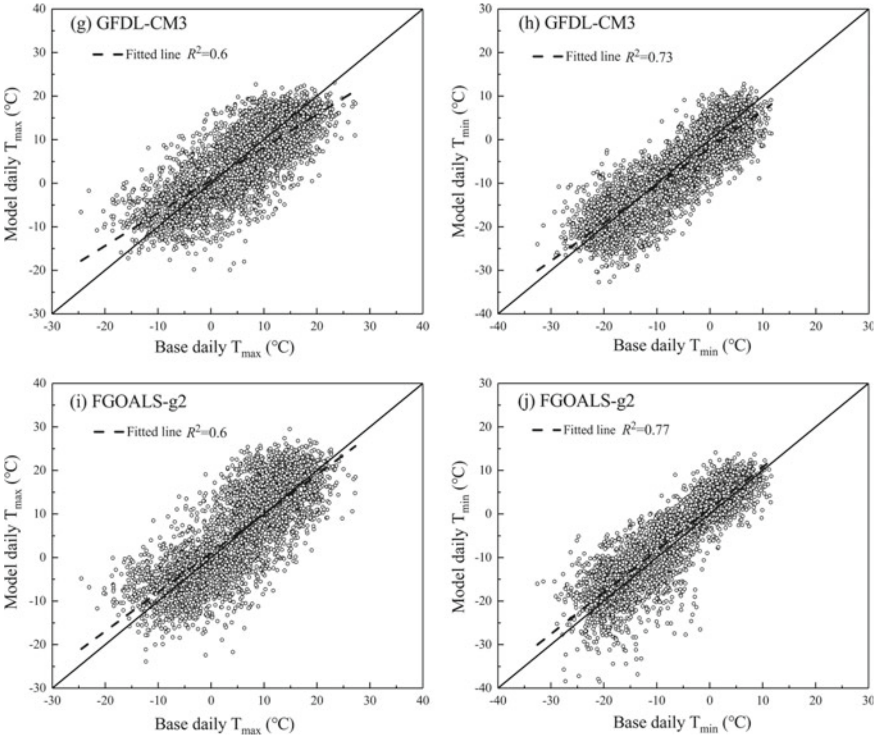


Fig. 3.5 (continued)

sidered. In Fig. 3.5 and the following part, T_{max} and T_{min} indicate the daily maximum and minimum temperature values of the climate model, respectively. The correlation between simulated temperature and reference temperature at other 16 reference sites was also counted, as shown in Fig. 3.6. The overall result of temperature downscaling showed that the simulated effect of maximum temperature and minimum temperature of each model was great and determination coefficient R^2 exceeded 0.5. The simulated effect of the minimum temperature of each model was better than of maximum temperature. The simulation results of the minimum and maximum temperatures of FGOALS-g2 and MRI-CGCM3 among the five models are higher than the other three models, and the R^2 of minimum temperature was between 0.72 and 0.76. Overall, the temperature downscaling method used in this chapter will have different effects on the temperature simulation values of different climate models during different reference site verification periods, but all models were within the acceptable range and the simulation results of the minimum temperature were excellent.

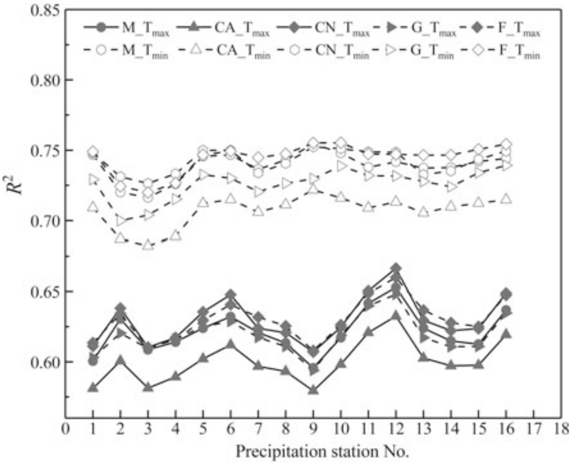


Fig. 3.6 R^2 between daily maximum, minimum temperature, and reference day temperatures of each reference site in climate models (where M, CA, CN, G, and F in the legend are the acronyms for climate model of MRI-CGCM3, CanESM2, CNRM-CM5, GFDL-CM3, and FGOALS-g2, respectively.)

3.2.4 Uncertainty of Runoff Prediction During Verification Period based on Climate Model

Uncertainty Analysis of Runoff Prediction Based on BIC Five climate models of MRI-CGCM3, CanESM2, CNRM-CM5, GFDL-CM3, and FGOALS-g2 in CMIP5 were selected, based on Bayesian information criterion (BIC) for Dongda River, Xiying River, Jinta River, Zamu River, and Huangyang River. Results of runoff simulation of multiple climate models from 2008 to 2013 were analyzed by the linear regression model of Bayesian model, as shown in Table 3.2, and index of BIC in BMA for five basins is shown in Fig. 3.7, where the meaning of each parameter in the table is: $p!$ indicates the posterior probability of the variable, the larger value of which means the contribution of climate model to BMA model is larger. SD represents the standard deviation. EV represents the average value of the variable coefficients in each model. BIC represents the Bayesian information criterion, and the smaller the value, the better the fitting effect of the model. The models with the most posterior probabilities selected by the model are listed in Table 3.2, and the last line in the table indicates the cumulative posterior probability of the selected model. In the figure, the legend of 1–5 corresponds to model 1 to model 5 in BMA in Table 3.2. Taking the Dongda River as an example, it can be seen from Table 3.2 and Fig. 3.7 that under the Bayesian information criterion, the posterior probabilities of the five climate models vary greatly, and the MRI-CGCM3 posterior probability is 100%, which is the best in the simulation. The proportion of the five models is the second, followed by GFDL-CM3 and FGOALS-g2, and the posterior probabilities are 58.2 and 38.9%, respectively. This means that these three climate models had a greater impact on and contribution to the Bayesian model's average calculation model, while the CanESM2 and CNRM-CM5 had low posterior probabilities, which is equivalent to a small contribution.

Table 3.2 Results of Bayesian model average based on BIC

Basin	Climate model	$p! = 0$	EV	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Dongda	Intercept	100	1.599	0.191	1.441	1.723	1.573	1.849	1.717
	MRI-CGCM3	100	0.32	0.055	0.288	0.326	0.348	0.392	0.313
	CanESM2	8.5	−0.004	0.033					
	CNRM-CM5	18.5	0.021	0.065					0.173
	GFDL-CM3	58.2	0.094	0.098	0.168		0.153		
	FGOALS-g2	38.9	−0.044	0.068			−0.088	−0.104	−0.159
Xiying	Intercept	100	0.621	0.125	0.671	0.543	0.597	0.689	0.636
	MRI-CGCM3	100	0.481	0.069	0.462	0.457	0.548	0.466	0.463
	CanESM2	48.3	0.098	0.124		0.157	0.254		
	CNRM-CM5	76.2	0.167	0.12	0.238	0.17		0.274	0.223
	GFDL-CM3	10	0.003	0.026					0.033
	FGOALS-g2	11.8	−0.004	0.028				−0.051	
Jinta	Intercept	100	1.191	0.205	1.238	1.152	1.25	1.182	0.778
	MRI-CGCM3	100	0.695	0.089	0.746	0.627	0.751	0.636	0.713
	CanESM2	10.8	−0.005	0.05			−0.024	−0.067	
	CNRM-CM5	43.2	0.088	0.123		0.204		0.211	
	GFDL-CM3	97.2	−0.378	0.133	−0.367	−0.416	−0.364	−0.41	
	FGOALS-g2	100	−0.412	0.101	−0.387	−0.454	−0.387	−0.455	−0.234
Zamu	Intercept	100	0.603	0.12	0.664	0.515	0.61	0.592	0.602
	MRI-CGCM3	100	0.643	0.066	0.677	0.582	0.645	0.666	0.666
	CanESM2	9	0.003	0.03					0.045

(continued)

Table 3.2 (continued)

Basin	Climate model	$p! = 0$	EV	SD	Model 1	Model 2	Model 3	Model 4	Model 5
	CNRM-CM5	32	0.045	0.081		0.14			
	GFDL-CM3	9.8	0.004	0.026				0.047	
	FGOALS-g2	10.6	0.004	0.026			0.052		
Huangyang	Intercept	100	1.199	0.108	1.224	1.117	1.169	1.195	
	MRI-CGCM3	100	0.403	0.048	0.411	0.388	0.372	0.405	
	CanESM2	8.8	0.004	0.027				0.041	
	CNRM-CM5	11	0.008	0.038			0.075		
	GFDL-CM3	15.2	0.011	0.034		0.069			
	FGOALS-g2	100	−0.24	0.062	−0.239	−0.221	−0.259	−0.25	

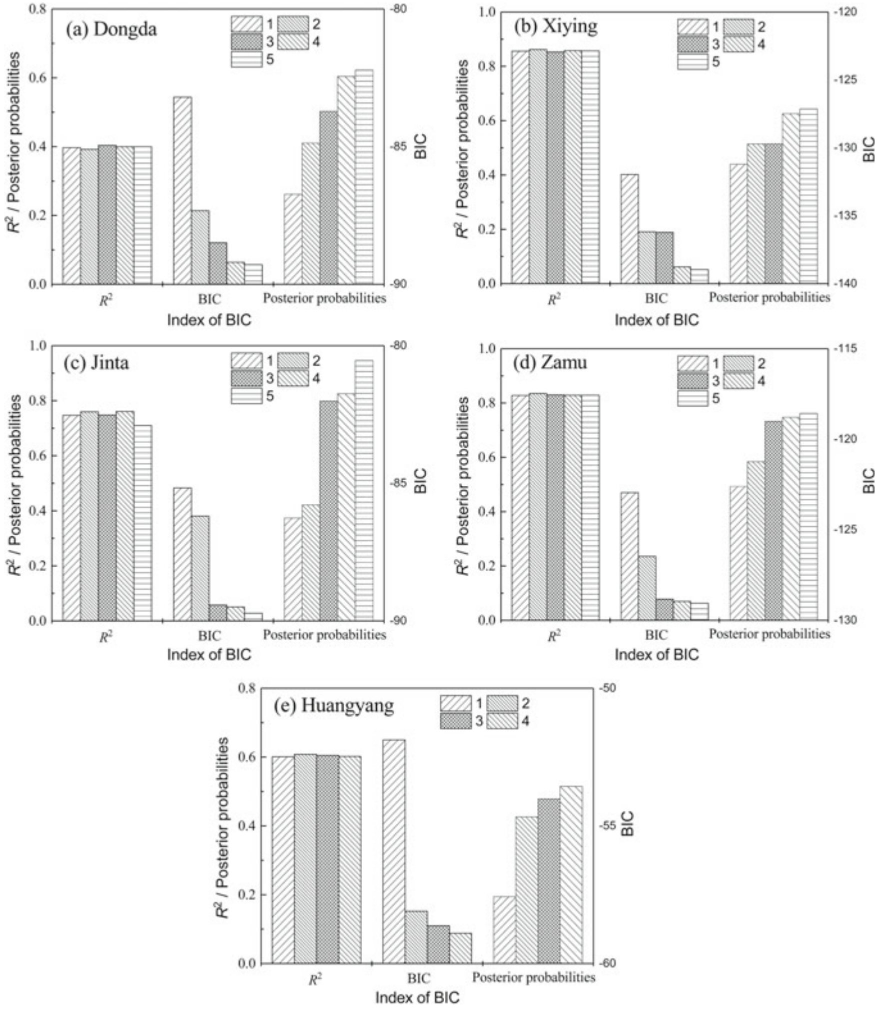


Fig. 3.7 Index of BIC in BMA for five basins (1–5 in the legend correspond to the model 1 to model 5 in BMA in Table 3.2)

The best model of the Bayesian model average result is model 1, of which the posterior probability was only 0.544, and the cumulative posterior probability of the first five models was 0.82, indicating that the uncertainty of the model was relatively large in the data set. In the table, the positive data in the column of model 1–5 indicate that the contribution of the corresponding climate model to the BMA model is positive, while the negative data indicate that the contribution is negative. Results showed that the MRI-CGCM3 model contributes to the average calculation of the Bayesian model in the five basins and has the largest contribution, and the other four climate models have different performances in different watersheds. Among them, GFDL-CM5 has a larger contribution in Dongda River and Jinta River, and the contribution values of FGOALS-g2 in Jinta River and Huangyang River are both larger.

Uncertainty analysis of runoff prediction based on EM. According to the BMA theory, the probability of hydrological model runoff simulation results input by each climate model is weighted, and the conditional probability density function of each model runoff forecast is weighted to obtain the probability density function of the forecast variable. The synthesis and probabilistic forecasting of runoff forecasting is done in multi-climate mode. Finally, the expectation-maximization algorithm is used to estimate the parameters of BMA.

The expectation-maximization (EM) algorithm is used to comprehensively predict the runoff forecast values during the five climate model verification periods, and the determination coefficient is used as the objective function to estimate the comprehensive forecast values obtained by the five model parameters. The evaluation of the accuracy of the results of the BMA comprehensive forecast runoff and the forecast values of the individual model of the five models are listed in Table 3.3. The bold data in this table indicates the individual climate model with *NS* greater than 0.5, as well as the evaluation results of BMA. The *RMSE* in the table is the root-mean-square error of monthly runoff, and *RE* is the relative error of the total monthly runoff. The BMA weights of the single climate model in the five basins are also shown in Fig. 3.8. It can be concluded from Table 3.3 that the runoff simulation effect of the single model is not qualified except for the performance of MRI-CGCM3 for the Xiying River and the Zamu River. At the same time, the simulation effect of BMA comprehensive forecast runoff in each basin is analyzed. The value of *NS* can reach 0.54 in the Xiying River Basin, which is a qualified range, but the effect is not good in other basins. At the same time, the comprehensive forecast value of each basin BMA is higher than that of some single models in the relative error of total runoff. However, the BMA comprehensive forecasting method has improved the runoff simulation effect in the five basins for single model input, except for the simulation effect of MRI-CGCM3 in the basins of Xiying River, the Zamu River, and the Huangyang River, and CanESM2 in the Huangyang River Basin.

Combining Table 3.3 and Fig. 3.8 for analysis, taking Dongda River as an example, CanESM2, CNRM-CM5, GFDL-CM3, and FGOALS-g2 have lower simulation accuracy than MRI-CGCM3, but the MRI-CGCM3 with the highest simulation accuracy among the five has the smallest weight in the BMA model. Similarly, in the Xiying River, the Jinta River, and the Zamu River, the simulation accuracy of MRI-CGCM3 is higher than that of other models, but the weight of the model in these three basins is lower than that of other models. So the weight of a single model is not necessarily proportional to the simulation effect and has a certain relationship with the uncertainty distribution of a single model. The weight synthesis reflects

Table 3.3 Simulation accuracy results of BMA comprehensive forecast runoff and forecast values of individual model

Basin	Climate model	R^2	*NS*	*RMSE*	*RE*
Dongda	MRI-CGCM3	0.43	0.01	7.34	0.19
	CanESM2	0.18	−0.04	7.54	0.26
	CNRM-CM5	0.22	−1.35	11.32	−0.21
	GFDL-CM3	0.16	−0.36	8.62	0.10
	FGOALS-g2	0.08	−2.26	13.34	−0.34
	BMA	**0.33**	**0.14**	**6.86**	**−0.02**
Xiying	MRI-CGCM3	0.66	**0.56**	4.73	0.13
	CanESM2	0.22	0.11	6.75	0.18
	CNRM-CM5	0.42	−0.79	9.59	−0.46
	GFDL-CM3	0.13	−0.23	7.94	0.04
	FGOALS-g2	0.32	−0.19	7.80	−0.28
	BMA	**0.57**	**0.54**	**4.86**	**−0.09**
Jinta	MRI-CGCM3	0.48	0.40	2.46	0.26
	CanESM2	0.08	−0.05	3.25	0.33
	CNRM-CM5	0.18	−1.45	4.96	−0.58
	GFDL-CM3	0.00	−0.43	3.78	0.20
	FGOALS-g2	0.03	−4.77	7.61	−0.71
	BMA	**0.09**	**−0.03**	**3.21**	**−0.12**
Zamu	MRI-CGCM3	0.69	**0.60**	3.88	0.01
	CanESM2	0.14	−0.05	6.30	0.05
	CNRM-CM5	0.37	−1.08	8.86	−0.55
	GFDL-CM3	0.09	−0.94	8.56	−0.17
	FGOALS-g2	0.29	−1.11	8.93	−0.49
	BMA	**0.55**	**0.42**	**4.67**	**−0.23**
Huangyang	MRI-CGCM3	0.42	−1.24	3.62	−0.21
	CanESM2	0.07	−1.19	3.58	−0.16
	CNRM-CM5	0.18	−8.45	7.44	−1.01
	GFDL-CM3	0.21	−3.76	5.28	−0.48
	FGOALS-g2	0.00	−8.96	7.64	−0.98
	BMA	**0.29**	**−1.65**	**3.94**	**−0.57**

Fig. 3.8 BMA weight for multiple climate models in five basins

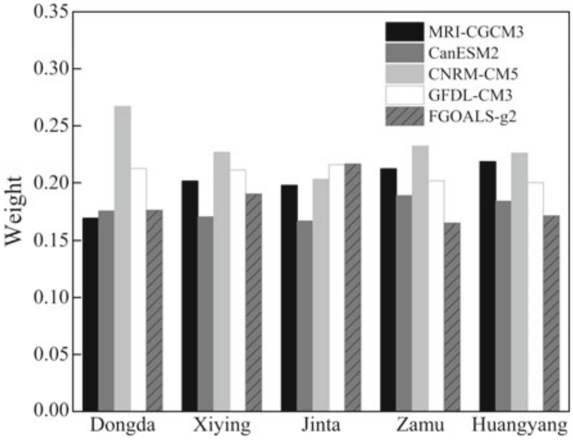
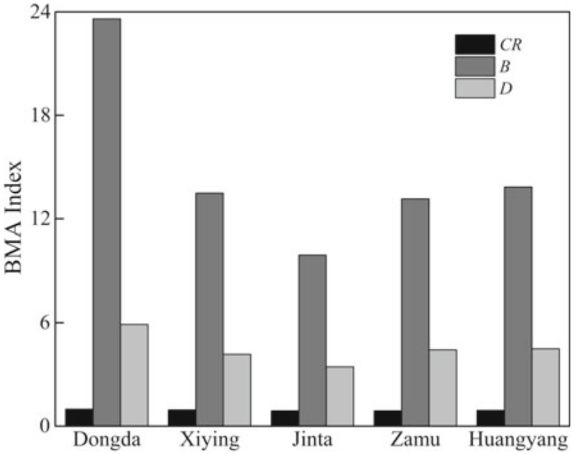


Fig. 3.9 Evaluation index of prediction uncertainty interval in BMA



the common effect of simulation accuracy and runoff prediction uncertainty. It can be seen that the model with the highest posterior probability for each watershed in the Bayesian model average calculation of the BIC method is MRI-CGCM3, that is, the weight of the model is the highest. While in the expectation-maximization algorithm, the weight of CNRM-CM5 and GFDL-CM3 is larger than of other climate models, followed by MRI-CGCM3. The results obtained by the two Bayesian methods are different but have something in common, indicating that both methods can obtain weights to reflect the contribution of a single model to the Bayesian model's comprehensive prediction.

The evaluation index of prediction uncertainty interval in BMA in each basin is shown in Fig. 3.9. Results show that the coverage ratio (*CR*) of the BMA comprehensive forecast runoff in the forecast interval of each basin is not much different, and the value range is 0.89–0.99. The coverage rate is relatively high. At the same time, the average bandwidth (*B*) of the Dongda River is significantly higher than that of other basins, and the average deviation range (*DE*) of the forecast interval is basically the same except for the Dongda River.

The 95% uncertainty interval for BMA runoff prediction for each basin is shown in Fig. 3.10 which shows that the observed values of runoff are indicated by small dots,

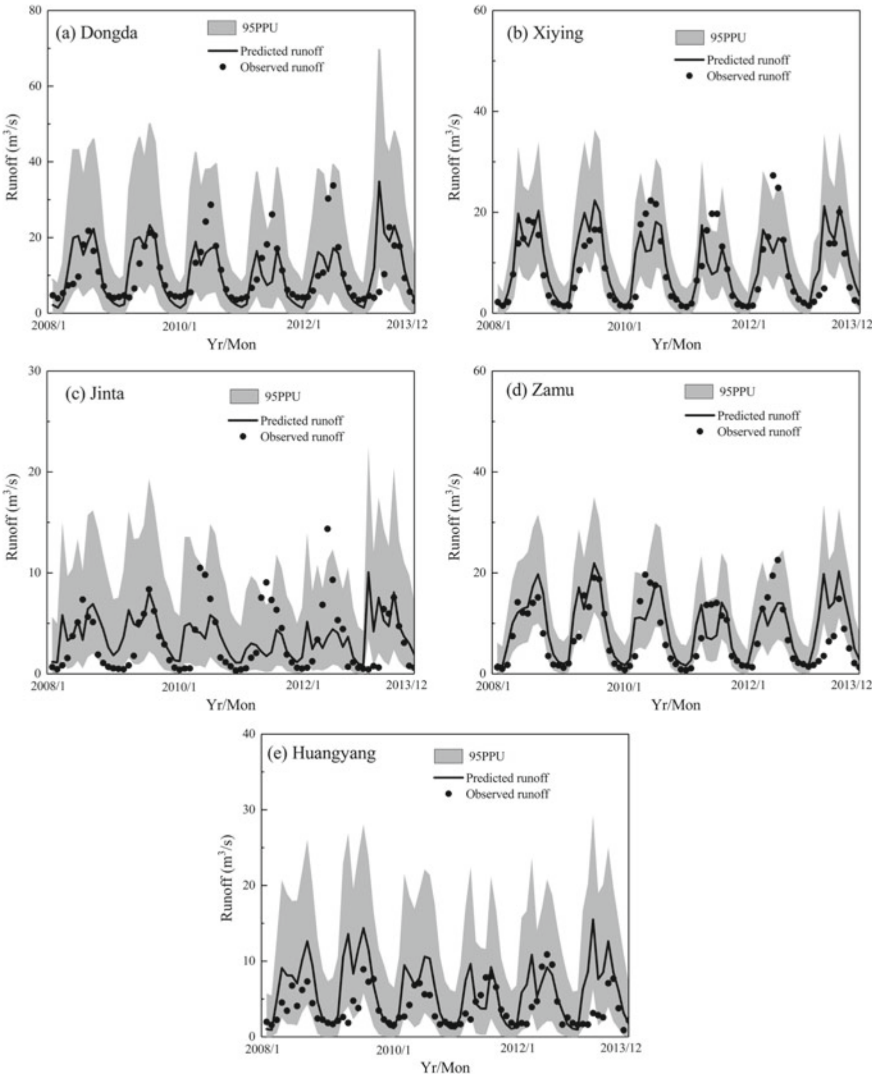


Fig. 3.10 95% prediction uncertainty interval in BMA in five basins

the comprehensive runoff predicted the value of BMA is indicated by the solid red line, and 95% prediction uncertainty interval in BMA in five basins is represented by the shaded gray. Combined with the analysis of the chart, it can be concluded that the comprehensive forecast value of BMA can reflect the runoff process of the observed flow, and the simulation effect in the low-flow area of the runoff is better, but the effect in the high-value area is not ideal.

3.2.5 Runoff Prediction and Trend Analysis Under Climate Model

For the Dongda River, the Xiying River, the Jinta River, the Huangyang River, and the Zamu River in the Shiyang River Basin, the series of downscaling daily precipitation and daily temperature data of the RCP4.5 scenario from 2018 to 2100 are used in the above five models as the input to the SWAT model to forecast the monthly runoff of each basin in the future period and compare with the runoff in the historical period (1990–1999) to assess the runoff variation. The monthly runoff forecast process in the future period is shown in Fig. 3.11.

The precipitation change rate (%), temperature change (°C), and runoff change rate (%) in the three future periods under various climate models are shown in Table 3.4. The absolute change rate of precipitation, runoff, and temperature (%) under climate models over the three future periods in the future is plotted in Fig. 3.12.

In Xida River Basin, it shows that different climate models have different significant change rate of precipitation, minimum and maximum temperature in the same basin during the same period and also cause the difference in the variability rate of the predicted runoff. For other watersheds, there is also the existence of this situation. By analyzing the variability results of the same model in different watersheds, it can be found that since the five watersheds are adjacent watersheds, the variability of each variable in each basin is different, but the variability trend for the whole time period is similar. In general, the maximum and minimum temperatures of each model show a significant increase between 2018 and 2100. For precipitation, CNRM-CM5 and FGOALS-g2 show an increasing trend in the future period. GFDL-CM3 has a trend of increasing first and then decreasing in the West River, the Dongda River, and the Jinta River and showing an increasing trend in the other three watersheds. At the same time, CanESM2 has a significant increasing and then decreasing trend, while for MRI-CGCM3, there is a clear first decreasing and then increasing trend. Under the combined effect of precipitation and temperature, the overall variability trend of different climate models in the future period of each basin is consistent with the trend of precipitation, indicating that precipitation input has the most significant impact on the process of runoff prediction. In other words, precipitation input is the main source of runoff prediction error.

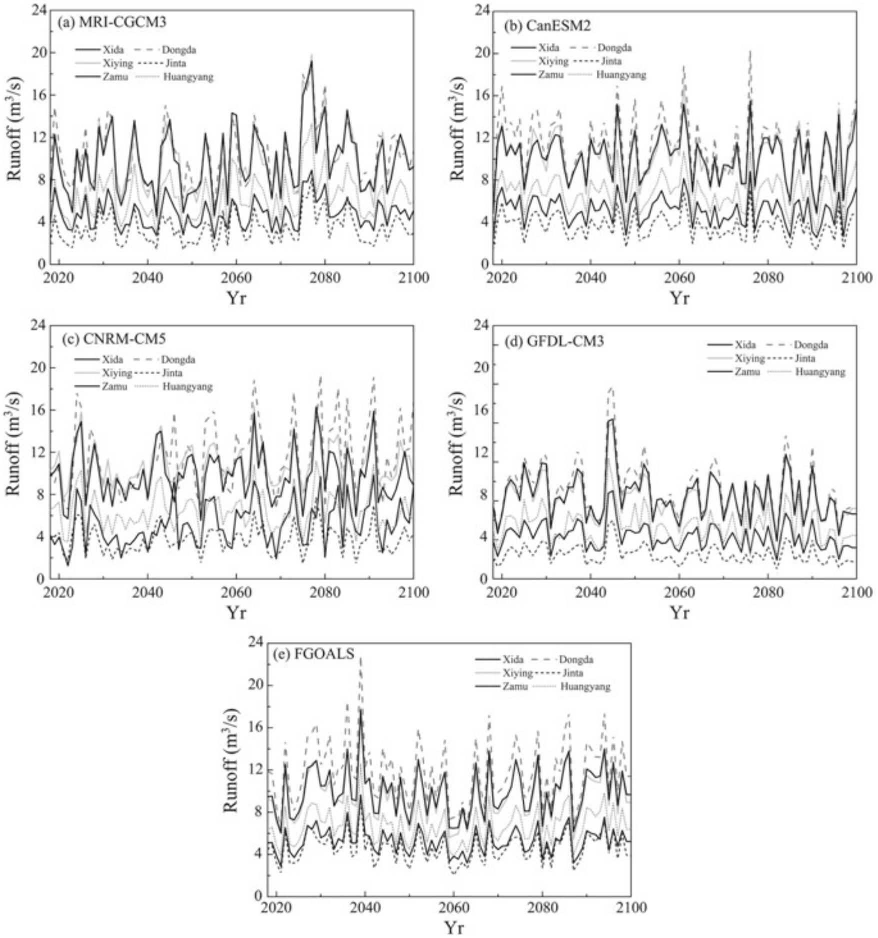


Fig. 3.11 Forecast of monthly runoff in the six rivers of Shiyang River Basin during 2018–2100

At the same time, as shown in Fig. 3.12, most of the model precipitation, maximum and minimum temperature, and runoff forecast values will be higher than the historical period (1990–1999), but the results of different models in the same basin have obvious differences. It is possible to visually see the uncertainty of future climate predictions for different climate models in the CMIP5 model group.

Table 3.4 Change rate of precipitation and runoff (%), and absolute change of temperature (°C) under climate models in the future

Basin	Variable	MRI-CGCM3			CanESM			CNRM-CM5			GFDL-CM3			FGOALS-g2		
		I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Xida	Precipitation	9.6	2.7	8.0	26.9	30.0	25.5	−11.2	5.0	14.3	1.1	2.3	0.1	12.2	12.2	21.7
	$T_{\max}$	0.1	0.5	0.9	0.6	1.3	1.7	0.4	0.6	1.0	0.9	2.0	3.0	0.2	0.9	0.8
	$T_{\min}$	0.5	1.0	1.5	0.2	1.0	1.4	−0.7	−0.2	0.4	−1.1	−0.1	1.0	2.0	2.9	2.7
	Runoff	−14.0	−15.5	−3.0	0.3	0.2	−7.7	−23.4	−2.8	10.7	−14.0	−14.4	−26.0	3.3	−6.7	0.7
Dongda	Precipitation	4.6	−1.9	3.3	18.1	22.8	17.9	−9.3	1.9	8.1	−3.3	−2.0	−3.6	6.6	6.5	16.1
	$T_{\max}$	0.1	0.5	0.9	0.6	1.3	1.7	0.4	0.6	1.0	0.9	2.0	3.0	0.2	0.9	0.8
	$T_{\min}$	0.8	1.3	1.8	0.4	1.3	1.7	−0.1	0.5	1.0	−0.3	0.7	1.8	2.8	3.8	3.6
	Runoff	2.8	−0.6	16.1	21.7	21.6	10.9	4.8	20.9	31.5	1.4	2.8	−13.7	31.1	15.2	27.2
Xiying	Precipitation	2.6	−2.4	3.2	17.7	21.3	18.7	−0.7	6.6	9.6	−3.5	−2.3	−1.8	4.2	3.6	14.9
	$T_{\max}$	0.1	0.5	0.9	0.6	1.2	1.7	0.4	0.6	1.0	0.9	2.0	3.0	0.2	0.9	0.8
	$T_{\min}$	0.4	0.9	1.4	0.1	0.9	1.4	0.0	0.6	1.1	−1.2	−0.7	0.5	1.4	2.4	2.2
	Runoff	−5.6	−7.3	9.5	6.5	6.5	3.9	7.0	14.5	15.3	−11.5	−11.7	−21.0	1.8	−8.2	2.8
Jinta	Precipitation	1.9	−3.6	1.7	17.4	20.4	17.0	−7.0	2.7	6.2	−5.8	−5.1	−6.2	2.1	1.9	12.9
	$T_{\max}$	0.1	0.6	1.0	0.7	1.4	1.9	0.4	0.7	1.1	1.0	2.3	3.4	0.3	1.0	0.9
	$T_{\min}$	0.0	0.2	0.8	−0.6	0.3	0.8	−1.2	−0.6	−0.1	−1.4	−0.4	0.8	1.8	2.7	2.6
	Runoff	−20.2	−19.4	−2.6	−1.9	−3.5	−12.1	−12.9	−2.7	−2.0	−31.0	−31.4	−43.3	24.6	6.9	24.1
Zamu	Precipitation	11.7	6.3	12.9	26.9	30.4	26.6	2.4	10.3	11.6	−9.1	−7.0	−7.0	11.9	11.9	23.7
	$T_{\max}$	0.1	0.5	0.9	0.6	1.3	1.8	0.4	0.7	1.1	1.0	2.1	3.2	0.3	1.0	0.9
	$T_{\min}$	−0.1	0.3	0.9	−0.4	0.4	0.9	0.0	0.6	1.1	−1.3	−0.2	0.9	1.9	2.9	2.7
	Runoff	26.7	28.7	48.2	41.6	44.9	41.1	31.5	42.3	41.1	23.7	24.8	9.0	41.3	29.9	43.8

(continued)

Table 3.4 (continued)

Basin	Variable	MRI-CGCM3			CanESM			CNRM-CM5			GFDL-CM3			FGOALS-g2		
		I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Huangyang	Precipitation	9.2	3.8	10.9	18.5	21.5	18.9	−1.7	6.4	8.2	14.9	17.7	17.7	9.5	9.5	20.9
	$T_{\max}$	0.1	0.5	0.9	0.6	1.3	1.7	0.4	0.7	1.0	0.9	2.1	3.1	0.3	0.9	0.8
	$T_{\min}$	0.2	0.7	1.2	−0.1	0.7	1.1	−0.5	0.1	0.6	−1.8	−0.8	0.2	1.2	2.1	1.9
	Runoff	61.9	64.1	92.2	86.7	93.1	86.4	12.7	26.3	24.5	−1.5	−0.1	−17.0	34.4	16.3	38.5

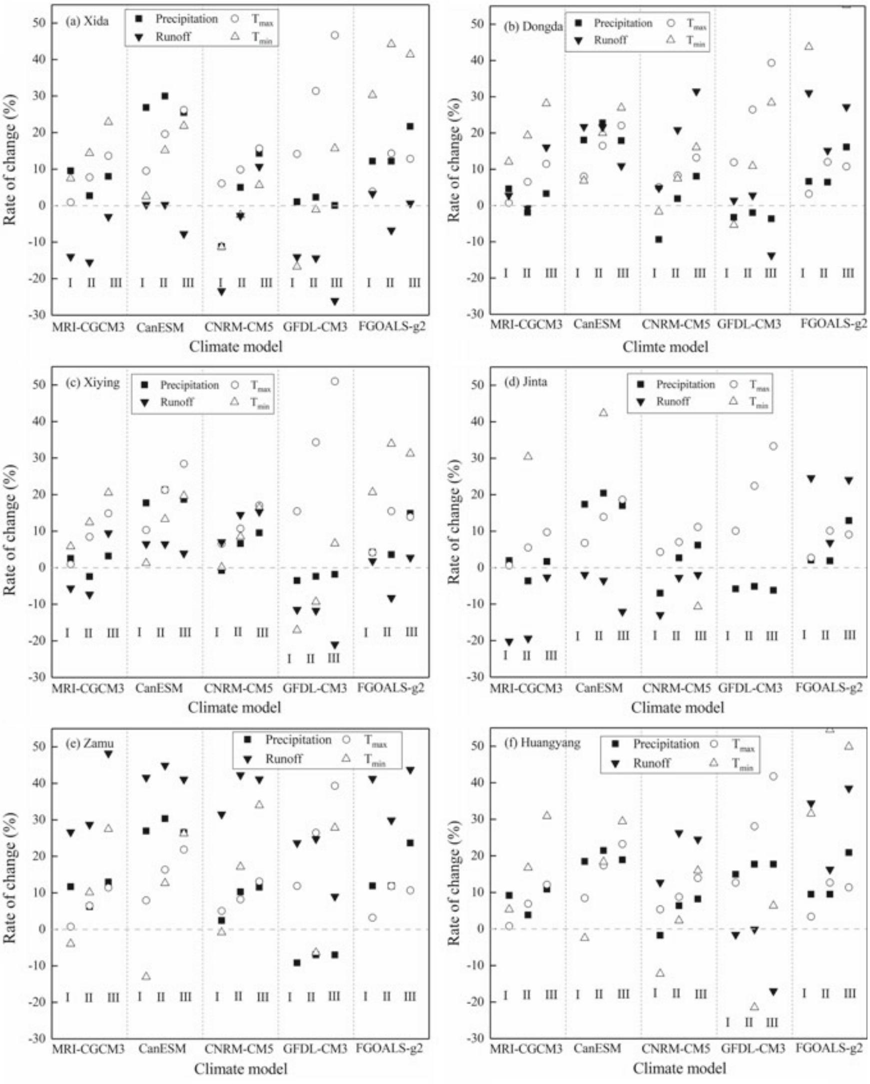


Fig. 3.12 Change rate of precipitation, runoff, and temperature (%) under climate models in the future

3.3 Conclusion

For the simulation accuracy analysis of precipitation and temperature of five climate models during the verification period of each basin in Shiyang River Basin, the determination coefficient R^2 of precipitation is mainly concentrated in the range of 0.42–0.58. For the results of precipitation downscaling in different basins of five climate models, most models are within acceptable limits. At the same time, the downscaling results of the maximum and minimum temperature of the climate models are excellent overall, and the determination coefficient R^2 is greater than 0.5. The simulated effect of the minimum temperature of each model is higher than the maximum temperature, among which the R^2 of minimum temperature from FGOALS-g2 and MRI-CGCM3 reached a range of 0.72–0.76.

The BMA comprehensive forecasting method has improved the runoff simulation effect under the single model input in the five basins, except for the simulation effect of MRI-CGCM3 in the Xiying River, the Zamu River, the Huangyang River, and CanESM2 in the Huangyang River. At the same time, the weight of a single model in BMA is not necessarily proportional to the simulation effect of the model. It also has a certain relationship with the uncertainty distribution of a single model. The weight synthesis reflects the common effect of simulation accuracy and runoff prediction uncertainty. Among the BIC and EM algorithms, MRI-CGCM3 and GFDL-CM3 contribute more to the BMA comprehensive forecast. At the same time, the comprehensive forecast value of BMA can reflect the runoff process of observed flow, and the simulation effect in the low-value area of runoff is better than that in the high-value area.

The maximum and minimum temperatures of each model in the future period are obviously increasing between 2018 and 2100. For precipitation, CNRM-CM5 and FGOALS-g2 show an increasing trend in the future, GFDL-CM3 in the Xida River, the Dongda River, and the Jinta River has a trend of increasing first and then decreasing, and showing an increasing trend in the other three watersheds. At the same time, CanESM2 has a clear trend of increasing first and then decreasing, while for MRI-CGCM3, the opposite is true. The future trend of runoff change is consistent with the trend of precipitation change, indicating that precipitation input is the main source of runoff prediction error. Compared with the historical period (1990–1999), precipitation, maximum and minimum temperatures, and predicted runoff in most models will increase. Results of different models in the same basin have obvious differences. It is possible to find the uncertainty of future climate predictions for different climate models in the CMIP5 model group.

For future research, multiple hydrological models can be used for runoff prediction to enhance the analysis of prediction uncertainty. At the same time, if the accuracy of precipitation input data in the climate model can be improved, it will help effectively use hydrological models to better understand the uncertainty of runoff prediction under climate change.

Acknowledgements The financial support from the National Natural Science Foundation of China (No. 51279166 and No. 51879222) is gratefully acknowledged.

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Chapter 4
Alteration of Groundwater Hydrochemistry Due to Its Intensive Extraction in Urban Areas from Mexico

Ariadna Ocampo-Astudillo, Sofía Esperanza Garrido-Hoyos, Edith Rosalba Salcedo-Sánchez and Manuel Martínez-Morales

Abstract The intensive groundwater extraction in Mexico over the years has caused adverse effects, included groundwater level decline, subsidence, and groundwater quality modifications. This study aimed at determining the hydrochemical changes produced by intensive groundwater extraction in Mexico divided into three sectors—north, central, and south of the country. The groundwater quality deterioration due its intensive extraction can be caused by many processes such as, upwelling geothermal or/and mineralized water from deeper aquifers in response to lowering of the potentiometric surface, due to heavy pumping that favors the induction of the flow-through of faults, geological fractures, or deeper wells with a higher concentration of some elements (Fluor, Arsenic, Sodium, Potassium, Nitrates, Sulfates, Chlorides, Vanadium and Boron). Also, the intensive groundwater use favors the infiltration of organic pollutants from the sewerage and percolation of rainwater, resulting in the rapid transport of groundwater and contaminants throughout the aquifer.

Keywords Groundwater · Intensive extraction · Urban areas demand · Pollutant transport

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4.1 Introduction

Groundwater is a vital natural resource for the reliable and economical provision of potable water supply in an urban and rural environment. It thus plays an essential role in human well-being, as well as that of some aquatic and terrestrial ecosystems (Kemper et al. 2003).

In many regions, groundwater is the only source for water supply, the population growth, industrialization, urbanization and changing land use patterns have placed high demand of groundwater resources and also this development makes groundwater a critical resource for human activities (Esteller et al. 2012; Martín del Campo et al. 2014; Gárfias et al. 2010; Carrillo-Rivera et al. 2008; Flores-Marquez et al. 2006).

During the last decades in Mexico fulfilling water demand continues to be a challenge for society due to the growth of urban and industrial centers and the environmental deterioration of water resources that restricts its use (Salcedo-Sánchez et al. 2013). Groundwater supplies 39% (33,819 Mm^3/yr) of the country's total water use (86,577 Mm^3/yr); this water is mainly used for agriculture 20,500, around 75 million people rely on this source for water supply, 50% of self-supplied industrial facilities use groundwater in their processes (Esteller et al. 2012).

Furthermore, groundwater demand put at risk the sustainability of aquifers, such as the intensive extraction that causes a significant decline in piezometric groundwater level. This adverse condition results in decreasing water volume and recurrently water quality changes (Esteller et al. 2012; Martín del Campo et al. 2014; Gárfias et al. 2010; Carrillo-Rivera et al. 2008; Flores-Marquez et al. 2006; Salcedo-Sánchez et al. 2013).

Water resources management is one of the most urgent environmental issues in Mexico (Gárfias et al. 2010; Moran-Ramírez et al. 2016; Salcedo et al. 2017). In the country, the National Water Commission based on water balance estimation classifies with the wrong connotation of "overexploited aquifers" those where exploitation exceeds the average annual recharge, and long-term continuation of this condition is expected to produce of adverse environmental impacts. In these terms according to this administrative agency, the country is divided into 653 aquifers, and 16% have the condition of over-exploitation (Fig. 4.1) (CONAGUA 2017). The number of overexploited aquifers has increased from 32 in 1975 to 36 in 1981, 80 in 1985, 97 in 2001, and 101 in 2008, 106 in 2013 and 106 in 2016 (Esteller et al. 2012; CONAGUA 2014, 2017).

However, water is relatively abundant in the poorer Southern states, nearly 80% of the population and approximately 85% of gross domestic product is concentrated in the Northern and Central regions, where water is limited (CONAGUA 2017). Therefore, over 50% of the volume of water consumed from groundwater sources in Mexico is drawn from aquifers situated in the semi-arid and arid parts of the country (Carrillo-Rivera et al. 2008; Esteller et al. 2012; CONAGUA 2017). Although demand for water in the industrial and the municipal sectors are suffering a steady increase, most of the water consumption remains concentrated in the agricultural sector (CONAGUA 2017; World Bank 2009).

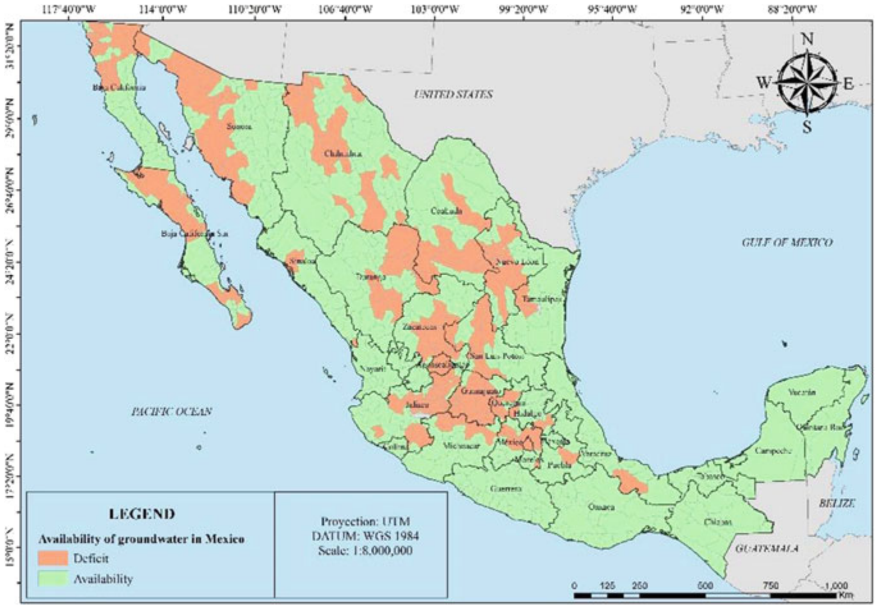

Fig. 4.1 Groundwater availability in Mexico

It is crucial to hold the problem of groundwater intensive extraction, and where its impacts will have the most immediate impact on the incomes of poor people. The causes of these problems are a combination of natural, economic and institutional factors (Esteller et al. 2012; Martín del Campo et al. 2014; Gárfias et al. 2010; Carrillo-Rivera et al. 2008; Flores-Marquez et al. 2006; Salcedo-Sánchez et al. 2013). In effect, economic and population growth has been concentrated in those areas where water availability is the lowest (World Bank 2009).

In other words, groundwater levels continue to decline, and as a result, increase the groundwater extraction costs, decreasing crops and finally, the total depletion of groundwater resources will have considerable impacts on economic activity (World Bank 2009).

4.2 Effects of Intensive Groundwater Extraction in Mexico

4.2.1 Northern Mexico

The most arid regions of Mexico are in the north of Mexico, with medium-to-low rainfall; the imbalance is critical due to intensive extraction. This chapter explains the problem of the intensive groundwater extraction in the area of the Comarca Lagunera region and Chihuahua (Fig. 4.2).

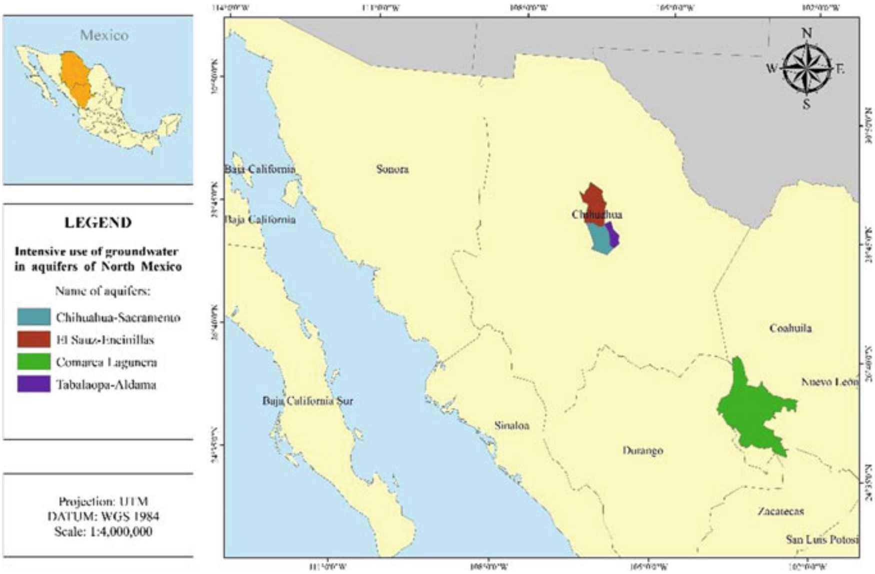

Fig. 4.2 Problematic intensive groundwater extraction in the northern area of Mexico

4.2.1.1 Comarca Lagunera

Groundwater has in arid and semi-arid areas from México a significant role in Mexican Welfare and economic development. The groundwater extraction naturally enriched in toxic elements is a concern in the country. Arsenic in groundwater has become a problem in regions such as La Comarca Lagunera, Salamanca, San Luis Potosi, Chihuahua, and La Laguna Region, among many others. The range of As values reported in Mexico commonly includes concentrations above the Mexican drinking water standards NOM-127-SSA1-1994 (0.025 mg/L) (DOF 2000), high concentrations are reported in some studies (Camacho et al. 2011; Reyes-Gómez et al. 2013).

One of the most significant problems of groundwater public supply in Mexico is the occurrence of arsenic in groundwater of “La Comarca Lagunera,” located in the central part of northern Mexico is one of the most important agricultural and livestock areas of the country. Due to its dry weather, groundwater extraction is a significant component of its economic growth.

Thousands of people have already contracted the symptoms of arsenic poisoning (such as changes in skin pigmentation, gastrointestinal disturbances, neurological changes, lung cancer, and muscular weakness, characterize arsenic poisoning in humans) and others are at risk of arsenic contamination from drinking well water. For the first time in 1958, the high levels of arsenic in drinking water were identified as the cause of adverse effects on health at Comarca Lagunera (Cebrián et al. 1994;

Rodríguez et al. 2004; Parga et al. 2005; Armienta and Segovia 2008; Avilés et al. 2013).

Groundwater contamination in Comarca Lagunera may produce high levels of arsenic in the pasture and contribute to increased arsenic levels in cattle and their products. This arsenic transfer is especially relevant since it is one of the leading milk producers of México (Rosas et al. 1999; Armienta and Segovia 2008).

Studies focused on the presence of arsenic in water and health effects have been carried out at Comarca Lagunera, where both natural and anthropogenic sources are reported. Armienta and Segovia (2008) and Camacho et al. (2011) have found that the presence of As in the Comarca Lagunera is attributed either to natural process such as mineral dissolution, hydrothermal system with high contents of Lithium, Boron, Arsenic, and Fluoride or mobilization of As from the aquifer clay to the groundwater, due to desorption of As retained on clay. Geochemical modeling was carried out to determine the evaporated surface water carried by the Nazas and Aguanaval rivers. Those could have contributed to the elevated As concentrations found in the lower parts of the alluvial aquifer in the Lagunera region of northern México or of contamination due to the use of organoarsenical pesticides in the cotton fields and also mining and smelting of ores containing arsenic (Parga et al. 2005; Armienta and Segovia 2008; Camacho et al. 2011).

Studies reported that the predominant species of As in La Comarca Lagunera was As(V). The trivalent form As(III) is more toxic than the pentavalent form As(V), but toxic trivalent forms have been found with the pentavalent forms.

4.2.1.2 Chihuahua

Groundwater contamination by Fluoride and Arsenic has been reported in Chihuahua State, northern Mexico, where the primary source of water supply is groundwater from the "Chihuahua-Sacramento," "Tabalaopa-Aldama" and "Sauz-Encinillas" aquifers. The estimated global water demands are met by pumping wells that extract 118 Mm^3 annually, which 41% corresponded to urban water consumption (Palma et al. 2018).

Arsenic and Fluoride reached maximum values of 0.039 and 4.55 mg/L, respectively, in groundwater samples in the year of 2010. Various studies have been developed in this area to determine the geochemical characteristics of rocks, sediment, and groundwater and the origin of As and F in the system.

Reyes-Gómez et al. (2013) determined several geochemical processes to investigate the origin of As and F in groundwater from central Chihuahua, encompassing three contiguous aquifers: Tabalaopa–Aldama, Aldama–Dolores, and Laguna de Hormigas. Their analyses' results were obtained from 37 wells samples during seven years, showing Arsenic and Fluoride concentration above the recommended limit for drinking water use (0.025 and 1.5 mg/L, respectively). These wells were located in the south and northeastern parts of the study area, which correspond to areas more heavily pumped and near the town of Aldama. The potentiometric levels in 2007 changed drastically in 2010, indicating more substantial groundwater withdrawals for 2010. For example, between 2004 and 2010, the depth to the groundwater table dropped approximately 40 m in some wells.

The highest F levels were detected in the transition zone of Tabalaopa-Aldama toward Laguna de Hormigas (encompassing the urban and suburban zones of Aldama) as well as in the southeast part of the study area, coinciding in a large extent with the location of the wells contaminated with As. Concentrations of Arsenic and Fluoride in groundwater samples had a positive correlation ($r = 0.738$ in 2007 and $r = 0.832$ in 2010), indicating a co-occurrence of As/F within the aquifer.

Based on geochemical interpretation, the presence of Arsenic and Fluoride in groundwater can be attributed to weathering processes such as fragmentation and dissolution of the volcanic and sedimentary rocks such as rhyolite and shale; adsorption and desorption processes from clays and iron oxides; oxidation of arsenopyrites in the soil. Also, external sources may translate substances to the aquifer, such as rivers from agricultural areas, or by mining activities. If the groundwater level declines, due to the increased groundwater extractions, the deeper layers become more exposed and present higher F and As concentration (Reyes-Gómez et al. 2013).

The geochemical process in the aquifer as possible sources of arsenic dissolved in groundwater is called alkaline desorption; consists of ion exchange, the calcium dissolved in groundwater exchanges with the sodium of the clays. By decreasing the calcium in the water, the calcite dissolves, which increases the pH due to the presence of bicarbonates. When increases the pH > 8.1, the net charge on the surface of iron oxide becomes negative and repels arsenic ions (negative charge) causing the desorption of arsenic (Mejía-González et al. 2014).

4.2.2 Central Mexico

The most populated and economically active area of Mexico is on the Trans-Mexican Volcanic Belt (TMVB) in central Mexico. The Trans-Mexican Volcanic Belt has a length of 900 km and an average width of 130 km. Its average height is 2500 m and extends across Nayarit, Puebla, Tlaxcala, Hidalgo, Estate of Mexico, Morelos, Querétaro, Guanajuato, Michoacán, Guerrero and Mexico City.

In central Mexico, many aquifers are intensively exploited by agriculture and urban water, which results in subsidence, faults, and fracture, decline in the groundwater table, decrease in river flow, the drying-up of springs and a deterioration of water quality (Esteller and Díaz-Delgado 2002; Morales-Arredondo et al. 2016). Figure 4.3 shows the study areas with the most significant problems of intensive groundwater extraction in central Mexico.

Many processes can cause the groundwater quality deterioration due to the intensive extraction. Two main causes are the following:

- upwelling geothermal or/and mineralized water from deeper to shallow aquifers in response to lowering of the potentiometric surface due to heavy pumping that favors the induction of the flow-through of faults and geological fractures pro-

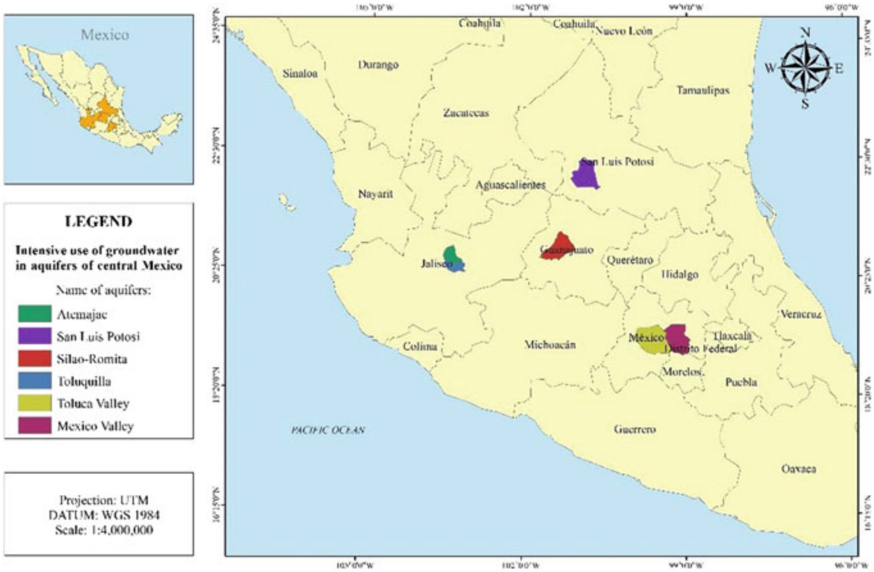

Fig. 4.3 Problematic intensive groundwater extraction in central Mexico

ducing a mixed fluid with relatively high concentrations of TDS (Flores-Marquez et al. 2006; Gárfias et al. 2010; Salcedo et al. 2017),

- contaminant input from the non-point surface (agricultural irrigation, exfiltration of wastewater in sewerage systems sources) due to infiltration processes through soil and rocks (Esteller and Diaz Delgado 2002; Félix-Cañedo et al. 2013).

4.2.2.1 Toluca Valley

The Toluca valley aquifer is in the central portion of the State of Mexico, covering an area of 2738 km^2 (Martín del Campo et al. 2014). It is one of the most studied aquifers because of its high population density and the water needs of the industrial park are almost exclusively met by groundwater. The intensive extraction of groundwater in the Toluca Valley aquifer has caused a decline in the groundwater level and physical–chemical changes in groundwater, due to an increase in salinity, nutrients, major and minor ions and trace elements (Esteller and Andreu 2005).

Some authors have carried out the inventory of pumping wells in order to determine the groundwater extraction volume in the Toluca Valley aquifer. Their results show the greatest accumulated declines (over 40 m) occurring in the central portion of the Toluca Valley aquifer from 1979 to 2010 and the maximum average rate of 2.5 m/yr. Also, quite a lot of fissures have been identified in the urban and industrial area where it could be related with both good density and extraction volumes,

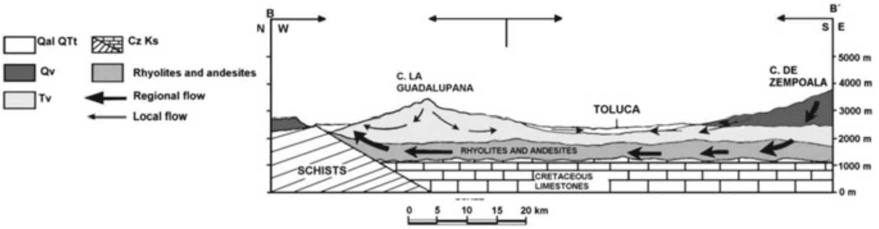

Fig. 4.4 Regional geological profile indicating the regional and local groundwater flows from Toluca Valley (Esteller and Andreu 2005)

and their main effects are groundwater contamination to wastewater discharges and sewage networks infiltrations (Martín del Campo et al. 2014).

The chemical characteristics of groundwater for 1984 to 1998 and 1991, 1998, 2004, and 2010 were studied. Initially, groundwater in a local flow zone was exploited; this water was of Mg^{2+}–Na^{+}–HCO_3^{-} type, and this composition did not change drastically over time, its origin comes from recharge of the aquifer by rainwater infiltration and lateral flows from adjacent basalt and andesite fractured aquifers. The intensive extraction of groundwater had produced changes in its chemistry, increasing the concentrations of NO_3^{-}, Cl^{-}, SO_4^{2-} K^{+}, Na^{+} over the years, due to the decline of the water table level, because waters from a regional flow zone had been induced to enter to water wells. This regional flow is characterized by longer contact time, a deeper circulation and recharge through the Tertiary (Oligocene) rhyolites and andesites (Fig. 4.4).

The water type of groundwater from the regional flow is sodium–magnesium bicarbonate, with high K+ (11 mg/L) and higher EC (978 μS/cm) and temperature (23 °C), as compared to temperature (18 °C) and EC (233 μS/cm) in the local flow. The chemical composition is shown in a Pieper diagram, demonstrating the existence of three water groups: GI, GII, and GIII. The GI corresponds to wells with a higher concentration of Cl^{-}, SO_4^{2-} K^{+}, Na. GII includes wells with a lower sulfate content. Finally, the GIII group shows less sulfate and could represent the aquifer without anthropogenic interference, which is characterized by calcium bicarbonate water (Fig. 4.5).

Also, the highest concentration of NO_3^{-} corresponded to the urban area, which contamination could be related to domestic sewage discharges and the high degree of SO_4^{2-} and Cl^{-} may be due to industrial and urban wastewater infiltration that was favored by the appearance of a drawdown cone in the aquifer (Esteller and Andreu 2005; Esteller et al. 2012; Martín del Campo et al. 2014).

4.2.2.2 Guadalajara

The Guadalajara Metropolitan Area is in the north-central portion of the state of Jalisco, in western Mexico, extends across the following municipalities: Guadala-

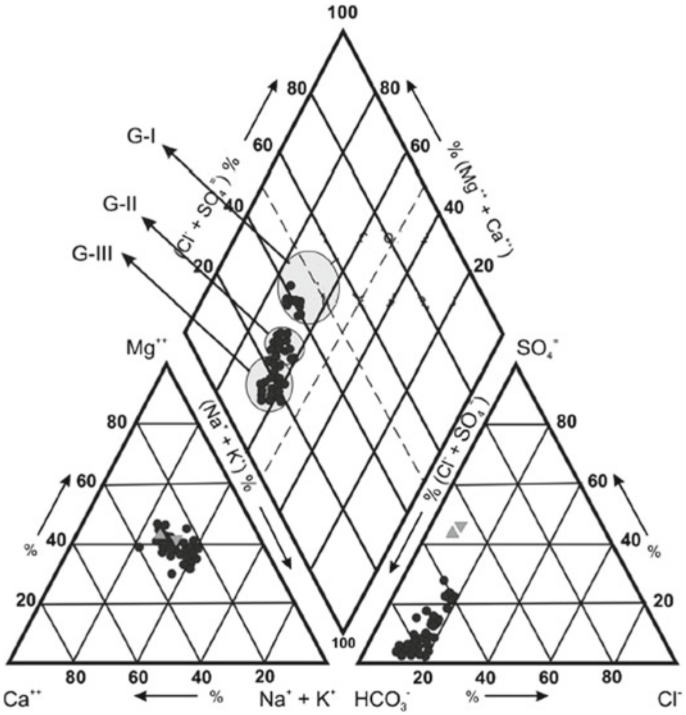

Fig. 4.5 Pieper diagram of hydrochemical data in Valley of Toluca (Martín del Campo et al. 2014)

jara, Zapopan, San Pedro Tlaquepaque, Tlajomulco de Zuniga, Tonala, El Salto, Zapotlanejo, Ixtlahuacan de los Membrillos, and Juanacatlan; is the second-largest urban area in Mexico where are 5 million inhabitants (IIEG 2017).

The water supply for The Metropolitan Zone of Guadalajara (ZMG) consists of two sources: principally from the Lake Chapala and the rest from springs and groundwater. The groundwater mainly comes from the aquifers Atemajac and Toluquilla. According to official data, the volume of extraction in Toluquilla aquifer is approximately 59.8 hm^3/yr, of which 39.4 hm^3/yr (65.9%) are designed for agricultural use, 12.8 hm^3/yr (21.4%) for public-urban use, 5.3 hm^3/yr (8.9%) for industrial use, 0.7 hm^3/yr (1.2%) for domestic use-trough, 1.1 hm^3/yr (1.8%) for service use and the remaining 0.5 hm^3/yr (0.8%), for multiple uses. The total volume extraction in Atemajac aquifer for all uses is 159.5 hm^3/yr, principally to supply Guadalajara. Secondly, Zapopan, followed by Tlaquepaque and finally Tonalá. The primary uses are for drinking water and industrial, after agriculture and livestock (CONAGUA 2009, 2010).

Some studies have been carried out to characterize groundwater chemistry and to assess the spatial variability of various physical–chemical elements in order to evaluate the groundwater pollution and understand the processes controlling water chemistry of Guadalajara's aquifer system. In hydrogeological terms, the type of groundwater is dominated by $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ while the anions are dominance of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$.

Hernández-Antonio et al. (2015) and Moran-Ramírez et al. (2016) showed that the geochemistry of the aquifers Atemajac and Toluquilla is mostly sustained by weathering of rock-forming minerals and anthropogenic activities and is classified into four groups: cold groundwater (CG), it is located in the recharge zones and the type of water is Na^+–HCO_3^-. Then, the mixed groundwater (MG) moves from the recharge zones and undergoes mixing and attains a Na^+–HCO_3^-. The thermal groundwater with highest salinity and temperature comes from Toluquilla valley (HG) features a Mg^{2+}–HCO_3^- and mixed HCO_3^- water type and polluted water (PG) is shallow water locally found in Guadalajara metropolitan area with a Na^+–SO_4^{2-} to mixed-HCO_3^- water type, with increased NO_3^-, SO_4^{2-}, and Cl^+ concentrations standing for anthropogenic pollution.

The nitrate concentrations are related with agricultural activities involving nitrogen components such as fertilizers such as urea ($(NH_2)CO$) and ammonium sulfate ($(NH_4)_2SO_4$) or organic byproducts, septic tanks and livestock manure. In urban areas, nitrate contamination is originated from infiltration of wastewater and leaching of waste disposal. The presence of fluoride in groundwater samples varies between 0.0 and 4.9 mg/L, and 15% of the samples exceeded the national drinking water standard (1.5 mg/L). The high concentrations of Fluoride can be attributed to natural origin from weathering of fluoride-bearing rock-forming minerals like fluorite, biotite, and muscovite. Finally, the primary ions are mostly sustained by weathering of rock-forming minerals and anthropogenic activities. The groundwater system is affected by local recharge, infiltration of poor water and hydrothermal fluids.

4.2.2.3 Salamanca City

Another significant case of aquifer exploitation and groundwater contamination in Central Mexico is Salamanca City located in Guanajuato State, where live 273,271 inhabitants and water needs are exclusively met by groundwater because there is no alternative source of surface water due to pollution of the Lerma River, which passes through the City but is heavily polluted by discharges of untreated municipal and industrial wastewater (Rodríguez et al. 2005; Esteller et al. 2012; INEGI 2015). The primary water consumption in Salamanca is agriculture with 70% of the total water extraction, secondly, the industrial consumption with 23%, for least, the domestic consumption that presents approximately 7% of the abstraction (Rodríguez et al. 2005).

The Salamanca city is supplied with water from the Silao-Romita aquifer; belonging to the Lerma-Santiago-Pacific Basin. The shallow aquifer is non-exploited. The urban wells are exploiting the intermediate formation, whereas the deep unit is only used for the thermoelectric plant. A regional fault is hydraulically communicating the shallow aquifer with the intermediate aquifer (CONAGUA 2011).

The intensive extraction of groundwater has led to a significant change in the distribution of the original underground flow. Also, the presence of layers of clay interspersed in the aquifer system, combined with their intensive extraction, has resulted in accumulated subsidence about 70–80 cm of the downtown of the urban area of Salamanca (Rodríguez et al. 2005).

Several studies have been carried out to show the vulnerability of pollution aquifer in Salamanca city. The results show that the most vulnerable area corresponds to the fault trace. The refinery lands are located in areas of very low vulnerability, but the fault, which crosses them in the southeast portion, makes the situation vulnerable. The high vulnerability area is located in the northern zone with the presence of Arsenic in groundwater, which was detected in almost all the urban wells in Salamanca area at concentration levels between 0.01 and 0.05 mg/L during 2003 and 2004. Vanadium was also detected in groundwater, as it shows maximum values of 0.08 mg/L (Rodríguez 2002, Rodríguez et al. 2005).

The vulnerable areas, in addition to the faults and fractures created by subsidence in the northern portion, have facilitated the migration of Arsenic from industrial surface emissions to shallow groundwater. Another process that is involved in groundwater pollution is the dissolution of solutes from the diffuse sources and its later leakages toward the aquifer; it is also possible that faults are increasing surface water inflow, oxidizing the Arsenic-bearing minerals, thus increasing Arsenic concentration in groundwater. The authors of the studies carried out in the Salamanca aquifer have concluded that pollution problems highlight the fact that intensive extraction of groundwater has caused subsidence, fractures of land and, consequently, greater vulnerability of the aquifer to pollutants from point and diffuse sources (Rodríguez 2002; Rodríguez et al. 2005; Esteller et al. 2012).

4.2.2.4 Valley of Mexico

The Metropolitan Zone of Valley of Mexico is the most significant urban zone in the country, where 21.4 million people live in a metropolitan zone of 8000 km^2, representing 17.9% of the total population of the country (INEGI 2010). The Valley of Mexico is a subregion of the Hydrological-Administrative Region XIII, with a territorial extension of 9739 km^2. The zone shows three types of surfaces: mountains, hills, and flat areas where the largest urban area is concentrated, known as the Mexico City Metropolitan Area, which has been suffered an urban population growth in recent years.

The requirements of water for the Metropolitan Zone of Valley of Mexico are estimated at 70 m^3/s, on average, and such demand is met using both surface and groundwater taken from Mexico City’s basin as well as from other surrounding watersheds. The local aquifer is the main source of water supply, covering 66% of the total demand for water. The intensive extraction of groundwater since the mid-nineteenth century and the aquifer gradually became sub-artesian. The groundwater table levels have declined by approximately 80 m and have led the collapse of the land in an essential part of Mexico City, therefore increased the vulnerability of the aquifer to pollution (Edmunds et al. 2002; Tortajada 2006; Félix-Cañedo et al. 2013).

Many researches in the aquifer that supplies urban area of Mexico City have been carried out in order to identify the groundwater quality deterioration due infiltration of pollutants, such as Félix-Cañedo et al. (2013), who studied the groundwater contamination by 17 organic micropollutant, namely clofibric acid, ibuprofen, salicylic acid, 2,4-dichlorophenoxiacetic acid (2,4-D),gemfibrozil, ketoprofen, naproxen, diclofenac, 4-nonylphenol (4–NP), pentachlorophenol (PCP), triclosan, bisphenol-A (BPA), butyl benzyl phthalate (BBP), di-2-ethyl hexyl phthalate (DEHP), estrone (E1), 17β estradiol (E2), and 17α ethynylestradiol (EE2).

Study results show concentrations higher than the limit of detection of salicylic acid, diclofenac, 4-NP, triclosan, DEHP, BBP, and BPA in groundwater samples. The highest incidence and concentration of organic micropollutants in wells coincides with the highest levels of nitrates-N, phosphate-P, and Total Kjeldahl Nitrogen. These wells were situated at the north of the city where the three large tunnels used to take wastewater out from Mexico City's valley are located. These results support the hypothesis of the infiltration of wastewater into the aquifer from the sewerage in the north of the city.

One of the most free-sale medications used in Mexico City is the analgesic drug acetylsalicylic acid, and salicylic acid is his major metabolite; this metabolite is excreted from human body through feces and has been recurrently found at concentrations of tens of μg/L in Mexico City's wastewater (Chávez et al. 2011; Gibson et al. 2007). Diclofenac is the third pharmaceutical compound more frequently found in Mexico City's wastewater, just after naproxen and ibuprofen; accordingly, its incidence in groundwater can be expected. The incidence of phenolic compounds such as 4-NP, triclosan, DEHP, BBP, and BPA in groundwater samples is also associated with infiltration from sewerage or landfills.

Another case of groundwater pollution by wastewater infiltration takes place in the Tula Valley in Hidalgo states where wastewater from the Mexico City is discharged mostly without treatment and is distributed via a system of canals and storage dams to irrigate farmland. The aquifers under the valley are being infiltrated with wastewater, but no adverse effects have been noted in the local population even though they have extracted their water supply from these same aquifers for more than 40 years. Their results showed that the infiltrated water quality was better compared to the irrigation water because there was less presence of microorganisms—however, the presence of Giardia spp. Cysts or helminth eggs is a risk to the health of the population if the groundwater is directly ingested and chlorination of the water does not effectively inactivate them. The total suspended solids (TSS) concentrations were significantly reduced in groundwater. Also, total dissolved solids values were slightly lower in the wells than in the spring water and dug wells. Finally, there was little evidence of contamination with heavy metals although aluminum and fluoride concentrations in some springs and dug wells exceeded permitted limits (Chávez et al. 2011).

During the most recent geological times, the Mexico basin was comprised of several lakes that have been progressively drained since the Tajo de Nochistongo was completed in 1789. Also, the intensive extraction of groundwater that supplies the Valley of Mexico has been inducing consolidation to the overlying soils since the beginning of the twentieth century resulting in rapid land subsidence and increasing the vulnerability of the aquifer to pollution (Santoyo et al. 2005; Chaussard et al. 2014; Ciruela-Ochoa 2016).

Compressible deposits occur along the coasts of the Trans-Mexican Volcanic Belt in two ways. First in the east–west-oriented belt of central Mexico where high population density is observed (Mexico City, Toluca, Querétaro, San Luis Potosi, Aguascalientes, Celaya, Salamanca, Abasolo, Leon, and Irapuato) (Carreón-Freyre 2010). There, volcanic structures and normal faults due to the extensive stress regime result in the formation of basins and grabens favorable to the accumulation of compressible deposits. Second, between the Sierra Madre Oriental and Occidental normal faults are found due to the Cenozoic extensive stresses, which favored the formation of grabens. The remaining parts of Mexico are constituted of compact deposits, such as metamorphic rocks, less likely to experience subsidence (Chaussard et al. 2014). These cities with subsidence and fracturing problems are located above horizontal plains. The sedimentary refill of these basins is highly heterogeneous in composition and texture ranging from conglomerate to clay-bearing sediments with numerous intercalations of volcanic rocks, for example, Queretaro and Mexico City Valley (Figs. 4.6 and 4.7) where there is no presence of metamorphic rocks (Carreón-Freyre 2010; Carreón-Freyre et al. 2016; Chaussard et al. 2014).

Several authors confirmed that the primary cause of land subsidence in the Trans-Mexican Volcanic Belt is the excessive groundwater extraction of the aquifer–aquitard systems for agricultural, urban, and in a few instance, industrial purposes leading to a decrease in water access and quality.

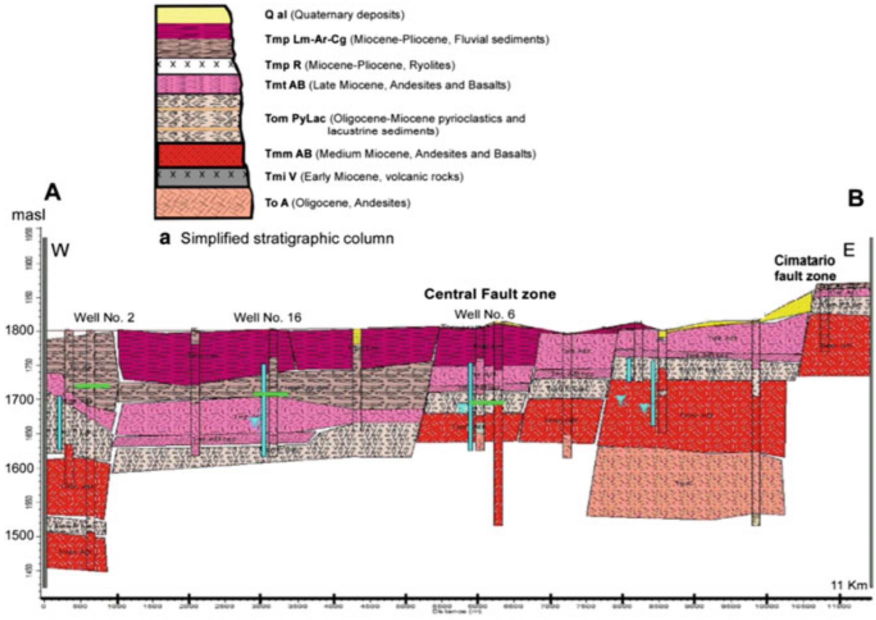

Fig. 4.6 Geological section of Queretaro Valley (Obtained from Carreón-Freyre et al. 2016)

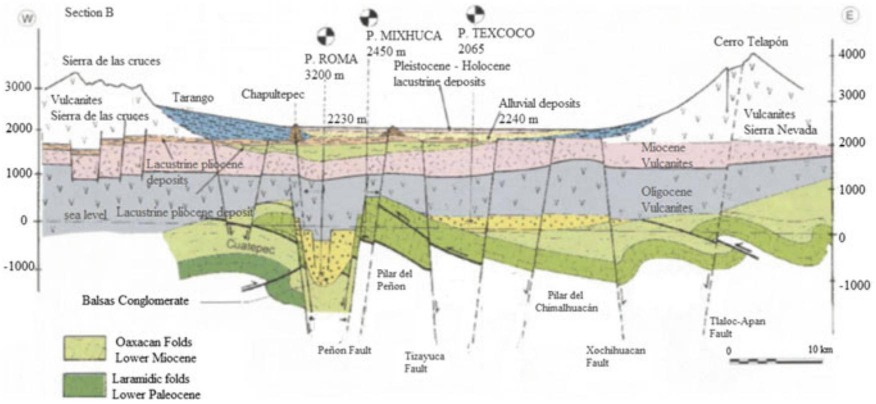

Fig. 4.7 Geological section of Mexico Valley (Adapted from Santoyo et al. 2005)

Carrera-Hernández and Gaskin (2007) found that at the north of Mexico City there are the significant drawdown rates where some wells were drilled as a temporary solution to Mexico City's water-supply problem. It is evident that the aquifer has changed from a confined to an unconfined condition in some areas, a factor that is responsible for the large subsidence rates (40 cm/yr) in some regions.

4.2.2.5 San Luis Potosi

The metropolitan area of San Luis Potosi and Soledad de Graciano Sanchez, in the semi-arid north-central part of Mexico, has around 1.1 million inhabitants. The San Luis Potosi Aquifer is the main source of water supply for these urban areas, almost 65–70% of total groundwater extraction from the aquifer is destined to supply the population (Esteller et al. 2012; Cardona et al. 2018).

About 94% of the total urban water supply is met using groundwater taken from the deep aquifer, and only 6% is provided from the San José Reservoir that collects intermittent runoff from the Sierra San Miguelito. The shallow aquifer covered most of the total water demand from the end of the sixteenth century until the 1950s when shallow wells were progressively abandoned due to contamination and the drinking-water network fed by deep wells was installed (Martinez et al. 2010; Edda Martinez et al. 2011).

The aquifer system of San Luis Potosí Valley is formed by a shallow unconfined aquifer and deep fractured volcanic aquifer, which are vertically separated by the compact fine silty–clayey layer. Three flow systems were identified in the aquifer: a local flow controlled by the clay layer (depth to water table between 5 and 35 m), an intermediate system in which water infiltrates beyond the boundary of the clay layer, and a regional system originating outside the surface catchment (depth to water table more than 450 m). Carrillo-Rivera et al. (2002, 2007) and Cardona and Carrillo-Rivera (2006) reported the presence of two flow systems in the deep aquifer unit.

One is a deep regional flow system represented by thermal water with temperate between 35 and 40 °C at borehole head and presents high concentrations of Boron, Fluoride, Sodium, and Lithium, indicating interaction with fractured volcanic rocks. The second one is an intermediate shallow flow system with a temperature of 23–28 °C and low concentrations of Boron, Fluoride, Sodium, and Lithium, indicating interaction with the basin-fill sediments.

In the last years, drilling of deep production wells up to 700 m deep, in rhyolite outcrops in the western region of the metropolitan area of San Luis Potosi, has become frequent. Some researchers have found that groundwater chemistry in the local flow path is dominated by natural water–rock reactions (Armienta and Segovia 2008; Esteller et al. 2012).

The intensive groundwater extraction from the aquifer system of San Luis Potosí Valley has caused a negative environmental impact in the aquifer, causing two drawdown cones. One is located in the urban area and the other one in the southeast, near the industrial park. That caused socioeconomic consequences due to the increased pumping costs, land subsidence and surface fracturing, and induced changes of the natural groundwater quality (Edda Martinez et al. 2011; Esteller et al. 2012).

Carrillo-Rivera et al. (2002) estimated the increase of high exposure to naturally occurring fluoride in the drinking water supply resulting in dental fluorosis cases. Eventually, Cardona et al. (2018) characterized the primary Fluoride source, to evaluate natural Fluoride control under observed increased groundwater extraction in the SLP.

Elevated concentration of fluoride was reported with maximum values as 3.7 mg/L in 1987 which come from thermal water–rock interaction with regional rhyolites in the deep aquifer, and it is related with the rate of groundwater extraction due to a vertical induction of Fluoride rich water flow into boreholes located in the center of the San Luis Potosí catchment (Carrillo-Rivera et al. 2002; Cardona et al. 2018).

Cardona, (2007) reported a mean annual drawdown between 1970 and 2007 at approximately 1.4 m/yr in the San Luis Potosi Valley Aquifer. The maximum drawdown accumulated in that period below San Luis Potosi urban area was about 70 m due to intensive water extraction and low hydraulic conductivity.

Esteller et al. (2012) and Cardona et al. (2008) reported a negative impact on the baseline water quality of local shallow groundwater that has been identified more than 45 years ago, and it has been affected by return flow from the reuse of raw wastewater for crop irrigation. A relation between shallow groundwater contamination and land use have been found, produced by the shallow depth to water table, hydraulic properties and the widespread distribution of dumps (Martínez-Revilla et al. 2006; Esteller et al. 2012).

Cardona (2007) and (2008) have evaluated the historical and spatial evolution of the primary pollutants reported with concentrations above Mexican drinking water standards in the aquifer, such as nitrate, nitrite, and pathogen. Other significant ions were also identified in some regions of the industrial park (bicarbonate, chloride, and sulfate).

In conclusion, the deeper wells from San Luis Potosi aquifer used for urban supply can extract water of different ages and/or quality, disturbing the natural hydrogeological conditions and producing a mixture. Therefore, water quality in these wells depends on pumping time, baseline chemistry, screen length and location concerning production units, flow rate and pumping conditions, hydraulic properties, anisotropy, and thickness of productive lithological units, and additional water–rock interaction during and after mixing.

4.2.3 South of Mexico

4.2.3.1 Yucatán

The state of Yucatan, Mexico, occupies the central portion of the Yucatan Peninsula with a surface area of about 165,000 km^2, comprising the Mexican federal states of Campeche, Yucatán, Quintana Roo, and parts of Tabasco (Bauer-Gottwein et al. 2011) (Fig. 4.8). The only source for drinking water supply in the region of the Yucatan Peninsula is the groundwater due to the lack of surface water (Rosiles-González et al. 2017; Arcega-Cabrera et al. 2018).

The aquifer from the Yucatán Peninsula consists of karst aquifer enriched with limestones, dolomites, and evaporites reaching thicknesses of >1500 which are lying on top of igneous and metamorphic basement rocks. Groundwater storage and flow occur in a regional karst aquifer with major cave systems; it is dominated by turbulent

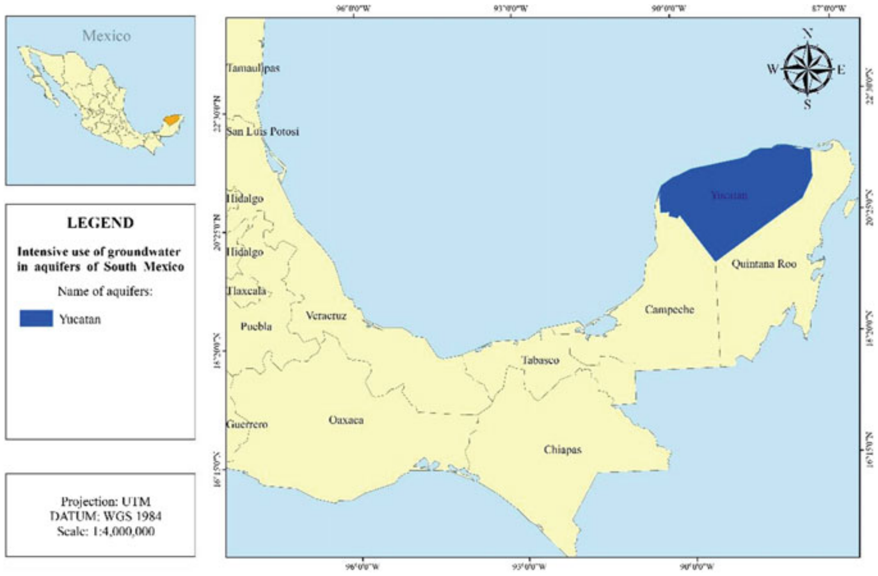

Fig. 4.8 Location of Yucatan

conduit flow, and it flows to three groundwater sinks: coastal outflow, pumping, and phreatic evapotranspiration (Bauer-Gottwein et al. 2011).

Groundwater, the only source of freshwater in the region faces two key threats: intensive extraction and contamination. The risk of groundwater contamination is high; one of the significant risks is seawater intrusion. Anthropogenic pollution of the aquifer has been increasing over the past few decades, due to economic development and population growth on the Peninsula. The highly permeable karst limestone facilitates the percolation of rainwater through its porous substrate from where it flows into the water table, resulting in the rapid transport of groundwater and contaminants throughout the system (Metcalfe et al. 2011; Hernández-Terrones et al. 2011; Leal-Bautista et al. 2013; Arcega-Cabrera et al. 2014; Bauer-Gottwein et al. 2011).

Escolero et al. (2000) obtained the total amount of groundwater pumping in the Mérida metropolitan area as 3.8 m^3/s (Bauer-Gottwein et al. 2011). Hernández-Terrones et al. (2011) evaluated the groundwater quality in Puerto Morelos, Yucatán, where the intensive tourist development has increased the demand for water supply. They collected 53 water samples from different environments along the aquifer-open sea gradient of the Eastern Yucatan coastal zone and used the salinity for seawater tracer and silicate as a groundwater tracer.

Their results showed a high nitrate concentration (268 μM) which 80% of the sampled wells exceed the threshold limit for potable water established by the World Health Organization. A high concentration of E. coli in wells was also found in Puerto Morelos. It suggests anthropogenic pollution derived from sewage percolation, considering domestic wastewater is generally collected in septic tanks, from which it eventually overspills and highly dynamic connection of the aquifer with coastal ecosystems.

The silicate concentration was an average of 110 mg/L (127.9 μM). The high values of silicates can be attributed to groundwater percolation, which dissolves silica under reductive conditions, and high rock mineralization rates in tropical climates. The source of silica could be underlying igneous rocks.

Other studies have been carried out to show the presence of organochlorine pesticides in the Yucatan aquifer and its impact on public health. In the Yucatan Peninsula, the use of this kind of pesticide increased during the 50 s.

Polanco-Rodríguez et al. (2018) made a review of the impacts of banned Organochloride pesticides in human health in the karstic Yucatan aquifer. The water study was carried out in an important fractured karstic area called the Ring of Sinkholes surrounding the east, west, and south of Merida, the capital city of Yucatan. Their results showed that pesticide pollution in the karstic aquifer is a multifactorial problem, due to the natural geohydrologic network that acts as a dumper and conduction of water, enabling the transportation of pesticides. Also, the high density of sinkholes, high deforestation, and faults and fractures in the soil facilitate the filtration of pollutants. They demonstrated a high groundwater quality degradation, mainly in the livestock area, with high levels of 13.61 and 12.54 ppm of heptachlor in the municipality of Dzilam Gonzalez at North-East of Yucatan.

Giácoman-Vallejos et al. (2018) have evaluated the quality of groundwater as well as the spatial and temporal distributions of pesticides in 29 wells located throughout the Mérida-Progreso, Yucatan. They reported an average concentrations of chloro-4-[2,2,2-trichloro-1-(4-chlorophenyl) ethyl] benzene (p,p′-DDT) and (1-(2-chlorophenyl)-1-(4-chlorophenyl)-2,2-dichloroethane) (p,p′-DDD) 0.53 and 0.50 ppb, respectively. The average concentration of (p,p′-DDE) during the "north winds season" was 1.29 ppb.

Finally, the hydrogeological researches are essential because they have determined that the limestone has been subjected to significant vertical movement of water and that many routes for rapid vertical fluid movement must be dispersed throughout the rock mass. The use of organochlorine pesticides in the state of Yucatan has increased not only the impacts on the natural environment and ecosystem but also public health.

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Chapter 5
Implications of Hydraulic Fracturing of Unconventional Oil and Gas Resources in Mexico

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Abstract After a brief description of the most relevant aspects of hydraulic fracturing technology, the main threats involved in its use for the environment, society, and human health are reviewed. Based on the situation of unconventional reserves in Mexico, an assessment is made of the risks involved in the use of technology for the country. It is concluded that the inappropriate use of fracking technology in non-conventional gas and oil reservoirs in Mexico, heretofore unregulated, may result in devastating impacts on the environment, water, air, and soil. Strong and timely actions are needed to prevent pollution of surface water sources as well as aquifers and groundwater—especially in the northeastern part of Mexico where water is scarce—and the atmosphere and to prevent health problems in neighboring communities and workers. The use of hydraulic fracturing in Mexico ultimately has to do with the availability of water in the regions where it is intended to be made. Consequently,

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Mexico is not yet prepared for the wide implementation of this technology; there are many issues to be dealt with before reaching a proper starting point.

Keywords Hydraulic fracturing · Mexico · Environmental implications

5.1 Introduction

Since about ten years ago, most of the oil and gas that was used came from what is called conventional deposits. The migration of the hydrocarbons from source rocks to reservoir rocks gives rise to accumulations in "traps" of gas, oil, and water, stratified according to their density. Primary recovery allows extracting up to 40% of the hydrocarbons, while techniques of secondary recovery (gas and water injection, etc.) and tertiary recovery (enhanced oil recovery), make it possible to significantly increase (up to 60%) the extraction of hydrocarbons from the deposits. Petroleum geology and geochemistry theory enabled the development of oil prospecting, exploration, and exploitation activities. However, the depletion of oil fields and the consequences of economic and geopolitical factors have shifted attention toward the strata in which the source and reservoir rocks coexist, due to the low porosity (at the Nanometric level) and the low permeability of the rocks. That is, toward shale, tight gas sands and coal bed methane deposits, today called "unconventional" reserves (Fig. 5.1).

That has created the need for new theoretical explanations of the generation and exploitation of such reserves (Zou et al. 2014; Jia 2017). Insufficient attention to renewable and cleaner energy sources (possibly less profitable for large companies) and the lower carbon footprint of shale gas have led to the rapid growth of hydraulic fracturing ("fracking") of these reserves. The resulting socio-environmental problems raise the question of whether the economic and geopolitical benefits are worth

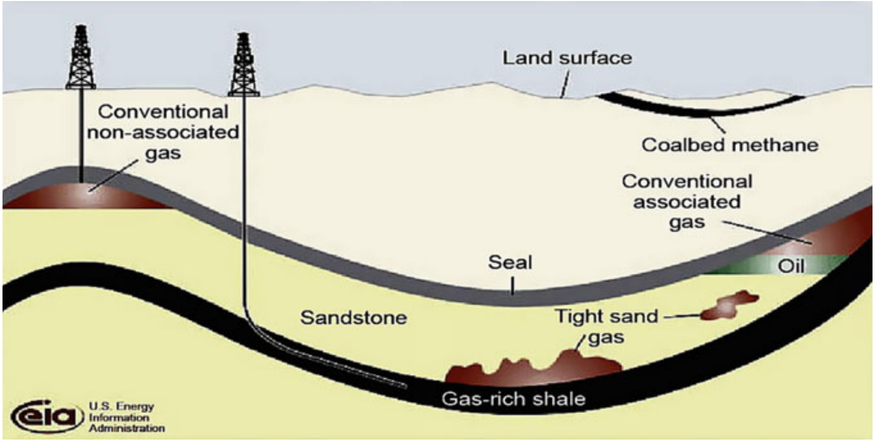

Fig. 5.1 Conventional and non-conventional oil and gas reserves (EIA 2010)

the risk of damaging the heritage of humanity, our planet. Will we have advanced enough in the theory, understanding and technological development for the safe exploitation of unconventional reserves? What implications does this have for Mexico? In the present work, some criteria are explored in this respect.

5.2 Fracking Technology

5.2.1 Brief History

The use of fracturing dates since 1865, when nitroglycerine was used to blast fractures in oil sands to improve production. In 1949, hydraulic fracturing was successfully performed in two wells located in Oklahoma and Texas. In its first applications, the technology was applied mainly to vertically drilled wells. Afterward, several technological improvements of oil well drilling techniques stimulated for the extraction of shale gas/oil were achieved, including the advanced hydraulic fracturing techniques and extraction methods in shale formations. They were developed by the United States (US) Department of Energy, and the revitalization of production with good horizontal drilling and multistage massive slickwater hydraulic fracture treatments in the Austin Chalk play by Union Pacific Resources. By 2012, there were more than 2.5 million fracking jobs of all kinds worldwide, over one million of them in the USA. Some of the factors driving the improvement of technology today are the energy needs of many countries, the delayed development of energy production from renewable sources, and the advances in the evaluation of hydrocarbon reserves in shale formations around the world that allow their exploitation through fracking. Fracking continues to grow with the help of research and development, micro-level modeling, and the search for less-invasive/more efficient technologies and fluid components concerning the use of water in the productive cycle. The debate over the pros and cons of fracking continues, together with the need to regulate its use adequately in a scenario of greater public awareness of climate change and the role of fossil fuels in the future (Merrill and Schizer 2013; Umich 2013; AOGHS 2018; Sovacool 2014; Apel et al. 2015; de Campos et al. 2018; Luís et al. 2018; Metze 2018).

5.2.2 Technology Summary

Fracking involves a combination of technologies, mainly horizontal deep drilling, injection of fluids under pressure to fracture the shale and a sequence of stages illustrated in Fig. 5.2.

The first stage consists of assessing the reserves using advanced geological and geophysical exploration methods. Once the appropriate shale is precisely located, the drilling platform is positioned on top of the drilling site. Vertical wells are drilled

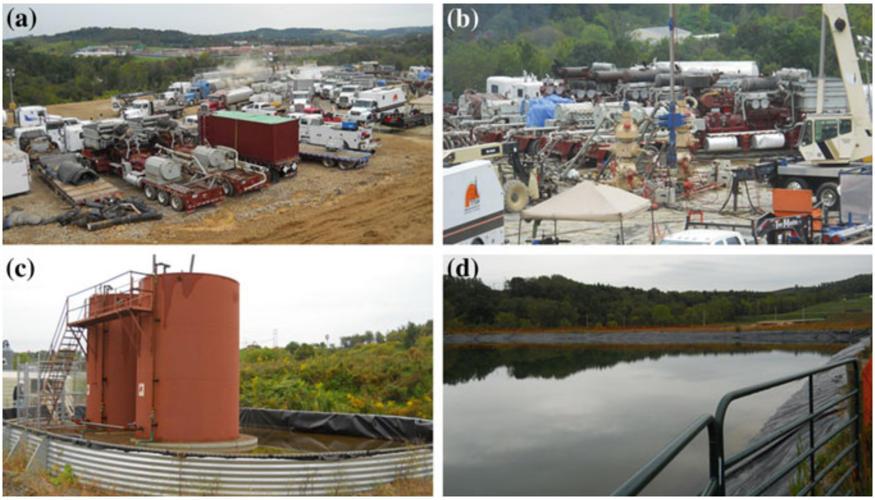

Fig. 5.2 Fracking in Marcellus Shale gas play in Pennsylvania: **a** Hydraulic fracturing drill site. **b** Fracking in-progress. **c** Water storage. **d** Water pound (USGS 2018)

to 640–5800 m of depth. Vertical boreholes are encased in concentric sleeves of steel and cement. At a certain point, the drilling bit is forwarded to gradually bend its path until it reaches a 90-degree trajectory at a designated depth. Afterward, the horizontal portion of the well is drilled right into the shale formation. In the well-completion stage, small explosive charges perforate the pipe to allow the fracking fluid (water, sand, proppants, and additives) to be pumped through the small holes in the pipe at a very high pressure (34.64–144.68 kg/cm^2) (34–142 MPa) to create microfractures in the rock. Once the fracture is initiated and widened by increasing the injection rate, a proppant material (rounded silica sand, gravel, and resin-coated sands, sintered and fused synthetic ceramic materials, most commonly sand, ceramic, sand-lined resin, and sintered bauxite), is carried into the fracture by fluid injection. It keeps open the microfractures to maintain a stable flow path along the fracture after the hydraulic fracturing pressure is released, allowing the hydrocarbons to flow to and through the pipe. This process may be repeated several times by fracturing the shale in different points with new pressurization. For the production stage, the top of the well on the surface is outfitted with a collection of valves that regulate pressures, control flows, and allow access to the wellbore in case further work is needed. At the outlet of these valves, the oil and gas flow is connected to a distribution network of pipelines and tanks. Flowback and produced water are collected for reuse or disposal. The American Petroleum Institute has issued general guidelines concerning fracking operations, well construction and integrity (API 2009; Jackson et al. 2014; Sovacool 2014; King and Durham 2015; de Campos et al. 2018).

The most significant challenges of fracking technology originate in the very essence of shale deposits, differing in their geology and spatial distribution from conventional deposits, which makes the prospecting, exploration and exploitation activities of these deposits more complex. The accumulation and flow of oil and gas differ substantially from those that occur in conventional reservoirs. That is due to the low porosity (4–12%), and micro- and nanoscale pore sizes, as well as low permeability ($<10^{-3}$ μm^2) and results in the coexistence of multiple phases and the absence of defined boundaries between water, oil, and gas. Thus, the study of unconventional reservoirs targets six characteristics: hydrocarbon source properties, lithology, physical properties, brittleness, hydrocarbon-bearing property, and stress anisotropy. In general, these characteristics change depending upon different locations. As a consequence, each unconventional play has unique characteristics, and its exploitation requires a custom-made approach. This, for example, is the case of Argentine's Vaca Muerta Shale, which differs from the Barnett Shale in the USA by the prevalence of ash beds, complex facies stacking, abnormally high pore pressure, and geomechanical stresses resulting from the proximity of the Andes Mountains nearby (Zou et al. 2014; Fernández-Badessich et al. 2016; Jia 2017).

One of the most important features of the fracking process is the shale's heterogeneity. Although less heterogeneous than other sedimentary rocks, small changes in their properties in different locations can make a significant difference in the fractures' geometry and development tendencies during hydraulic fracturing. The sedimentary process and the changing depositional environment determine the presence of rock layers with different characteristics, natural fractures, bedding planes, and brittle or ductile rocks, making differences in the shapes of the fractures. For example, in shale rocks without natural fractures, heterogeneity (represented by the Brittleness Index, BI) in the matrix can determine the trend and patterns of hydraulic fractures. Furthermore, the lack of laboratory data of geomechanical and fluid properties, coupled with the high costs of lab analysis and a prevalent pragmatism in the acquisition of field parameters, mainly focusing on empirical relationships among properties to solve daily problems, might make the proper evaluation of the heterogeneity difficult. The variability of rock microstructure means that under the same fracking conditions (applied loads, fluid pressure, temperature, etc.), pores at different dimensional scales may be subject to different physical and chemical processes. This affects all the fracking stages. For example, the selection of both fluid and proppant depend on the geologic characteristics of the rock. The initial production rates and decline curves are also determined by these variables (King and Durham 2015; Kirkman et al. 2017).

In addition to geology, other geographic and even socioeconomic factors make the exploitation of shale gas and oil dependent on the specificities of each location, which is unquestionably another factor of uncertainty in addressing this activity. The convenience of the fracture depends on obtainability, type, and location, technological infrastructure, corporate governance, water availability, regulations concerning wastes discharges, the infrastructure of roads and transportation. Also, prices of natural gas, the existence of labor and specialized personnel, land ownership relationships, including the preservation of those belonging to indigenous communities and especially environmental costs, must all be taken into account when undertaking the exploitation of shale deposits. Thus, when all costs are added, fracking may not be profitable according to the size of the investment made. Even the size of the company that undertakes this operation influences its profitability (Eyer 2018; López-Bárcenas 2018).

5.2.3 The Fracking Boom

For many years, the world's leading country of natural gas production was Russia. In 2010, the USA surpassed Russia in natural gas production due to its success in exploiting gigantic shale gas plays. In 2015, US natural gas production registered 167×10^9 cubic meters, a volume that positioned the USA ahead of Russia as a natural gas producer (CIA 2015). Fracking has overgrown in the USA and now accounts for almost 50% of the oil production and over 60% of the natural gas production in the country. Much of the growth in fracking has occurred in the past few decades and has been driven by some technological developments in the USA. As a result of this revolution in fracking technology over the past decade, the production capabilities of the USA have increased dramatically, far surpassing the previous production peak that occurred in 1973. The recent rise in its production capabilities began in 2008. Dry natural gas production in the USA in 2005 totaled 5.111×10^5 m^3. By 2014, dry natural gas production reached 7.285×10^5 m^3, representing a 42.5% growth. This rise has been accompanied by a surge in the number of unconventional natural gas wells, whose share in the US gross gas production has increased dramatically in recent years. By 2010, approximately 60% of all new crude oil and natural gas wells worldwide were using hydraulic fracturing. With new technologies and continued improvement of fracturing processes, fracking has emerged as one of the most prominent and important techniques for the extraction of crude oil and natural gas around the world. In the USA, fracking has provided a boom in profits and jobs and has raised US oil production from 5.6 million barrels a day in 2010 to about 10.9 million in 2018. As such, hydraulic fracturing is an integral part of the US economy and will continue to be for the foreseeable future (Apel et al. 2015). The U.S. Energy Information Administration recently released its *Annual Energy Outlook 2018,* AEO 2018 (EIA 2018). This report forecasts that the US tight oil production will increase through the early 2040s when it surpasses 8.2 million barrels per day (b/d) and account for nearly 70% of total US production (Fig. 5.3). Tight oil production made up 54% of the USA total in 2017. Development of tight oil resources is more sensitive than non-tight oil to different assumptions of future crude oil prices, drilling technology, and resource quality; nonetheless, tight oil remains the largest source of US crude oil production in all the AEO 2018 sensitivity cases. By 2040, EIA projects that the combined production from tight oil, oil sands, and offshore deep-water will reach 21 million barrels per day (b/d) and will account for almost a quarter of the world's total crude oil production (EIA 2018).

Thanks to the high availability of shale gas, the price of natural gas in the US decreased from $USD 15/MJ in 2008 to about $4 in 2014. This price is twice to three times lower than in Europe and four to six times lower than that in Asia (BP Statistical Review, 2016; Le 2018). As of 2014, with the almost twofold increase in

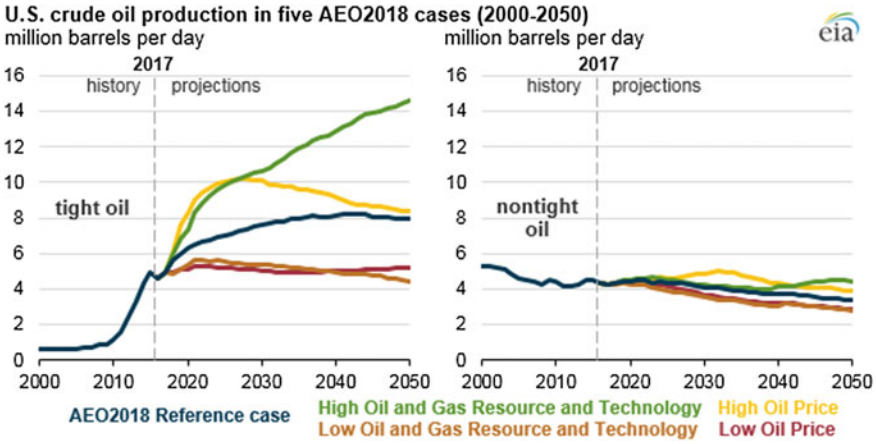

Fig. 5.3 Projections of tight and non-tight oil productions (EIA 2018)

US oil and natural gas production, a trade war started between Saudi Arabia and the USA for market share in the international oil arena. The surplus of gas and oil led to a price downfall. In 2016, many fracking operators announced the closing of their activities. This situation has dramatically changed with the oil price in September 2018 being above $USD 75/b.

The exploitation of unconventional resources is still relatively recent. Today, high uncertainties remain about recoverable resources and the potential evolution of associated production costs, one of the driving forces of the fracking boom. An even greater uncertainty surrounds shale oil exploitation outside of the USA (McLean, 2018; Mistré et al. 2018). Despite the existing uncertainties, it is undeniable that the fracking revolution has had a significant impact on the economic growth of the USA. However, it by no means implies that the US fracking success may be replicated in other countries with identical results.

5.2.4 *Water Requirements*

Fracking requires a considerable amount of water and generates high volumes of polluted wastewater (WW). The water use per fracking (in the first four years of production) has been about 14,500,000 ± 490,000 L. The wastewater generated per well is 7,200,000 ± 4,500,000 L and the water intensity for fracking and extraction 7.6 ± 1.4 and 8.6 ± 1.6 L GJ^{-1}. Advances in fracturing fluid technology plus technologies to treat flowback and produced water may enable production companies to recycle and/or reuse the same water for hydraulic fracturing and other operations depending on technology, transportation, and economic factors. Being a very complex matrix produced water is subjected to treatment before reuse or disposal; its direct use is not recommended, because this water may not meet the quality requirement for the specific fracking process. Land disposal of flowback water is not recommended either because of the environmental impacts it may cause, for example, in the soil's biological and biochemical properties. The main treatment processes include: removal of organics, including oil and grease; removal of solids such as suspended particles and sand; disinfection; removal of dissolved gas; removal of light hydrocarbon gases, carbon dioxide, and hydrogen sulfide (if needed in the production region); softening; removal of excess water hardness and reduction in scaling; removal of naturally occurring radioactive material; and removal of dissolved salts, or desalination.

It should be noted that the treatment scheme highly depends on the specific site process, due to the high variability of the produced and flowback waters. It seems that membrane technologies will have a high impact in the future, especially in water reuse for agriculture. The main technical measures that can reduce the fracking impact on water use are the brackish water; selection of less water-intensive technologies; and reuse of produced water and recycling of fracturing fluid. Some WW management options are shown in Table 5.1 (API 2010; Jackson et al. 2014; Chen et al. 2017; Vieth-Hillebrand et al. 2017; ACS 2018; Adham et al. 2018; Dolan et al. 2018; Entrekin et al. 2018; Jiménez et al. 2018; Liden et al. 2018; Onishi et al. 2018; Yao et al. 2018).

Table 5.1 Wastewater management options (Liden et al. 2018; Onishi et al. 2018)

Option	Pros	Cons	Observations
Deep underground injection	Economic benefits	Potential induced seismic activity; groundwater and soil pollution	The preferred method in the USA (95% of the WW generated)
On-site primary and secondary treatment and reuse	Economic advantages; diminishes freshwater use; diminishes WW disposal to the environment	Transportation costs, capacity, and practical constraints limit its application	On-site treatment plants include removal of total suspended solids, oil and greases, and scaling materials
Desalination and reuse	Zero liquid discharge potentially possible; allows safe water reuse in other activities, for example, agriculture	Economic limitations. Desalination technologies are in a developing and introductory stage	Thermal and membrane technologies. Up to 90% water recovery ratio. Need economic incentives to compensate costs

5.3 Environmental and Public Health Threats

Despite the technological advances and the optimistic expansion projections aforementioned, natural gas production from tight shale formations has some serious social and environmental implications (some of them depicted in Fig. 5.4) mainly associated with the depletion of freshwater resources and the generation of polluting wastewater.

These consequences motivated the publication by the American Petroleum Institute of a guidance document addressing the mitigation of some of the environmental impacts of fracking. Many of the environmental impacts of shale exploitation have an impact on public health. Air pollution, exposure to polycyclic aromatic hydrocarbons, harmful effects on greenhouse gases, noise pollution and other stressors undoubtedly influence public health. Many of these risks are the same as those found in any other type of oil exploitation, but ultimately, they respond to the increase in fracking activity. The advocates of fracking believe that industry and government are capable of effective regulation and that the technology poses little threat to public health.

The opponents consider that there are short-, middle-, and long-term risks to community, national and global public health. This controversy merits a more in-depth approach by the governments in the allocation of harms and benefits, based on the principles of environmental justice—distributive justice, and the public's involvement in the decisions that affect one's life, and participatory justice. For example, an exhaustive cost-benefit analysis, considering the economic, social, and environmental consequences of the shale gas exploitation, conducted in Romania, showed that in the long run, the costs considerably outweigh the benefits (API 2011; Fry et al.

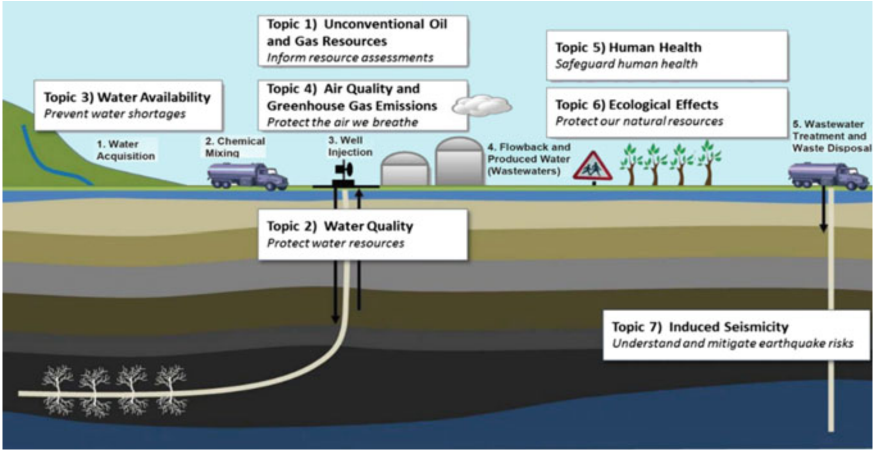

Fig. 5.4 Environmental topics and water cycle in fracking (Adapted from DOE, DOI and EPA, 2014 and EPA drawings)

2015; Clough, 2018; O'Connor and Fredericks, 2018; Grecu et al. 2018; Onishi et al. 2018; Paulik et al. 2018; Watterson and Dinan 2018).

5.3.1 Human Health and Social Impacts

Despite some evidence of direct health risks of fracking activity for those working in the industry or living near the plays, more research is needed in this field to collect supporting evidence for decision making. Considering that many of the chemicals used in the process have severe health effects including skin, eye, and sensory organ damage; respiratory distress including asthma; gastrointestinal and liver disease; brain and nervous system damage; cancers; and reproduction risks—the need for prospective health studies in the fracking sites is evident. Also, there are secondary social impacts with adverse effects on public health: aesthetic and amenity value loss, failing the outdoors and wildlife habitats, housing, and infrastructural shortages. They lead to price increases and housing poverty, environmental injustice, and heightened crimes rates, in turn leading to an elevated incidence of psychosocial stress, risky behaviors and their consequences, substance abuse and depression. For example, a positive relationship between the good density of a county in Colorado and both violent and property crimes showed that the resource boom caused an increase in both crime rates. Similarly, a study conducted in the UK showed that the number of oil and gas wells is positively correlated with violent crime rates (Kovats et al. 2014; Sovacool 2014; Beleche and Cintina 2018; Cotton and Charnley-Parry 2018; Gourley and Madonia 2018; Hill 2018; Stretesky et al. 2018).

5.3.2 Land and Seismic Impacts

The ecosystem services provided by natural and semi-natural landscapes are often under-appreciated by the public. Moreover, access to unconventional reserves around the world has not considered the carrying capacity of the surface or subsurface footprint and how severely the current surface environment restricts site placements. Land-use changes can have huge impacts on these ecosystem services through the conversion and modification of land, a process that degrades its ecological function. Fracking accounts for large amounts of land conversion across the USA (more than 200,000 estimated sites in 2015). The spatial footprint of a shale gas development (well pads and access roads), pipelines, and other infrastructure affects the landscape and can convert it into degraded or modified habitats. Some measures can be taken to mitigate degradation: ecosystem service assessments, wise placement of new development, and restoration that could reduce the impact of degradation. As non-conventional resource exploitation is just a short-term solution to energy needs, it should be considered, in the long view, if this short-term activity is worth long-term damage and significant costs to the future generations (Clancy et al. 2018a; McClung and Moran 2018). Earthquakes can be induced by anthropogenic activities such as mass extraction or introduction in the subsurface. The concern is growing about the earthquakes induced by fracking operations, which all induce earthquakes. Seismic monitoring is currently done because the earthquake locations indicate the location and volume of the fracture network created. It is true that only a very small fraction, not all, of the fracking jobs have been reported to have induced earthquakes with a >3 magnitude. The case of Oklahoma in the USA is a unique case as seismicity is 300 times higher than before the fracking boom. Nevertheless, this poses an additional constraint to fracking operations: They should be conducted preferably in regions of low population density (Foulger et al. 2018; Roach 2018).

5.3.3 Greenhouse Gases and Climate Change

An advantage that is attributed to shale gas is its lower carbon footprint, compared, for example, with coal, when burned. It is an unquestionable fact. However, it must be carefully analyzed when simultaneously evaluating carbon and water footprints. Recent studies showed that there is a trade-off between water and carbon impacts. A reduction of 49% in total water consumed or a 28% reduction in the water scarcity footprint in the shale gas production process could be achieved at the cost of a 38% increase in global warming potential if the wastewater management shifted from business as usual to complete desalination and reuse of produced water. It may be a critical issue for regions with water scarcity.

It should be noted that there is supporting evidence that methane emissions increase during shale gas production and transport. Methane has a greater low-term impact on climate change than CO_2; USEPA estimates that pound for pound, the comparative impact of methane on climate change is more than 30 times greater than CO_2 over 100 years. Methane emissions from natural gas production and transportation facilities, if not responsibly managed, may be high enough to be significant (ACS 2016; Absar et al. 2018; Williams et al. 2018).

5.3.4 Fracking Impact on Water Availability

The most prominent environmental impact of fracking is related to the high demand of water, affecting its availability and quality. Little is known about the amount of water withdrawn from small streams for fracking operations. Studying the stress that fracking in the Fayetteville Shale play poses on small catchments that also provide drinking water for communities and homes for species with already declining populations, it has been estimated that 7–51% of the catchments could be potentially affected in the populations of aquatic organisms, 3–45% if wastewater is recycled. It should be noted that potential risks of surface water pollution arise as a consequence of leaks and spills of contaminated liquids during production and transport (Jackson et al. 2014; ACS 2016; Clancy et al. 2018b; Onishi et al. 2018).

Despite some controversial evidence that shows an increase of methane levels in groundwater, some published research data indicate that high levels of biogenic CH_4 can be present in groundwater wells independent of hydraulic fracturing activity and affirm the need for isotopic or other fingerprinting techniques for proper CH_4 source identification. Baseline data of water wells' methane contents is critical to ensure that groundwater quality is not altered as hydraulic fracturing activity develops in a specific region. Nowadays, shallow aquifers may be at risk because of the hydraulic connectivity with deep shale gas formations (Vengosh et al. 2013; Sovacool 2014; ACS 2016; Botner et al. 2016, 2018; Rester and Warner 2016; Montcoudiol et al. 2017).

5.4 The Case of Mexico

5.4.1 Mexico's Oil and Gas Reserves and Energy Demands

Figure 5.5 shows Mexico's unconventional resources, whereas Table 5.2 breaks down Mexico's Tight Gas and Light Tight Oil Reserves, and Table 5.3 details Mexico's prospective resources (CNH 2018). It must be noted that Mexico's non-conventional reserves are almost twice its conventional resources. They are distributed mainly in the northern part of the country, far away from the large gas processing centers and petrochemical plants located in the southern states of Tabasco, Chiapas, and Veracruz, in areas that do not have the required infrastructure of pipes, compression centers, and pumping. Also, it should be noted that the unconventional reserves are estimated to be 2P and 3P, which contrasts with the conventional ones that are 1P and 2P (Proved, **1P** and Proved plus Probable, **2P reserves** are commonly used throughout the oil and gas world, but **3P reserve** information, i.e., Proved plus Probable plus Possible, is relatively seldom used).

The demand for natural gas in Mexico represents a significant portion of the national energy consumption of fossil fuels, with participation estimated at 43.8% of the Total Energy Balance (SENER 2016). It has increased from 7020 MMSCFD in 2010 up to 8000 MMSCFD in 2018, a growth of 14%, due to a rise of natural gas utilization in combined cycle power plants. Even so, domestic production has consistently declined, and imports have increased. An additional problem is the contamination of natural gas with nitrogen, which originated from the injection of the inert gas to increase production of oil as of 1999 in conventional reservoirs and now emerges with the produced gas (SENER 2018b).

Due to production decline, the increase in the demand is covered by imported natural gas, which has increased from 905 MMSCFD in 2005, up to 5200 MMSCFD

Major Mexico Oil & Gas Resource Plays

Source: NGI's 2018 Map of Shale/Resource Plays & North American Natural Gas Pipelines. Visit www.naturalgasintel.com/shalemap

Fig. 5.5 Mexico's non-conventional resources (CNH 2018)

Table 5.2 Mexico's tight gas and light tight oil reserves (CNH 2018)

Oil and gas resource plays	Oil (MMMB)	Gas (MMMMSCF)	BOE (MMBD)
Tampico-Misantla	30.7	20.7	34.7
Burgos	0	53.8	10.8
Sabinas-Burro-Picachos	0.6	37	13.9
Veracruz	0.6	0	0.8
Total	31.9	141.5	60.2

Table 5.3 Mexico's prospective resources (CNH 2018)

	Conventional	Unconventional	Total
Oil	37.3	31.9	69.2 MMMB
Gas	76.4	141.5	217.9 MMMMSCF
BOE			112.8 MMMBOE

BOE barrels of oil equivalent. *MMMB* Billions of barrels (US, 1000 millions); *MMMMSCFD* Million of million standard cubic feet (Billion, international units); *MMMBOE* Billions of barrels of oil equivalent in July 2018, almost six times (5.75 times). The reserves 1P of gas have also diminished to 10 MMMMSCF (10 TCF), and the 2P to 19.4 MMMMSCF. Considering the current volume of production, it is estimated that domestic gas availability will be depleted in 5.4 years. These data indicate that Mexico has a significant dependence on imported natural gas from the USA. On the other hand, the nitrogen that contaminates Mexican natural gas has caused a reduction of its heating value, affecting the operation of three-phase separators on marine rigs and causing attrition in compression modules. The lowering of natural gas heating value has hurt the entire production chain that depends on this fuel, including self-processing, power generation, and some conversion processes. An additional issue is the need to inject ethane to improve the heating value of the nitrogen-natural gas mixture, affecting the ethylene and petrochemical derivatives industry. These problems have forced authorities in Mexico at the Department of Energy (SENER) to look toward the possibility of exploiting unconventional gas deposits (shale gas).

5.4.2 Fracking and Water in Mexico

The drop in domestic natural gas production from conventional reservoirs and the rise of demand, combined with the success of the USA in exploiting its non-conventional reserves, surely persuaded the Mexican Government authorities (2012–2018) to begin promoting natural gas production from non-conventional sources. As of 2010, Mexican Oils (PEMEX) Exploration and Production began focusing its attention on hydrocarbons from shale (Escalera 2012), but it was not until 2018 that the first exploratory wells were officially reported (PEMEX 2017). Studies on Mexican shale oil/gas reserves were carried out by the International Agency of Energy in 2011 (EIA 2011). This organization placed Mexico at the second position in Latin America for its shale reserves: 545 TCF of gas reserves and 13.1 MMMB of oil. The information that explains the calculations used to arrive at these reserve figures is not known to the authors or the public.

Fracking operations began in the northeastern part of the country with little public information about them. After a formal request for the information was filed in 2014, PEMEX admitted having hydraulically fractured at least 924 wells in Mexico from 2003 onwards (*Proyecto Terciario del Golfo, Primera Revisión*). Accordingly, wells were drilled in Coahuila (47), Nuevo León (182), Puebla (233), Tabasco (13), Tamaulipas (100), and Veracruz (349), 924 in total. Meanwhile, SENER and CNH announced that 1323 wells had been hydraulically fractured at Chicontepec's Channel. This inconsistency emphasized the urgency of making available accurate information about fracking operations in Mexico (Petición de Acceso a la información #1857500000714. Mexico, DF, 2014).

It became apparent that Mexican institutions lacked specific knowledge on the environmental issues related to the exploitation of its reserves of hydrocarbons in compact or tight formations. Thus, the project: "Assimilation and Development of Technology in Seismic Data for the Design, Acquisition, Processing, and Interpretation of Information 3D-3C with Focus on Plays of Shale Oil/Gas in Mexico" was awarded to the Mexican Petroleum Institute (IMP), with funds allocated by SENER through the National Council for Science and Technology (CONACYT). The project was labeled as classified information reserved for 12 years, based on the Mexican Federal Law of Transparency and Access to Public Information. The project sought to catalog the environmental assets in the municipalities where the activities of exploration and exploitation of shale gas and oil would be carried out. The case of Limonaria in the State of Veracruz includes a complete report on the conceivable affectation on existing environmental assets (climate, soil, hydrology, flora and vegetation, wild fauna, seismology, and human settlements) from the potential activities of exploiting shale gas and oil. This project constitutes the most important effort completed in Mexico to assess the effects on the environment due to the exploration and exploitation of compact formations.

The main problem with fracking in Mexico is related to its water resources. Mexico's social and economic development has been criticized for wasting valuable strategic resources. The exploitation of its water resources has failed to consider strategies of sustainability and has seriously jeopardized the possibilities of further development, aggravated by the current circumstances of climate change and international competition.

As in many countries, in Mexico, the sector that uses most of the available water is agriculture, 77% of the total. This consumption is followed by the public supply, 14%, and the industrial sector, 9%. Population growth has resulted in an ever-increasing demand for goods and services, especially of tap water. Currently, this demand amounts to 78.4 million cubic meters a year, and there are some indications that in the year 2030 it will increase to 91.2 million cubic meters a year. Reutilization of the wastewater discharged in urban centers is scarcely 27.6%. The natural average availability per capita of water has diminished drastically, from 18,000 m^3/inhabitant/year in 1950 to a mere 4433 m^3/inhabitant/year in 2010 (CONAGUA 2017).

This situation is aggravated by the uneven population distribution within the country, the climate conditions, and the pollution of surface and aquifer sources (CONAGUA 2017). Due to its geographical characteristics, rainwater distribution in Mexico is not uniform. The regions of the Mexican Southeast have at their disposal about two-thirds of the renewable freshwater, with a fifth of the population contributing to the gross national product (GNP), whereas the regions of the North, Center, and Northeast only have access to a third of the water of the country despite their greater contribution to the GNP. Thus, it can be observed that the zones where the basins of unconventional reserves are found have the fewest water resources available and the lowest rainfall rate (Fig. 5.6a) (CONAGUA 2017). In 2018, CONAGUA published an update of the underground aquifers and water availability in the shale plays (Fig. 5.6b and Table 5.4) (CONAGUA 2018).

This information confirms the fact that the northeastern portion of the country has a severe water shortage that would prevent drilling as many fracking wells as in neighboring Texas. To this, it should be added that the disposal of wastewater would seriously aggravate the situation, both of groundwater and surface water. Note that the geological characteristics of the areas of southeastern Mexico, abundant in limestone rock formations, make it practically impossible, with current technological

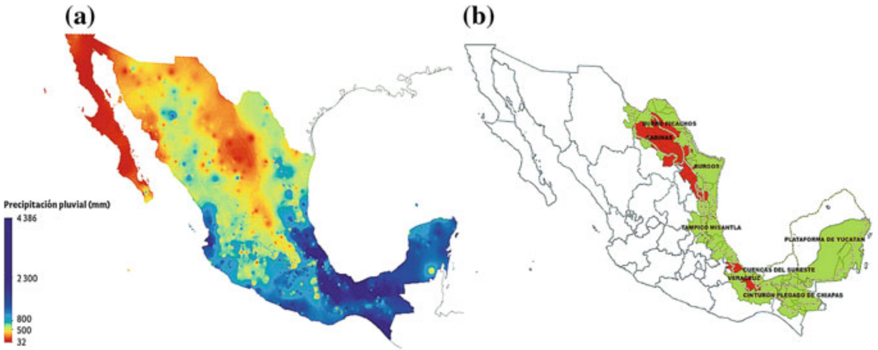

Fig. 5.6 Water availability: **a** Rainfall distribution; **b** Aquifers in regions of shale reserves (in red-aquifers without water availability, in green-with water availability)

development, to dispose of the fracking waters, if this activity was to be undertaken in great magnitude, without contaminating the groundwater.

5.4.3 Legal Framework in Mexico Concerning the Environment

In the last 20 years, the use of hydraulic fracking technology in the USA and some other countries have been supported by the growth of legal frameworks of reference on its environmental impact. Actions on regulatory matters needed to be in place in order to protect the water resources of the regions where gas and oil extraction have been carried out. This experience represents an important reference point for Mexico, and thus, before beginning the exploration and production of natural gas and oil from tight formations, regulatory frameworks must be updated, particularly in the states of Chihuahua, Coahuila, Nuevo León, Tamaulipas, and Veracruz. Mexico has a rather robust legal framework regarding the environment, developed in 1988 after some unfortunate incidents (LGEEPA 2016). The Department of Environment and Natural Resources is the regulatory body in charge of the protection of surface and subterranean water resources, as well as soil and subsoil resources, both susceptible to being harmed by fracking.

In order to control the quality of the liquid and gaseous effluents of industrial facilities, particularly oil and gas, SEMARNAT issued on June 24, 1996, the Official Mexican Norm NOM 001-ECOL-1996, which establishes the maximum limits of pollutants in wastewaters. Previously, between 1977 and 1987 SEMARNAT issued a set of regulations for the sampling and determination of settleable, dissolved, and suspended solids; fats and oils; floating matter; temperature; pH; total nitrogen; biochemical demand of oxygen; phosphorus; total and fecal coliforms; arsenic in water; cyanides; and metals: lead, mercury, copper, zinc, nitrogen and nitrites. This reg-

Table 5.4 Underground aquifers in oil production and not conventional gas plays (2008)

Play	Number of aquifers	With salinization	Availability hm^3 y^{-1}
Burgos	6	1	**235.45**
With water availability	4		235.45
Without water availability	2		0
Burro-Picachos	**11**		**115.4**
With water availability	9		115.4
Without water availability	2		0
Sabinas	**19**	1	**112.75**
With water availability	8		112.75
Without water availability	11		0
Tampico-Misantla	**17**		**444.29**
With water availability	14		444.29
Without water availability	3		0
Veracruz	**9**		**352.21**
With water availability	6		352.21
Without water availability	3		0
Cuencas del Sureste	**6**		**4591.25**
With water availability	6		4591.25
Yucatán Plateau	**10**	1	**5241.2**
With water availability	9		5241.2
Without water availability	1		0

ulation was developed to control industry discharges, including oil and gas, using conventional methods of extraction and processing, as at that time there was no experience with residuals and discharges resulting from hydraulic fracking of wells to exploit non-conventional formations. On June 7, 2013, the Federal Law of Environmental Responsibility (DOF 2013) was published, wherein several laws were reformed.

After the Energy Reform of 2013, a new regulatory agency was created by the Security-Energy and Environment Agency (ASEA). This decentralized body reports to SEMARNAT, which is in charge of regulating and supervising industrial operative safety and the protection of the environment from the activities of the hydrocarbons sector, through the Law of the National Agency of Industrial Security and of Environmental Protection of the Sector Hydrocarbons, published on August 11, 2014 (DOF

2014). ASEA issued the NOM-014-ASEA-2017 establishing specifications of environmental protection that mandatory to follow in drilling, completion, maintenance, and plugging of petroleum wells in marine zones and the norm ANTE-PROY-NOM-015-ASEA-2017 that establishes criteria of environmental protection for the injection of drilling bits in subsoil formations.

On August 30, 2017, specific limits for the protection and conservation of national waters from activities of exploration and extraction of hydrocarbons in non-conventional basins were issued by the National Commission of Water (DOF 2017).

Some authors consider the legal framework to be robust, for it indeed protects the environment, but more specific and updated fines need to be established, as in the USA, to punish violations by companies. It is also important to define how environmental regulations can be enforced effectively in complex situations such as the impermeable layers in the middle of the ocean or desert lands. Also, regulatory agencies in charge of preventing environmental damage, such as the CNH and ASEA, need to be strengthened, since both have fewer engineers than required to be able to address oversight and monitoring, considering the number of potential contractors ("Regulated ones"). The disturbing possibility that radioactive elements might be released into the subsoil during gas and oil exploitation has not been even considered. Beyond the identification of the isotopic characteristics of the site before starting, nothing more was further mentioned, and the consequences for the environment and the communities involved could be devastating. Unfortunate antecedent occurred when the spillage of a Mexican copper mine in Sonora in 2014, and still has not been any reparation of the environmental damage and the communities are still at the mercy of the corrupt authorities involved (Fernández 2015; Wilton 2015).

5.4.4 Social and Political Issues

The Energy Reform approved on December 20, 2013, gave rise to structural changes aimed at igniting the potential of the energy sector with the participation of companies from the private sector, along with PEMEX. The goal was to contribute to the country's development using sustainable and efficient utilization of its natural resources, facilitated by a change in the industrial organization for the exploration, extraction, and processing of hydrocarbons (SENER 2016).

The Energy Reform is considered to represent the opposite policy of what was done in 1938, when President Cardenas nationalized the petrochemical industry, by facilitating private and foreign investment in the energy industry. This Reform promotes the exploitation of tight gas/oil reserves (SENER 2016). The Reform has required some Constitutional modifications, one of them affecting the industrial organization of the energy sector: The National Commission of Hydrocarbons (CNH), instead of PEMEX, is now in charge of providing information on prospective oil and gas reserves in Mexico (SENER 2016).

As fracking projects began in Mexico, a movement of social opposition emerged. One recent publication warns that if Mexico does not take into account the negative experiences that the USA has reported on this subject, then it will commit the same mistakes instead of learning from them (Castro-Alvarez et al. 2017). A strongly titled recent publication focused on energy justice, "Projects of Death: Energy justice conflicts on Mexico's unconventional gas frontier," highlights the fact that the development of non-conventional plays requires large amounts of water, thus affecting the supply of this vital and scarce resource to the local communities (Silva-Ontiveros et al. 2018). Coincidentally, in the rural areas near the sites where the non-conventional projects of oil and gas extraction would be developed, a high degree of marginalization prevails, as the population, mainly peasants, depends on the cultivation of land for survival.

SENER, on the other hand, has used the popular argument of energy security, considering it as a key factor favoring the development of non-conventional gas. The Energy Reform has been hailed as a source of economic development through the creation of job positions. These megaprojects have been labeled as a national priority for their public benefit and have been given priority over any other use of the land, thereby forcing landowners to cooperate, at times by the use of public force. At the Forum of Analysis of the Energy Reform, August 17, 2017, Energy Secretary Joaquín Coldwell announced the decision to promote the exploitation of unconventional reserves located in the northeastern part of the country for gas production. He revealed that a bid among private companies was to be opened for the Burgos Basin and the Tampico-Misantla province that extends to the states of Coahuila, San Luis Potosí, Hidalgo, Veracruz, and Puebla. People from these areas have expressed concern that these projects will negatively impact the environment and economic development due to the high use of water and the generation of wastewater, damaging the local agriculture vital for the communities and their exports, since some Mexican agricultural products are present in the international markets. SENER and the Department of the Environment and Natural Resources (SEMARNAT) endorsed a project presented before the Senate by the Mexican Institute of Water Technology (IMTA) and the Mario Molina Center for Strategic Studies on Energy and Environment with SEMARNAT's patronage to counterweigh these arguments. It claims that the impact of 1000 wells for fracking would only marginally affect water availability. Accordingly, water consumption in the state of Chihuahua would be 3222.9 MM m^3, an amount less than 1% of the available water there. For the state of Coahuila, the volume of water needed would be 1867.4 MM m^3, a volume that would also be less than 1% of the available water. In the case of the state of Nuevo León, the volume required would be 657.7 MM m^3, less than 4% of the available water. For the state of Tamaulipas, the figures would be 262.5 MM m^3, less than 2.5% of the water available (Gutiérrez-Ojeda 2017).

Although the estimation of water consumption per well is correct (Castro-Alvarez et al. 2017), it is known that 670,000 wells have been perforated in the USA since the year 2000. Accordingly, increasing the number of wells raises the water requirements but not in a linear proportion (Castro-Alvarez et al. 2017). Thus, the perception of the people might have a solid base. Besides, it is not possible to predict the effects of the blastings and sand erosion on the permeability of lutites, contamination of aquifers, etc., since each mineralogical formation is unique.

This opposition movement has been endorsed by the academia that has published some papers on the ethical and moral concerns of fracking. A non-governmental organization, the Mexican Alliance against Fracking, was created. It groups more than 40 environmental, civil, and international organizations, including Greenpeace. Some of these organizations have been able to halt pipes and wind turbine projects. The political impact of these groups has had some success. With the advent of the new government in Mexico (December 2018–November 2024), the incoming President declared in the city of Monterrey that hydraulic fracture would not be used in his administration, partly in response to the public concern. In an open letter, the Environmentalists' Association of the States of Nuevo León and Coahuila, "Movement in defense of Mother Earth and Life," had asked him to outlaw this practice (Proceso 2018), enumerating the negative impacts of fracking, for hundreds of houses have cracked in the municipality of Los Ramones, 130 km north of Monterrey, the state capital. They claim that this is the result of water injection into the wells Tangram 1 and Nerita located in the zone and add that some quakes have also been felt in broad sectors of the metropolitan area since 2012.

5.5 Conclusions

Scientists and engineers have the responsibility of conducting research in the laboratory, implementing the technology in the field, and communicating with the public about the risks related to hydraulic fracturing and subsequent extraction. Social mobilization regarding the benefits and threats of fracking is also needed. The government, companies, and citizens should work together to prevent overall fracking risks and hazards.

The inappropriate use of fracking technology in non-conventional gas and oil reservoirs in Mexico, heretofore unregulated, may result in devastating impacts on the environment, water, air, and soil. Secure and timely actions are needed to prevent pollution of surface water sources as well as aquifers and groundwater—especially in the northeastern part of Mexico where water is scarce—and the atmosphere and to prevent health problems in neighboring communities and workers. The use of hydraulic fracturing in Mexico ultimately has to do with the availability of water in the regions where it is intended to be made.

Mexico is not yet prepared for the broad implementation of this technology; there are many issues to be dealt with before reaching a proper starting point.

The outgoing government (2012–2018) promoted the exploitation of non-conventional reservoirs, limiting conventional gas production as being non-profitable. Massive quantities of gas in offshore rigs and marine terminals are flared, which has led to the increase in the imports of natural gas. On the other hand, natural gas is contaminated with nitrogen-reducing its energy value. The government has kept the exploitation and exploration of non-conventional reservoirs secret, limiting itself to declarations that exploitation must be sustainable, in the national interest, and should have priority on the property where the plays are located. At the same time, it provides no legal elements to enforce compliance with operation regulations.

Some authors consider it to be a priority that public opinion is taken into account and that the government defends and protect the environment and the communities from the dangers created by contractors who will start exploiting non-conventional resources with the view on maximizing their returns. For this reason, Mexican scientists and technology experts should reach a satisfactory level of knowledge and confidence before endorsing the approval of any contract.

It is essential to communicate facts, in order to foster confidence in the population and to educate them for actions to reduce the negative impact of any negligent practices of this industry, as is practiced in the USA. The relevant information should be released to the public before any project starts and during the whole life of the operation cycle, as part of sustainable development achievement.

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Part II
Water Quality

Chapter 6
Addressing Stressors to Riverine Waters Quality: The Case of the Nexapa River

Amado Enrique Navarro-Frómeta and David Navarrete-Rosas

Abstract A review of some of the stressors to river water quality shows that the inappropriate use of water in agriculture and the use of rivers as sinks for agricultural, industrial and domestic pollution are the main stressors of water quality. The above is aggravated by the effects of climate change on water availability. Often, authorities at all levels pay more or less attention to priority pollutants. However, the problem of pollution is accentuated by the massive use of many chemicals in our daily lives. These substances, which are in ppb and ppt concentrations, are the organic micropollutants. The above was addressed in the sub-basin of the Nexapa River, Puebla, Mexico. The results indicate that the excessive use of water in the irrigation and the transfer of highly polluted water from the Atoyac River, are the factors that condition the ecological flow of the river is not respected, which remains without water in several sections as well as the riverine water quality impairment.

Keywords Stressors · Riverine water quality · Water abstraction · Presence of micropollutants

6.1 Introduction

Water is indispensable for life on our blue planet. It is known that rivers have sculpted the development of our species, being the cradle of ancient civilizations. Even the wandering nomad has had to find a river to quench its thirst. However, the tremendous anthropogenic pressures, derived from demographic and economic growth, have not been mitigated by an understanding of the care we must give to the flowing of water. The pollution that originates from large cities, various sources of wastes that end up in rivers, the diffuse of pollution due to agricultural runoff and the interception, regulation and abstraction of its waters—for different uses and purposes, threaten the existence of many rivers. Whether large or small, the quality and quantity of these

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rivers are affected, thus contributing to water scarcity. In addition, we must also include the consequences of climate change. For example, there are a few perennial water currents that have become almost sewage channels and, when exposed to extreme pollution events, the different species of fish that inhabit them gradually become extinguished (Navarro et al. 2017; Wen et al. 2017; Whitehead et al. 2018; Bond et al. 2019). What will happen in Izúcar de Matamoros, a city in the center-south of Mexico, if one day the sound of the running water of the Nexapa River can no longer be heard? This chapter deals with some of the stressors that compromise the quality and quantity of water in the rivers and finally, they are illustrated with the case of the Nexapa River.

6.2 Riverine Waters Quality

6.2.1 Rivers Water Quality and Availability

The supply of water in sufficient quantity and quality is essential for the health and well-being of human beings and ecosystems, providing also the basis for socioeconomic development. Against this conspire water pollution, the desertification of forests and jungles, the somewhat irrational use of the liquid within production activities, urban concentration and its observed territorial disorder, the uncontrolled changes in land use, the lack of transversal culture between normative design and society and of course, poverty and inequity. To this must be added the exogenous component of climate change. An additional component of this problem is the nexus between water and energy. The extraction, transportation, distribution and collection of the water used, along with its treatment, require energy. In turn, the production, transmission and use of energy involve a consumption of water.

Although all people benefit from it, only a few know-how, and even fewer actually take part in its management. In general, society is not sufficiently informed to understand how the use of water affects both the quantity and the quality of the resource and its economic impact. The foundations of water management are affected by changes in levels of doubt due to the changes in demographic trends, consumption patterns, migration and climate change, resulting in an increase in risk levels. Adapting to these uncertainties and developing strategies that mitigate the emerging risks makes the management policies, institutions and regulations more resistant, with higher social returns, in a world where everyone can benefit from greater social equity, coupled with a fair consideration of the biophysical limits of our planet (Steffen and Stafford Smith 2013; USEPA 2013; WWAP 2012, 2014; Lomsadze et al. 2016; Hutchins et al. 2018; De Paul Obade and Moore 2018; Rowles et al. 2018).

The quality and availability of water directly influence the economy and human health. In Mexico, data published by the WHO indicate 895 deaths and 54, 447 DALY (disability-adjusted life year) in 2016, due only to diarrhea caused by unsafe water. Likewise, in 2016, the costs attributable to the deterioration and contamination of surface water amounted to 4.9% of the total losses due to environmental degradation, which is equivalent to 45, 169 million pesos (INEGI 2018; WHO 2018).

The quality and availability of river water are affected by multiple stressors that are interconnected through very complex relationships. The different ways of manifesting anthropic pressures leading to the main stressors affecting surface water currents include the disposal of wastewater (with or without treatment in their channels), the intensive use of river water in agriculture, the runoff of an agriculture with intensive use of agrochemicals and pesticides, highly contaminated discharge from mining, increasing urbanization, changes in land use distressing riparian vegetation, hydromorphological changes affecting the course and flow of rivers, as well as the abstraction of water without considering the environmental flow that protects habitats and aquatic organisms (Glenn et al. 2017; Elosegi et al. 2019).

When evaluating the ecology of a specific place, it is necessary to consider that man has made changes, in many cases irreversible, in the status of ecosystems. These changes are not always necessarily negative. For example, in many arid and semi-arid regions, the network of irrigation channels is already part of the landscape and its riparian vegetation and fauna can contribute to ecosystem services, being affected by the same factors as natural flows. Thus, riparian vegetation improves stream bank stability and mitigates agricultural diffuse pollution. This is important when considering its care and necessary maintenance (Carlson et al. 2019; Krzeminska et al. 2019; Turunen et al. 2019).

Regarding water quality (WQ) evaluation, it has been proven that the Water Quality Index (WQI) is indeed a practical method, considering critical environmental variables which represent the pollution conditions in water body (Simões et al. 2008). Moreover, WQI can facilitate comparisons between different sampling sites and identify the changing trends of water quality. However, the calculation of WQI has been developed with different methods. In general, similar physical-chemical variables are considered, but the statistical integrations of variables are different among these methods, as it is outlined in different reports. Undoubtedly, remote sensing techniques along with lab and field methods will confer more reliability to water quality evaluation, helping to achieve greater water security. It is important to consider the use of sampling strategies that increasingly reflect the true concentrations of pollutants in the waters of rivers. In this sense, the use of passive samplers can increase the reliability of the analytical results of organic pollutants, giving the possibility—for example, of discriminating watersheds from each other, according to the concentrations of neonicotinoid pesticides in the water (Sun et al. 2016; Gupta et al. 2017; De Paul Obade and Moore 2018; Mutzner et al. 2019; Metcalfe et al. 2019; Bernard et al. 2019; Xiong et al. 2019).

6.2.2 Main Sources of Water Pollution

Water pollution origins in point and diffuse sources. Point pollution originates in discharges of easily identifiable municipal or industrial effluents that, at least in theory, are regulated, must have discharge permits and can be monitored to verify compliance with discharge regulations. Nonpoint source pollution, on the other hand, cannot be associated with a defined point in which pollutants impact, so it is monitoring, and regulation is complex. It is interesting to note that water pollution can even come from the atmospheric deposition of pollutants, as has been pointed out in the case of dioxins generated from the burning of waste (Minomo et al. 2018).

One of the main pollution sources of surface water is the discharge of municipal and industrial wastewater. Although the supply and treatment of water are among the activities that require the most investment of financial resources in developing countries, in practice, only a small percentage of wastewater is discharged to the receiving bodies after adequate treatment. As a consequence, the rivers are heavily polluted and there are even currents (once naturally perennial) now lacking in base flows, which are practically made up of wastewater. This situation is more serious in arid and semi-arid regions, where there is a shortage of water. It is a fact that cities have a great contribution to the alteration of the hydrological cycle, not only due to the discharge of a large quantity of wastewater, including huge quantities of very refractory pollutants from the wastes generated by the industrial activity and the extraction of water for different uses, but also due to the alteration of the natural drainage of the watersheds and the recharge of aquifers, intimately linked to the availability of surface waters. There is evidence of significant positive correlations between water quality parameters and urbanization indexes such as population density. Perhaps it is necessary to rethink the scheme of the aquatic urban environment and consider the interaction between the natural, economic and the social water environments, as it has been proposed (McGrane 2016; Liyanage and Yamada 2017; Zaharia et al. 2016; Li et al. 2018; Whitehead et al. 2018; Yu et al. 2018).

The most important sources of nonpoint source pollution are agriculture and livestock production. The prevalence of gravity irrigation (surface) and persistence of the practice of flooding the land, in the plots near the watercourses, means that the fertilizers, manure and other applied products run off to them. This increases the water contents of nutrients, causing eutrophication and thus contributing significantly to water impairment. Direct discharges from livestock and poultry farms, pasture runoff, as well as straightforward access of livestock to surface waters, can cause a substantial increase in the concentrations of nitrogen (especially ammonia) and phosphorus. Their assessment represents a challenge in developing countries (including Mexico) because there are not enough reliable sources of information and tools to do so. These anthropic contributions are greater in the plains and smaller in the mountainous areas where natural factors concur. For example, in China in the Haihe Basin, 10 t N km^{-2} and 2 t P km^{-2} were quantified. In addition, the indiscriminate changes in land use and river deforestation increase nonpoint source pollution, with the loss of the useful soil layer and a greater incorporation of chemical fertilizers into the streams. It is noteworthy that even the prices of fertilizers can impact the concentration of nutrients in river water. It is also important to mention that the positive effects of applying environmentally friendly policies, such as improved crop management and the reduction of crop intensity, may be observed after 1–10 years, but can be validated only after longer periods of time—between 4 and 20 years, a fact which should be considered when monitoring and evaluating the results of such measures (Melland et al. 2018; Kim et al. 2019; Zhao et al. 2019).

Mining generates large volumes of wastewater contaminated with different minerals and elements, such as the discharge of acid mine drains, that affect human health. Artisanal gold mining is a clear example of the contamination of freshwater bodies with mercury. To mitigate its effects, management policies and remediation are required to restore, as much as possible, the affected ecosystems and legal regulations that effectively protect the environment before, during and after mining exploitation, such as: restoration of soil fertility by liming, fertilizing and mulching, revegetation and application of amendments, as well as seed selection of plant species suitable for disturbed sites. Furthermore, social programs targeting poverty reduction and the regulation of artisanal and informal mining are also factors contributing to the restoration and protection of the environment (Villa-Achupallas et al. 2018; Grande et al. 2019; Skousen et al. 2019).

6.2.3 Fecal Pollution

Many streams of water have high fecal contamination. For example, it is reported that in Texas 67% of those listed by the Environmental Quality Commission, present contamination by pathogenic bacteria. Contaminated surface water can contain a wide variety of pathogenic microorganisms, including bacteria, viruses, protozoa and other parasites. The main origin of these pathogenic microorganisms is the feces of humans and warm-blooded animals, which are taken to aquatic environments through effluent discharge of sewage, surface runoff and leaching of soil. The transmission of these pathogens poses severe risks to human health. In most cases, the transmission occurs through the fecal-oral route, especially by the ingestion of contaminated water or food that has been in contact with contaminated water, including aquaculture products from food that have been in contact with wastewaters and especially fresh vegetables irrigated with them. Other important routes of transmission also include the inhalation or aspiration of micro-drops of water and the direct exposure by contact of skin and mucous membranes, during work and recreational activities. Therefore, to a large extent, health risk depend on the use of water, the concentration of pathogens and the degree of exposure to them. It should be mentioned that the indiscriminate dumping of antibiotics into rivers has led to the emergence of strains of Escherichia coli, resistant to these drugs, putting at risk the use of rivers for recreational purposes (Alegbeleye et al. 2018; Jeong et al. 2019; Klase et al. 2019; O’Flaherty et al. 2019).

6.2.4 Organic Micropollutants

One of the main threats to aquatic systems comes from the discharge of waste containing a wide variety of chemical substances, called organic micropollutants (OMP). These include personal hygiene, industrial and household products, drugs for human and veterinary use, as well as metabolites and/or degradation products. In surface waters, these substances are usually found in the order of ppb and ppt concentrations, whereby their determination requires the combination of analytical and bioanalytical methods. Many are compounds designed to persist in aqueous matrices. In addition, their constant discharge into the environment allows them to be classified as pseudopersistent. That is why more and more attention is being paid to these unregulated pollutants, many of which are also called emerging pollutants. When evaluating the presence of OMP in river streams, it is necessary to consider their accumulation in the sediments and re-suspension or redissolution in the aqueous phase, especially in times of increased flows (Navarro et al. 2014; Geissen et al. 2015; Starling et al. 2018; Toušová et al. 2019).

The effects of the OMP for the environment are not completely known. Considering the toxicity of OMP and their evaluation, the focus has been on endocrine disruptors, pharmaceutical products—both for human and animal use, for personal care and also biologically active compounds used in agriculture. A classic example is the alkylphenols, whose most relevant effects in fish are feminization, in addition to other non-estrogenic effects and their bioaccumulation. The pharmaceuticals are designed to interact with biological systems which are found within the environment in a complex mixture, and thus the effects, they can cause in those systems due to the synergies of their individual effects, may accentuate some of their dangerous properties. Another aspect to consider when evaluating the OMP is the possibility of its bioaccumulation in human tissues and fluids, as is the case of some synthetic musks and triclosan. OMP can be introduced into the food chain through the vegetables that incorporate them from the irrigation water or from the soil. In general, there is still not enough information about the alterations that OMP can cause within ecosystems and the effect on human exposure. Although in the legislation of many countries the evaluation of the effects of chemical substances on the fluvial fauna focuses on methods related to the survival of the species, it is necessary to consider that the relationships between the survival, growth and reproduction of the species are of a complex character, not necessarily linear. The action of endocrine disruptors can be manifested in the dynamics of populations and, ultimately, in ecosystem services differently as per distinct species (Fetter et al. 2014; Kuzmanović et al. 2014; Lei et al. 2015; Forbes et al. 2019).

On the other hand, the removal of OMP in the treatment systems is a controversial aspect, although it is considered as the main route of introduction of OMP in the aquatic environment. Everything indicates that the effectiveness of the treatment depends on the type of process, operational conditions of the plant or system, the population it serves, etc., placing enormous weight on the properties of the contaminant (solubility in water, Kow, Koc, Koa, etc.), giving rise to contradictory information and showing the need to evaluate each treatment plant or treatment system in particular. In short, it is a known fact that significant group of OMP are not removed to the desired levels in conventional treatment systems, so they are found in concentrations of the order of ppb and ppt in the WWTP effluents. It is important to mention that the way in which OMP enters fluvial ecosystems depends on the degree of development of the country or region. In countries with a high level of income, these compounds are mainly discharged in effluents from treatment plants. In countries with low or medium income, this occurs mostly through discharges of untreated wastewater (Salimi et al. 2017; Dharupaneedi et al. 2018; Egea-Corbacho et al. 2019; Krzeminski et al. 2019; Paíga et al. 2019; Williams et al. 2019).

6.2.5 Pollution of Mexican Rivers

Mexico's rivers and streams form a 633,000 km-long hydrographic network, with 51 main rivers through which 87% of the country's surface runoff flows, and whose watersheds cover 65% of the country's mainland surface area. The evaluation of water quality is carried out by using three indicators that are monitored in 5,068 sampling sites of the National Monitoring Network, being: (1) five-day biochemical oxygen demand (BOD_5), (2) chemical oxygen demand (COD) and (3) total suspended solids (TSS). In this case, fecal pollution is not taken into account. In Table 6.1, the percentage distribution of sites according to established criteria is shown. Although no significant changes were observed, there was a minor increase in excellent sites in BOD_5 and a slight worsening in COD and TSS distribution (NWC 2013, 2017).

A significant part of the water issues in Mexico is the way in which the authorities report the information to the citizens. Further, the problems that are necessary to be solved have not been prioritized, nor have the goals and actions with intermediate verification mechanisms that allow to see the progress (both regionally and nationally) and to solve them, been suitably addressed (Ibarrarán et al. 2017). For example, fecal pollution is not considered among the criteria to evaluate water quality by the NWC. However, this is one of the most frequent and serious problems that stand out in the investigations made on the rivers and surface water bodies of México, as illustrated in Table 6.2.

Table 6.1 Mexico's rivers water quality in 2012 and 2016 (NWC 2013, 2017)

Quality		BOD_5, mg L^{-1}		COD, mg L^{-1}		TSS, mg L^{-1}	
		2012	2016	2012	2016	2012	2016
Excellent	Criterion	<3		<10		<25	
	% of sites	40.7	27.5	32.1	24.2	57.6	50.0
Good	Criterion	3–6		10–20		25–75	
	% of sites	26.2	13.9	15.2	19.3	29.3	33.1
Acceptable	Criterion	6–30		20–40		75–150	
	% of sites	21.3	18.6	21.0	24.8	6.5	11.1
Polluted	Criterion	30–120		40–200		150–400	
	% of sites	9.6	6.4	26.2	24.9	4.7	4.8
Heavily polluted	Criterion	>120		>200		>400	
	% of sites	2.2	3.6	2.5	6.8	1.9	1.0

Table 6.2 Problems reported in Mexican rivers WQ 2006–2018

River, State	Main problem	Main cause	Reference
Amajac, Hidalgo	DO, FP	GA	Amado Alvarez et al. (2006)
Taxco, Guerrero	HM	Mining	Armienta et al. (2007)
Lerma, Central México	BOD, FP	SW, Agriculture	Sedeño-Díaz and López-López (2007)
Tula, Hidalgo	BOD, DO, NP, HM, FP	SW, Industrial	Montelongo Casanova et al. (2008)
Sabinal, Chiapas	BOD, NP, FP	SW	Castañon González and Abraján Hernández (2009)
Atoyac, Puebla	DO, BOD, HM, FP	SW, Industrial	Sandoval-Villasana et al. (2009)
Magdalena, MC	FP	SW	Jujnovsky et al. (2010)
Lake Chapala, Jalisco	NP	Fertilization	Badillo et al. (2015)
Dam la Purísima	Nitrates	Agriculture	Bonilla Hernández et al. (2015)
Atoyac, Puebla	DO, NP, FP	Industrial, SW	Bravo Inclán et al. (2015)
Santiago, Jalisco	DO, FP	SW, Industrial	Rizo-Decelis and Andreo (2015)
Papagayo, Guerrero	Hardness, FP	Lack of sanitation	Almazán-Juárez et al. (2016)
Magdalena, MC	Disturbances BC	GA	Caro-Borrero et al. (2016)
Atoyac, Puebla	BOD, NP, FP	SW	Handal-Silva et al. (2016)
SW, Central México	FP	SW	Arredondo-Hernandez et al. (2017)
Grijalva, Chiapas	HM, FP	GA	Musálem-Castillejos et al. (2018)

Notes: *FP* Fecal pollution, *DO* dissolved oxygen, *HM* heavy metals, *NP* nutrients, *BC* benthic communities, *GA* general anthropic, *SW* sewage discharges (mostly untreated)

The only way to achieve positive results in the reduction of water pollution is to address the problem at its root—that is, to decrease the impact of municipal and industrial discharges. With regard to treatment, there are breaches of the regulations for discharges at all levels and, even in the case of compliance, the quality of the treated water is insufficient to protect the ecosystems, along with the treated volume of municipal wastewater, which is also inadequate (approximately 58.3% of that generated in 2016). So far there has been a lot of emphasis on the construction of treatment plants, but the payment of energy and inputs for the municipalities in which they operate is a further problem. In addition, centralized treatment technologies are not always viable to treat small volumes of wastewater, typical of small-scale, socioeconomic enclaves, which must also be taken care of. Due to the insufficiency of water with the needed quality, the reuse of treated wastewater can be a supplementary source of water in the management of water resource (de la Peña et al. 2013; NWC 2017; WWAP 2017).

6.3 The Nexapa River

6.3.1 Experimental

6.3.1.1 The Nexapa Sub-basin

The Nexapa sub-basin (NSB, Fig. 1) is in the Hydrological Region No. 18, Balsas River (Alto Balsas), Atoyac Basin. It has a surface of 4,440.54 km^2, a perimeter of 407.6 km and its upper part extends the Atlixco-Izúcar Valley. The most important fluvial stream is the Nexapa River, which is born approximately 20 km north of the city of Atlixco, on the slopes of the Popocatépetl Volcano, at an elevation of 4,610 m above sea level and flows to 677 m above the Atoyac River with a length of 217.5 km and an average slope of 1.808%. It has as tributaries the Atotonilco and Atila rivers. The Nexapa River is of permanent regime fed in its high portion by the thaw of the volcano. On its western portion, it receives contributions from some creeks. Through the Portezuelo Channel, the Nexapa River receives an approximate flow of 4 $m^3 s^{-1}$ of transferred water from the Atoyac River, which, in turn, collects the discharges from the highly industrialized Upper Atoyac Basin which includes the city of Puebla. The dry season lasts from the end of October to the beginning of June and the rainy season from the start of June to the finish of October.

The NSB has an approximate population of 558,038 inhabitants. The cities of Atlixco and Izúcar de Matamoros account for 32 and 24%, respectively, of the urban population. The predominant economic activity is agriculture—of which the main crops are corn, sugar cane, vegetables, gladiola and beans; aquaculture—with the culturing of mojarra-tilapia and catfish; as well as recreation and tourism with pre-Hispanic and colonial sites. Within the area 75% of private homes possess piped water, 62.7% have connection to sewage systems and 97.3% use electric power. According to the studies of water availability in the 757 watersheds of México (DOF 2016), the NSB has a hydrological deficit of $-1{,}158$ hm^3 per year. This affects the availability of water for various uses, which, in the case of the Nexapa, implies an important impact for irrigation agriculture. Intensive irrigation agriculture is a fundamental economic activity in the region. Along the Nexapa River bed, 19 diversion dams have been registered, benefiting 57 irrigation units and 67 users with concessions.

The volume extracted from the Nexapa River is 2, 762,578.51 hm^3 $year^{-1}$ to irrigate 14,858.45 ha. In the common irrigation practices, an excess volume of water is applied, causing soil erosion and dilation of irrigation intervals, causing the plants to suffer from hydric stress and subsequently, affecting crop yields. The most obvious changes in the use of land in the sub-basin territory include the degradation of forests, as well as the increase of urbanization. According to the analysis of the series of land use and vegetation of INEGI 2000–2016, in the NSB, there has been a loss or degraded 43,934.6 ha of deciduous forest between 2000 and 2016 and 12,780.6 ha of forests in the same period—corresponding to the increase in the area of degraded forests (secondary vegetation). In this same period of analysis, we can see that the urban area increased from 3,064.74 ha in 2000 to 12,227.93 ha in 2016, concentrating in the cities of Atlixco and Izúcar de Matamoros and observing conurbation phenomena with neighboring localities.

6.3.1.2 Sampling and Analysis

In general, sampling and analysis were done according to the most accepted sampling, conservation and analysis procedures, namely the: ISO 5667-1, -3 and -6 Standards, APHA-AWWA Standard Methods, EPA Methods and, in conjunction with the concordant Mexican Standards. The analysis of the OMP by solid-phase extraction and gas chromatography/mass spectrometry is described elsewhere. The statistical methods used have also been reported. The cartography was elaborated with the ESRI ® ArcMap TM 10.1 software. The data of coordinates of the sampling sites (channels and rivers) were obtained using a GPS navigation device, using the Horizontal Datum WGS 84. Digital elevation models and vector information were downloaded from the online system called "National Geostatistical Framework" (INEGI 2018; Navarro et al. 2013, 2014; Biache et al. 2015).

6.3.2 Spatial and Temporal Trends of Water Quality

It is observed that the highest values of BOD_5, COD and TSS occur after the S6 station, at the point of impact of the water transfer from the Atoyac through the Portezuelo Canal (Fig. 6.1). After that point, the values of the mentioned parameters decrease, with slight increases after the populated points. This is shown for the BOD_5 in Fig. 6.2a, using the data of NWC from 2012 to 2016. After S16, there is a sudden fall of the three variables, which is due to the fact that the river is practically diverted for irrigation after this point and the water that flows further is contributed by other outcrops, already with much less pollution. A decrease in organic contributions was observed, evaluated by the BOD_5/COD ratio (Fig. 6.2b). This tendency is somewhat more pronounced after S16, which indicates that the most refractory pollutants remain in the river.

Although the WQI used for several years by the NWC is no longer in use, the data from the three studies carried out by the UTIM, as well as the information provided by NWC WQI, was calculated according to the methodology of the NWC and in

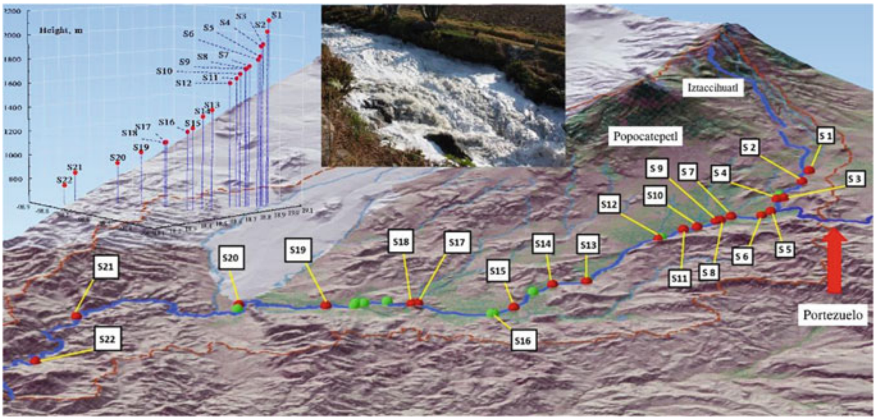

Fig. 6.1 Nexapa sub-basin. The sampling stations, the river profile and a photography of the water transfer from Puebla are shown

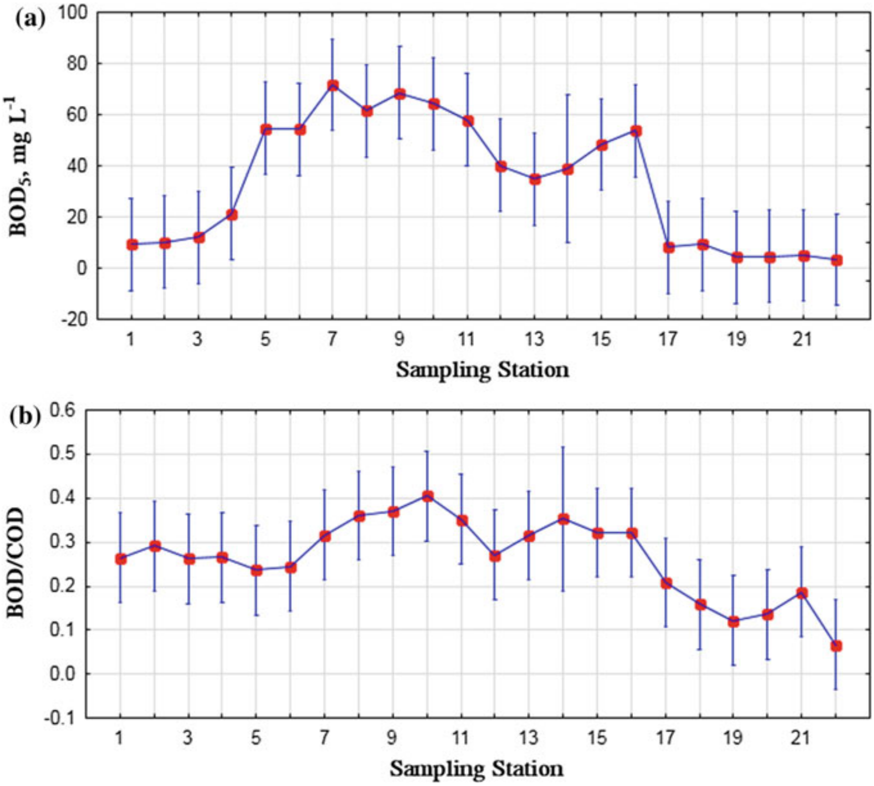

Fig. 6.2 Results of the ANOVA of the BOD_5 and of the BOD/COD ratio, 2012–2016

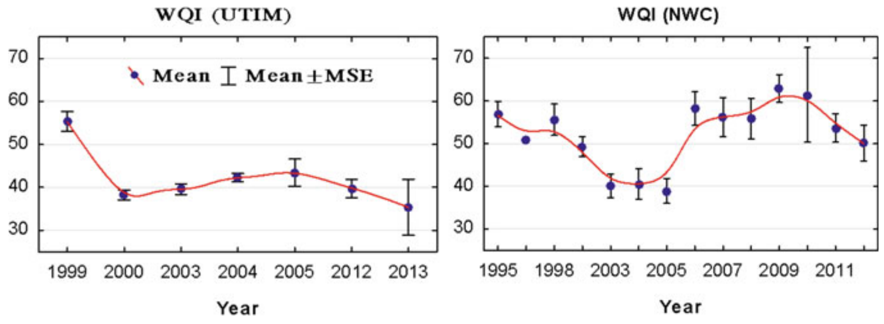

Fig. 6.3 Trends of the WQI determined in UTIM and in the laboratory of the NWC

Fig. 6.3; the average results per year are shown. A coinciding trend can be observed in both cases, although with better values in the NWC results. It is worth noting the negative trend for the values from 2009 to 2013, as influenced by the increases in NO_3, NH_4 and BOD_5 (Navarro et al. 2013).

6.3.3 *Fecal and Organic Pollution*

Unquestionably, regardless of the classification of river waters after station 4 to station 16, ranging from contaminated to heavily polluted, the most severe problem is fecal contamination. Figure 6.4 shows the Fecal Coliform values, from 2003 to 2004, 2012 to 2013 and 2018 samplings. Although we are considering a river, it can be seen that

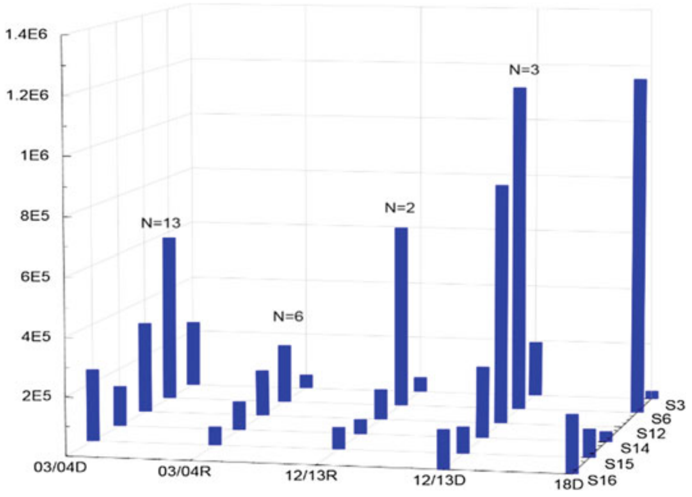

Fig. 6.4 Fecal coliforms in the upper Nexapa sampling stations

the pathogens exceed the values that correspond to the monthly average of wastewater to be discharged to receiving bodies, according to NOM-001-ECOL. Regarding the temporal variation, the values of 2018 are similar to those obtained in 2012–2013, indicating little change in the situation of microbiological contamination, although the values of the later years are higher than those obtained in 2003–2004. The fecal pollution attains levels like those found in the highly polluted Atoyac River (Navarro et al. 2013).

Nearly 400 organic compounds were identified. A considerable amount of the identified compounds have been applied to fragrances, food flavorings or additives and/or personal care products (Table 6.3). This is related to the fact that many of these products are found in nature, and thus obtaining them from their natural sources does not satisfy the demand and it is necessary to synthesize them. Therefore, it is not surprising to find them frequently in the river. It must also be considered that many of the commercial products that are used in the domestic environment contain many OMP that are not even declared by the manufacturers. The spatial analysis of the concentrations of the OMP (Table 6.4) allows us to conclude that their presence in the river is mainly due to the transfer of heavily contaminated water from the Atoyac River—a phenomenon that has been detected in cases of water diversion (Yan et al. 2018). It should be noted the high values of concentrations well above the detection and quantification limits for the studied compounds (0.17–5.57 and 0.56–18.57 ng L^{-1}, respectively).

In the Nexapa River, most of the OMP have the highest concentrations in the dry season, due to the decrease in flow and dilution in the absence of the rainy season, as is also observed in other river basins (Table 6.3). The opposite occurs only with the 24D and PAR. In the case of 24D, this is logical, due to the application of herbicides, preferably in the summer rainy season in the sub-basin, as is observed in other rivers. With regard to the PAR, the cause is not so obvious and may be related to the presence of this compound as a UV filter to extend the useful life of pesticides in the environment. Therefore, its concentration would also be linked to the application of these products.

6.3.4 Possible Actions

Below are several proposals to mitigate the impact of the studied stressors of the quality and quantity of riverine waters. They are valid not only for the Nexapa River sub-basin but also for the small to medium hydrological basins of Mexico and other countries. They include:

Evaluate the environmental flow of the river as a tool for its restoration, eliminating the practice of total abstraction of its water. Promote the care of irrigation channels, their vegetation and fauna as a source of environmental services (Glenn et al. 2017; Stamou et al. 2018; Carlson et al. 2019).

Updating of irrigation concessions, considering real needs per plot based on technical criteria and the use of new technologies. In this sense, to give privilege to

Table 6.3 Descriptive statistics of the studied OMP, ($\mu g\ L^{-1}$)

OMP	Mean ± Std Dev|Median (Min;Max)		
	Annual	Dry season	Rainy season
24D	19.83 ± 24.30|9.07(0.81;92.37)	7.64 ± 11.13|3.52(0.81;43.93)	32.02 ± 27.94|23.65(1.78;92.37)
MDHJ	3.86 ± 3.39|3.10(0.13;17.80)	4.57 ± 4.15|3.50(0.69;17.80)	3.15 ± 2.36|2.18(0.13;8.42)
CAF	2.49 ± 2.53|1.77(0.11;9.76)	3.64 ± 2.86|2.58(0.99;9.76)	1.34 ± 1.48|0.59(0.11;4.35)
GAL	0.98 ± 0.93|0.67(0.20;4.06)	1.35 ± 1.18|0.82(0.34;4.06)	0.62 ± 0.35|0.58(0.20;1.36)
TON	0.12 ± 0.11|0.08(0.03;0.54)	0.13 ± 0.15|0.07(0.03;0.54)	0.11 ± 0.07|0.09(0.03;0.30)
BHT	0.17 ± 0.11|0.13(0.08;0.52)	0.21 ± 0.15|0.20(0.08;0.52)	0.13 ± 0.03|0.13(0.09;0.20)
26DTBP	0.74 ± 1.15|0.37(0.12;5.42)	1.01 ± 1.58|0.36(0.12;5.42)	0.47 ± 0.33|0.39(0.25;1.60)
TCS	1.89 ± 2.06|0.94(0.00;6.27)	3.28 ± 2.10|3.17(0.39;6.27)	0.49 ± 0.45|0.37(0.00;1.36)
AP	14.82 ± 18.30|7.38(1.00;65.48)	23.51 ± 22.58|12.02(1.27;65.48)	6.13 ± 4.73|4.52(1.00;18.66)
MEOAP	3.64 ± 3.91|2.04(0.18;13.12)	5.30 ± 4.60|3.50(0.21;13.12)	1.98 ± 2.15|0.91(0.18;6.70)
DEOAP	1.38 ± 1.55|0.83(0.15;7.83)	1.79 ± 1.98|0.96(0.15;7.83)	0.96 ± 0.81|0.67(0.23;2.76)
NAP	1.43 ± 1.61|1.04(0.03;8.69)	1.89 ± 2.02|1.49(0.08;8.69)	0.97 ± 0.93|0.72(0.03;3.04)

(continued)

Table 6.3 (continued)

OMP	Mean ± Std Dev|Median (Min;Max)		
	Annual	Dry season	Rainy season
SCR	0.73 ± 0.67|0.52(0.11;3.10)	0.83 ± 0.74|0.55(0.24;3.10)	0.63 ± 0.59|0.41(0.11;2.36)
PAR	1.23 ± 1.19|1.03(0.07;5.39)	0.68 ± 0.86|0.28(0.07;2.77)	1.78 ± 1.24|1.15(0.75;5.39)
COP	145.8 ± 118.7|105.7(9.2;508.2)	168.6 ± 139.8|101.7(9.2;508.2)	123.0 ± 92.5|109.7(15.3;321.5)
TMDD	11.72 ± 13.92|6.94(0.00;54.04)	19.64 ± 15.53|16.61(0.56;54.04)	3.80 ± 5.06|1.39(0.00;19.33)
VAN	0.55 ± 0.54|0.31(0.00;2.02)	0.71 ± 0.52|0.84(0.14;2.02)	0.40 ± 0.53|0.14(0.00;1.62)
TERP	4.09 ± 12.45|0.23(0.03;59.98)	7.29 ± 17.17|0.35(0.05;59.98)	0.88 ± 2.07|0.18(0.03;8.14)
BFA	10.44 ± 22.68|3.92(0.65;115.98)	16.79 ± 31.23|3.90(0.65;115.98)	4.08 ± 2.08|3.94(1.15;8.45)
TBF	6.05 ± 7.01|4.10(0.04;29.40)	8.97 ± 8.68|6.53(0.30;29.40)	3.14 ± 2.88|2.43(0.04;8.95)
DCFN	0.12 ± 0.13|0.08(0.00;0.55)	0.17 ± 0.16|0.11(0.03;0.55)	0.07 ± 0.05|0.07(0.00;0.18)

24D 2,4D, *MDHJ* methyldihydrojasmonate, *CAF* caffeine, *GAL* galaxolide, *TON* tonalide, *BHT* butylhydroxytoluene, *26DTBP* 2,6-ditertbutylphenol, *TCS* triclosan, *AP* alkylphenols, *APMEO* alkylphenols monoetoxylates, *APDEO* alkylphenoldietoxylates, *NAP* naproxen, *SCR* sunscreen UV-15, *PAR* parsol MCX, *COP* coprostanol, *TMDD* 2,4,7,9-Tetramethyl-5-decyne-4,7-diol, *VAN* vanillin, *TERP* α-terpineol, *BFA* bisphenol A, *TBF* 4-tertbutylphenol, *DCFN* diclofenac

Table 6.4 Concentrations of CAF, GAL and AP (μg L^{-1}) in the sampling campaigns since 1999

Sampling station	CAF			GAL			AP		
	1999–2000	2002–2005	2012–2013	1999–2000	2002–2005	2012–2013	1999–2000	2002–2005	2012–2013
S3	0.06	4.84	0.59	0.05	3.21	0.31	0.18	1.48	2.04
S6	4.13	21.36	4.41	2.75	8.73	1.73	34.80	98.87	39.6
S12	2.08	16.51	3.61	1.21	3.50	1.61	19.42	25.83	36.5
S14	0.30	10.31	1.71	0.12	2.63	0.70	3.59	7.98	11.9
S15	0.91	10.14	1.60	0.68	3.37	0.50	5.57	8.32	7.27
S16			2.67			0.69			10.2

Note Station S16 was not sampled in 1999–2000 and 2002–2005 dialogue, as a factor that has been shown to positively influence water governance and to consider the needs and preferences of local stakeholders, considering their socio-demographic conditions (Alcon et al. 2019; Aldaco-Manner et al. 2019).

To mitigate the impact of WWTP discharges and urban and agricultural runoff on river water quality, introduce natural technologies for remediation, as well as secondary and tertiary treatment (Aguilar et al. 2018; Herrera and Navarro 2018; de Macedo et al. 2019).

Local and regional governments must invest in establishing a program of real-time monitoring of the quality and quantity of the river waters and the drivers of change, such as air temperature, flow, population density and agricultural area. Given the temporal variability of the OMP, it is necessary to use not only active sampling methods, but also the passive ones, which have been shown to adequately reflect these changes in the concentration of the said compounds. Further, to re-establish the use of the water quality index, this will allow better control of it and will make more sense of the information provided to the public. Attention must be paid to contamination by microplastics (Ewaid and Abed 2017; Diamantini et al. 2018; Rodrigues et al. 2018; Mutzner et al. 2019).

Strengthen informal environmental education. In this sense, the academic sector must take a more active role. Given the temporary nature of government administrations and the validity over time of Higher Education Institutions, especially those located near surface water bodies, it should lead efforts to prepare environmental education materials and disseminate them, along with information of the state of surface waters, through web pages supported by geographic information systems. Finally, local and regional governments must coordinate the allocation of resources to carry out this action and the monitoring of water quality by academic institutions.

6.4 Concluding Remarks

The review of the literature draws the conclusion that there are many environmental stressors that affect the "health" of rivers. It is very important to make its multifactorial evaluation up to the quantification of their effects and the evaluation of their hierarchies and interactions, since not only is there synergies and antagonisms, but also opposite effects that sometimes lead to unexpected results. Although river rehabilitation cannot be evaluated in the short term, it has been demonstrated that community participation with little economic investment can give good results (Tedford and Ellison 2018; Lima and Wrona 2019; Marshall and Negus 2019).

The problems detected in the NSB are typical examples of the main stressors found in many places, such as untreated, or poorly treated, sewage discharges and excessive water abstraction for agriculture. The volume extracted corresponds to an average flow of the river of 8.76 m^3 s^{-1}. If it is considered that this volume is extracted from a river that has a flow in station 4 between 1 and 3 m^3 s^{-1} (as measured by the authors) and that it receives 4 m^3 s^{-1} in station 5, it is easy to understand that the ecological flow is not respected and the absence of water in the river channel after station S12 in the dry period, until the current is recovered with other contributions some kilometers downstream. Furthermore, the transfer of the heavily polluted waters from Puebla is the main source of pollutants and the river water quality impairment, with very high levels of organic and fecal pollution. This needs commendable coordination of local and state authorities.

Systematic water quality monitoring, technological innovation in wastewater treatment, information to the public and a valuable environmental education are key factors to facing and ultimately overcoming these challenges.

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Chapter 7
Enhancing Environmental Services in Candelaria River by Restoring Ecological Connectivity

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Abstract This paper evaluates the conservation status of the trans-border basin of the Candelaria River and its environmental services, with an emphasis on land cover-water quality statistical relationship. The diagnosis indicates that, as a result of the human activities of the last fifty years, the basin has lost 60% of its natural vegetation and increased the contribution of solid waste and sewage. The nutrient that most exports the basin is silicates ($SiO_4{}^{4-} = 79.82$ kg ha yr^{-1}), followed by total nitrogen ($TN = 10.7$ kg ha yr^{-1}) and total phosphorus ($TP = 2.1$ kg ha yr^{-1}). There was a significant positive correlation between the percentage of disturbed areas adjacent to the river (non-forest) and the concentration of TN and TP for the dry season ($r^2 = 0.72$ and 0.52, respectively) and between the disturbed areas and the concentration of silicates in the rainy season ($r^2 = 0.82$). This close relationship between the land cover type and water quality is significant because the river is a natural bridge between two of the most important protected areas in the country (Calakmul and Terminos Lagoon), with environmental services value of 600–1500 US\$ ha^{-1}. As an alternative for its conservation, a program of ecological connectivity is proposed.

Keywords Hydrologic basin · Ecological connectivity · Nutrient loads · Water quality

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7.1 Key Concepts About the Environmental Services of a Hydrologic Basin

7.1.1 Land Use and Land Cover

Although land use and land cover are used indifferently in the current literature, they refer to different concepts. Land use refers to the way in which humans use the land. It is classified from a utilitarian point of view, defining actual and/or potential usage by man (e.g., agriculture, developed land). Land cover, on the other hand, refers to the physical state of the land surface. It describes the feature that covers the surface and the immediate subsurface of the land (e.g., vegetation, soil, anthropogenic elements) (Lillesand and Kiefer 2014; Meyer and Turner 1996; Turner et al. 2001).

The lack of discrimination between land use and land cover may cause misunderstanding of the changes that occur on the land. The causes and effects of land use and land cover changes vary; for instance, "forest" is a class of land cover that may or may not have an anthropogenic use. This forest may be removed for a different kind of land use such as "agriculture." In this case, the cause (change in land use) and the effect (land cover conversion) are directly related. However, changes in land use do not always cause a shift in the land cover classification (Lambin et al. 2000); for instance, forest used as a recreation area may be used afterward for timber extraction, without changing its definition of forest land cover.

Similarly, changes in land cover do not always mean a change in land use. "Grasslands" designed for biological protection (a kind of land use) may go through the processes of natural succession and change to "forest" (a different kind of land cover). However, the protected land use remains unchanged. Thus, although land-use change is usually the primary cause of land cover change, significant changes in land use do not necessarily imply an effect on land cover and vice versa.

Another cause of misunderstanding of the alterations that occur on the land is the lack of separation of the components of land cover change (Table 7.1). Environmental scientists have paid more attention to the substitution of one land cover for another (land cover conversion). However, once the land is converted to another class, it may be modified without changes in land use or conversion to another land cover, and in some cases, land cover modification may be more critical for the environment. The increased use of fertilizers in a cornfield is an example of this situation. Land use (agriculture) and land cover (cornfield) are still the same classes, while the attributes of the management practices are not. The land cover modification (fertilizer application, in this case) may cause a more severe impact to the environment than the land cover conversion because the application of fertilizers leads to a long-term increase in nutrient export (Bohlke and Denver 1995) and degrading water quality (Tu 2011).

Table 7.1 Definitions and applied examples for some of the basic concepts used in this chapter

Concept	Definition	Example 1	Example 2
Land use	The anthropogenic use of the land	Agriculture	Forestry
Land use change	Change from one anthropogenic *land use* to another	Agriculture to urban	Forestry to recreational
Land cover	The physical state of the land	Cropland	Perennial forest
Land cover change	The change from one land cover to another	See examples below for conversion and modification	See examples below for conversion and modification
Land cover conversion	Change from one land cover to another	Cropland to forest (reforestation)	Forest to agricultural land (deforestation)
Land cover modification	Change in the properties of the land without changing to another class	Modification of the intensity of fertilization in the *land cover cropland*	Modification of the intensity of logging in the land cover *forest*

Definitions and examples are based on concepts summarized by Lillesand and Kiefer (2014), Meyer and Turner (1996)

7.1.2 *Land Cover Change and Nutrient Exports*

Land cover change is one of the parameters that explain much of the variability in stream nutrient concentrations (Huang et al. 2015; Shen et al. 2015). The capacity of the land to transform, retain, and also export nutrients is affected by land cover changes, which alter the landscape composition (Allan 2004; King et al. 2005), its geochemistry (Chen et al. 2016), and its relationship with the hydrologic system (Shuster et al. 2005; Walsh and Kunapo 2009). For this reason, *land cover* management is a necessary component to improve stream water quality (Valle et al. 2015).

As it was mentioned earlier, land cover conversion is the change from one land cover to another (e.g., deforestation or urbanization), while land cover modification implies a broad range of variations on the land, not always evident, that may represent an intensity factor (e.g., the population density of urban areas, fertilizer application rates or crop yields of agricultural fields). In contrast to land cover conversion, which indicates an alteration in land cover proportion, land cover modification usually occurs through subtle modifications without changes in land use or without conversion to another land cover (Benitez 2002). Thus, land cover modification may represent variations inside the same class or transition conditions between the two classes. For instance, a forest may be used for logging activities that may cause a reduction in the number and composition of the trees. In the beginning, it may not matter how many or what kinds of trees are extracted, and the area will remain as the cover class “forest.” At a certain point, however, the reduction of the tree densities (the most apparent modification) will lead to variation in retention, evapotranspiration, and infiltration of precipitation, which in turn increases annual water and nutrient yields (Valko 2006). Another example is the modification of the forest structure by natural factors. Eshleman (2000) have shown that defoliation of forest due to the gypsy moth larva increased the annual N export up to ~830 kg ha^{-1}. In this example, the land cover class "forest" remained the same, but its modification had a significant impact on nutrient yields.

The land cover change affects nutrient yields by modifying the capacity of the land to export, transform, and retain nutrients. Export of nutrients is more critical in land cover induced by human activities than from natural forest. For instance, feedlots and crops under irrigation may exhibit very high export coefficients (680–7979.9 and 2.1–79.6 kg TN ha^{-1} yr^{-1}, respectively); urban drainage is second (1.48–38.47 kg TN ha^{-1} yr^{-1}), and non-row agriculture is third in importance (0.97–7.82 kg TN ha^{-1} yr^{-1}) (Harmel et al. 2008). Transformation and retention processes, on the other hand, seem to be more critical in natural *land cover*. Forests accumulate nutrients with age (Fisk et al. 2002), and their export coefficients range from 1.38 to 6.26 kg TN ha^{-1} yr^{-1}. Likewise, in some native prairies, the annual losses of nutrients are lower than nutrient inputs in precipitation (Pratt and Chang 2012). Also, wetlands can reduce loads of nitrates (NO_3^-) from the watershed due to trapping and denitrification (Kronvang et al. 2005; Hoffmann et al. 2011).

The *land cover* change also affects nutrient yields due to the alteration of the hydrologic system. Studies in the Hubbard Brook valley (Bernal et al. 2012) showed that during the first three years after the elimination of forest, streamflow increased 30%, while the average stream concentration of NO_3^- increased up to 40 times. Hardin (1994) states that since there is usually a direct relationship between water yields and nutrient loads, more flux through the soil matrix produces more nutrients. Giri and Qiu (2016) found that clearing forests reduce evapotranspiration, which in turn increases annual water yields. Thus, an increase in nutrient loads occurs due to deforestation. Some studies indicate that different kinds of forest composition (Huang et al. 2015), and different stages of forest succession (Jones and Grant 1996), have different levels of rain interception and, consequently, diverse values of water yields. Thus, when a forest area is cleared and then abandoned to regrow, nutrient loads may change according to the new vegetation composition, and the time needed for this new vegetation to reach a mature state.

Besides the effect of removing natural vegetation for agriculture, some management practices such as channelization and tillage increase the volume of subsurface drainage (baseflow), allowing greater infiltration of rainwater into the soil profile (Houlahan and Findlay 2004; Dow 2007). Because NO_3^- has no affinity for the negatively charged clay particles in the soil, it leaches readily to deeper soil layers. For this reason, an increment of the ratio of subsurface drainage to runoff may result in a significant amount of NO_3^- to groundwater and subsequently to streams as baseflow.

Two of the most common classes of *land cover* responsible for the changes in nutrient (N and P) yields are agriculture and Built-up (Allan 2004; Busse et al. 2006). The expansion of these human activities and the elimination of other cover classes such riparian forest and wetlands, which play an essential role in the reduction of nutrient concentrations, cause an accumulated effect at the watershed level that increases nutrient yields exponentially (Valko 2006). However, higher application rates of fertilizers (Lambin et al. 2000), channelization of the land (Pratt and Chang 2012), among other practices, may cause variations in stream nutrient concentrations without an increment in the proportion of the land dedicated to agriculture or Built-up. It means that modifications to existing *land cover* may have been as significant or even more important than the *land cover* conversion to non-forest class.

Due to the tight relationship between *land cover* and water quality, forested buffer zones along watercourses provide essential services by filtering nutrients, sediment and other contaminants coming from the land (Bechtold et al. 2006). In this relationship, the first 100 m buffer zones along rivers and streams have a more significant influence on this cleaning process than the entire catchment (Houlahan and Findlay 2004; Shen et al. 2015). For this reason, land cover protection policies along watercourses should be addressed to mitigate point and non-point pollution problems (Chen et al. 2016).

7.2 Land Cover Change and Water Quality as Environmental Service

7.2.1 Study Area

The Candelaria River is binational basin share between Mexico (80% of its surface), and Guatemala (20%) (Fig. 7.1). The annual rainfall in the region ranges from 1000 to 1500 mm. The basin has a well-defined rainy season running from June to October, where about 70% of precipitation occurs, and a dry season from March to May. The period that separates these climatic periods (November-February) is affected by invasions of polar masses or "nortes," which can contribute up to 25% of the annual rainfall (CONAGUA 2008). The average annual temperature is around 26 °C, with the lowest values from November to January (16 °C) and the highest values from May to September (38 °C). Higher temperatures coincide with the wet season and give rise to high rates of evapotranspiration. From June to October, and less frequently in May and November, the basin presents the passage of tropical storms and cyclones that generated in the North Atlantic, Caribbean Sea, and the Gulf of Mexico. The torrential rains derived from these phenomena recharge the aquifers of the basin, causing extensive flooding.

From the geological point of view, the Candelaria River runs on a stratified platform of carbonates (dolomite/limestone) and evaporites (gypsum/anhydrite), up to six kilometers thick, which is the product of marine biological activity that gave rise to the entire Block of Yucatán (Fedick et al. 2003). The average annual runoff of the river is approximately 1600×10^6 m^3 (CONAGUA 2008). Due to the karstic nature of the soil that allows a high infiltration of rain, most of the surface currents are intermittent and very scarce in the upper basin of the river. For this reason, the permanent channels of first-order occur mainly toward the middle portion of the basin, leaving

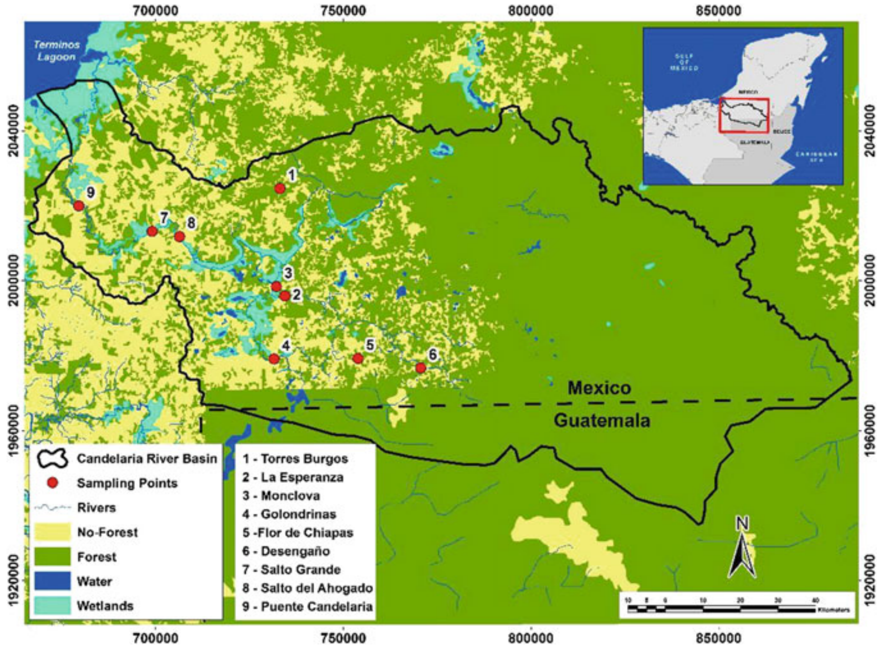

Fig. 7.1 Study area and water sampling stations

a third of it without critical riparian elements. The flat topography of the middle and lower portions gives rise to extensive floodplains with extensive wetlands (Benitez and Couturier 2006).

Human activities have eliminated 20% of natural forest within the basin, and another 35% are in different degrees of disturbance. If corrective measures are not taken, deforestation processes will eliminate 15% more of natural vegetation in the next decade (Benítez 2010a, b). According to Benítez et al. (2010), environmental services value derived from the basin, range from 600 to 1500 US$ ha^{-1}. Thus, the elimination of 10% of the forest in the region would have an economic cost of more than 140 million dollars due to the loss of these natural areas. One of the environmental services most affected by this deforestation will be the quantity and quality of the water that drains into the Terminos lagoon, thereby committing both biodiversity and the fisheries of this coastal lagoon body (Benítez 2010a, b). This problem would happen because the high permeability of the land gives the vegetation a preponderant role in the regulation of the discharge of the rivers since the plant cover increases the evapotranspiration, which decreases the hydrological flow and erosion.

7.3 Methods

7.3.1 *Sampling and Analytical Determinations*

We set a monitoring network of nine sampling stations distributed in the upper, middle, and lower parts of the Candelaria River basin. These sampling sites were representative of the three Candelaria River tributaries, which are the Esperanza River, Golondrinas River, and the San Lorenzo River (Fig. 7.1). Surface-water samples according to NAWQA protocols were collected (Meador and Goldstein 2003). Each sample was transferred to the laboratory for nutrient and silicates determinations, while physicochemical parameters were quantified in situ. Table 7.2 indicates the complete set of water quality variables measured at each monitoring station. The sampling was carried out monthly for 12 months to cover the dry and rainy seasons that characterize the study area (Toro Ramírez et al. 2017).

Table 7.2 Quantified water quality parameters in Candelaria River basin according to NAWQA protocols

Water quality parameter	Analytical principle
Total nitrogen (TN), mg L^{-1}	Conversion to ammonia for subsequent quantification by distillation
Ammonia-nitrogen, mg L^{-1}	Indophenol reaction in basic solution
Nitrate-nitrogen, mg L^{-1}	Reduction by copperized cadmium and formation of azo compound
Nitrite-nitrogen, mg L^{-1}	Reduction by copperized cadmium and formation of azo compound
Organic nitrogen, mg L^{-1}	Difference between total and inorganic forms
Total phosphorus (TP), mg L^{-1}	Stannous chloride method in acidic solution
Orthophosphates, mg L^{-1}	Stannous chloride method in acidic solution with previous digestion
Organic phosphorus (OP), mg L^{-1}	Difference between total and inorganic forms
Silicates ($SiO_4{}^{2-}$), mg L^{-1}	Reaction of soluble silica in acidic condition with molybdate, yielding a yellow complex
Dissolved oxygen (O_2), mg L^{-1}	Reduction to OH− into AgCl and subsequent current flow measurement
Redox potential (ORP), mV	Measurement of electron activity compared to reference electron activity
pH	Measurement of hydrogen ions generated
Temperature (T), °C	Resistance variation in platinum material measured by a sensor
Conductivity (Cond), $\mu S\ cm^{-1}$	Measurement, by sensor, of the capacity of water to conduct electricity

7.3.2 Geographical and Statistical Data Analyses

7.3.2.1 Principal Component Analysis (PCA)

To identify the most critical or sensitive variables facing environmental and anthropogenic changes, PCA was applied considering both, the spatial and temporal distribution of water quality (Sliva and Williams 2001). This method reduces the number of variables from the data in a set of orthogonal axes or components, to detect probable linear combinations between variables that explain the highest amount of variation (Tong and Chen 2002).

7.3.2.2 Regression Analysis

The land use map of the Candelaria River was reclassified to a *Land Cover* map. For this task, all the areas of natural vegetation from the original map (primary and secondary grow) were assigned the value of 1 and were reclassified as the class "Forest." Then, the agricultural areas (agriculture, cattle, and grassland) were reclassified as non-forest, and they were assigned a value of 1.3 (Table 7.3) considering that on average they contribute 1.3 times more nutrients than natural forest areas (Pratt and Chang 2012). The urban areas (Built-up) were reclassified as non-forest too and assigned the value of 6.5 considering that on average they export five times more than the agricultural areas (Tu and Xia 2008; Tu 2011). In this way, the generated map represented the two components that most influence the water quality: land cover conversion (from forest to non-forest) and land cover modification (the intensity use factor).

The proportion of the non-forest class, from the land cover map, was measured around each of the water quality sampling stations. For this task, buffers of variable length and width were made (Table 7.4) using GIS Arc/View 3.2. The different proportions of non-forest were correlated with the concentration of the water quality variables (Table 7.2), selected from the PCA, applying linear regression models

Table 7.3 Classes and factors used to create the land cover modification map

Original class	New class	Ponderation factor
Forest	Forest	1
Wetlands	Forest	1
Abandoned areas of secondary vegetation	Forest	1
Non-row agriculture	Non-forest	1.3
Cattle	Non-forest	1.3
Grasslands	Non-forest	1.3
Built-up	Non-forest	6.5

Table 7.4 Dimensions of the different buffers applied around each sampling point

No buffer	Width (m)	Large (m)	Area (m^2)
1	5000	1000	5,000,000
2	3000	1000	3,000,000
3	5000	100	500,000
4	3000	100	300,000
5	300	1000	300,000
6	5000	10	50,000
7	3000	10	30,000
8	300	100	30,000
9	300	10	3000

(Giri and Qiu 2016). With this information, we obtained the coefficients correlation between the loss of forest cover and nutrients concentration in the river.

7.3.2.3 Nutrient Loads

To calculate the nutrient loads from the watershed, we used the monthly nutrient data from 1999 to the present, provided by CONAGUA, in concert with the monthly data of the current study. These values were multiplied by the average river discharge (2.41×10^9 m^3) and divide by the drainage area of the basin to estimate the total discharge of nutrients in kg ha^{-1} yr^{-1}.

For all statistical analyses, software S-PLUS for Windows was used (Insightful, Inc. 2001). In such analyses, monthly, yearly and seasonal (dry, rainy, and northern) data were used.

7.4 Results

7.4.1 Principal Component Analysis (PCA)

The PCA results showed in Table 7.5, and Fig. 7.2 indicate that the variation of the water quality in the Candelaria River Basin is majorly represented by four components, from which, the first two represent the 94.52% of the total data variation. The number reduction of variables was of 65%, indicating a positive result in the multiparametric analysis (Serdobolskii 2008). In this way, Fig. 7.2 indicated the quality water variables which characterize the tributaries of the Candelaria River basin. Thus, silicates and redox were the representative parameters for the first compound and total nitrogen and total phosphorus for the second one. The rest of the water quality parameters were not considered relevant to this analysis, due to their eigenvalue being less than 0.40 (Serdobolskii 2008).

Table 7.5 Statistic components conformed by the hydrologic variables and the percentage of variance

Component	Eigenvalue	Variance, %	Cumulative variance, %
1	16.05	83.54	83.54
2	5.82	10.98	**94.52**
3	3.93	5.01	99.53
4	1.12	0.41	99.94
5	0.41	0.05	99.99

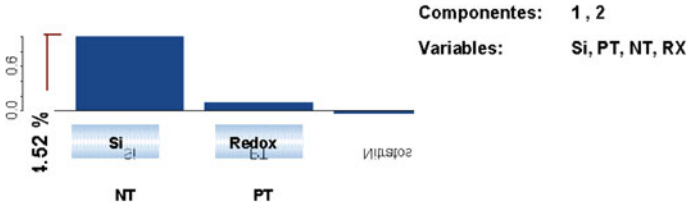

Fig. 7.2 New set of quality water variables by principal component analysis

Silicates were the most critical variable in the PCA (Fig. 7.2), because of the types of soil that can be found in the basin are mainly leptosol, lithosol, and gleysol, and are characterized for containing materials rich in silicates as clays and limestones. These materials are drawn and discharged into the body water for groundwater flows (Moquet et al. 2014), that vary mainly in the basin, depending on the natural drainage basin.

The redox potential was an essential variable for the hydrological characterization of the basin (Table 7.5) due to being sensitive to the activities that surround the water bodies, principally, agriculture, livestock and human settlements, as mentioned by Teixeira et al. (2014). These activities vary in type and intensity, causing the heterogeneity in the redox results.

As for the TN and TP, the cycle of both nutrients vary considerably in the tropical woods with different land uses and vegetation (Bu et al. 2014), being this the case of the Candelaria River basin due to the presence of grasslands, low forest, middle forest, and high forest. This characteristic could explain the variation and, therefore, the importance of both variables in the representativeness of water quality.

7.4.2 Linear Correlations Between Cover Land and Water Quality

In Tables 7.6 and 7.7, it is presented the determination coefficients obtained for each buffer in each of the four representative variables of the water quality in the Candelaria River basin. Except the TP and redox in the rainy season and silicates in

Table 7.6 Coefficients r^2 obtained from the linear correlation between TN and TP and the different proportions of the non-forest class

Buffer (m)	TN			TP		
	D	*R*	*N*	*D*	*R*	*N*
5000–1000	0.045	0.06	0.069	0.008	0.215	0.045
3000–1000	0.012	0.053	0.074	0.13	0.598	0.112
5000–100	0.139	0.015	0.334	0.292	0.592	0.229
3000–100	0.066	0.071	0.23	0.128	0.074	0.169
300–1000	0.001	0.032	0.036	0.271	**0.545**	0.277
5000–10	0.076	0.013	0.306	0.056	0.288	0.034
3000–10	0.014	0.086	0.001	0.352	0.285	0.247
300–100	0.165	0.007	0.026	0.293	0.096	0.242
300–10	**0.573**	**0.179**	**0.003**	**0.647**	0.117	**0.397**

D Dry season, *R* Rainy season and *N* Northern season
Values in bold indicate the highest determination coefficient among the buffers

Table 7.7 Coefficients r^2 obtained from the linear correlation between silicates and redox and the different proportions of the non-forest class

Buffer (m)	Silicates			Redox		
	D	*R*	*N*	*D*	*R*	*N*
5000–1000	0.057	0.019	0.383	0.652	0.011	0.011
3000–1000	0.095	0.004	0.354	0.644	0.016	0.008
5000–100	0.141	0.022	0.222	0.567	0.022	0.065
3000–100	0.375	0.245	0.02	0.455	0.068	0.015
300–1000	0.058	0.03	0.308	**0.757**	0.015	0.003
5000–10	0.257	0.103	0.106	0.272	0.087	0.009
3000–10	**0.51**	0.386	0.113	0.133	0.09	0.031
300–100	0.098	0.148	0.439	0.64	0.004	0.117
300–10	0.123	**0.843**	**0.853**	0.155	**0.243**	**0.186**

D Dry season, *R* Rainy season and *N* Northern season
Values in bold indicate the highest determination coefficient among the buffers

the dry season, the highest correlation was observed in the buffer with less influence area equal to 3000 m^2 around the sampling points.

In Figs. 7.3 and 7.4, it is observed that the four variables tend to increase their concentration as the non-forest cover rises, observing determination coefficients up to 0.85 that ecologically represents an accurate trend. The previous is related to the accumulation of nutrients that characterize the woods with their age (Mosquera and Hurtado 2014), causing the increase of average nutrient export coefficients. Nevertheless, when the forest coverage is removed, these coefficients are increased by up to a magnitude order, due to the increase in the mass of plant residues on the

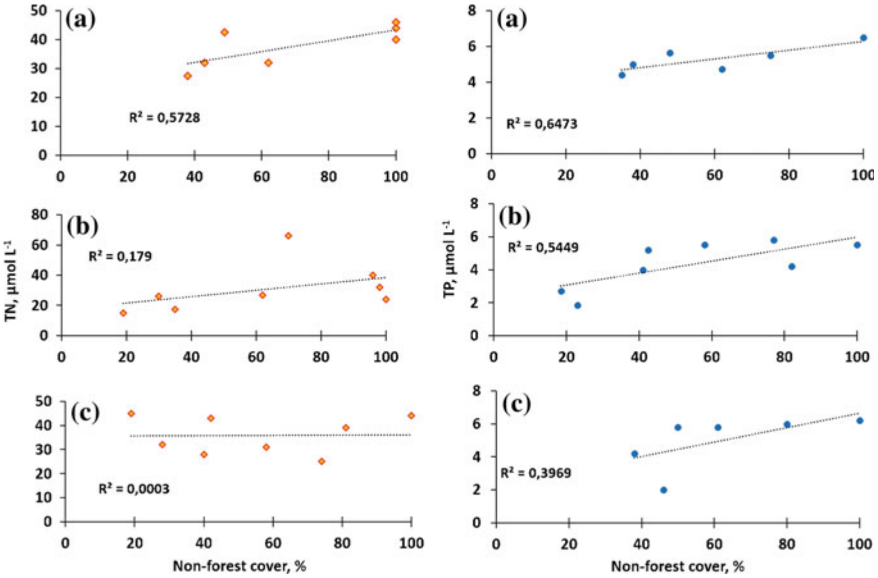

Fig. 7.3 Relation between the percentage of non-forest and the TN and TP concentration for the dry (**a**), raining (**b**) and northern seasons (**c**)

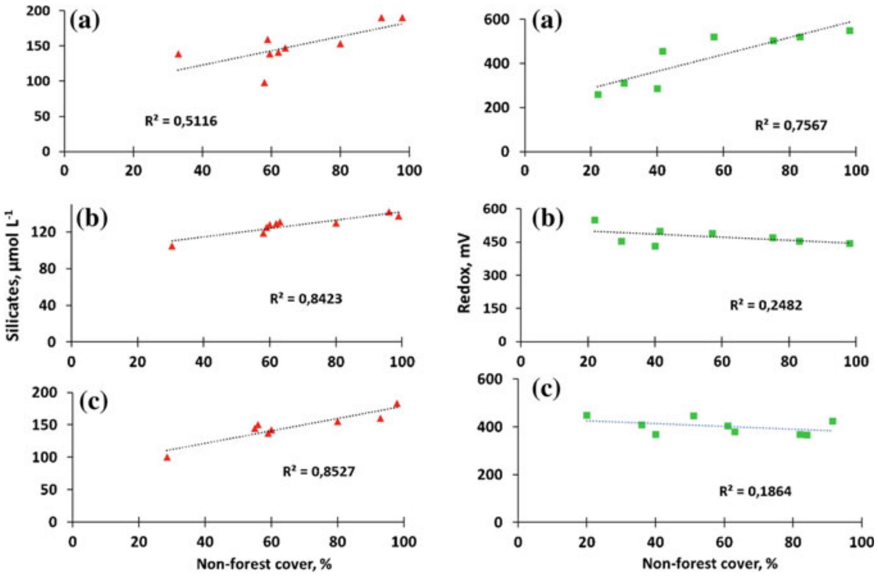

Fig. 7.4 Relation between the percentage of non-forest and the Si and redox values for the dry (**a**), raining (**b**) and northern seasons (**c**)

soil, the reduction in the degree of soil consolidation and the presence of point source of water pollution, which are anthropogenic contributions (Bernal et al. 2012).

Excepting the silicates, the most significant determination coefficient was observed during the dry season (Figs. 7.3 and 7.4). In this season, the dilution process of nutrients in water bodies is practically inexistent, due to the river flow being slower as a result of the decrease of the infiltrated and runoff water (Espinal Carreón et al. 2013). Thus, the activities that surround the water bodies have a direct impact on the water quality.

The above coincides with the significant determination coefficient corresponding in almost all of the cases, with the buffer with the less area (3000 m^2) (Tables 7.6 and 7.7), this implies that the activities surrounding the sample points have the highest impact in the water quality. In point of fact, in the Candelaria River basin, agriculture, livestock and traditional aquaculture are practiced, all being important pollution sources for the surface water bodies (Bu et al. 2014).

Concerning the redox parameters, TN and TP, the determination coefficients were between 0.003 and 0.55 during the raining season and northern. Consequently, it was not possible to establish a tendency connected to the concentration and proportion of the non-forest cover (Figs. 7.3 and 7.4). The foregoing was associated to the fact that during the raining season and part of the northern, the dilution of dissolved and floated particles is present due to the flow velocity (85 m^3 s^{-1}) (Montes et al. 2013), caused by the groundwater being pressed by the infiltrated and runoff water (Espinal Carreón et al. 2013). Therefore, the concentration of nutrients decreases and is homogenized due to being diluted into a larger and continuous water volume (Andrade 2011).

It is important to mention that during the northern season the linear silicates and TP correlations indicate a certain tendency to increase their concentration as the deforestation percentage rises, as in the dry season (Figs. 7.3c and 7.4c). This exception may occur due to the terrigenous origin of both nutrients (Ramos et al. 2017), so that they are discharged into the water bodies during the whole year, through the underground flow, which is even more significative in the Candelaria region for its karstic edaphology (Pratt and Chang 2012).

Specifically for TN, the most significative correlation, during the three climatological seasons, corresponding to the buffer with the less area (300–100 m) (Table 7.6). Together with the TP, during the dry season, it was observed a tendency to increase the nutrient concentration in direct proportion to increase in non-forest coverage, with a relatively high determination coefficient in ecologically terms due to being higher than 0.5 (Varol et al. 2012). On the other hand, during the raining and northern season, the nutrient concentration remained stable in being independent of the vegetation coverage proportion, except the TP in the rainy season, as it had a similar behavior to the dry season (Figs. 7.3 and 7.4).

For the silicates, the determination coefficients were of 0.84 and 0.85 for the raining and northern seasons, respectively (Fig. 7.4). Ecologically, the previous pattern represents an extremely high correlation between the variables because they are not controlled conditions (Giri and Qiu 2016; Varol et al. 2012). There is a clear tendency to increase the silicates concentration as non-forest coverage increases, which is related to the high content of silica in the basin soil, as they lose vegetation, a reduction in the mineral consolidation on them is presented, enabling them to being transported fast and continuous to the surface water (Valiela et al. 2014).

Regarding the correlation between the redox potential and the proportion of the vegetation cover, only in the dry season was the determination coefficient significant with a value of 0.757 as shown in Fig. 7.4. In addition, the correlation with positive slope suggests a greater mechanical aeration of the river derived from a higher flow rate as the vegetation cover decreases, which is related, in effect, to a more significant flow of groundwater derived at the same time from a reduction in soil consolidation, mentioned in recent research as increases in soil permeability (Gandois et al. 2013).

Unlike nutrients, it is not possible to establish a correlation between the redox potential and the proportion of vegetation cover, since the physicochemical parameter is related to various processes such as nitrification, the presence of organic matter, turbulence, and others (Montes et al. 2013).

7.4.3 Nutrient Loads Exported

The nutrient that was discharged the less in the Candelaria River basin was phosphorus, with 2.13 kg h^{-1} yr^{-1}, distributed in organic phosphorus with 1.86 ha^{-1} yr^{-1} representing the 87.56% of TP and inorganic phosphorus with 0.2651 ha^{-1} yr^{-1} equivalents to 12.44% of TP (Table 7.8).

The TN discharged quantity was of 10.73 ha^{-1} yr^{-1} (Table 7.8), with 7.44 ha^{-1} yr^{-1} (69.3%) corresponding to inorganic nitrogen, from which 0.422 ha^{-1} yr^{-1} was ammonia-nitrogen, 0.086 ha^{-1} yr^{-1} was nitrite and 6.93 ha^{-1} yr^{-1} was nitrate. The other 30.7% of TN corresponded to organic nitrogen, with 3.29 ha^{-1} yr^{-1} discharged.

The nitrogen and phosphorus discharge dynamic in the Candelaria River basin is similar to the one in other basins located in tropical areas under 40° north latitude according to the reported by Gandois et al. (2013), Wohl et al. (2012), in which it was observed a discharge of 12.76 ± 4.5 and 4.2 ± 1.8 kg ha^{-1} yr^{-1}, respectively.

Table 7.8 Nutrient discharge in gauging station Salto del Ahogado

Nutrient	Load (kg ha^{-1} yr^{-1})
Ammonia–nitrogen	0.42
Nitrites–nitrogen	0.086
Nitrates–nitrogen	6.93
Organic nitrogen	3.29
Total nitrogen	10.74
Inorganic phosphorus	0.26
Organic phosphorus	1.86
Total phosphorus	2.13
Silicates	79.82

On the other hand, the nutrient that most export the basin is silicates with 79.82 kg ha^{-1} yr^{-1} (Table 7.8). This amount equals up to five times other basins located in similar latitudes (Li et al. 2008), which is related to the carsotectonic nature of Candelaria River basin, composed by micritic and loamy limestones, which leads to a wide silicates circulation (Ramos et al. 2017).

7.5 Restoring Ecological Connectivity

The empirical data described in this chapter show an inversely proportional relationship between the vegetation cover along watercourses and the water quality of the streams. This relationship means that the higher the proportion of natural vegetation around the surface currents, the higher the water quality of the same. For this reason, to the extent that deforestation of the riparian areas advances, the primary response of the basin will be to increase the export of nutrients and water. These changes can have a direct impact on the primary productivity of the Terminos lagoon and can cause an adverse synergistic effect on the fisheries of this coastal lagoon body (Sosa et al. 2005; Ramos-Miranda et al. 2005). As mentioned previously, the hydrological discharge of the Candelaria River constitutes an efficient mechanism of ecological and fishing production. This mechanism of production takes place because the water, nutrients, and sediments carried by these rivers play a critical role in primary productivity and the biology of coastal fishing species, especially in juvenile stages (Miranda et al. 2008).

In addition to the importance of vegetation in regulating the hydrological and water quality of the river, the conserved areas maintain high biodiversity. The upper basin of the river presents long extensions of forest that give continuity to the flora of the Yucatan peninsula and the Guatemalan Peten (Galindo-Leal 1999). In these areas, 80% of the peninsular flora is concentrated, which corresponds to approximately 2200 species of vascular plants (de los Angeles Sanchez-Dzib et al. 2009). Likewise, they contain nearly 100 species of mammals, 282 species of birds (17 of them endemic), 50 species of reptiles, about 400 species of butterflies and a great variety of insects (Benítez 2010a, b; Maya-Martínez 2005; Vargas-Contreras et al. 2005). Due to the importance of the region for the refuge of flora and fauna, the upper basin of the river has essential areas subject to protection such as the Reserva Maya, Calakmul, and Balam Ku. In addition to the above, the Candelaria River flows into the Terminos-Centla reservation system, for which more than 550 species of plants, around 100 species of mammals, more than 60 species of reptiles, 52 species of fish, and 27 species have reported of amphibians. More importantly, they house 328 species of local and migratory birds, representing one-third of all birds reported for Mexico (Arriaga et al. 2000; Córdova Avalos 2007; Hidalgo-Mihart et al. 2017). The middle part of the Candelaria River, currently unprotected, has essential areas of freshwater wetlands and lowland jungles in excellent condition, for which at least one-third of the species present in both the Calakmul region and the Terms-Centla region (Benítez et al. 2010). This percentage is even higher for the group of migratory birds

(Griselda Escalona personal communication). In this region, there are records of threatened or endangered species such as the otter (*Lontra longicaudis*), the jabiru (*Jabiru mycteria*), the jaguar (*Pantera onca*), the tapir (*Tapirus bairdii*), the saraguato (*Alouatta pigra*), the spider monkey (*Ateles geoffroyi*), and the swamp crocodile (*Crocodylus moreletii*). The high biodiversity of this region is more evident in areas where permanent water sources and vegetation in good condition are similar (Benítez 2010a, b).

To change the deterioration trends of the basin, we propose newly reforested areas that, as a whole, increase the quality of the water and increase the connectivity of the river as a biological corridor. As mentioned in the introduction to this chapter, reforestation policies along watercourses have a significant influence on improving water quality (Houlahan and Findlay 2004; Shen et al. 2015; Chen et al. 2016). Also, the reforested areas would form a biological corridor between the protected areas of the upper basin and the protected areas of the lower basin. The areas proposed for reforestation covers 720 km^2. According to the National Forestry Commission, reforestation and maintaining prices for this area are around 1000 US$/ha, which is a lower number than the environmental services value of 1500 US$/ha calculated by Benítez et al. (2010) for the areas surrounded watercourses. Moreover, reforestation and maintaining prices would decrease, as long local authorities encourage sustainable practices such as nature tourism, forest plantations and the use of non-timber products into the vegetated corridor, to increase revenue and minimize the pressure of changing the land cover.

7.6 Concluding Remarks

The methodology used made it possible to correlate the loss of vegetation cover with the water quality of the Candelaria River, which enabled to quantify the impact of deforestation regarding water quality. Subsequently, the deterioration of the Candelaria River Basin is imminent. In addition to the effects at the species level caused by the loss of vegetation cover, the effect on the water quality recognized causes the environmental impact to be regional and possibly global. Nevertheless, experiences in other countries and environmental economics studies conducted in the basin suggest that environmental restoration is still possible. In this way, it is recommended to evaluate in a multidisciplinary way the reforestation along watercourses, which is approximately 720 km^2, since the environmental services of the basin would be improved considerably.

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Chapter 8
Unveiling Groundwater Quality—Vulnerability Nexus by Data Mining: Threats Predictors in Tulancingo Aquifer, Mexico

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Abstract The objective is to propose an approach to care the groundwater quality from anthropogenic threats with minimum funds or poor data, where statistical methods such as popular principal components analysis and K-means, afford non-significant results. It is a frequent dilemma in developing countries. To overcome it, data mining (DM) techniques were applied to evaluate hidden patterns between 15 hydrogeochemical parameters from 29 production wells and the DRASTIC vulnerability index (DVI), to identify the specific parameters related to the threat, even

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natural or anthropogenic. The DM classifiers afforded four wells' clusters, located in correspondence to their DVI-scaled areas in the map. The DM informational and differential weights, with the interaction and multi tests procedures, pointed the key water quality parameters as reliable forecasters and no need for others. The approach would be useful to foresee warning criteria for policy-makers, saving funds in the groundwater quality control analysis. The groundwater quality was adequate, but high and moderate DVI values areas need prevention. DM identified critical physicochemical parameters as predictors for the aquifer vulnerability (Mg^{2+}, HCO_3^-, Cl^-, K^+, Na^+ concentrations, electric conductivity, and total dissolved solids characterize highest DVIs). The main surface threats were the urban and industrial activities in the center, agriculture along the flanks, and cheese manufacturing in the north.

Keywords Groundwater · Vulnerability-water-quality nexus · Data mining · Spatial analysis · Tulancingo aquifer

8.1 Introduction: Vulnerability Related to Pollution Approaches

Environmental scientists endeavour to research, despite frequently low-data accessibility in developing countries. The quantitative criteria to rank either individual parameters or data set require statistical models to provide reliability for the information analysis. However, inadequate funds for sampling and quality parameters determination are common problems (Curtis et al. 2018). Increasing demand for food, housing, drinking water, and environmental services by human activities, trigger global scale impacts and considerable pressure on natural resources. Aquifers are the primary drinking water suppliers, frequently overexploited by residential, agricultural, and industrial demands. Therefore, the security of groundwater requires an appropriate strategy that should be designed based on vulnerability and threats.

Pollution and overexploitation prevention are significant groundwater challenges, endangered by population and industrialization growth. Anthropogenic contaminants leak into underground zones and become the primary threats to water quality. Shallow aquifers are mostly affected by industrial and municipal discharges, promoting the pollutant transportation to other parts (Leduc et al. 2017). Methods to assess and prevent pollution are usually expensive such as isotopic database (Martinelli et al. 2018).

The aquifer vulnerability was earlier assessed by the DRASTIC model, based on soil and physical qualitative features (Aller et al. 1987). The model was improved in the last decade (Caniani et al. 2015) by factor weighing techniques (Pacheco et al. 2015), as well as the spatial analysis with geographical information systems (Hernández-Espriú et al. 2014; Khan et al. 2014). Thus, the DRASTIC approach highlights the most vulnerable areas due to anthropogenic activities on the surface, such as the industry and urban wastes, leading "groundwater vulnerability to contamination" (Yin et al. 2013). It was applied to the Mexico Megacity aquifer (Ramos et al. 2010).

Authors improved the DRASTIC methodology by including more representative issues, which were considered better vulnerability indicators in specific cases. For example, the vulnerability in an alluvial aquifer toward contamination was performed by introducing the "Land Use (LU)" parameter instead of "Topography (T)." LU is best related to the increasing industrial and urban areas, and T was not, because the region is flat (Umar et al. 2009). The authors found a meaningful relationship between high hydraulic conductivity and contamination vulnerability.

In the last decade, attempts to explain the DVI caused by pollution were recently reported by the correlation between various groundwater quality parameters (Ojuri and Bankole 2013). Hanini et al. (2013) reported a linear correlation between the DVI in a coastal aquifer and combined the following quality data: electrical conductivity (EC), chloride (Cl^-), and total dissolved solids (TDS). They found the most significant correlation was between both EC plus Cl^- highest values and the maximum DVI values. The parameters were validated as sea-threatening indicators.

Neshat et al. (2014) studied the relationship between spatial nitrate concentration data and the most vulnerable areas in an aquifer surface. They found a substantial linear connection between the highest nitrate concentrations and the maximum DVI values. Likewise, (He et al. 2018; Neshat and Pradhan 2017) tested a modified DRASTIC model with nitrate concentrations for an agriculture-exposed aquifer, with remarkable results. Further studies enhanced the contaminant criteria (Busico et al. 2017) and introduced sulphate ion (Zhang et al. 2016). The DVI has been related to landfill risks in a recent paper (Uddameri et al. 2014).

Vulnerability related to pollution studies require enough physicochemical data to achieve trustworthy relations between DVI and water quality data. Recognized methods find relationships between parameters, such as principal component analysis (Belkhiri and Narany 2015), multivariate analysis (Charfi et al. 2013; Li et al. 2015; Zhao et al. 2012), fuzzy neural systems (Agoubi et al. 2018), K-means/spatial analysis (Marín-Celestino et al. 2018) and hierarchical methods (Caniani et al. 2015; Sener and Davraz 2012), with enough data to reach representative and reliable findings. Nevertheless, scientists in developing countries are frequently faced with incomplete and limited water quality data, making it difficult to get statistical significance by using the methods mentioned above. There is no previous existing report about the data mining approach applied to explain the aquifer vulnerability causes on groundwater data analysis.

In groundwater quality studies, statistical techniques are applied to analyze interrelations within hydrogeochemical data sets, to discard non-significant factors, seeking reliable conclusions (Chu et al. 2018; Zhao et al. 2012). As they are nonspatial approaches, they are usually combined with geographic information systems.

Nowadays multivariate statistical techniques: Principal component analysis (PCA) and cluster analysis (CA) have been used widely in environmental studies for simplifying and organize large sets and make easier the relation between them together with spatial analysis. In groundwater quality studies, the multivariate statistical techniques are employed to analyze interrelations among different hydrogeochemical data sets and the discarding of non-significant factors, looking for reliable conclusions (Belkhiri and Narany 2015; Charfi et al. 2013).

The principal component analysis (PCA) is a pattern recognition technique that describes the variance in a broad set of intercorrelated variables by converting them into a smaller set of independent variables (Belkhiri and Narany 2015; Li et al. 2015; Uddameri et al. 2014; Zhao et al. 2012).

Cluster analysis (CA) is a recurrent statistical approach that describes how the objects are organized in a data set, assembled by categories and according to the similarities between each entity. CA has been widely used in environmental studies to classify and organize large data sets. As such, some works had shown relations between quality parameters and pollution sources (Aggarwal 2015; Blaylock et al. 2017; Körting et al. 2013).

In recent decades, data mining (DM) has become a computing area that provides several processes (classification, association rule mining, sequential pattern mining, and clustering) to discover hidden knowledge in data sets, representing relationships among parameters, clusters or classified objects (Bhardwaj and Pal 2012; Han et al. 2012). DM is a useful strategy to unveil hidden patterns in a dataset and has been applied in many fields with fulfilling results, including the discovery of unknown associations (Han et al. 2012). It is valuable for decision-making issues, such as health (Amin et al. 2013; Chaurasia and Pal 2013; Zhang et al. 2014), energy (Ferreira et al. 2015), economics (Mittal et al. 2015), and education (Kaur 2015; Prabha and Shanavas 2014), among others. DM is highly recommended to handle a large dataset, but it is also so powerful that it could be used in an opposite situation, when scarce data is available and statistical methods fail.

DM has been applied to numerous water studies, such as the water quality index (WQI) evaluation to identify threats to water quality and remote sensing spectral indices (Wang et al. 2017), to understand the environmental stress on a Panama River due to mining industry on the WQI (Simmonds et al. 2018), the selecting of meaningful operating rules for an Iranian reservoir (Sattari et al. 2012), for predicting Carlson's Trophic State Index in 20 reservoirs in Taiwan (Chou et al. 2018), to forecast the urban water quality on meteorology, water usage patterns, and land uses data (Liu et al. 2016) and decision support system (Hadjimichael et al. 2016), as well as building an integrated Water–Land Use Database for benchmarking and increasing sustainability in cities (Dziedzic et al. 2014), among others.

A recent paper briefly reviewed data mining algorithms reported for the prediction of water quality (Singh and Kaur 2017). The sensitivity to groundwater pollution based on hydrogeological properties, such as input variables, include: water depth, net recharge, aquifer media, soil media, topography, vadose zone media, and hydraulic conductivity (Yoo et al. 2016). Vulnerability depends on multiple factors, and few reports have been found to study its relation to pollutant concentrations or physicochemical parameters by DM (Simmonds et al. 2018).

No previous studies have reported the suitableness of DM to quantitatively determinate the relation between the spatial DVI values of an aquifer and the water physicochemical parameters. To find a way to measure the bonding grade between both sets is quite interesting because of the experimental data in one side and semi-qualitative nature on the other, due to the DVI definition and how it is calculated, based on assigned figures to some characteristics.

The main contribution of this study is to demonstrate the convenience of data Mining techniques to explain the relationship between water quality parameters and groundwater vulnerability, expressed as DVI values. This paper illustrates the DM's efficiency to unveil hidden patterns related to DVI, which could be useful to identify the aquifer susceptibility toward natural and anthropogenic threats. GUHA clusterization, informational and differential weights, interaction, and multi-test procedures would expose the critical threats to groundwater quality. Further, several methods can be applied for clustering, feature selection and generation of association rules, which would contribute to the identification of the relevant threats to groundwater quality. Also, this work demonstrates that significant and reliable information can be achieved by DM with little data available, which is contrary to DM's convenience for complex interpretation due to massive data.

This work aims to evaluate the DM suitability in the study case of the Tulancingo Valley aquifer, whose hydrology pattern was previously reported (Lesser et al. 2007; Lesser and associates 2006). The valley is settled in the Mexican Central Plateau and presents different anthropogenic threats, such as urban wastes disposal sites, agriculture, dairy production, cattle breeding, textile and food industries (Árcega-Santillan et al. 2015). The study handles physicochemical data of 29 wells to find their significative relationships with DVI values by using the DM approach, and subsequently, the spatial analysis adds the information about the surface pollution threats. The whole method provides a comprehensive vulnerability map of Tulancingo Valley aquifer.

8.2 Study Case

The Tulancingo Valley aquifer is in the southeastern region of Hidalgo State, 100 km northeast of Mexico City (Fig. 8.1). It provides water for more than 250,000 inhabitants and is distributed in eleven municipalities. The aquifer covers about 4.98% of the state territory (1021 km^2, between 98° 40.4′ 24″ W and 19.7° 26.8′ 37.1″ N, with an average elevation of 2150 masl. There are textile and food industries in the city centre of the Tulancingo Valley. Cheese manufacturing is predominantly in the north, whereas agriculture and livestock are principal activities in the entire area.

Figure 8.1 shows the main threats. The blue points represent the sinkholes, whose geo-referenced data were supplied by the Groundwater Technical Committee Civil Association of Tulancingo Groundwater (COTAS-Tulancingo A.C.).

Geology. Volcanic elevations from Tertiary stand out at the east, west, and south of the valley. Some are relevant with 3400 masl causing essential runoffs. In the south, Quaternary volcanic mountains (2250–2750 masl) are formed by cinerite cones and basaltic lava spills (Lesser et al. 2007; Lesser and Associates 2006).

The basement of the volcanic rocks and sediments is constituted by shales and calcareous rocks of the Mesozoic, which were intensely folded during the Laramide

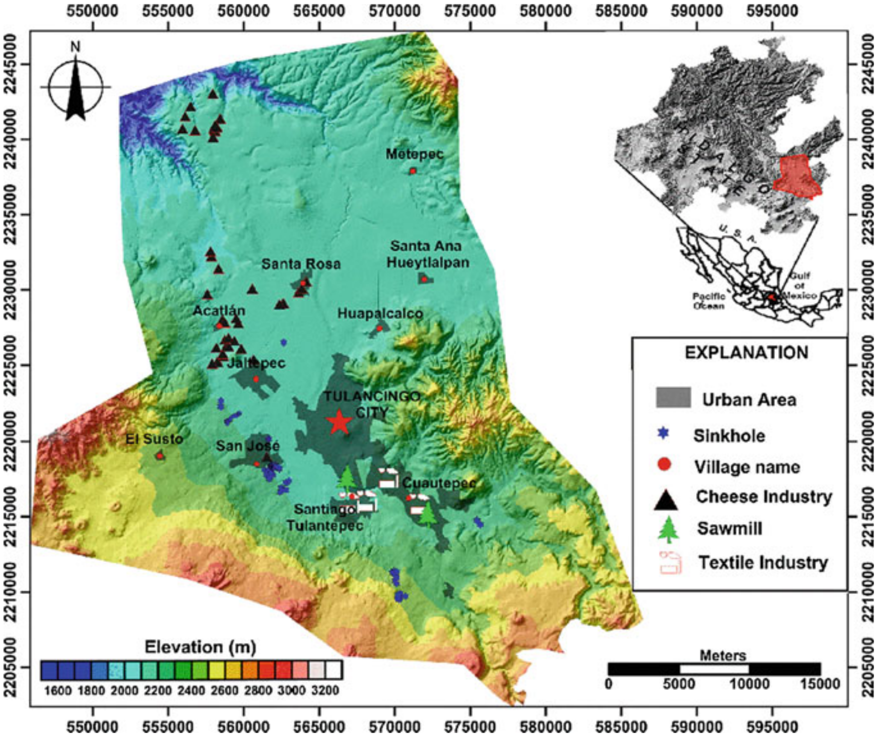

Fig. 8.1 Study area location and aquifer's threats. Modified from Arcega-Santillán et al. (2015)

orogeny, as seen in the Canada de Alcholoya, the northwest portion of the aquifer. During the beginning of the Tertiary and once the folding stopped, normal faulting developed, forming tectonic pits. The Valley of Tulancingo corresponds to one which was filled firstly by clastic materials, followed by pyroclastic deposits and volcanic rocks, originating from two fractures and fault systems. The larger geologic fault (32 km) is orientated toward N30°E, while the smaller fault system (12 km) points in the N50°W direction.

According to the surface information and subsoil geology, the aquifer is formed by a granular medium in its upper portion, composed of sedimentary clastic materials with varied granulometry and pyroclastic. In its lower part, it is created by fractured volcanic rocks. The geological sequence is observed in horizontal layers and is only affected in the central region by normal faults. Clastic clay–sandy and conglomerate materials cover the basaltic and pyroclastic spills from the Atotonilco El Grande Formation (100 m thick) and the volcanic rocks of the Pachuca Group. Under these materials, dwell the calcareous rocks of the Cretaceous, Jurassic, and Triassic, which emerge in the northeast.

The permeable materials correspond to the alluvial and clastic clay–sandy and conglomeratic deposits (>200 m thick) with basaltic intercalations. Basalts and volcanic ash occur in the south and northeast, constituted by fractured lava and pyroclastic flows, allowing the rainwater infiltration in the recharge zones. The low-permeability rocks correspond to the Navajas Rhyolite and the Pachuca Group, established by massive rocks of rhyolitic composition, forming the lateral borders and barriers of the underground flow, as well as the hydrogeological basement of the aquifer.

Hydrography. The main flow is the Grande-Tulancingo River, originating from the south—that is, Chico and San Lorenzo, flowing north toward the fault Barranca de Meztitlan. The secondary infiltrations are Huitzongo, Tortugas Camarones, and La Cueva y Acocul. They supply the district's agricultural irrigation demand. The drainage system is dendritic. Small springs are present in the south and north. At the southeastern zone, the Esperanza Dam was constructed, and the Zupitlan Lagoon sits in the north. Other smaller waterbodies are distributed throughout the valley.

Hydrogeology. The Tulancingo aquifer hydrology has been reported (Lesser et al. 2007; Lesser and Associates 2006). It lodges in a valley surrounded by mountains, in which hills and hillocks are present. It is defined as a free aquifer, composed of two hydrologic units in a granular vadose, consisting of fluvial–alluvial sediments and pyroclastic materials, in a fractured media formed by volcanic rocks with clay deposits.

The hydrologic units were described as (1) a shallow, unconfined aquifer in the southern part, is 20–40 m wide, embedded in fractured basalt and little-consolidated pyroclastic sandy–clays, with static levels lower than 5.5 m, over a 50 m thick basaltic flow, and (2) a deep aquifer, 300 m high, covering the entire valley and composing of pyroclastic layers interbedded with tuffs, fractured basalt and alluvial with different granulometry. It is restricted and exploited by most of the wells, whose static level varies from 50 to 180 m depth (Fig. 8.1). This aquifer supplies 90% of the total 2006 water demands, principally the agricultural (78.5%) and urban/public (18.8%) sectors. Recharges come from irrigation activities and the rain mountains that surround the valley, mainly at the south side of Sierra (Lesser et al. 2007). More than 200 sinkholes in the basaltic southern part of the aquifer were not considered in the calculated recharge. In 2015, the aquifer was prevented from new water concessions, as a -6.77 hm^3/y deficit was estimated (CONAGUA 2015). Previous papers did not report overexploitation. At greater depth, calcareous rocks constitute a confined aquifer over shales and siltstones.

The groundwater's main flux direction is south to northeast, enhanced by secondary inflows from the south, east, and western mountains recharges. The water outflow occurs at the northwestern boundary of the valley, where the water is poured into the Barranca del Mezquital canyon (Fig. 8.2).

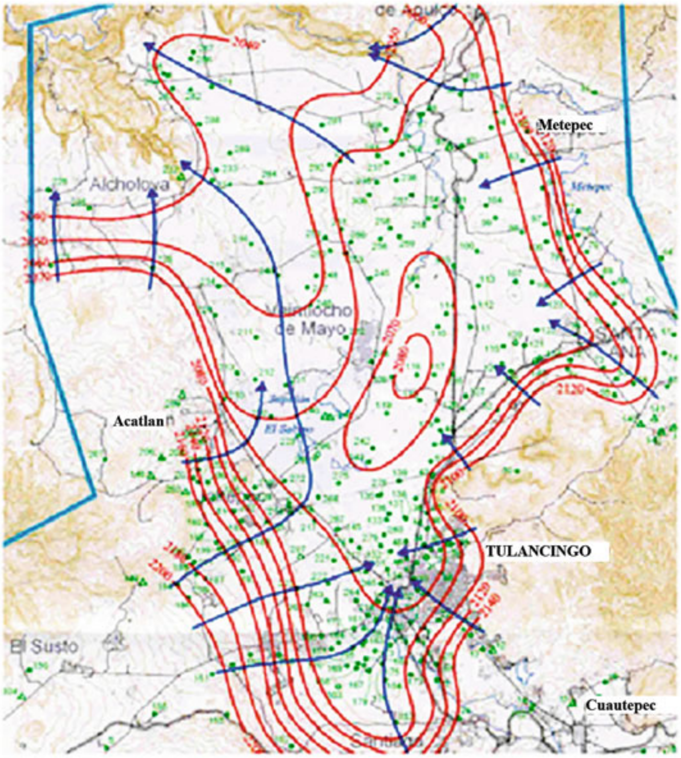

Fig. 8.2 Aquifer's recharges and groundwater flux (Lesser et al. 2007)

8.3 Hydrogeochemical Data

The concentrations (mg L^{-1}) data (Ca^{2+}, Mg^{2+}, Na^+, K^+, Mn, Fe, HCO_3^-, Cl^-, SO_4^{2-}, SiO_2, NO_2^-, NO_3^-, PO_4^{3-}), total dissolved solids (TDS, mg L^{-1}), and electric conductivity (EC, mmhos cm^{-1}) of 29 wells were determined in October 2013 and May 2014 (Environmental Geochemistry Laboratory at UNAM Geo-Sciences Centre, Queretaro). Water samples were collected six times—three times in a rainy season and a further three in the dry season. Variance analysis yielded no significant differences between sampling campaigns and data from 2006 (supplied by COTAS-Tulancingo A.C.).

Table 8.1 shows the statistics data and the Water Pieper classification in Fig. 8.3. The water quality meets the Official Mexican Standard (NOM-127-SSA1 1994). Isoconcentration lines were processed by Surfer software (v 12.0), via spline tension interpolation. Figure 8.4 displays the maps obtained for each parameter.

Hydrogeochemical data (2007 COTAS campaign and this work, 2013 and 2014) showed no significant differences. All parameters fit the standards reported in the Mexican NOM-127-SSA1 1994, although not matching the EPA and WHO standards (EPA 2018; WHO 2011). Hence, the groundwater is suitable for human intake. TDS, HCO_3^-, SiO_2, and SO_4^{2-} display large dispersion. Table 8.1 shows the statistic parameters. Figure 8.3 displays the isoconcentration lines (SURFER, v12.0) for the physicochemical results (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, SiO_2, TDS, NO_2^-, NO_3^-, PO_4^{3-}, and EC).

Table 8.1 Hydrogeochemical parameters. Statistics

Parameters[a]	Min	Max	Mean	S.D
Ca^{2+}	4.0	34.5	15.0207	7.7
Mg^{2+}	2.0	14.1	7.6103	4.2
Na^+	13.2	51.8	31.0998	11.2
K^+	0.3	9.7	5.9078	2.6
HCO_3^-	59.9	255.3	158.5552	58.5
Cl^-	2.7	29.9	10.8103	7.6
SO_4^{2-}	3.9	50.5	16.3352	12.1
EC	0.2	0.7	0.3594	0.1
Fe	0.09	0.1	0.0907	0.004
Mn	0.16	0.16	0.1600	0.0000
SiO_2	61.39	115.62	81.1783	12.9
TDS	35.0	384.0	242.0345	87.9
NO_3^-	0.049	8.485	1.7368	1.9
NO_2^-	0	0.05	0.0117	0.014

[a] Ion concentrations (mg L^{-1}), EC (μS m^{-1}), TDS (mg L^{-1}). *SD* Standard deviation

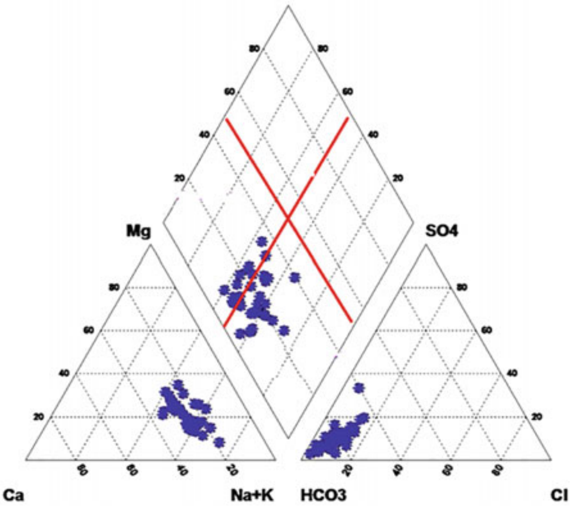

Fig. 8.3 Water Piepper classification

The concentration values are influenced by the geologic composition, formed with basaltic and sedimentary materials. Pieper's diagram classifies the water as calcium–magnesium–bicarbonate (Fig. 8.3). Carbonated rocks compose the vadose zone, which explains the elevated Ca^{2+} levels, principally in the northwest area. High Mg^{2+} concentrations could be attributed to magnesian limestone rocks and dolomites dissolution, as well as those of $HCO_3{}^-$ and $CO_3{}^{2-}$.

The primary industrial and urban wastewater discharges are in the center and south. Agricultural activities are present in the whole aquifer but more intensively in the north. Figure 8.3 shows an anomalous zone near the Acatlan municipality, where whey and salty wastewater from cheese manufacturing discharge. For more than 30 years, 200,000 L whey have been pouring into the environment without any treatment and ignoring its nutritional value. This setting causes negative soil impact and a significant threat to the aquifer (Guerrero et al. 2010).

The preliminary spatial analysis shows high concentrations of Na^+, Ca^{2+}, TDS, and $SO_4{}^{2-}$ caused by textile industries and cheese manufacture wastewater discharges. The presence of Cl^-, $NO_3{}^-$ y $NO_2{}^-$ is attributed to agriculture and livestock activities (Fig. 8.1). Fe and Mn might be leaked from dumps' leachates.

TDS and Na^+ elevated levels might be caused by the surface runoff through more than 200 sinkholes present in the southern zone, threatening the water quality by the south-to-north flow direction. The central and south parts show Na^+ elevated levels, originated by urban and industrial wastewater, rich with sodium sulfate and acetate, due to discharges from textile factories. In the northern region, the high TDS concentrations can be attributed to livestock and agriculture. High K^+ concentrations come from the urban and agricultural effluents, as well as the feldspar weathering.

Cl^- levels and Na^+ are between 20 and 40 mg L^{-1} in the northwestern zone, due to discharges from more than 200 local artisanal cheese making. The southeastern area also presents high Cl^- (20–44 mg L^{-1}) and $SO_4{}^{2-}$ levels, where mainly urban

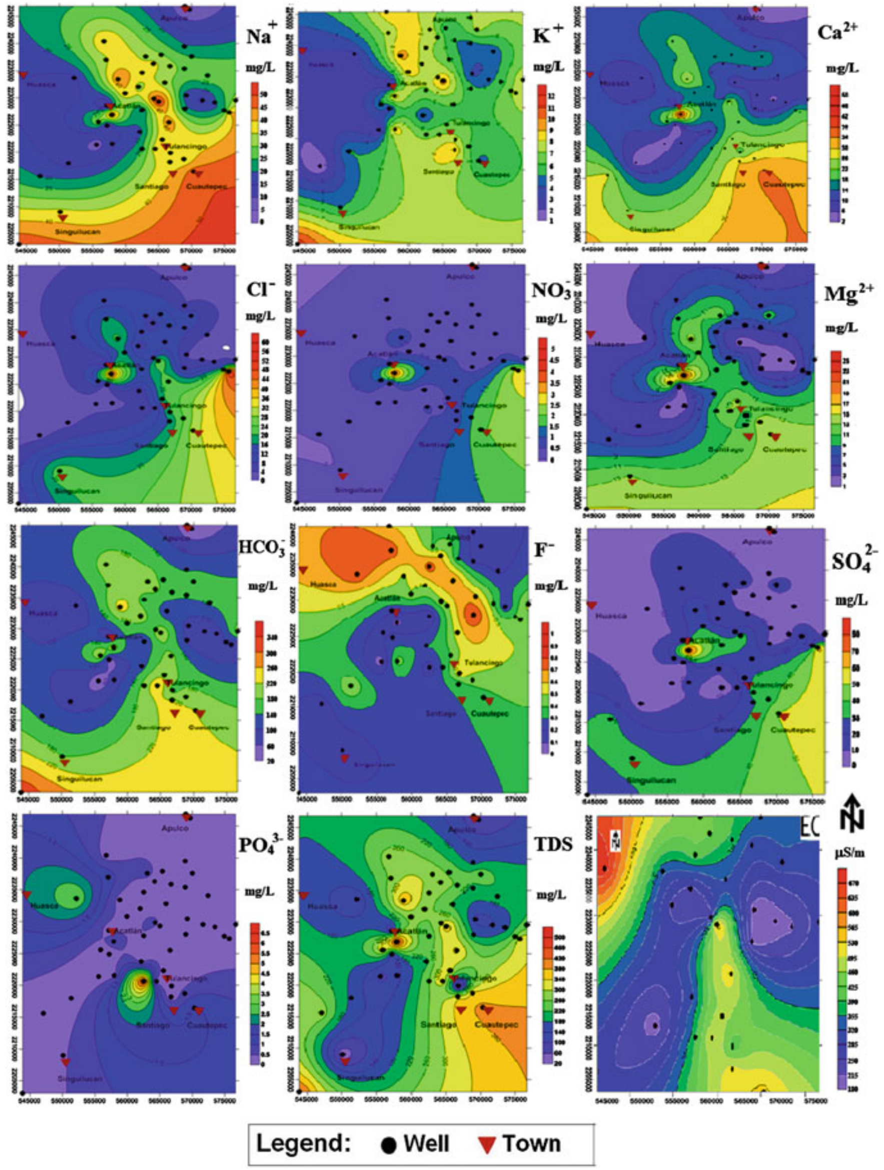

Fig. 8.4 Ion, electric conductivity (EC), and total dissolved solids (TDS) isoconcentration lines maps (SURFER)

and industrial wastewater discharges occur. PO_4^{3-} concentrations (2.5–4.5 mg L^{-1}) are found in the southeast because of the detergents present in municipal wastewater discharge. Furthermore, high NO_3^- concentrations in the southeast are originated from fertilizers and livestock practices (Fig. 8.3).

8.4 DRASTIC-Land Use Modified (DRALUTIC) Vulnerability Index (DVI)

The process for DVI determination in the Tulancingo Valley aquifer is briefly represented in Fig. 8.5. COTAS Tulancingo A.C. (Technical Committee on Groundwaters, C.A.) and Hidalgo State Water and Sewerage Commission (CEAA) provided the wells' geo-referential data. Software ArcGIS v10.3 performed the data and the spatial calculated vulnerability index (DVI) interpolation.

The rating and weighting values for each feature are shown in Table 8.2. Values were assigned, and each map was built by using factor weights. Then, the charts were multiplied by their suitable weight, resulting in the vulnerability map (Fig. 8.5, right).

The linear combination of all factors computed the DRALUTIC DVI by Eq. (8.1):

$$\mathrm{DVI} = D_\mathrm{r}D_\mathrm{w} + R_\mathrm{r}R_\mathrm{w} + A_\mathrm{r}A_\mathrm{w} + \mathrm{LU_r LU_w} + T_\mathrm{r}T_\mathrm{w} + I_\mathrm{r}I_\mathrm{w} + C_\mathrm{r}C_\mathrm{w} \tag{8.1}$$

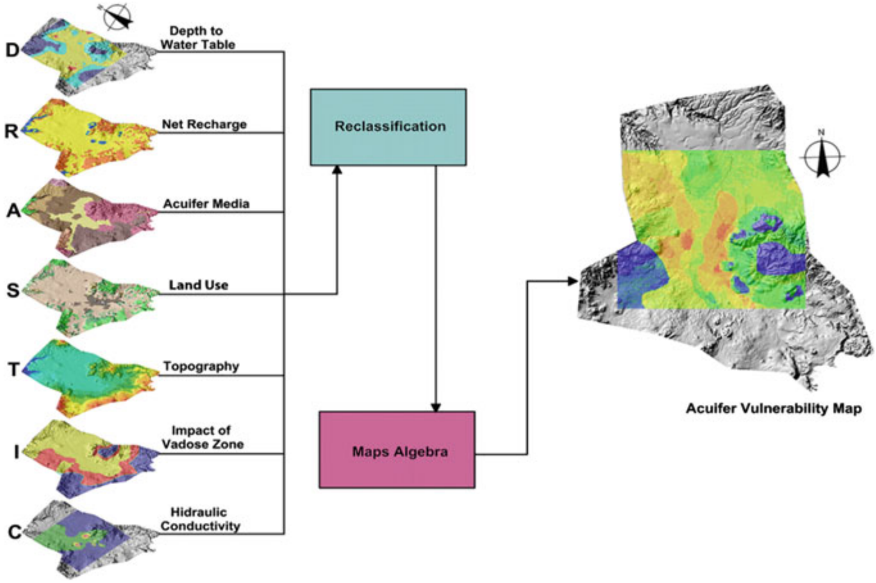

Fig. 8.5 DRASTIC vulnerability index calculation. Named DRALUTIC due to "Soil" changed by "Land Use"

Table 8.2 DRALUTIC rating and weighting values assigned to the hydrogeological parameter

Parameters		Range	DRALUTIC modifiers		
			Weight	Rating	Total weight
D	Groundwater depth (m)	30 to <50	5	5	25
		50 to <75		3	15
		75–100		2	10
		>100		1	5
R	Net recharge (mm/year)	50–102		1	4
		102–178		2	8
		178–25		8	24
		>254		10	40
A	Aquifer media	Basalt	3	9	27
		Lacustrine sediments		8	24
		Rhyolitic tuff		7	21
		Rhyolite		5	15
		Dacitic tuff		4	12
		Shale		3	9
		Pyroclastic materials		2	6
LU	Land use	Urban zone	5	6	40

(continued)

where: *D*, *R*, *A*, LU, *T*, *I*, and *C* parameters are the Depth, Recharge, Aquifer Media, Land Use, Topography, Vadose Zone, and Hydraulic Conductivity, respectively. Subscripts r and w correspond to the range and weight of parameters.

Table 8.2 (continued)

Parameters		Range	DRALUTIC modifiers		
			Weight	Rating	Total weight
		Agricultural fields		5	35
		Grassland-heathland		2	10
		Forest		1	5
T	Topography (slope°)	0–7	1	9	9
		7–15		6	6
		15–23		3	3
		23–33		2	2
		>33		1	1
I	Impact of vadose	Compacted volcanic spills		1	5
		Fractured volcanic rocks		6	30
		Fractured basalt spill		8	40
		Pyroclastic tuffs		9	45
C	Hydraulic conductivity (m/s)	$<10^{-7}$	3	1	3
		10^{-6} to 10^{-7}		2	6
		10^{-5} to 10^{-6}		6	18
		10^{-4} to 10^{-5}		8	24
		10^{-3} to 10^{-4}		9	27

8.5 Data Mining Analysis: Hydrogeological Data and DVI

DM found relations between the hydrogeochemical dataset and DVI values, classified into four groups and its areas' percentages. The applied DM approach consists of clustering, feature selection, and the GUHA methods. The results are discussed in the following sections.

Data were organized in a matrix; the rows represented the wells and features values in the columns. The DM steps were performed preliminary with SIRP software and the generated groups were further input to the Waikato Environment for Knowledge Analysis (WEKA) allowing the features ranking and the General Unary Hypotheses Automaton (GUHA), as described:

a. Clustering was achieved by WEKA (Hall et al. 2009) to find similarities between the wells' features. Seven hierarchical methods afforded the exploratory analysis data, namely: single connection (MIN), complete connection (MAX), centroid, median, forming group average, new group average and Ward. With the exception of the single connection method, the others provided six dendrograms (Fig. 8.6) which visually describes the clustering processes summary, groups data relations in tree diagrams according to the wells' similarities and based on quantitative likeness criteria (Charfi et al. 2013). Table 8.3 shows the clusters based on independent hydrogeochemical variables.

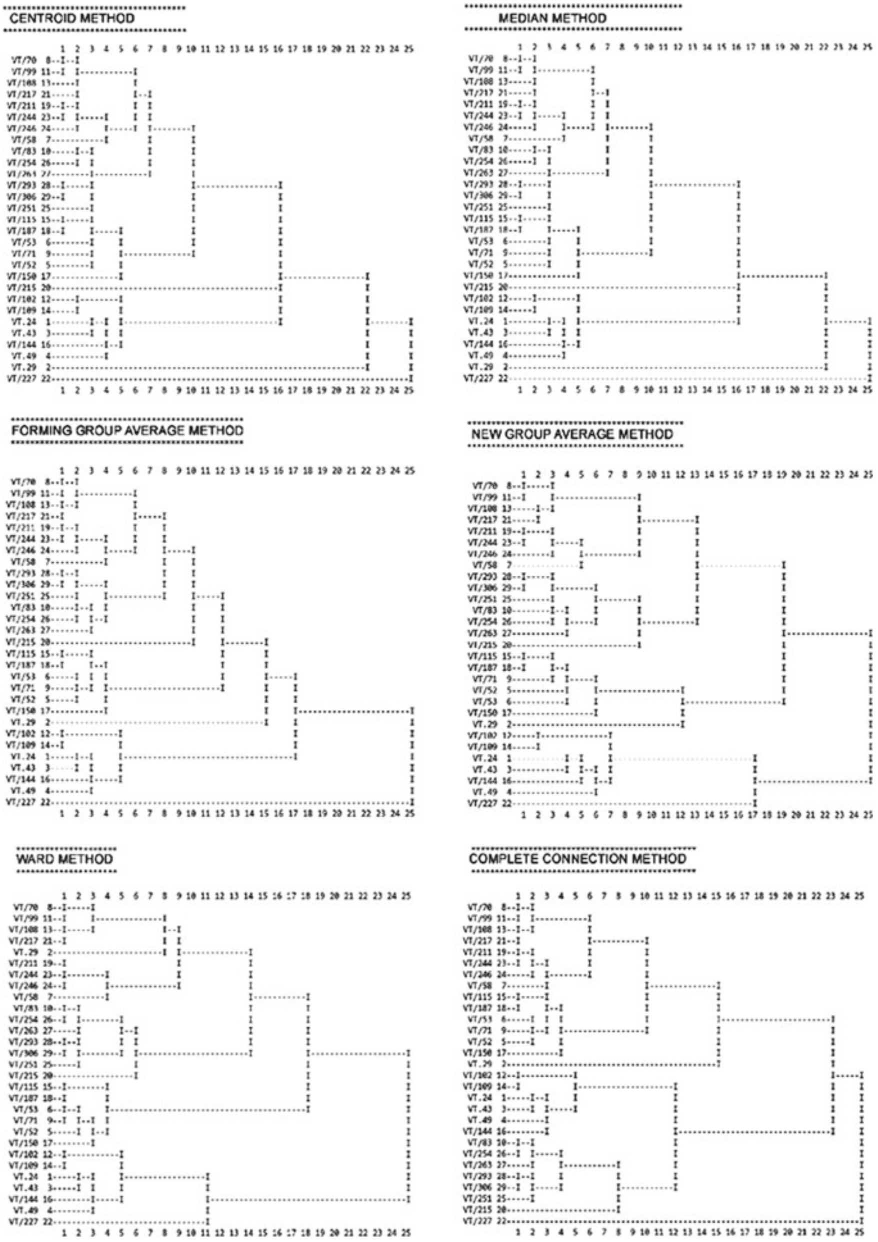

Fig. 8.6 Dendrograms

Table 8.3 Descriptive hydrogeochemical data grouped by clusters

Parameters		Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	EC	SiO_2	TDS	NO_2^-	NO_3^-	PO_4^{3-}
Cluster 1 (*N* = 6)	Min	21	9.8	37.59	4.82	191.8	8.2	12.16	0.47	68.82	312	0.003	1.56	0.14
	Max	34.50	13.70	51.79	9.73	255.30	29.9	50.48	0.56	79.94	384	0.05	8.49	1.58
	Mean	26.07	11.97	42.95	7.12	220.77	20.25	30.08	0.52	74.38	347.67	0.02	3.86	0.48
	Median	24	11.95	41.14	6.57	220.7	21.05	27.77	0.52	73.81	345	0.01	3.47	0.28
	S.D	5.03	1.76	5.86	1.89	20.40	7.55	12.65	0.03	4.95	27.14	0.02	2.42	0.55
Cluster 2 (*N* = 8)	Min	8.00	2.00	17.55	3.97	110.40	2.70	4.20	0.24	75.85	202.00	0.00	0.40	0.17
	Max	17.60	11.20	46.11	8.65	200.80	16.80	28.83	0.32	115.62	286.00	0.01	1.19	0.62
	Mean	12.10	6.79	32.43	6.40	159.35	8.16	12.58	0.28	88.41	237.00	0.005	0.70	0.29
	Median	12.00	7.10	32.15	6.79	160.95	7.95	10.83	0.29	84.98	228	0.005	0.61	0.24
	S.D	3.16	3.00	8.32	1.88	34.01	4.81	8.51	0.04	14.11	33.97	0.003	0.30	0.16
Cluster 3 (*N* = 6)	Min	12	5.9	24.34	5.05	156.9	4.5	3.92	0.35	70.77	254	0.005	0.049	0.06
	Max	17.60	12.70	36.65	7.69	207.40	13.20	14.45	0.43	96.25	286.00	0.04	2.59	6.32
	Mean	14.80	8.87	31.13	6.83	179.50	9.08	9.80	0.40	85.85	269.33	0.01	1.04	1.24
	Median	14.40	8.50	32.39	7.21	179.55	9.75	10.24	0.40	88.26	267.00	0.01	0.58	0.13
	S.D	2.13	3.17	5.39	0.96	21.36	3.17	4.52	0.03	8.52	15.63	0.01	1.05	2.50
Cluster 4 (*N* = 6)	Min	4.00	2.00	13.57	0.32	59.90	2.70	3.95	0.19	61.39	128.00	0.004	0.24	0.06
	Max	8.00	3.40	21.60	8.77	86.50	5.40	27.94	0.26	104.41	176.00	0.05	4.61	0.39
	Mean	6.80	2.52	16.69	3.97	76.03	3.93	11.06	0.21	80.22	151.00	0.02	1.17	0.18
	Median	7.60	2.40	15.84	4.45	80.45	4.10	8.80	0.20	74.24	150.00	0.01	0.53	0.14
	S.D	1.66	0.55	3.21	3.28	10.86	0.93	8.92	0.02	17.01	20.81	0.02	1.70	0.12

Ion concentration (mg L^{-1}), pH (Standard Units), EC (∂S m^{-1}), TDS (mg L^{-1}). *SD* Standard deviation. *N* Number of wells in the cluster

b. Features selection was performed by WEKA to estimate the ions quantitative ranking. The resulted informational (Table 8.4) and differential (Table 8.5) weights were calculated among quality parameters (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, SiO_2, TDS, NO_2^-, NO_3^-, PO_4^{3-} and EC) and DVIs. The differential weight for each physical-chemical parameter is different for each cluster, demonstrating its contribution to vulnerability and validation of the grouping of the wells.

c. The generation of association rules allowed to identify hidden relations between physicochemical parameters and DVI. An open-source data mining library (SPMF) (Fournier et al. 2014) was used to explore data by first-order finite models' identification. GUHA permits recognition of the most significant connections within the data (Hájek et al. 2010; Piché et al. 2014). These methods authorize the acknowledgment of the leading parameters of vulnerability.

8.5.1 Cluster, Informational (IW) and Differential Weight (DW) Analysis

Data relating to wells was analyzed by seven hierarchical methods to obtain a cluster structure in the study case. The single connection method was rejected because of its inconsistency. The dendrograms were obtained by the remaining six methods (Fig. 8.6), grouping the wells in four clusters. The mean values of the physicochemical clusters are displayed in Table 8.3. Three outliers were identified (VT-29, VT-227, and VT-215) and discarded. They were spatially analyzed (white dots in Fig. 8.7) to explain their anomalous behavior.

VT-29 well is in Tulancingo City, next to a graveyard, a contaminated river, a wastewater canal, and surrounded by three textile industries and a swine farm, explaining its unusually high Na^+, Ca^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and NO_3^- concentrations. VT-227 is in the eastern aquifer boundary, near the mountain forest, which is potentially influenced by rainfall and another geographic context. VT 215 sits in the northern agriculture zone where anomalous ion concentrations are seen.

The clustering showed unforeseen patterns and the clusters were embodied into the vulnerability map to find the spatial relationship between geographical features and pollution sources. Their characteristics are described as follows:

First Class. It includes six wells with the highest EC, TDS, HCO_3^-, Cl^-, NO_3^-, Ca^{2+}, Mg^{2+}, and Na^+ concentrations, as primary parameters. Also, the wells present the highest DVI values (136–163) (Red dots in Fig. 8.7), demonstrating their meaningful relationship with the parameters mentioned above. The cluster is in the central part, within the urban area, the most affected by leachates infiltration from landfills, textile manufacturing, and municipal wastewater discharges and shows a south-to-north linear trend. According to IWs, SO_4^{2-}, NO_2^-, NO_3^- ions are the signaling indicators usually present in fertilizers and pointing to agriculture as the primary

Table 8.4 Cluster definition by informational weights (IW) and parameter combinations

Cluster	Parameters	IW	Number of hits in typical tests Combinations of # parameters		
			#4	#3	#2
1	SO_4^{2-}	**0.5769**	2	**13**	0
	NO_2^-	**0.5769**	3	**12**	0
	NO_3^-	**0.4131**	0	**11**	0
	Cl^-	**0.3462**	3	6	0
	Na^+	**0.3462**	4	5	0
	SiO_2	0.2692	0	7	0
	PO_4^{3-}	0.2692	0	7	0
	Ca^{2+}	0.2308	1	5	0
	K^+	0.1154	3	0	0
2	SiO_2	**0.6296**	**17**	**13**	0
	Cl^-	**0.4630**	**17**	8	0
	Na^+	0.2778	3	**12**	0
	TDS	0.2778	10	4	0
	EC	0.2778	10	4	0
	Mg^{2+}	0.2593	0	**14**	0
	K^+	0.2593	9	5	0
	PO_4^{3-}	0.2593	3	9	0
	Ca^{2+}	0.2407	8	5	0
	SO_4^{2-}	0.2407	4	8	0
	HCO_3^-	0.2037	8	1	0
	NO_2^-	0.1852	7	0	0
3	Cl^-	**0.4651**	5	**15**	0
	NO_2^-	**0.4186**	**14**	2	**1**
	SiO_2	**0.3953**	0	**16**	**1**
	Mg^{2+}	0.3023	5	8	0
	EC	0.3023	6	7	0
	SO_4^{2-}	0.3023	5	8	0
	NO_3^-	0.2326	2	8	0
	Ca^{2+}	0.2326	2	8	0
	K^+	0.2093	2	6	0
	PO_4^{3-}	0.1628	2	5	0
	Na^+	0.1163	0	3	**2**
4	K^+	**1.000**	0	3	**2**
	NO_2^-	**0.5000**	0	2	0

(continued)

Table 8.4 (continued)

Cluster	Parameters	IW	Number of hits in typical tests Combinations of # parameters		
			#4	#3	#2
	NO_3^-	**0.5000**	0	2	0
	SiO_2	**0.5000**	0	2	0
	SO_4^{2-}	0.2500	0	0	**1**

Table 8.5 Differential weight tests results

Ion	Differential weight	Number of hits in typical tests Combination of # parameters	
		#2	#3
Cl^-	**0.693**	0	2
SO_4^{2-}	**0.456**	0	2
K^+	**0.386**	0	0
NO_2^-	**0.350**	0	0
Na^+	0.307	0	0
PO_4^{3-}	0.298	0	0
SiO_2	0.289	0	3
TDS	0.254	1	5
Ca^{2+}	0.254	1	0
EC	0.219	4	4
HCO_3^-	0.210	0	4
Mg^{2+}	0.184	1	0
NO_3^-	0.157	0	0

threat. Also, Cl^- and Na^+ presented hits in three- and four-component interactions, indicating the cheese and textile industries menace.

Second Class. The cluster contains eight wells with moderate EC, TDS, and HCO_3^- concentrations as the most characteristic parameters and shows medium-to-high DVI values (117–136) (orange dots in Fig. 8.7). The group is situated in the north, where cheese industries occur in a curved area surrounding the central urban sprawls. The highest IW pointed to SiO_2 (four and three components), and Cl^- (four components). Also, Na^+ and Mg^{2+} showed many interaction hits (three components), so they are representative. These results suggest the geologic component's presence in the water quality and, concurrently, the salinity induced by the cheese and textile industry.

Third Class. Six wells represent this cluster. As in the previous class, the main parameters are moderate EC, TDS, and HCO_3^- concentrations with intermediate DVI values (99–117). Other ion's concentration range is slightly higher than the second one (Ca^{2+}, Mg^{2+}, Na^+, K^+, and SiO_2). The wells are in the northern aquifer

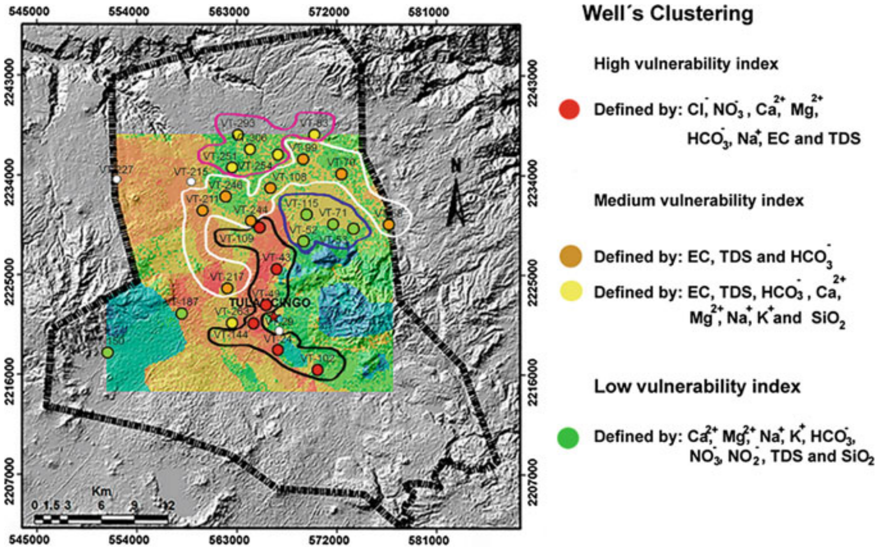

Fig. 8.7 Wells' clustering and DRALUTIC vulnerability index map

border and are affected by the cheese industry (yellow dots in Fig. 8.7). The highest IW identified NO_2^- (four-component hits), Cl^- and SiO_2 (three-components hits) as the most typical features. Also, 2-two components interaction between NO_2^- and SiO_2 is a key feature. These results suggested that geology and agriculture activities are the primary influence on the water quality.

Fourth Class. Six wells belong to this cluster, whose dominant characteristics are Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, and TDS lowest concentration and DVI (66–99) values. Informational weights suggest that the K^+ concentration defines the cluster, followed by NO_2^-, NO_3^-, and SiO_2. It is noteworthy that this cluster presents the lowest ion concentrations and DVI values. It is located near the base of the eastern mountain, formed by mafic and intermedium igneous rocks, such as basalts and ignimbrite (green dots in Fig. 8.7). Geology and agriculture primarily influence the water quality.

8.5.2 *Feature Selection Based on Informational (IW) and Differential (DW) Weights*

Table 8.4 shows the informational weight (IW) attributes in each cluster (the most relevant values in bold). An ion with high IW indicates strong interactions with others, making the difference within the group. Therefore, this ion is identified as ***the class pacesetter***. The amount of combinations it presents in a vulnerability group affords extra information to consider in the analysis.

The features selection technique based on IW shows combinations of two, three, or more components describing the clusters relation with DVI. In the case of two components selection, the key combinations involve the EC with other parameters, such as TDS, Mg^{2+}, Na^+, and Ca^{2+}. The three components combinations involved EC and SO_4^{2-} interacting with NO_2^-, NO_3^-, and K^+.

The individual analysis affords outstanding results. The Cl^- is the first ranked, with 71 combinations related to high DVI values. Thus, wastewater salinity is corroborated as a significant pollution risk due to cheese manufacturing and the textile industry. Another essential ion is SO_4^{2-} and was found in 52 combinations. Hence, agriculture is also a considerable threat to the aquifer water quality.

The DW values give more in-depth information with an emphasis on the differences between clusters. Table 8.5 shows the results. Cl^- and SO_4^{2-} presented the highest DW values, followed by K^+ and NO_2^-. Their uppermost values suggest the DVI differences related to the pollution sources. Therefore, those ions' will play as markers of high vulnerability, and much attention should be paid to them in the Tulancingo aquifer.

DM gave the detailed information that explained how and why the clustering is based. The case study presents a few wells; nevertheless, the results are highly significative due to the DM multi tests procedures. Differential tests identified the hydrogeochemical variables related to DVI and allowed the identification of the most influencing natural and anthropic sources in the groundwater quality. DM approach highlights the nexus between the physicochemical parameters' interactions and vulnerability.

8.5.3 GUHA Analysis. Influential Levels

GUHA analysis contributes to a valid hypothesis about the associations between parameters of distinct categories. The GUHA rules were configured by selecting the vulnerability index as the target variable and the physicochemical parameters as independent variables. Once the regulations were obtained, they were divided into those that produce the high and moderate DVIs. Then, the most significant values (95% confidence level or higher) were selected (see Tables 8.6 and 8.7). The results were spatially analyzed and summarized as follows:

(a) High DVIs are primarily related to very high Mg^{2+} and HCO_3^- concentrations, followed by Na^+, K^+, EC, and TDS high values. Thus, carbonate rock composition and plagioclases, in conjunction with the cheese industry and agriculture, forecast high vulnerability. TDS is also related to human settlements and livestock. NO_2^-, NO_3^-, and Cl^- showed no associations with any other ion.

(b) Moderate DVIs are related to the coinciding of Mg^{2+} and K^{+-} high values. Once again, the soil composition and the same anthropogenic activities threaten the aquifer, but at a lower intensity than the previous condition as the EC and

Table 8.6 Influence levels. Relationships among variables and high DVI values (most relevant in bold)[a]

The most important	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	EC	SiO_2	TDS	NO_2^-	NO_3^-
Mg^{2+}	**NS**	–										
Na^+	**NS**	**H/VH**	–									
K^+	**NS**	**NS**	**H/H**	–								
HCO_3^-	**NS**	**NS**	**H/H**	**NS**	–							
Cl^-	**NS**	**NS**	**NS**	**NS**	**NS**	–						
SO_4^{2-}	**NS**	**MH/VH**	**MH/H**	**MH/H**	**MH/H**	**NS**	–					
EC	**NS**	**H/VH**	**H/H**	**H/H**	**H/H**	**NS**	**H/MH**	–				
SiO_2	**NS**	**L/VH**	**L/H**	**L/H**	**L/H**	**NS**	**L/MH**	**L/H**	–			
TDS	**NS**	**VH/VH**	**VH/H**	**VH/H**	**VH/H**	**NS**	**VH/MH**	**VH/H**	**VH/L**	–		
NO_2^-	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**L/VH**	–	
NO_3^-	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	–
PO_4^{3-}	**NS**	**VL/VH**	**VL/H**	**NS**	**NS**	**NS**	**VL/MH**	**VL/H**	**VL/L**	**VL/VH**	**NS**	**NS**

Concentration: *VL* Very low, *L* Low, *ML* Medium low, *M* Medium, *MH* Medium high, *H* High, *VH* Very high, *NS* Not significant

[a] Interpretation example: 2nd row (Na^+) interaction with 2nd column (Mg^{2+}) resulted H/VH. It means that high Na^+ concentration with very high Mg^{2+} one, points to high DVI values

Table 8.7 Influence levels. Relationships among variables and Medium DVI. Most relevant in bold[a]

The most important	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	EC	SiO_2	TDS	NO_2^{-}	NO_3^{-}
Mg^{2+}	NS	–										
Na^{+}	NS	NS	–									
K^{+}	NS	**H/VH**	NS	–								
HCO_3^{-}	NS	NS	NS	NS	–							
Cl^{-}	NS	NS	NS	NS	NS	–						
SO_4^{2-}	NS	NS	NS	NS	NS	NS	–					
EC	NS	NS	NS	NS	NS	NS	NS	–				
SiO_2	NS	ML/VH	NS	NS	NS	NS	NS	NS	–			
TDS	NS	NS	NS	NS	NS	NS	NS	NS	NS	–		
NO_2^{-}	NS	H/ML	NS	NS	NS	NS	NS	NS	H/ML	NS	–	
NO_3^{-}	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	–
PO_4^{3-}	NS	L/VH	L/H	L/H	L/H	NS	L/MH	NS	NS	NS	L/H	L/L

Concentration: *VL* Very low, *L* Low, *ML* Medium low, *M* Medium, *MH* Medium high, *H* High, *VH* Very high, *NS* Not significant

[a] Interpretation example: 3rd row (K^{+}) interaction with 2nd column (Mg^{2+}) resulted H/VH. It means that high K^{+} concentration with very high Mg^{2+} ones, points to medium DVI values

TDS are not present. The lower groundwater salts concentrations correspond to moderate DVIs.

DM demonstrates the importance of the geological structure and spots the principal anthropogenic pollution sources in the aquifer water quality. The DM strategy shows up the best groundwater quality predictors and foresees warning criteria for policy-makers. Also, it saves funds by reducing the number of groundwater quality parameters needed to prevent aquifer vulnerability. Reports about isotopic methods are too expensive for routine control planning (Re et al. 2018; Ryan et al. 2018).

8.6 Spatial Analysis

The spatial analysis was carried out by superimposing the clusters with the vulnerability map including the location of each anthropogenic activity and the soil composition. The chart (Fig. 8.7) denotes the geographical relation between clusters and DVI areas: high (146–187), medium (105–146), low (60–100), and very low (23–60). Very high DVIs (187–230) were not found in this aquifer.

The highest DVI values were found in the urban areas of Tulancingo and Acatlan municipalities, where the solid wastes, industries, and main sewage could contaminate the Tulancingo River and irrigation channels, rising the aquifer pollution threats. The ion concentrations increase in the flow direction (south-to-north); thus, any incoming contaminant from the southern industry discharges and sinkhole recharge will impact on the most vulnerable zone.

The very low DVI is observed in the forests and mountain areas, with low anthropogenic activities (Arcega-Santillán et al. 2015).

8.7 Conclusions

In the Tulancingo aquifer, the DM found associated patterns between the DVI and water quality parameters with scarce data is available. Despite this limitation, DM gave significant and reliable results, establishing Mg^{2+}, HCO_3^-, EC, TDS, Cl^-, K^+, and Na^+, as the most relevant parameters related to the vulnerability index.

The four- and three-component interactions among SO_4^{2-}, Cl^-, NO_3^-, NO_2^-, Mg^{2+}, and Na^+ are relevant because they have more impact on vulnerability index than those between two parameters. Cl^- and SO_4^{2-} mostly affect vulnerability, as they are present in 71 and 52 hits, respectively. Thus, the wastewater from cheese manufacturing and textile industry, the agriculture fertilizers, as well as the urban population, textile industries and wastes are corroborated as significant anthropic threats in the most vulnerable areas. On the other hand, SiO_2 from igneous rock weathering was not associated with the DVI, despite its high concentration values and frequent hits in the informational weight.

This work demonstrates the suitability of DM to find unknown relations between semi-qualitative indicators, such as the DRALUTIC vulnerability index, and the experimental physicochemical water parameters. The relationships between the most vulnerable areas and the pollution sources allow hierarchization. Data Mining has been applied to study components relationships in water quality analysis, but not to explain vulnerability in relation to groundwater quality studies. The proposed methodology is recommended for researchers in developing countries who frequently work with limited data set.

Most important is the identification of signaling parameters, that could rationalize funds for water quality control, providing low-priced clues to detect the main threats to the aquifer contamination as a tool for policy-makers planning preventative programs for the groundwater resources management.

The main advantaged of the DM approach are summarized as follows: (a) higher reliability and in-depth information than statistical methods, (b) improved trustworthiness, even with limited available data, (c) outliers' identification, (d) hierarchization in clustering processes, (e) identification of signaling physicochemical parameters, and (f) differences and similarities between clusters. The spatial interpretation of physicochemical data is essential to explain the vulnerability causes; otherwise, the analysis would be incomplete. It requires a multidisciplinary team to integrate the DM nonspatial results with the anthropic activities on the surface.

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Chapter 9
Effects on Groundwater Quality of the Urban Area of Puebla Aquifer

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Abstract Groundwater is the most important source for water supply in the urban zone of Puebla. Economic and industrial growth has caused a high demand for water. Intense extraction of groundwater has led to a significant decline in groundwater levels and degradation of quality. This study aimed to define the groundwater quality with the assessment of the hydrochemical changes produced by intensive water exploitation in the urban area of Puebla City. A general decline in the groundwater level has been found over the years, at a rate of as much as 1–2 m/y. Two ground fissures were identified in the same location as the drawdown cone. An evolution in the chemical composition and a change in the water-type classification were observed over the years. The increase of sulfates, calcium, and magnesium concentrations in the upper aquifer has been caused by upwelling mineralized water from the deep aquifer, where the hydraulic gradient of the groundwater table levels favors the induction of the flow-through of the fault and geological fracture and mixes with water from the upper aquifer. Concentrations above the limits recommended by the criteria established for Mexican law of trace elements and heavy metals were detected for the first time, and their origin can be attributed to natural and anthropogenic sources.

Keywords Puebla aquifer · Intensive extraction · Groundwater · Contamination

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9.1 Introduction

Groundwater is one of the most important natural resources and the main source of water supply around the world. Some big cities are dependent on groundwater. In Latin America, many of the continent's largest cities obtain a significant proportion of their municipal water supply from groundwater. In Mexico, the groundwater is a vital source of supply; it is primarily used for irrigation, population, and industrial facilities (INEGI 2010). Groundwater sources are the most important means of fulfilling the water requirements of the country, representing more than 70% of the water supply for industry and providing a water source for more than 70% of the 110 million inhabitants (CONAGUA 2015; Esteller et al. 2012; Carrillo-Rivera et al. 2008).

This fact caused the intense exploitation of aquifers, bringing about significant changes in flow regime and groundwater quality (Naik et al. 2008; Howard 2007). In the country, clear examples of groundwater dependency include Mexico City (Carrera-Hernández and Gaskin 2007; Ramos-Leal et al. 2010), Toluca (Martín del Campo et al. 2014), Querétaro (Gutiérrez-Carrillo et al. 2002), and San Luís Potosí (Esteller et al. 2012; Carrillo-Rivera et al. 2008).

The urbanization and industrialization phenomena happening in these cities affect water resources in some ways, for example: impermeabilization of aquifer recharge areas, subsidence, modification of the course of rivers, variations in water level of surface bodies of water and aquifers, water contamination, and water-quality changes, etc. (Martín del Campo et al. 2014; Carrillo-Rivera et al. 2008; Foster et al. 2011).

Groundwater is the most important source for water supply in the urban zone of Puebla. This city is subject to a process of industrialization and accelerated population growth; the intensity of these phenomena has been very high since the 1990s with the creation of five industrial parks "Norte FINSA", "5 Mayo", "San Jerónimo" "Resurrección" and "Puebla 2000" (Ayuntamiento de Puebla 2014). This growth in both population and productive activities has created a high demand for water, which is almost entirely met by groundwater. Intense extraction of groundwater has led to a significant decline in groundwater levels, and degradation of quality (Ayuntamiento de Puebla 2014; CONAGUA 2015).

Also, the development of this area makes groundwater a critical resource for human activities; the most significant effect is the degradation in the quality of freshwater in the upper aquifer due to mixing with sulphydric water which rises from the deep aquifer. This mineralized water contains concentrations of sulfates and sulfurs above WHO's quality standards for drinking water (250 and 0.05 mg/L, respectively; Salcedo-Sánchez et al. 2016; Gárfias et al. 2010; Flores-Márquez et al. 2006).

The objective of this investigation was to define the groundwater quality with the assessment of the hydrochemical changes produced by intensive water exploitation in the urban area of Puebla City.

9.2 Study Area

The urban area of Puebla City, located in the central part of Mexico, is one of the most important developed areas of the country. It is surrounded by the state of Tlaxcala on the north, on the south by the municipality of Teopantlán, on the southwest by Ocoyucan, on the east by Amozoc and Cuautinchán and the west by Nealtican, Juan C. Bonilla and Huejotzingo. The study area is located at 19° 00′–19° 10′ N y 98° 00′–98° 20′ W, it has an average altitude of 2149 masl (meters above sea level), covering an area of 524.31 km^2 (Fig. 9.1).

The climate is temperate subhumid with cold winter and rainy season in summer, and the average annual temperature is between 16.6 °C, with a minimum of 10.8 °C in February and a maximum of 21.3 °C in May. Total precipitation varies between 650 and 900 mm/y, the highest precipitation is recorded in La Malinche volcano, with 1000 mm/y as the average annual value, and the lowest is toward the Valsequillo dam with an average annual precipitation of about 770 mm/y (SEMARNAT-CONAGUA 2005; Flores-Márquez et al. 2006; Gárfias et al. 2010; Salcedo et al. 2013).

Since the 1990s, there has been observed an urbanization–industrialization phenomenon in the Puebla City and the municipalities of San Pedro Cholula and San Andrés Cholula. At the north of the city, there has been established an industrial zone that has produced the urban expansion toward the west (Salcedo Sánchez et al. 2017; Ayuntamiento de Puebla 2014).

Puebla City has a population of 1,576,259 inhabitants (INEGI 2015). The population growth in the study area has been 57% in the period from 1990 to 2015 (Fig. 9.2).

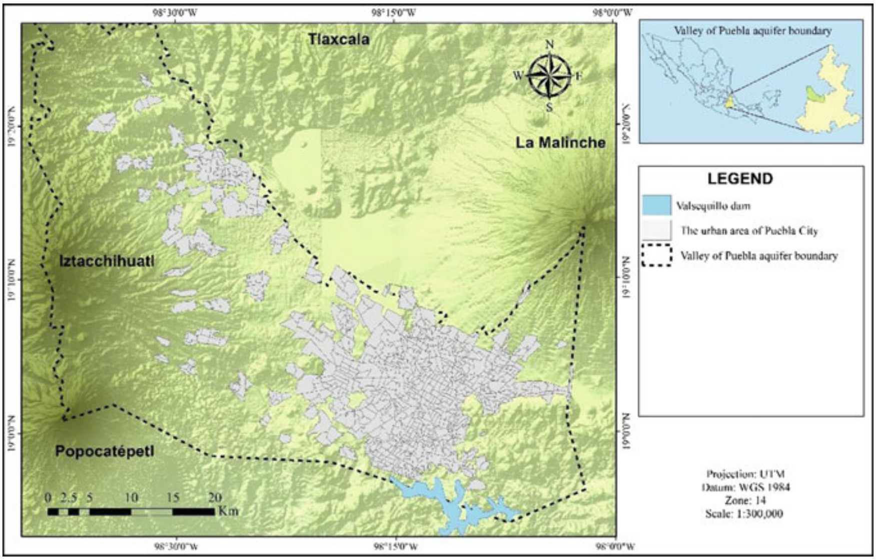


Fig. 9.1 Location of the study area

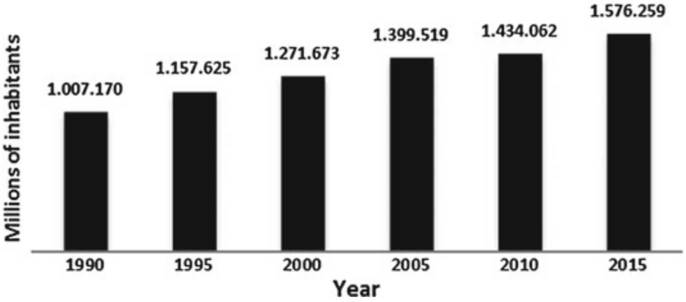


Fig. 9.2 Population growth in the Puebla City, period 1990–2015 (INEGI 2015)

This growth has turned the city into one of the most populated in the country and is mainly related to its vicinity to the cities of Mexico and Veracruz.

The economic development in the area has increased the demand for groundwater resources, which is entirely met by groundwater from the Puebla Valley aquifer. The intensive water exploitation has caused adverse effects on the aquifer, such as groundwater-level declination, the cracking of the ground, reduction of wells productivity, change of water quality (the increase constituents dissolved in the water like calcium, magnesium, and sulfates) and consequently water quality deterioration (Flores-Márquez et al. 2006; Gárfias et al. 2010; Salcedo Sánchez et al. 2017).

9.2.1 Hydrogeological Setting

The Puebla Valley aquifer is made up of four hydrogeological units: an upper aquifer, an aquitard, a middle aquifer, and a deep aquifer. A fault was identified in the aquifer with northeast–southwest direction and a regional fracture that has northwest–southeast direction (SEMARNAT-CONAGUA 2005; Flores-Márquez et al. 2006; Gárfias et al. 2010; Salcedo et al. 2013).

The upper aquifer comprises granular sedimentary formations and fractured rock formations constituted by andesitic and basaltic igneous rocks of Quaternary age, coming from the lava flows of the different volcanoes. The aquifer is unconfined, in general, has high hydraulic conductivity, water has good quality and is acceptable for human consumption (Flores-Márquez et al. 2006; Salcedo et al. 2013).

The aquitard is the lower border of the free aquifer, and the upper border consists of clay lacustrine deposits of Pliocene. In some places, they are embedded in a matrix of volcanic sands and gravels (Jiménez 2005).

Materials from the Balsas formation compose the intermediate aquifer (semi-confined), as well as volcanic rocks from the Eocene, Miocene, and Oligocene; the fractures show secondary porosity (Jiménez 2005; Salcedo et al. 2013).

The deep aquifer is composed of heterogeneous materials, the predominantly marine deposits of the lower and upper Cretaceous, mainly limestone. It also contains

Table 9.1 Components of the groundwater balance (units in millions of m^3/yr) (DOF 2016)

Inflow				Outflow				Change of storage
Ih	Iv	Ir	Total	Db	Dm	Sh	Total	ΔV
196.8	116.5	47.4	360.7	327.7	19	42.2	388.9	−28.2

Ih horizontal inflows, *Iv* vertical infiltration, *Ir* return flows, *Sh* horizontal outflows, *Spr* springs, *Db* extraction by deep wells, ΔV change in storage

deposits of dolomites and evaporites. This unit has experienced tectonic processes over time, resulting in folding and fracturing of the rocks, and therefore a secondary permeability. The existence of a fault in the deep aquifer has allowed the upwelling mineralized water (Flores-Márquez et al. 2006; Gárfias et al. 2010; CONAGUA 2015; Salcedo Sánchez et al. 2017).

CONAGUA (DOF 2016) published the availability of groundwater and the water balance for the period 1997–2010. According to this report, the total average annual recharge received by the Puebla Valley aquifer is 360.7 million of m^3/yr. The results of the balance indicate that the Puebla Valley aquifer has a change in annual average storage "negative"—28.2 hm^3/yr, due to the intensive exploitation of the groundwater as shown in Table 9.1 (CONAGUA 2015; DOF 2016; Salcedo Sánchez et al. 2017).

9.3 Methods

An analysis of the variability of groundwater quality produced by intensive groundwater extraction was carried out considering the historical data collected from 11 drinking water supply wells in 2011, 16 drinking water supply wells in 2013, and 20 drinking water supply wells in 2016. The physicochemical parameters, major ions, trace and heavy metals included in the criteria established for the human use and consumption by Mexican standards NOM-127-SSA1-1994 (DOF 2000) and the criteria of the World Health Organization (WHO 2008) were considered to determine the temporal variation in their concentrations.

The piezometric level data were consulted, and a database was generated to determine the variations in groundwater table levels in the urban area of Puebla City. The information was obtained from the National Water Commission (CONAGUA). Once the database was complete, temporal evolution graphs were generated, plotting groundwater level against year. With the aid of "Arc Map" software (ESRI 2011), contour maps were generated to know the elevation of the groundwater table level. The interpolation was performed using the Kriging method. The evolution of the water level was calculated throughout 10 years (2002–2012), and the results were interpolated on a map indicating the decline in groundwater level.

In order to characterize the groundwater hydrogeochemical composition of the drinking water supply wells, the predominant water families between 2013 and 2016 were identified through Pieper and Stiff diagrams, elaborated with the hydrogeochemical simulation program The Geochemist's Workbench 11.0 (Aqueous Solutions 2016). Then, they were plotted on a study area map to determine the hydrogeochemical spatial evolution. The data for the years 2011, 2013, and 2016 were represented through box and whisker diagrams to analyze the temporal variability of the main physicochemical parameters and were compared with the criteria established for human consumption by the World Health Organization (WHO 2008) and NOM-127-SSA1-1994 (DOF 2000).

9.4 Results and Discussion

The intensive exploitation has caused a decline in the piezometric levels of 1–2 m/y in the urban area. The map of drawdown isopleths for the period 2002–2012 shows the greatest accumulated declines (20 m) occurring in the central of the urban area of Puebla City, defining a drawdown cone that encompasses most of the urban zone (Fig. 9.3).

The results showed a significant increase in total dissolved solids concentrations of more than 1000 mg/L from 2011 to 2016. The maximum values exceed the criterion of the Mexican standard and the WHO during the years evaluated; however, the average value is below the regulations (1000 mg/L) (Fig. 9.4a).

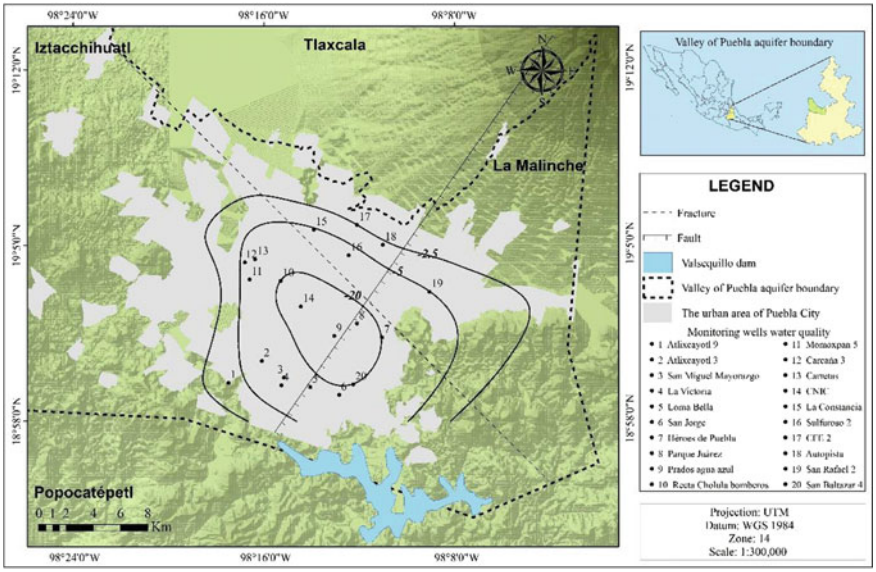


Fig. 9.3 Map of drawdown isopleths in meters between 2002 and 2012 in the urban area of Puebla City

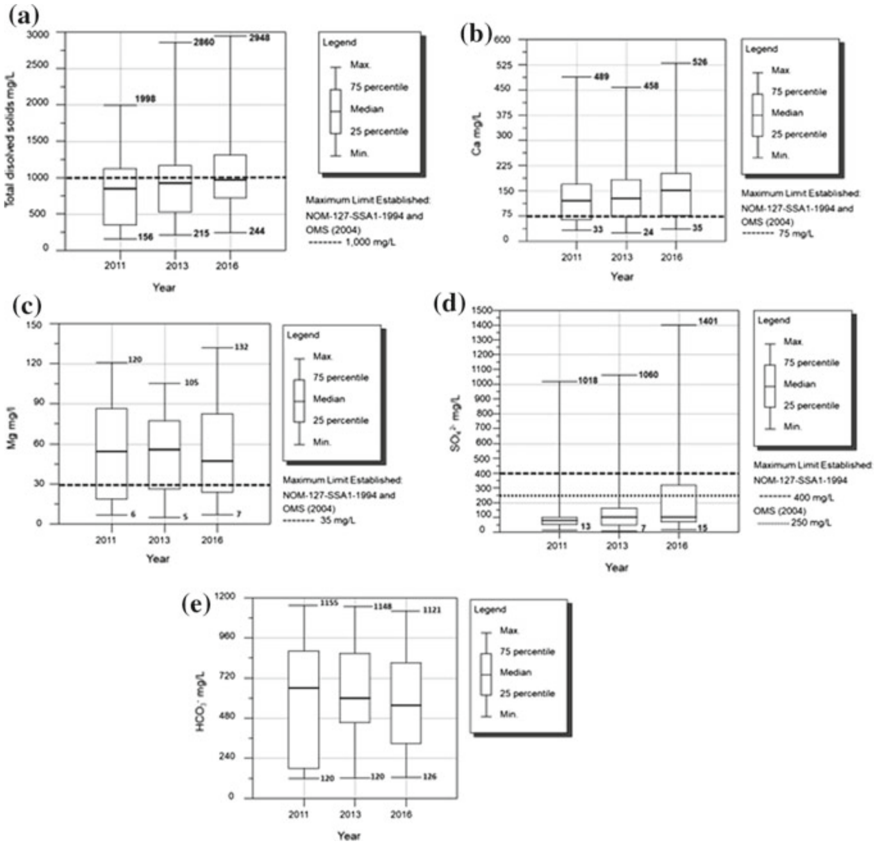


Fig. 9.4 Diagram of boxes and whiskers for total dissolved solids

In the case of calcium and magnesium, there is no maximum limit established by the Mexican normativity, as a reference, the WHO criteria (75 mg/L) and (35 mg/L), respectively, were taken. Figures 9.4b, c show that the average values of calcium and magnesium exceed the criteria for all years evaluated, and it demonstrated that the average and maximum concentration has increased from 2011 to 2016.

Concerning sulfates, there is a concentration increase over the years. The maximum concentration between the years 2011 and 2016 has increased more than 400 mg/L, and the average sulfates concentration remains below the limit (Fig. 9.4d). The bicarbonate concentrations showed a decrease in the average between 2011 and 2016 (Fig. 9.4e).

Based on the dominance of major cations and anions, three predominant water families have been identified in the urban area of Puebla City in 2013 as follows: (1) calcium bicarbonate in seven drinking water supply wells, mixed bicarbonate in nine drinking water supply wells and calcium sulfate in one drinking water supply well (Fig. 9.5a). Four predominant water families were identified for 2016: Calcium

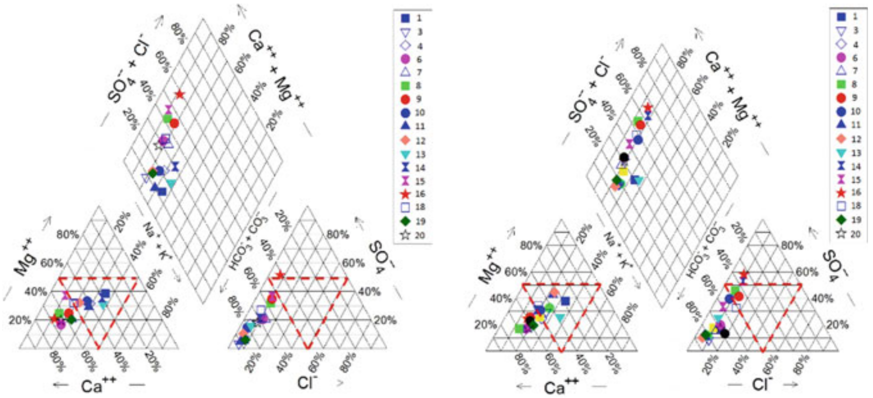


Fig. 9.5 Piper diagram with data 2013 and 2016

bicarbonate in eight drinking water supply wells, mixed bicarbonate in eight drinking water supply wells, calcium sulfated in two drinking water supply wells and a new classification was obtained, called mixed calcium presented in two drinking water supply wells because their proportions of carbonates and sulfates are similar (Fig. 9.5b). An evolution in the chemical composition and a change in the water family classification in three drinking water supply wells were observed (wells 8, 9, 14).

Stiff diagrams were used for the analysis of the spatial evolution of water facies from 2013 to 2016 and plotted on the map of the urban area of Puebla City. The migration of calcium bicarbonate groundwater type to calcium sulfate in some drinking water supply wells in the city was identified.

In 2013, there was one drinking water supply well with sulfated water (well 16) and for 2016, two drinking water supply wells were registered as sulfated water (well 14 and 16) (Fig. 9.6). Also, the presence of two drinking water supply wells with mixed water was obtained (wells 8 and 9); this is due to the upwelling of mineralized water that has been regionalized toward the south of the city and has caused an increment in calcium magnesium and sulfates concentrations.

The increase of sulfates, calcium and magnesium concentrations in the upper aquifer have been caused by upwelling mineralized water from the deep aquifer, which is contained in dolomite and evaporite limestone rocks; this water rises through fractures and geological faults and mixes with water from the upper aquifer.

Several processes contribute to the mixing of water between the profound and upper aquifers, such as differences in hydraulic heads between the two aquifers, the existence of a fault system that would provide a route for rising flow and the hydraulic connection produced by drinking water supply wells at different levels of the aquifer (Flores-Márquez et al. 2006; Salcedo Sánchez et al. 2017).

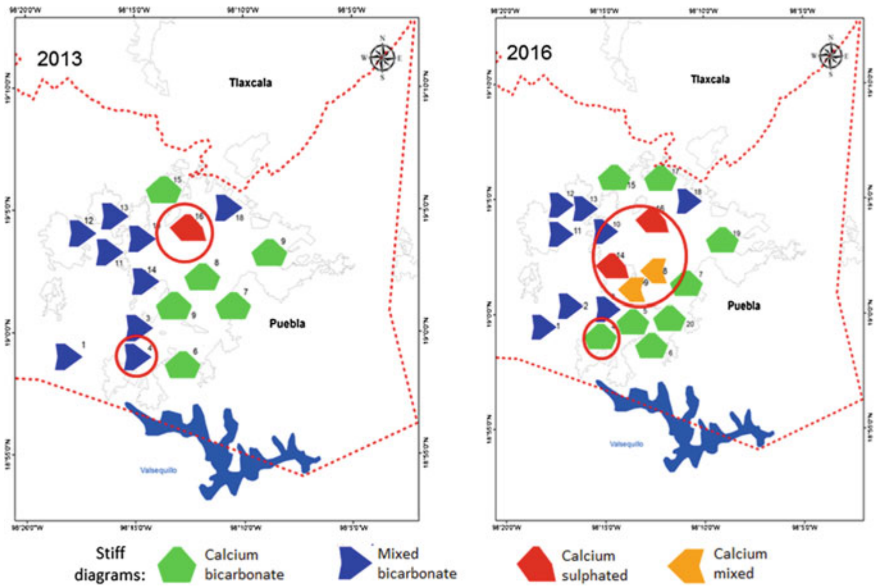


Fig. 9.6 Spatial evolution of the chemical composition of groundwater in the city of Puebla (2013–2016)

Figure 9.7 shows the mineralized water (sulfated and mixed with calcium and magnesium) from the deep strata of the aquifer, in the most exploited area of the aquifer (drawdown cone) where the hydraulic gradient of the groundwater table levels favors the induction of the flow-through of the fault and geological fracture. The bicarbonate calcium and mixed bicarbonate water types are characterized as the water of recent infiltration, with high quality for drinking water supply and are in the groundwater flow of the recharge zone and the south of the city.

9.4.1 Trace Elements

The data showed detectable concentrations of Pb, B, Mn, Ba, Fe, F, and Zn. For the other trace elements, such as phosphate, Al, As, Be, Bi, Cr, Sb, Sn, Tl, and Mo, their concentrations were under the detection limit for the analytical method used.

The elements that exceed the national and international criteria established for human use and consumption are boron, lead, and manganese for the data collected in 2016. These drinking water supply wells are located throughout the north, south, and

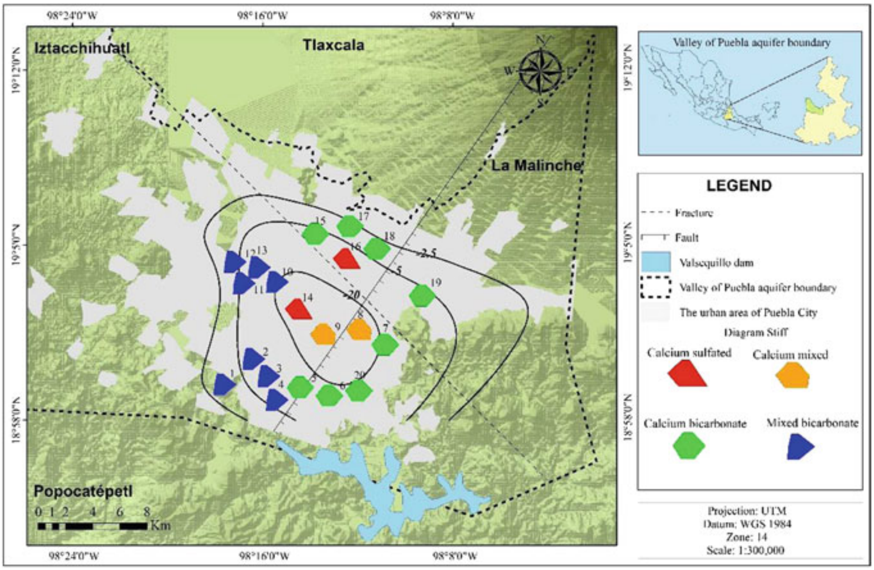


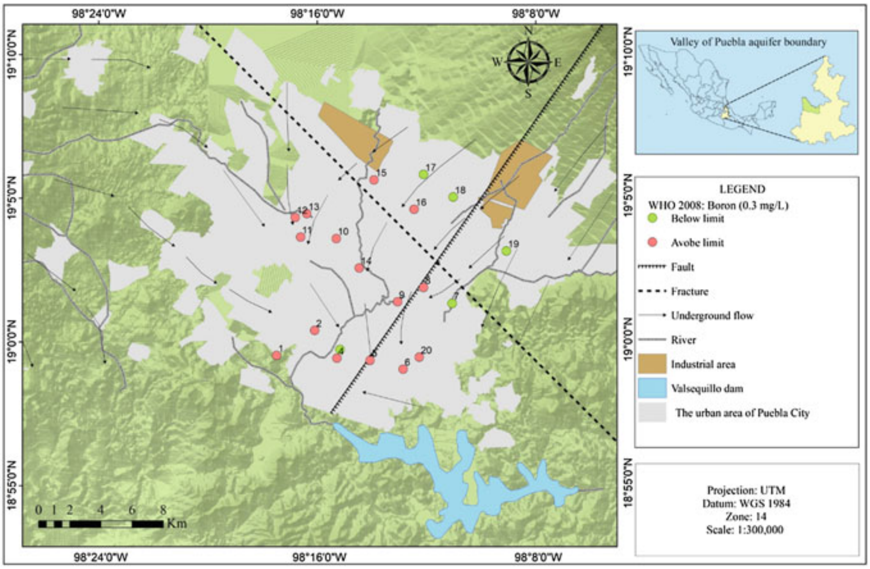
Fig. 9.7 Map of the spatial distribution of the types of water in the urban area of Puebla and drawdown cone

west of the city. The origin of these elements can be attributed to the rock's erosion, mineralization process, and anthropogenic activities.

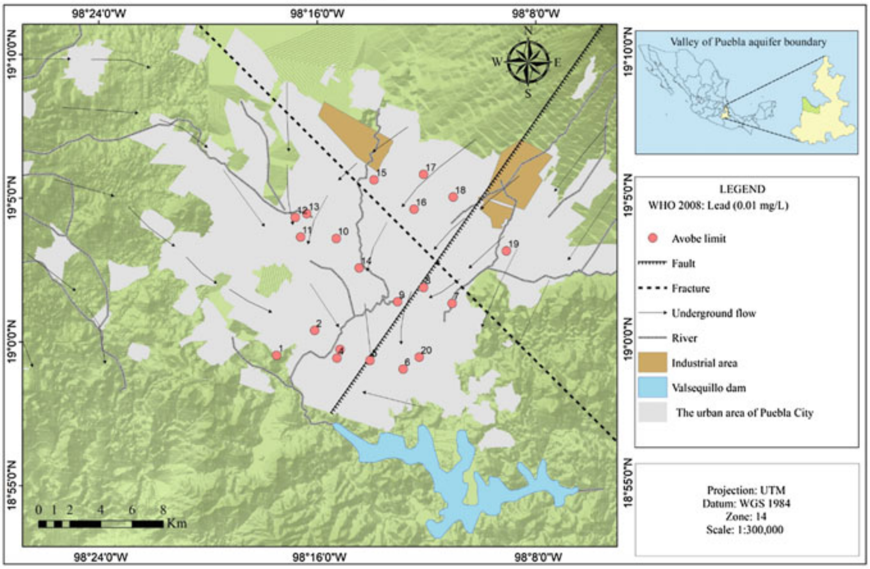
In seven of the drinking water supply wells, manganese was found above the established limit by the Mexican standards (0.15 mg/L; wells 1, 2, 10, 11, 12, 13 and 14) and in four wells (10, 11, 12 and 14) for to WHO criteria of 0.4 mg/L. Manganese is present in the Puebla Valley aquifer by the erosion of minerals commonly found in volcanic igneous rocks, basalts, and sedimentary rocks that include limestones and dolomites.

Boron concentration in monitored wells varies widely (0.12–3.41 mg/L), in fifteen drinking water supply wells the concentration was above the established limit for to WHO criteria (0.3 mg/L) (Fig. 9.8a). Boron is commonly found in volcanic areas, due to the gases emitted. It can be dissolved in groundwater by the weathering of sedimentary and volcanic rocks from the Puebla aquifer. It also can be presented by wastewater infiltration into the aquifer, where boron is derived from cleaning products and waste paint industries and varnishes, textiles, leather tanning, and electronics, among others (Butterwick et al. 1989; Hem 1992; Salcedo Sánchez et al. 2017).

Lead concentration in monitored wells ranged from 0.01 to 0.03 mg/L, in all drinking water supply wells the concentration was above the WHO criteria (0.01 mg/L) and six wells (2, 9, 11, 14, 17 and 18) for the established limit by the Mexican standards (0.025 mg/L) (Fig. 9.8b). Lead can occur in groundwater by anthropogenic pollution due to wastewater infiltration. Another source can be industrial wastewater



(a) Boron.



(b) Lead.

Fig. 9.8 Water quality assessment with the criteria established by WHO 2008 for boron and lead in Puebla City discharged through the rivers (Alseseca and Atoyac) that reach the aquifer by level difference or by fractures and faults. -NoValue-

9.5 Conclusions

The information obtained in this study corroborate the data presented by different authors (Flores-Márquez et al. 2006; Jiménez 2005; Gárfias et al. 2010; Salcedo-Sánchez et al. 2016, 2017) who reported that the water quality of the urban zone of Puebla Valley aquifer is negatively affected by upwelling mineralized water. The results of this study demonstrated that wells located in the most exploited area of the aquifer (drawdown cone) show a deterioration in water quality due to the hydraulic gradient that favors the induction of mineralized water from the deep aquifer to the upper aquifer through faults and fractures.

According to the analysis of the historical variability of water quality (2011–2016), it was corroborated that when increasing sulfate concentrations, bicarbonate concentrations have decreased. That indicates that the extraction of sulfated water comes from a deep aquifer and with a greater residence time in the aquifer because the bicarbonate water is representative of meteoric origin of recent infiltration. Also, an evolution in the water chemistry was identified, which shows the migration of calcium bicarbonate water to calcium sulfate and an intermediate modification to mixed water.

Concentrations above the limits recommended by the criteria established for Mexican law and WHO of trace elements, and heavy metals were detected in data collected in 2016. For Manganese and Boron, their origin can be attributed to weathering processes of the rocks in the aquifer, but Boron and Lead also can be present in groundwater from wastewater as of cleaning products and waste paint industries and varnishes, textiles, leather tanning, and electronics, among others.

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Chapter 10
Polluted Wastewater for Irrigation in the Mezquital Valley, Mexico

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Nellybeth Rodríguez-Martínez and Susana G. Sánchez-Herrera

Abstract Since 1912, it arises one of the irrigation districts oldest and most extensive in the world called "Irrigation District 03" (DR03), and it is in the Mezquital Valley in the State of Hidalgo, Mexico. This area is characterized by the reuse of wastewater from the City of Mexico to irrigation of oats, barley, cauliflower, turnip, wheat, zucchini, green chili, beans, green tomato, corn, and alfalfa, these last two crops being the economic potential in the region. The water coming from the Valley of Mexico is a mixture of urban, industrial, and rain wastewater presents a high load of pollutants organic, inorganic, and microbial contaminants that can be used as nutrients by the crops, increasing the yields of the region. However, health risk could be represented by putting at danger the safety of the food produced in this type of system due to its bioaccumulative properties. In addition to the above, the present work has the purpose of compiling cases studies on chemical contaminants in the agricultural system of the Mezquital Valley. Ranges of 3.9–47.0 mg kg^{-1} of lead have been reported in soils of the region, pharmaceutical waste (trimethoprim, erythromycin, naproxen, ibuprofen, and diclofenac) in wastewater, 0.9 mg kg^{-1} of cadmium in alfalfa, and 0.06 mg kg^{-1} of lead in corn plants among other compounds and pollutants. Consequently, it is essential to cover this demand without stopping economic development considering as a basis of the sustainable development and rational use of wastewater used for agricultural irrigation.

Keywords Mezquital Valley · Heavy metals · Wastewater · Agriculture

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10.1 Introduction

The Mezquital Valley is located 80 km north from the Metropolitan Zone of Mexico City (ZMCM). It constitutes a Paleogene-age alternation of lacustrine sediments with lava and pyroclastic deposits (Tarango Formation), which are covered with a thin layer of Quaternary alluvium. This valley is bordered by hills and mountains composed by volcanic and calcareous sedimentary rocks, and the altitude varies from 2100 masl (meters above sea level) in the south to 1700 masl in the north (Lesser et al. 2018; Oviedo et al. 2018). The dominant soils in the valley are Phaeozems associated either with Leptosols or Vertisols. The climate is semiarid, with a mean annual temperature that varies from 16 to 18 °C, and rainfall ranging from 400 to 700 mm (Justin Cajuste et al. 2001).

Since the beginning of the century, the wastewater of the Valley of Mexico is sent to the Mezquital Valley. Also, due to the high salinity of the soil of the Mezquital Valley as well as for the contribution to the agricultural land of organic matter, nitrogen and phosphorus, farmers use high blades of irrigation, which has led to artificial recharge of the aquifer. This recharge could be exploited again in the Valley of Mexico as a supply. However, the concern for the quality has given rise to various studies.

However, among the contaminants that are incorporated into the soil by the wastewater are heavy metals and other toxic chemicals, which are related to crop, soil, and groundwater. These elements and compounds can accumulate in the soil with varying degrees of availability or the plant tissue, due to their uptake by some plant species. In the soil, their activity is dependent on physical transformations and chemical solubilization, precipitation, adsorption and the changes in its oxidation state, processes that determine the stability of the contaminants in the soil. The relative mobility of contaminants in soils is of paramount importance regarding its availability and its potential for being leached from the soil profiles into groundwater. On the other hand, the contamination of crops by uptake and subsequent accumulation of toxic substances depend on the plant species. Usually, it is given by the interaction of the soil with the root of the plant.

There are reports on the degree of contamination of the wastewater of the Mezquital Valley (Lesser et al. 2018; Lesser-Carrillo et al. 2011; Ontiveros-Capurata et al. 2013; Siemens et al. 2008), in the soils of the area (Vázquez-Alarcón et al. 2005; Ramírez-Fuentes et al. 2002; de Vries et al. 2007; Elgallal et al. 2016; Lucho-Constantino et al. 2005a) and in plants that have been grown in soils irrigated with wastewater in the region (Chávez et al. 2012; Oviedo et al. 2018; Lara-Viveros et al. 2015; Salazar-Ledesma et al. 2018; Forjan Castro 2017). Even though few studies have found evidence of metal contamination in human (García Monroy Roberto 2011), the use of wastewater for agricultural irrigation has led to a series of concerns in the agri-food sector.

The use of wastewater in agriculture has not been analyzed in detail in the environmental legislation in Mexico. So, when it comes to diagnosing the degree of accumulation of trace elements or other contaminants in the soils of Mexico, it used standards of other countries as comparison criteria. That is to say, the first problem that faces the Mezquital Valley is the absence of permissible limits of concentration in soils and plant tissues at the regional and national level.

The importance of wastewater for agriculture has increasingly been recognized not only for a valuable water resource but also for its nutrient value. However, inappropriate management of irrigation with wastewater can pose substantial risks to public health and the surrounding environment as a result of its microbial and toxic components.

In addition to the above, the present work has the purpose of compiling cases studies on chemical contaminants in the agricultural system of the Mezquital Valley. In this way, urge the government authorities to establish basic guidelines in the use and optimization of water resources, as well as inviting the producers to make agronomic management more sustainable.

10.2 Use and Distribution of Irrigation Water in the Mezquital Valley

The residual water of the Valley of Mexico, sent to the Mezquital Valley, is used for agricultural irrigation since 1912. Currently, the area receives approximately 50 m^3 s^{-1} of wastewater not treated (Lesser et al. 2018; Lesser-Carrillo et al. 2011, Navarrete López), and such water is used to irrigate about 80,000 ha of the Mezquital Valley through a complex system of nine dams (three freshwater and six wastewater reservoirs) and 850 km of open canals. Mexico City drains its sewage into the Mezquital Valley through the so-called Grand Canal from the Drain, Interceptor Poniente, and the Emisor Central. The first two cross the watershed between the basins of Mexico and Mesquite through the tunnels of Tequisquiac and the Tajo of Nochistongo, for joining the rivers Salado and the Jump, respectively (Fig. 10.1). The river Jump downloads in dam Requena, from where it continues as the river Tula circulating to the north.

This agricultural area is essential to produce crops such as maize (*Zea mays*), alfalfa (*Medicago sativa*), bean (*Phaseolus vulgaris*), tomato (*Physalis ixocarpa*), onion (*Allium cepa*), green pepper (*Capsicum annuum*), lettuce (*Lactuca sativa*), radish (*Raphanus sativus*), and cauliflower (*Brassica oleracea var. botrytis*).

To carry out the distribution of the residual water, the area with legal regulations and institutional arrangements ensures the distribution of resource for the development of agriculture in the Mezquital Valley. The National Waters Law, in force since 1993, has a section devoted specifically to the prevention and control of water pollution. Also, the Technical Standards of Ecological 32 and 33 (now Official Mexican Standards) establish the requirements for the use of wastewater for agricultural irrigation. The National Water Commission (CNA) was officially created in 1989 (CONAGUA) as an entity of the Federal government responsible for promoting the construction of infrastructure, irrigated farming, as well as its operation, to ensure

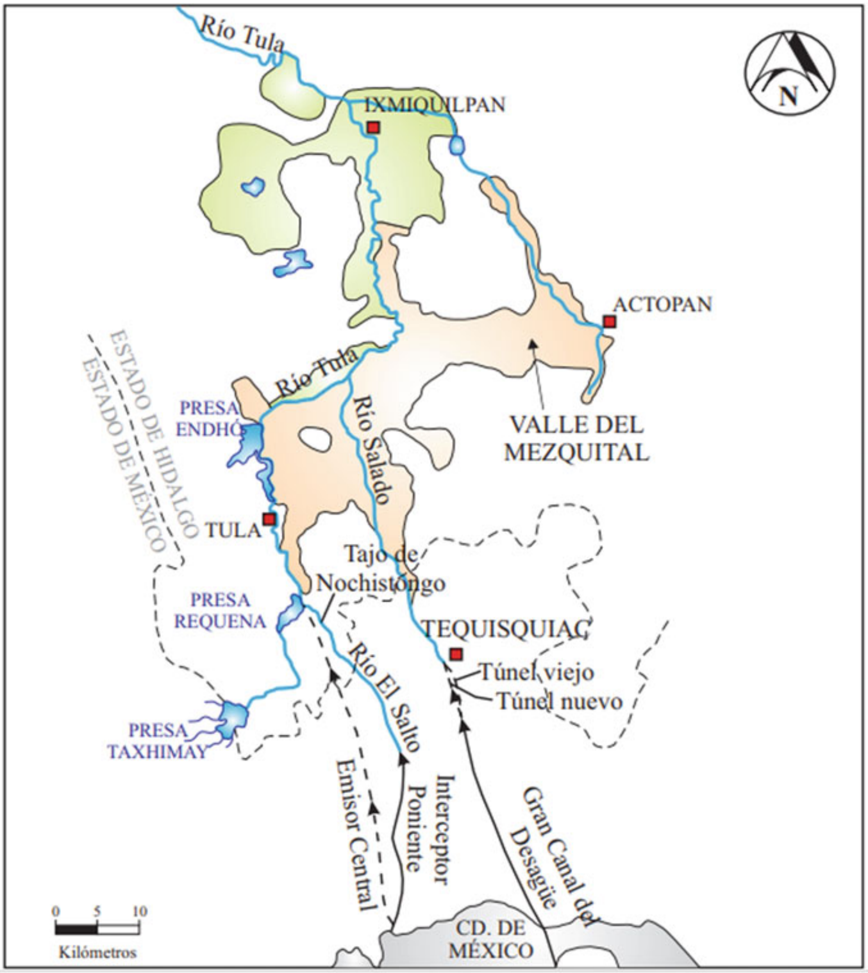

Fig. 10.1 Flow of wastewater from Mexico City to the Mezquital Valley. *Source* Lesser-Carrillo et al. (2011)

compliance with laws and regulations related to the efficient use of water and its quality control.

The Federal government, specifically the CONAGUA, has overseen the irrigation districts since 1949. Each district is under the administration of a chief engineer appointed by the CONAGUA so that being under the control of a single authority there are many facilities for the management of the watering plan. There is also a table of management, composed of representatives of the state governments and central, water user associations, and banks for local credit. Some farmers are organized in cooperatives, although many others work individually when their extensions of land are minimal (approximately 1.5 ha for a person).

The farmers have their water needs at the Local District Office, specifying where and when will require water. The district chief prepares a proposal for the first program of watering, analyzing several factors, for example, the volume of available water, schedule of water demand, crop priority for farmers, policies of the agricultural authority, crops, restricted, and available resources. The final program of irrigation (watering Plan) is performed, prior discussion and approval by the farmers.

High levels of organic and inorganic pollutants, which are present in wastewater and soil used for agricultural irrigation, are because these metals can be accumulated into these systems, of significant importance for agriculture. Because there are compounds that aren't biodegradable, the possibility of toxicity in crops is increasing and with it the bioavailability of the contaminants may result hazardous.

10.3 Contaminants Present in Irrigation Water in the Mezquital Valley

Studies have been conducted on the quality of wastewater used for agricultural irrigation, and among them is the Lesser et al. (2011) who found that the sodium and the total dissolved solids are generally found above the maximum permissible limit. In this same study, arsenic was also detected in seven uses located to the south of Tlaxcoapan, half of the sites analyzed have fluoride above the standard, and most exceed the limit of the standard concerning lead. Phosphates and boron are also present in high concentrations in many of the samples, and seventy-five bacteriological analysis is made in drinking water wells, 30 of them presented total coliforms.

The total concentration of lead was 0.13 mg L^{-1} in the water of the Grand Drainage channel, while in the water from the Endho dam the concentration was 0.054 mg L^{-1}. At the same time, it mentions that the concentration of cadmium in water during the present study exceeded the maximum allowable value of water quality for agricultural irrigation in Mexico (Justin Cajuste et al. 2001).

Five volatile organic compounds (VOCs) and nine semi-volatile organic compounds (SVOCs) were detected in the wastewater used for irrigation. Only two SVOCs [bis-2-(ethylhexyl) phthalate and dibutyl phthalate] were detected in all the wastewater canals and groundwater sources. Of the 118 pharmaceutically active compounds (PhACs) and seven reproductive hormones measured, 65 PhACs and three hormones were detected in the wastewater (Lesser et al. 2018).

According to the ecological criteria and Mexican standards in force current (CE-CCA-001/89; NTE-CCA-032/91; NOM-127-SSA1-1994), with the exception of pH, the waters of the three channels (Grand Drainage channel, Central Outlet Tunnel, and El Salto River), they are not recommended for direct use in irrigation without treatment due to its high level of turbidity (Ontiveros-Capurata et al. 2013).

On the other hand, the amount of dissolved metals in the wastewater is a parameter crucial to choose the method of treatment required before reuse (Tchobanoglous et al. 2003). A study reports that the portion of dissolved metals (43.5 mg L^{-1}) is higher than that of metals, suspended (17.0 mg L^{-1}) for all the cations of Na^+, Mg^{2+}, Ca^{2+}, and K^+; similarly, the average numbers of sodium, dissolved (83 mg L^{-1}) potassium, dissolved (39.5 mg L^{-1}) at all sites was higher than that of other cations ($Ca = 34$ mg L^{-1} and $Mg = 17.9$ mg L^{-1}). The amounts of anions and cations found in the channels are shown in Fig. 10.2; ions are dominant in the three channels are sodium and bicarbonate. The amounts vary across the three channels, but we observe the same sequence of the concentration of cations: Na > Mg > Ca > K and anions $HCO_3^- > Cl^- > SO_4^{2-} > CO_3^{2-}$, although with greater variability in the river the Salto (Ontiveros-Capurata et al. 2013).

Some authors (Coskun et al. 2010; Davis 2010) suggest that to treat high amounts of dissolved solids, the methods of treatment recommended are the membrane, such as reverse osmosis, electrodialysis, and nano-filtration; in this particular case, Tchobanoglous et al. (2003) suggested that the high amounts of settleable and suspended solids should be treated first, by primary treatment (sedimentation) and advanced primary treatment before any other further treatment. Therefore, the wastewater treatment plant was constructed in Atotonilco de Tula for the wastewater that comes to the Mezquital Valley. It reduces the biological pollution and suspended solids by sedimentation processes and further chemical treatment (chlorination); however, the elimination of dissolved solids was not considered. The treatment of wastewater under these conditions does not decrease the dissolved salts in the water, but this soluble fraction is more important in terms of the quality of irrigation water because of their adverse effects on crops and agricultural soil properties (Ontiveros-

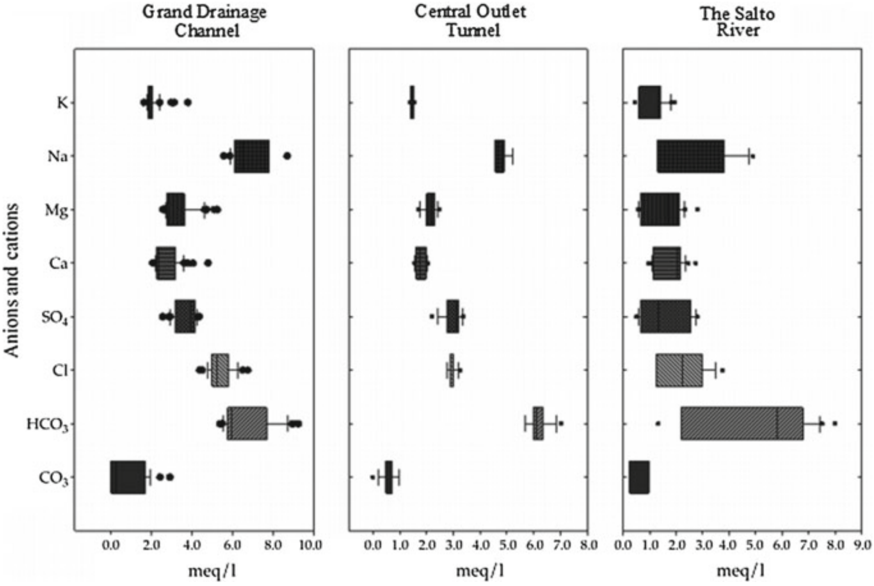

Fig. 10.2 Amount of cation and anion totals in the channels studied and the variability of the samples analyzed

Capurata et al. 2013; De La Mora 2012). Crops have been irrigated for years with the waste of pharmaceutical of trimethoprim, erythromycin, naproxen, ibuprofen, and diclofenac present in wastewater (Siemens et al. 2008).

Several studies reported the poor quality of wastewater for agricultural irrigation, and others have shown the same pollutants in the Mezquital Valley soils, increasing the environmental impairment. However, the problem lies not only in the unsustainable use of the resource.

10.4 Contaminants Present in Soils of the Mezquital Valley

In general, the Mezquital Valley is constituted by an alternation of pyroclastic material, lava and lake sediments known as the Formation Tarango in the Paleogene, which is covered by a thin layer of alluvium of the Quaternary. The mountains that border the Mezquital Valley are formed by volcanic rocks, mainly lava and to a lesser extent tuff of Paleogene (Lesser-Carrillo et al. 2011). The irrigation district 03 distributes the wastewater across four series of soils: the Actopan type with layers and haplic feozems, the Tepatepec with Vertisol pelic soils and feozems; the Lagunilla one with layers and calcareous feozems; and the Progreso type with Leptosols and calcareous feozems with petro-calcium phase (Hernández-Silva et al. 1994).

Even though the heavy metals are usually found as natural components of the earth's crust, various studies published the soil contamination due to the use of wastewater. For example, studied soils with different pH, clay and organic matter content, concentrations of Pb and Zn were added intentionally, confirming the absorption capacity in each type of soil; those parameters are modified by the contaminated water entering into the field (de Vries et al. 2007).

The factors that influence the mobilization of toxic compounds or elements in the soil are pH, redox potential, ionic composition of the soil solution, cationic exchange capacity and/or anionic, presence of carbonates, organic matter, texture, and among others (Sauquillo et al. 2003).

There have been reported concentrations of cadmium from 25.1 to 66.5 kg ha^{-1} in soils of the Mezquital Valley higher than the permissible limit of 7.5–14.6 kg ha^{-1} recommended in European Community. The maximum permissible concentration for the lead was 3.7–21.3 kg ha^{-1}, interval which includes soils contaminated with Pb, within the region of the valley. The maximum permissible concentration for Ni in soils with a history of contamination was from 307 to 1324 kg ha^{-1} (Vázquez-Alarcón et al. 2005).

The amount of Pb, Ni, and removable Cd of the soil was positively associated with the time use of residual water (Justin Cajuste et al. 2001). Other author refers that high salt and nitrogen concentration are the most significant environmental risks (Elgallal et al. 2016).

Total Mg, Hg, Mo, Ca, Cu, Cr and available concentrations of Pb, Cd, and Cu in soils increased significantly with irrigation time ($P < 0.05$), but were not at hazardous concentrations. Although organic C, total N, microbial biomass C and N, and microbial activity, as witnessed by CO_2 production, increased with the length of irrigation, N mineralization did not. Oxidation of NO_2^- was inhibited and could be due to the increase in salinity, toxic compounds, or heavy metals (Ramirez-Fuentes et al. 2002).

One study evaluated several plant species, in which they have reported concentrations in the range of 675–1176 mg kg^{-1} de K, 277.9–1001 mg kg^{-1} de Na, 6708–81,854 mg kg^{-1} de Ca, 23,800–106,974 mg kg^{-1} de Mg, 9.2–123.8 mg kg^{-1} de B, 0.6–1.9 mg kg^{-1} de Cd, 11.6–27.4 mg kg^{-1} de Cr and 3.9–47.0 mg kg^{-1} de Pb. Samples of topsoil (0–30 cm) were extracted using a modified Tessier method according to a six-fraction scheme: easily soluble, exchangeable, bound to carbonates, associated with oxides of iron and manganese, bound to organic matter and sulfides, and the residual fraction (Lucho-Constantino et al. 2005a, b).

10.5 Contaminants Present in Crops Irrigated with Wastewater

The absorption and later accumulation of contaminants in the plant depend on the first instance of the species plant. The pollutants are transported from the solution in the soil to the root of the plant, to the different structures of the same (Prieto Méndez et al. 2009).

In plants, the concept of bioaccumulation refers to the aggregation of contaminants; some of them are more susceptible to be phyto-available with others (Forjan Castro 2017; Lázaro 2009).

In the area of the Mezquital Valley, there have also been some studies on the bioaccumulation of contaminants including heavy metals and atrazine in crops irrigated with wastewater.

Prieto-García et al. (2007a) mentioned that there exists a direct correlation between the content of organic matter present in the soil and the years of irrigation, which makes it possible for the metals (Pb, Cd, Cr, and Hg) and the metalloid As filtered in alkaline media pH moderately.

Plant bioavailability of Ni is influenced by pH, the content of organic matter, clay, oxides, and hydroxides (Rooney et al. 2007).

The behavior of atrazine in the maize crop has been studied mainly in laboratory experiments because the herbicide atrazine has been applied to maize for weed control during 20 years in the Mezquital Valley. Batch experiments showed that the soil has a higher affinity for atrazine ($Kd = 5\ L\ kg^{-1}$) than for HyA and DEA ($Kd = 1.3\ L\ kg^{-1}$). The atrazine half-life is 16 days under field conditions. (Salazar-Ledesma et al. 2018). The paper mentioned that the moderate filter capacity of the soil and the relatively fast degradation rates seem to prevent the transport of atrazine and its metabolites into the unsaturated zone.

The diagnosis was the accumulation of cadmium, nickel, and lead in maize (*Zea mays L.*), wheat (*Triticum aestivum*), and alfalfa (*Medicago sativa*), these being the most economically important crops in the Mezquital Valley. The study concludes that the Cd tends to increase in crops as the irrigation time of residual water. However, these are higher in alfalfa, maize, and wheat as shown in Fig. 10.3 about years of residual water use (Justin Cajuste et al. 2001).

Some crops, such as corn, when it grows in soil, typically clay, have an assimilative capacity higher than for the limit of absorption of Cd, Ni, Pb, and Cu than in the other soils, and that makes a difference also with other crops (Mahdy et al. 2007).

In Lagunilla soil, maguey presented the highest concentrations of Pb (22.86 and 29.58 mg kg^{-1}, in the pulp and cortex, respectively). In addition, the nopal samples from Francisco Villa town (Series of soils Tepatepec) showed the highest concentrations of As (0.55 and 0.69 mg kg^{-1} in pulp and cortex, respectively). The levels of Hg in beans were in all parts of the crop and the concentrations ranged from 0.22 to 1.45 mg kg^{-1} for the soil series of Progreso, Tepatepec, and Lagunilla (Prieto-García et al. 2007b).

The United Nations Organization for Food and Agriculture (FAO) reports that Mexico ranks the seventh place in the production of corn grain, contributing 2.2%, with 23,273,567 tons (Estadísticas FAOSTAT 2014). On the other hand, the Secretary of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA 2016) reported Hidalgo state as the twelfth place in the production of the grain, contributing 2.6% to 731,471 t. Likewise, the municipality of Tezontepec de Aldama ranked the first in the state for the production of corn grain, providing 6.04% (44,196 t), followed by Mixquiahuala de Juárez (42,005 t) and Tula de Allende (33,038 t), positioning San Salvador (32,877 t), Huichapan (32,374 t), and Francisco I. Madero (29,371 t)

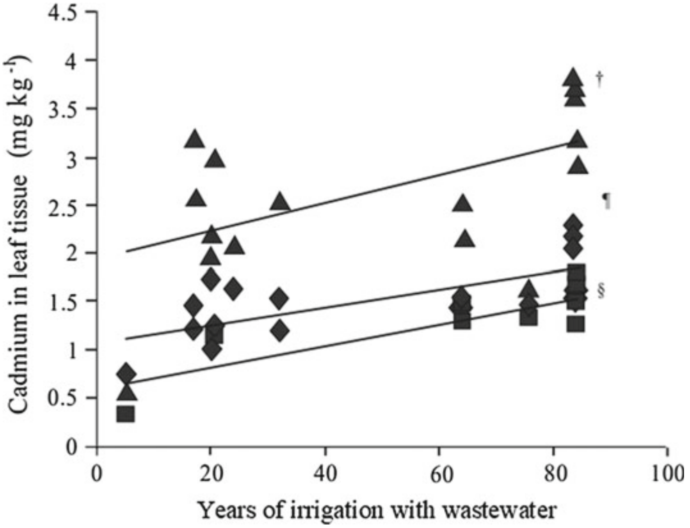

Fig. 10.3 Cd content in foliar tissue of alfalfa, maize, and wheat and its relation to years of residual water use in some selected sites of the Mezquital Valley. *Source* Justin Cajuste et al. (2001). [†]Maize = 1.86 + 0.011 (time)*. Alfalfa = 1.05 + 0.009 (time)**. [§]Wheat = 0.57 + 0.0011 (time)**

in the fourth, fifth, and sixth place respectively (Anuario Estadístico Nacional de la Producción Agrícola 2016). These municipalities are settled in the Mezquital Valley. Some authors have carried out studies about the concentration of lead and cadmium in the maize crop (Lara-Viveros et al. 2015) reporting the degree of absorption and mobility of Cd and Pb within the plant. To do this, they sampled soils, as well as two varieties of corn, two alfalfa and sunflower. Table 10.1 shows the concentration of Cd and Pb in maize, alfalfa, and sunflower, irrigated with wastewater in the Mezquital Valley.

For soil cultivated with alfalfa, Cd contains were reported lower than the present study in some vegetables. Previous studies claim that the cultivation of alfalfa can germinate, grow, and accumulate metals in their tissues (Peralta-Videa et al. 2002, 2004). The results shown in Table 10.1 suggest that corn plants have a limited capacity for Cd uptake since the concentration in the soil was higher than the concentrations found in the plant, and the sunflower presented the lowest values of both metals (Lara-Viveros et al. 2015).

On another hand, it was found that with the current wastewater quality in the Tula Valley, it may be possible to be reduced on the application rate by 43% without negative effect on crop nutrition. A reduction in leachate organic matter by 35% and leachate salts (Na, K) by 40% would be achieved. After the new treatment plant start-up, an intermediate irrigation rate would reduce organic matter leaching to the aquifer by 45% and salts (Na) by 25%, without affecting the productivity and quality of alfalfa, or the retention of nutrients and organic matter in the soil. The results of this exploratory study need to be confirmed and expanded on land fields (Chávez et al. 2012).

It was determined that in the last 25 years the soil texture was modified with a tendency to acidification and the loss of exchangeable bases due to the increase of organic matter as a resulted of used of wastewater. The agricultural practices, for example, the flood irrigation which leads to physical and chemical degradation of soils to impact on agricultural productivity. The foregoing has led to the presence of heavy metals in the agriculture of the region, causing a risk to health and the environment. With the above, there have been reported concentrations of Ni and Cd of 3.01 mg kg^{-1} and 0.9 mg kg^{-1} respectively in alfalfa (Oviedo et al. 2018).

Previous studies suggest analyzing the influence of emergent contaminants uptake by the plant (Elgallal et al. 2016).

10.6 Risk to the Public Health for the Use of Wastewater

Lead, mercury, cadmium, thallium, and other metals are found in the air and water as environmental pollutants and are associated with multiple adverse health effects, being several organs and systems that are affected by metals such as: kidney, lung, liver, gastrointestinal system and hematopoietic, but mainly the central and peripheral nervous system. The severity and damage of the metals depend on the time, level of exposure, susceptibility of the person, and the route by which the metal can be

Table 10.1 Concentration of Cd and Pb (mg kg^{-1} dry weight) in crops irrigated with wastewater in the Mezquital Valley, Hidalgo, Mexico

Instead of absorption	Maize variety "Caiman"		Maize variety "Ocelote"		Alfalfa variety "San Miguel 1"		Alfalfa variety "San Miguel 2"		Sunflower	
	Cd	Pb	Cd	Pb	Cd	Pb	Cd	Pb	Cd	Pb
1	0.096 a	0.480 a	0.093 a	0.42 a	0.030 b	0.453 a	0.035 b	0.051 a	0.103 a	0.613 a
2	0.060 bc	0.260 ab	0.053 b	0.30 ab	0.076 a	0.236 ab	0.076 a	0.393 a	0.000 c	0.026 c
3	0.063 b	0.230 b	0.001 b	0.26 b	0.01 b	0.000 b	0.080 a	0.400 a	0.013 c	0.000 c
4	0.060 bc	0.273 ab	0.010 b	0.24 b	0.07 a	0.326 a	0.006 c	0.50 b	0.070 b	0.316 b
5	0.043 c	0.196 b	0.036 b	0.22 b	–	–	–	–	0.007 c	0.000 c
6	0.056 c	0.230 b	0.042 b	0.25 b	–	–	–	–	–	–

Different letters indicate statistically significant differences (Tukey, $P = 0.05$). **Where**: 1 is the Cd and Pb concentrated in soil, 2 is the Cd and Pb concentrated in the first-third of the structure of the plant, 3 is the Cd and Pb concentrated in the second-third of the structure of the plant, 4 is the Cd and Pb concentrated in the third of the structure of the plant, 5 is the Cd and Pb concentrated in the seeds, and the 6 is the Cd and Pb concentrated in the leaves cob absorbed (Nava-Ruiz and Méndez-Armenta 2011). Exposure to cadmium, lead and, to a lesser extent, the mercury is a concern, as many epidemiological studies have shown a strong association between exposure to these heavy metals, markers of renal damage, and the progression of chronic kidney disease (CKD). As well as the exposure to arsenic because millions of people are exposed to sources of water with levels above the limit (Weaver et al. 2011).

Terms defined as "provisional tolerable weekly intake," which for Cd is 400–500 mg if the critical concentration in the renal cortex is 200 mg g^{-1}. However, an essential factor that should be considered is the average weight of the adults of the exposed population (Vázquez-Alarcón et al. 2005). Heavy metals may be recognized as health risk more than an environmental concern (Elgallal et al. 2016).

One of the alternatives that is projected to the City of Mexico to provide clean drinking water to its inhabitants in the next fifteen years is to return the water that comes from artificial recharges the aquifer of the Mezquital Valley. However, this aquifer is supplied by leakage from the irrigation of wastewater without treatment, and there is a high risk to recycle the water infiltrated. It was found that in order to perform this reuse, it is necessary that the water be previously treated to eliminate or to reduce the fecal coliform and total (0–2 MPN/100 mL), nitrate (10 mg N-NO_3/L), ammoniacal nitrogen (0.5 mg N-NH_4/L), and mercury (0.001 mg/L), lead (0.025 mg L^{-1}), sodium (200 mg L^{-1}), and total dissolved solids 1000 mg L^{-1} (Pérez et al. 2009; Lesser-Carrillo et al. 2011).

García Monroy Roberto et al. (2011) and Cifuentes et al. (1994) presented the preliminary results of the impact of occupational exposure to irrigation with wastewater in the irrigation districts 03 and 100 of the Mezquital Valley.

One of the researches had as objective to evaluate the prevalence of diarrheal diseases and intestinal infections, by using cross-sectional surveys conducted in two different periods of the agricultural cycle (Cifuentes et al. 1994). Table 10.2 shows a summary of the study.

Table 10.2 shows the prevalence rates of diarrheal disease detected in the population. The highest rates correspond to the most exposed group and the younger age (children of 0 up to 4 years), showing that the lower levels of exposure reduced the prevalence.

Table 10.2 Prevalence of diarrhea diseases according to exposure and age

	Exposure groups		
	Exposed	Control	Semi-exposed
0–4 years	30.1 (104/345)	23.2 (103/443)	26.7 (11/416)
5–14 years	18.7 (41/219)	10.8 (125/1149)	12.4 (68/548)
15+ years	11.7 (86/733)	9.4 (184/1961)	10.7 (99/922)

Source Cifuentes et al. (1994)

Another study evaluated fluids of blood and urine, as well as body tissues (hair and nails), and the authors discovered cadmium, chromium, lead, and aluminum. The author relates the concentrations of pollutants with the consumption of vegetables and plants wildlife, as well as the consumption of grains harvested in the area (García Monroy Roberto 2011) (Table 10.3).

Compared these results with those obtained in samples of fluids and tissues of the eyewitnesses (residents of another area is not contaminated), it can be said that there are 5–20 times higher concentrations of Cd and Cr in the fluid of the blood and urine and 2–5 times higher in the tissues of nails and hair. That makes clear and proves that there is a potential risk to health in people living in these contaminated areas, either by the use and reuse of sewage water, as well as by other factors anthropogenic, which allow the metal contamination of these media.

Table 10.3 Results averages found for each metal assessed in body fluids and tissues sampled in the population of the Municipality of Xochitlán.

	Cadmium	Chrome	Lead	Aluminum
Nails (μg/kg)				
Average	4.95	0.032	0.037	0.133
Maximum	7.09	0.073	0.082	0.318
Minimum	<0.024	<0.002	<0.002	<0.009
Des Est	0.01	0.03	0.07	0.46
n	244	244	244	244
Blood (μg/L)				
Average	1.18	12.05	4.76	31.31
Maximum	6.45	81.00	44.00	210.00
Minimum	<0.024	<0.002	<0.002	<0.009
Des Est	0.27	0.28	0.11	0.38
n	253	253	253	253
Urine (μg/g of creatinine)				
Average	4.55	1.79	<0.002	11.16
Maximum	16.55	6.55	0.36	67.27
Minimum	<0.024	<0.002	<0.002	<0.009
Des Est	0.18	0.02	<0.002	0.21
n	237	237	237	237
Hair (μg/kg)				
Average	2.99	43.56	0.27	3.88
Maximum	3.18	71.00	1.59	33.00
Minimum	0.03	7.00	<0.002	<0.009
Des Est	0.16	0.25	0.40	0.39
n	240	240	240	240

Source García Monroy Roberto et al. (2011)

The concern is that because the inhabitants of the Mezquital Valley, by previous studies, consumes almost all the plants that can be conceived as edible; several of them grow in areas of temporary or irrigation. Also, people consume a wide variety of worms and insects which feed on the crops of the area and/or are in direct contact with the agricultural soil of the region. In this way, the population achieves an extremely varied diet (Anderson et al. 2009).

10.7 Perspectives and Conclusions

The high levels of heavy metals, such as lead, nickel, cadmium, and manganese, present in soils, crops, and black water, used for agricultural irrigation, lie mainly that can be accumulated in these systems and are of utmost importance for agriculture. In the last two decades, it is important to establish basic guidelines of management and environmental management of crops. It is of interest, the development and the growth of sustainable agriculture, which in turn keep a strict control and conservation of water resources.

The use of wastewater in agriculture has not been analyzed in detail in the environmental legislation in Mexico. So, when it comes to diagnosing the degree of accumulation of trace elements or other contaminants in the soils of Mexico, it used standards of other countries as comparison criteria. That is to say, the first problem that faces Mexico is the absence of permissible limits of concentration in soils and plant tissues at the regional and national level.

The treated water represents a source of constant and safe water even in the driest years. On the other hand is a constant supply of nutrients to plants due to its large amount of organic matter to some macro elements (N, P, K), which represents a saving in costs of fertilization for producers in the region. The disadvantages are mainly focused on two sections; the risks to health are arising from the use of wastewater and the contamination of surface water and groundwater, as well as soils and crops.

As a result of these increases of concentrations of metals in the irrigation water and by inappropriate practices in the agricultural system, it has increased the bioavailability of the same on the soil and variety of crops, causing damage, phytotoxicity, and with it, causing a latent risk to the health of animals and human beings.

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Chapter 11
The Importance of Informative Data Base of the Wetlands in the Lake Cajititlán, Previous Step for the Proposal as a Ramsar Site

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Abstract Wetlands are ecosystems of strategic value to the ecological balance of a region and are vital for its rehabilitation and sustainable use. Lake Cajititlán suffers from severe environmental degradation by anthropogenic activities. This circumstance prompted residents of the region to seek rehabilitation alternatives. As a result, there has been a relevant study on the lake and its watershed from 2014, to determine if that body of water meets the necessary criteria to be declared as a wetland of importance. The studies were cross-sectional, descriptive, through environmental, social and economic indicators. Further information on the physical, hydrological, water quality, flora and fauna of the lake and its basin were obtained, including historical, archaeological, social, cultural and touristic aspects of the area. The results indicate that the lake is in a critical condition and existential risk caused by anthropogenic factors. Criteria that meet the standards of the Ramsar Convention to classify the lake as susceptible to declare it as a wetland of importance were identified. It was concluded that physical and cultural characteristics and biodiversity that justify actions for rehabilitation, conservation and management can be confirmed. Achieving recognition as a Ramsar site should improve the economic, social, and environmental condition of the wetland and its watershed.

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11.1 Introduction

The wetlands are ecosystems of great strategic value for the ecological balance and regularly are affected by anthropogenic factors. His conservation, rehabilitation and sustainable use are vital importance for the conservation of flora and fauna already existing in the region. The Lake Cajititlan suffers an environmental deterioration such as overexploit of aquifers and overloads of wastewaters.

Despite the benefits that wetlands bring to ecosystems, most of the time it is thought that they are of little value, in fact, more than half of the world (Zedler and Kercher 2005). The Information Sheet on Wetlands is the preliminary document for carrying out a series of actions in the short- and medium-term, including the elaboration of the Conservation, Protection and Management Plan in the Lake Cajititlan.

The Lake Cajititlán is in a critical situation and at risk of survival, according to technical studies the lake is a body of water that is contaminated by direct reception of urban discharges and precarious functioning of treated or partially treated wastewater treatment plants dumped in the lake, agricultural returns with excess fertilizer and pesticides.

The three essential factors that distinguish wetlands are the following: hydrological regime, soils, and vegetation. According to the above, hydrophilic vegetation has frequently adapted to the prevailing conditions of a specific site through physiological and morphological changes that lead to the development and preservation of native or endemic plant species.

Environmental benefits provided by wetlands are numerous. They include the recharge of aquifers, reduction of impacts by floods, sediment control, capture, transformation, and elimination of pollutants substances in water and soil, nutrient absorption, conservation of plant cover and others. Notwithstanding the importance that wetlands have on our environment, it is that they are increasingly affected by various factors of natural and anthropogenic origin, which substantially alter the processes and conditions that they take place in them, which is why vital its rehabilitation, conservation and sustainable use (Ramsar Convection 1994).

Also, they are sites that promote biological diversity, as they make the permanence and conservation of plant and animal species that may be threatened or in danger of extinction. Also, basins are areas where the migratory wildlife species can take refuge, feed and reproduce. Usually, wetlands are sites of high aesthetic appeal and economical due to the high number of visitors attracted by the possibility of carrying out of activities of fishing, hunting, and tourism, as the sites that allow and facilitate the development of research and education about the environment and sustainability.

Mexico has many worldwide recognized wetlands. In 2014, the country ranked 4th with 142 sites included in the Ramsar List of Wetlands of International Importance, of which thirteen bodies of water belong to the State of Jalisco. Among them are Lake Chapala, Sayula, Atotonilco, Barra de Navidad, to name a few.

> Other bodies of water that are in the state of Jalisco and have physical-chemical characteristics of wetlands such as Basilio Vadillo dam and Lake Zapotlán. Lake Cajititlán has a wide variety of species of flora and fauna of the region; it is a place of rest and feeding for migratory birds and has valuable archaeological and social resources.
>
> According to the Köppen Climate Classification System (modified by E. García 2004), the weather of the basin corresponds type to semi-warm to sub-humid climate, with an average rainfall of 883 mm, with a maximum of 900 mm and a minimum of 600 mm. In its temporary distribution, 88.5% of this occurs between June to October 8.3% of the rain occurs between January and May and the remaining 3.2% in November and December.
>
> The annual average temperature conditions are around 19.9 °C, with average values less than 7.7 °C and a maximum average of 31.7 °C. The thermal oscillation present is 24 °C, with 200 h of cold on average, even when there are areas with up to 500 h of cold a year (ibid).
>
> Another aggravating factor is the availability of water resources, since the basin is located in a region of dry weather most of the year, and the rainy months are from June to September, with areas where rainfall does not reach 700 mm. It causes a reduced surface runoff affecting the coverage for the needs of drinking water supply and its quality that could be determined by the hydrological balance of the basin.
>
> The deficit has been aggravated by the significant manufacturing settlements and industrial services the territory, which in turn has generated trade runners and services. In addition to this, there is a considerable increase of the inhabitants, with a population growth of the basin raising in the last 30 years. For example, in 1970 the Lake Cajititlán population was 5000 people, while in 2010 reached 60,000.
>
> It should be noted that since the 1990s the population increased 100%, which caused the rise of the urban area to about 10,000 ha, and there is a risk that in a few years this surface will double, according to the current authorities in the five towns that make up the lake (Mendoza-Perez and Venegas-Herrera 2003).
>
> The physiographic characteristics classify Lake Cajititlán as an endorheic basin but has been modified with the construction of the Cedros Channel for irrigation water. The principal water resources in the basin are the lake itself, groundwater and runoff coming from Madroño mountain and Cerro Viejo in the rainy season. Both surrounding areas serve as a watershed to the own basin, which generates the formation of streams, mainly in the municipalities of Tlajomulco and Ixtlahucan de los Membrillos.

The goal then is to assess whether that body of water meets the necessary criteria to be declared as a wetland of importance and thus develop the Sheet of Wetlands, the necessary documentation before it is declared as a Ramsar site. The above is proposed with the aim of detecting both hydrological and environmental problems to propose structural actions, considering the conditions of the environment to lead to an improvement of sustainability.

For the development of this project, two stages were proposed:

- Development of hydrological and biological analysis to have the physiographic and physical–chemical data that allow identification of pollution sources in the lower part of the basin.
- Analysis of samples to determine water quality parameters between them: temperature, transparency, dissolved oxygen, alkalinity, electrical conductivity, biochemical oxygen demand BOD, pH, nitrate, phosphorus, mercury, etc.

11.1.1 Background

Talking about the basin Lake Cajititlán, we can evoke different landscapes, cultural features, situations and conflicts that often go beyond its natural limits. This territory can be given many statistics that highlight its importance, for example, the 22% of the state is population lives within its limits and produce 31% of the census value-added of the industry, but at the same time maintains a high rate of marginalization and strongly contrasting population densities (Direction of Integrated Management of Watersheds-National Ecological Institute 2003) (Fig. 11.1).

> The lake (Fig. 11.2) represents a symbol of identity for the population of Tlajomulco and its surroundings. Also, it is an important income source, particularly for coastal settlements, with tourism, recreation, and fishing activities. The lake is at risk of severe damage and degradation.

Fig. 11.1 Location of Lake Cajititlán. *Source* Caro Becerra et al. (2017)

Fig. 11.2 Riverside of Lake Cajititlán. *Source* https://www.adelto.co.uk/contemporary-cajititlan-pier-jalisco-mexico/

> Currently, Cajititlán Lake undergoes a process of environmental deterioration, caused by the geomorphologic characteristics of the region, and exacerbated by anthropogenic factors such as new housing developments, aquifers overexploitation, domestic and industrial sewage discharges, agricultural irrigation returns, hydrological changes, and a lack of rehabilitation and protection plans (Lujan Gódínez et al. 2016).
>
> The average depth of the lake is just 2.5 m, which is characterized as a shallow body of water. The average length and the shallowness of the reservoir raise the particles suspended, dissolved nutrients, biological contaminants and the proliferation of aquatic vegetation in its waters. Drying events have also reduced the presence of native fish species (Lopez 2002).
>
> The sewer network of the Tlajomulco de Zuñiga municipality provides drainage services to this population which poured partially to the lake. These and other reasons most exposed in this work diagnose that the municipal wastewater treatment plant does not fit the appropriate functioning according to the Official Mexican Standards (NOMs), and has caused severe environmental harm in the region.

11.2 Development of the Theoretical Framework

The wetlands are areas where water is the main factor of control of the environment and the plant and animal life. They constitute a fundamental and irreplaceable link in the water cycle and are among the most productive environments on the planet. Their conservation and sustainable management can ensure the biological wealth of a region, such as a flood control, recharge of aquifers, protection against storms, retention and sediment control, recreation, tourism, and climate change mitigation (National Water Commission 2007).

An intergovernmental treaty was signed with the Iranian city of Ramsar in the year 1971, known as the Ramsar Convention which has three pillars: the rational use of wetlands, the list of wetlands of international importance and international cooperation (Anonymous 2007). Lake Cajititlán is in a critical situation, and at risk of survival, up to this point. The lake complies with 4 of the 7 criteria of the Ramsar Convention, so the lake classifies as susceptible and declares it as a wetland of importance. It was concluded that physical characteristics, water, biodiversities, historical, social and cultural rights justify the actions for their rehabilitation, conservation, and management. Authorities should improve the environmental conditions, social, economic, and political plans for the wetland and its catchment area to declare it as a Ramsar site.

According to technical studies, Lake Cajititlán is a body of water that is contaminated by direct reception of urban discharges and improper operation of the wastewater treatment plants treated or partially treated sewage discharged into the lake, returns or runoff of agricultural irrigation with remains and traces of fertilizer and pesticides.

Lake Cajititlán is without a doubt of most significant interest in the Hydrological Region XII and the environmental impact highlights the high pressure to which it is exposed for its transformation. Its importance as a monitor to understand the hydrological behavior facilitates the decisions making and actions for its proper management, as they have identified aspects that should be studied in more detail, and shows the need for a platform to intensify the ongoing analysis, streamline the viewing and consultation of the elements involved.

11.2.1 Description of Fauna

11.2.1.1 Zooplankton

We identified 35 varieties belonging to two large zoological groups: rotifers and crustaceans. The most representative genres for its abundance and its frequency are formed by 15 varieties (López Muraira and Reyes Rueda 2014).

11.2.1.2 Fishing

The faunal resource of introduced fish is handled through periodic plantings, which allows the fishing activity developed by 422 fishermen, who belong to four legal figures called Fishing Cooperative Societies: (1) Cooperative Society of Cajititlán, (2) Cooperative Society San Juan Evangelista, (3) Cooperative Society San Lucas Evangelista and (4) Cooperative Society of Cuexcomatitlan. The scan in the Lake

Cajititlán is greatly diminished, and there is environmental damage both by natural events such as anthropogenic factors of the type, for which the Ministry of Health has ruled a precautionary quarantine on the fishing activity until a definitive diagnosis can be sustained.

11.2.1.3 Fish

Fish species of Lake Cajititlán and which are susceptible of cultivation and marketing are: common carp (*Cyprinus carpio*), mirror carp (*Cyprinus carpio var specularis*) 32%; tilapia (*Oreochromis* sp.) 68%; which are exotic and represent an average production of 20 kg for day/fisherman and partial support to 422 families. On the other hand, existing native species are three species: Sardinite (*Astyanax fasciatus*), fish shot (*Goodea atripinnis*) and guppy (*Poeciliopsisinfans*); while the family *Atherinidae* is a species: guppies that have commercial importance.

11.2.1.4 Birds

As indicated in Criterion 4, Section 12, birds are the largest group of vertebrate's representativeness in the wetland. Also, the group of fauna that has been most affected in the history of the development of human communities existing there.

11.2.1.5 Mammals

The group of mammals of Lake Cajititlán has been little studied., However, the knowledge and conservation of this group of vertebrates allow the maintenance of ecological processes and relationships given in the lake ecosystem, as well as in the basin. Mammals form a group that will be significantly affected by anthropogenic activities carried out in any natural area. Forty species have been identified, distributed in seven orders and fourteen families.

11.2.1.6 Reptiles, Amphibians, and Fish

There have been thirteen species of reptiles, grouped in two orders and five families; six species of amphibians are grouped in three families, and seven species of fish grouped in five orders and five families.

The studies on fauna included the classification of species of invertebrates (zooplankton) and vertebrates (mammals, birds, reptiles, amphibians, and fish) of the lake. Among the invertebrates were identified thirty-five (35) genera belonging to two (2) large zoological groups: rotifers and crustaceans. There are 15 most representative genres based on its abundance and its frequency.

Up to date, the identification and inventory of fish are done, that includes seven (7) genres and twelve (12) species. Four (4) exotic and three (3) native ichthyologic species in Lake Cajititlán are identified with more relevance. Of the total, four (4) species are susceptible of cultivation and marketing.

The birds are the largest group of vertebrate's representativeness in the wetland. Current existence includes an inventory of 58 species of identified birds, that belong to 17 families and 8 orders, of which 16 are residents and 42 species are migratory (Reyna 2011).

In the lake, there have been identified 40 species of mammals, distributed in seven orders and 14 families. We have identified 13 species of reptiles grouped in two orders and five families; five species of amphibians are grouped in one order and two families, and seven species of fish grouped in five orders and five families.

The historical and archaeological importance of the lake and its environment is significant. The lands bordering the lake have been identified as sites of archaeological interest, while direct evidence of the first populations who were settled in the vicinity of the lake, such as paintings, low height pyramids, and religious ceremonial areas. There is also evidence of tule exploitation, basaltic stones, and mud for the elaboration of molcajetes, metates, and pots for everyday use, as well as settlements and petroglyphs.

There is evidence that from the sedentary nature of man in the area, originated several populations: Cuyutlán, Cuexcomatitlán community, and Cajititlán, which preserved in his name the Hispanic origin and two of them; San Juan Evangelista and San Lucas Evangelista were repopulated in March 1530 to the arrival Nuño de Guzmán.

There are buildings of historical interest such as the Franciscan Path, which connects the main towns in the region and includes ten temples and hospitals built in the 17th and 18th centuries. The Franciscan buildings show religious images of three hundred years of history and natural areas where visitors carry out rural, natural, religious and ecological tourism activities

The area around the lake is an important producer of vegetables, grasses and legumes. The economic activity prevalent since ancient times has been fishing, although it is to a lesser extent today. There are four fishermen's cooperative societies, formed 422 families that make a living from fishing activity. As part of the local culture, the use of local wild plants for religious purposes is also a detonator of these activities.

The National Waters Law in Mexico states that the existing bodies of water are the property of the nation. One of the exceptions to the law is Lake Cajititlán because although it is mostly federal property, 400 ha (988 acres) belong to the members of the community, which makes them owners of the corresponding allocation of water.

Current land use in the watershed of the lake is varied. It is estimated that 50% of the total area is allocated to agricultural uses, the 27% to the foresters, 11% is forest, the 8% is pasture, urban uses account for 2%, and the surface of the water body represents the 2%. The extensive cattle activity occurs throughout the basin. In the basin are areas whose tenure of land is owned by the federal, state, municipal, communal and private, which include significant areas of agricultural production and livestock, and several human settlements.

11.3 Materials and Methods

11.3.1 Description of the Study Area

Lake Cajititlán is located in the municipality of Tlajomulco de Zuñiga in the state of Jalisco, Mexico, a municipality which is part of the Guadalajara Metropolitan Area (GMA) and is located in the middle portion of the central region of that state between the coordinates 20º 28′ north latitude and 103º 27′ west longitude (Fig. 11.1). From the hydrological point this lake is the 2nd most important natural reservoir in the state of Jalisco, since it has a length of 7.5 km, an average width of 2 km and a depth of 2.5 m; it is storage capacity is estimated at 54 million m^3 (CONAGUA 2007) in a reservoir area of 1700 ha (4200 acres) an average altitude of 1551 m above sea level (masl) (Chavez-Hernandez 2009).

Lake Cajititlán is a body of perennial natural water that appertains to the XII hydrological region Lerma-Chapala-Santiago, in the eastern part of the micro-basin called Tlajomulco-Cajititlán. According to the Priority Hydrological Regions Program of the National Commission for the Knowledge and Use of Biodiversity (CONABIO), Lake Cajititlán belongs to the 58th Chapala-Cajititlán Hydrologic Region.

The studies were cross-sectional and descriptive, carried out through fieldwork and the environmental, social and economic indicators. Information was obtained about the physical, hydrological, water quality, the presence of flora and fauna of the lake and its basin, as well as historical aspects, archeological, social, cultural, and tourist places.

Work was carried out of topography to delineate the flood area of the lake, as well as the use and protection. The Delimitation of the basin was based on the identification of its watershed in the topographic charts F13D76 (Chapala), F13D75 (Jocotepec), scale 1:50.000 of the National Institute of Statistics, Geography, and Informatics (INEGI 2000).

The research on the flora of the region included the general ecological features of the area, the types of vegetation and plant communities such as terrestrial vegetation, aquatic and semi-aquatic.

Studies identified the various types of terrestrial vegetation, characterized main by types of pine forests, pine-oak, oak-pine, oak, tropical deciduous forest, grassland induced, aquatic and semi-aquatic vegetation, and secondary vegetation. There were 330 genera and 530 species distributed in 100 botanical families.

Within the category of aquatic vegetation, several types of plants are found, such as tulares and reeds as dominant genera. As part of the floating vegetation, there are microcephaly species in addition to hydrophytes. The semi-aquatic vegetation is the one that occupies the second place regarding an extension. They are present as herbaceous stratum composed mainly of grasses. About the types of vegetation, the herbaceous plants are better represented, followed by shrubs, trees, vines, the parasites, and epiphytes. The lake includes genera of phytoplankton belonging to 5 large groups: Cyanophytes, Chlorofites, Euglenoites, and Crisofites.

11.4 Results

The Ramsar Convention establishes nine criteria for identifying wetlands of international importance, divided into three groups. The group A includes sites of rare or unique wetlands, which does not apply to Cajititlán Lake. The group B refers to sites of international importance to conserve biological diversity. Of these, criteria 2 include the presence of endangered wildlife species by national standards. In the lake area of Cajititlán are identified, according to the standard Mexican NOM-059-SEMARNAT-200 to three (3) species of birds, three (3) Reptile Species, two (2) of amphibians, and two (2) of mammals.

Criterion 4 establishes that a wetland should be considered of international importance if it supports species of plants and animals when they are at a critical stage of their biological cycle or offers them shelter when adverse conditions prevail. Within species of flora of Cajititlán Lake are two species that are in danger; two other species existing in the region of the lake, while critical conservation status, can be affected by the size of their populations by modifying the ecosystem or exploitation according to the NOM-059-SEMARNAT-2010 concerning environmental protection-Mexico native species of flora and fauna.

According to studies carried out in the record of the large footed frog (*megapod frog*), an endemic species of ecological and economic importance, considered as vulnerable on the red list of International Union for Conservation of Nature (IUCN), threatened species and under special protection in the NOM-059-SEMARNAT-2001. Therefore, a total of nine species of birds present on this site are found in Mexican law, six of which are subject to special protection and three are considered threatened.

Criterion 5, which is a specific criterion based on waterfowl, indicates that a wetland should be considered of international importance is based on a regular basis a population of 20,000 or more birds. On average, the lake has a population of approximately 24,000 birds using the lake as a resting point, shelter and food. Of these 56 are aquatic species and 3 species are associated with the body of water, belonging to 17 families and 8 orders; 17 are residents and 42 species are migratory. Birds are the largest group of vertebrate's representativeness in the wetland under Lake Cajititlán is part of a migration corridor of wild birds.

Criterion 7: a wetland should be considered of international importance if supports a significant proportion of the subspecies, species or families of fish species, stages of the life cycle, interactions of species and/or populations that are representative of the benefits and/or the values of wetlands and contribute in this way to the biological diversity of the world. Lake Cajititlán meets this criterion as it supports three (3) native fish species is of importance.

On the other hand, the species under special protection at the same standard include: the ferruginous hawk (*Buteo albonotatus*), also in Appendix II of The Convection on International Trade in Endangered Species of Wild Fauna and Flora (CITES); the rattlesnake (*Crotalus basiliscus*); the common turtle (*Kinosternon integrum*), the american stork (*Mycteria americana*); the ferruginous hawk black banner (*Parabuteo unicinctus*), also in Appendix II of CITES; the rascon water (*Rallus aquaticus*), the lizard necklace (*Sceloporus grammicus*), the shrew (*Sorex saussurei*), the lesser diver (*Tachybaptus dominicus*), and the taxed turtle (*Trachemysscripta taxed*).

11.4.1 Diagnosis of the Cajititlan Lake

The samplings were carried out in five stations: San Juan Evangelista, San Lucas Evangelista, Cuexcomatitlan, Cuexcomatitlan plant and Cajititlán as part of the research performed by Michel-Parra et al. (2014a, b) from March 2009 to September 2014. They reported the limnological study of Cajititlán Lake which included physical, chemical and biological parameters:

- Temperature: from 10–24 °C
- Dissolved oxygen: 0.392–1.738 mg/L. Observed variations depend on the time, light intensity and sampling site
- pH: 8.84–9.52
- High concentration of dissolved phosphate and ammonium
- Chlorophyll: Up to 0.088 mg/L
- Salinity: 0.30–0.34 mg/L
- COD: 394–14.76 mg/L
- BOD: 27–9.6 mg/L
- Total solids: 0.405–0.454 mg/L
- Total coliforms: 5–2400 CFU/100 mL (Fig. 11.3)
- Fecal coliforms: 7–2400 CFU/100 mL (Fig. 11.4)
- Mercury: 0.0005 mg/L in water; 0.0250–0.0517 mg/kg in sediments; 0.0250–0.0478 mg/kg in plants and 0.025–0.0478 mg/kg in fish

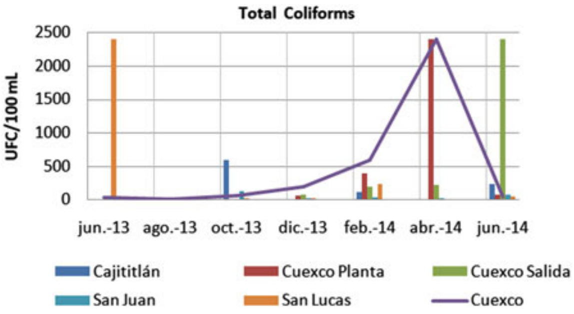

Fig. 11.3 Totals Coliforms Graph. *Source* Vizcaíno et al. (2014)

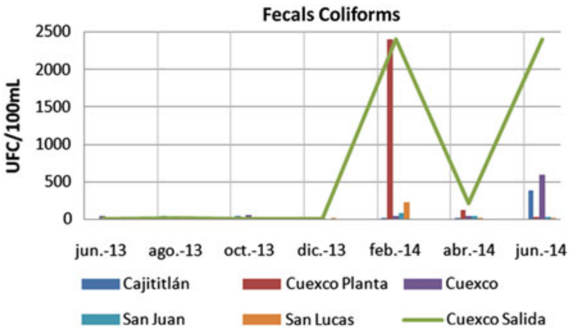

Fig. 11.4 Fecal Coliforms Graph. *Source* Vizcaíno et al. (2014)

11.5 Conclusions

The need to have an inventory of natural resources in the basin of Cajititlán Lake, and the ability to develop land maps corresponding to soil, vegetation cover, hydrography, population density, etc. the advisability of develop a Geographic Information System (GIS) that is specific to the area, composed of three subsystems relating to physical conditions, natural resources and urban settlements. Lake Cajititlán presents valuable characteristics that need urgent and priority actions for their conservation to avoid its deterioration process. It meets the criteria of the Ramsar Convention as a wetland of international importance since the declaration of the lake as a Ramsar site would make it possible to improve the condition ones environmental, social and economic. The physiographic features of the basin, such as surface, shape, circular relationship, elongation, and earrings, allow us to conclude that it is a basin of rapid response to meteorological events. The above indicates the need to develop protocols for the protection of the population where there are extreme events of rain, and additional studies on flood risk.

Acknowledgements This article is dedicated to Network of Cajititlán by a “living lake” that presides, Master Felipe Iñiguez Pérez; the network will continue to be the main actor in this long road to conserve, manage and protect our Lake Cajititlan, as well as Lake Zapotlán Basin Commission that preside by Ph.D. J. Guadalupe Michel Parra. Thousand thanks to both groups for their teachings, and especially to Master in Language Hector Ortiz Partida who was the translator in this project.

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Part III
Water Allocation

Chapter 12
Irrigation Water Challenges: A Study Case in the State of Puebla, Mexico

Amado Enrique Navarro-Frómeta, Humberto Herrera-López and Conrado Castro-Bravo

Abstract The largest volume of water that humanity uses is dedicated to agricultural irrigation, vital to ensure food for the growing population of our planet. This poses many challenges since the concentration of the population in urban areas confers a new dynamic on the relations between the countryside and the city. Additionally, climate change creates scenarios that imply the need for improved irrigation water management, which cannot be achieved only through irrigation technologies, but with a global approach to the problem that also includes economic aspects such as incentives for producers to adoption of the most appropriate technologies for each region, as well as the conscious intervention of producer associations. Considering the mentioned conditions, in the present work the situation of the use of the irrigation water in the valley Atlixco-izúcar of the State of Puebla, Mexico is shown. The demonstration of the profits of technified irrigation was performed in three plots dedicated to sugar cane which led to increases in yields and savings of 50% and more of the irrigation water used.

Keywords Irrigation water · Challenges · Atlixco-Izúcar valley · Technified irrigation · Water savings

12.1 Introduction

The relationships between urban and rural environments are increasingly strengthened, showing closer linkages through the flow of people, production, commodities, capital and income, information, natural resources, waste, and pollution. All this results in more diffuse urban–rural limits. Thus, it is necessary to conceive rural (and peri-urban) areas as part of the regional development, supporting urban growth and sustainability. This, of course, is of a complex nature—for example, in Mexico medium cities seem to have a positive influence in rural development, rather than

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small or large cities (Steinberg 2014; Berdegué and Soloaga, 2018; López-Goyburu and García-Montero 2018). Water supply has great unbalances that threaten its sustainable use, with agriculture being the most demanding sector (Cosgrove and Loucks 2015). In this sense, the sustainable management of irrigation water, at the final stage, impacts in the regional welfare and resilience. Through facilitation, the universities have an important role in improving the use of irrigation water. This includes the development of scientific and technological research, as well as applications in this context, its dissemination, and accompaniment to producers for their implementation (Ison et al. 2007; Nykvist 2014; Samian et al. 2015; Yuma County Agriculture Water Coalition 2015). The present work illustrates the problems present in the Atlixco-Izucar Valley, southeastern Mexico, and the impact of technified irrigation in water saving.

12.2 Some Global Challenges

12.2.1 Problems with the Use of Water for Irrigation

Food demands continuously increase and, consequently, cropland areas also escalate. At a global level, agriculture uses more than 70% of the water, which means its water footprint is much greater than that of other sectors, especially at the production stage. This includes the energy costs and its impact on climate change issues associated indissolubly to water use. Agricultural irrigation is essential to ensure food security. Specifically, 40% of world crops is produced in less than 20% of the total area of cultivation, thanks to irrigation. In the future, it is expected that the irrigated agricultural surface will increase to cope with the demand for food. From here, stems the decisive role that the responsible use of water in the agricultural sector has in the future of the sustainable management of this resource. Some of the actual problems with the water and soil degradation, due to improper irrigation management, are the salinization of soils and groundwater pollution by excessive use of fertilizers, deforestation and desertification, increases in the price of agricultural inputs, land concentration, uncertainty in irrigation water supply, etc. These problems have a strong interdependence. For example, the changes in the groundwater quantity and availability are more related to the uses of surface water than with its abstraction. Even energy prices have a direct influence on the efficiency of irrigation water. It should be considered that furrow irrigation, despite its lower efficiency when compared with more technical methods, prevails in most parts of the world, and may show advantages in some cases (Alexandratos and Bruinsma 2012; WWAP 2012, 2014; Fuchs et al. 2018; Johnson et al. 2016; Singh 2018; Smith et al. 2018; Tellez-Foster et al. 2018).

12.2.2 The Impact of Climate Change

The forementioned problems also place the consumption and pollution of water in the agricultural sector as a matter of priority in the national agenda of water, even more, if it is wanted to adequately manage the conflicts and interdependence between urban and rural systems. However, also keep in mind that this scenario is compounded by the effects of climate change, which further add to the problems of groundwater demand and irrigation costs. Likewise, the effects of climate change in agricultural conditions indirectly impacting on public health should also be considered (Ahmed et al. 2016).

A warmer climate will involve, for example, longer periods of growth and increased evaporation losses, with an upsurge in the speed of drying of the soil. A decrease in crop yields is expected, demanding more planted area or special measures for increasing irrigation effectivity. There is evidence suggesting that the decreased precipitation attributed to climate change is the main cause of the low sugar cane yields obtained in Mexico in recent years. Decreased soil moisture was most evident in the agro ecoregions, where the crops were not irrigated or managed with supplementary irrigation, thus affecting the crop yields in Mexico. To meet the growing demand for food, it will be necessary to develop short and mid-term irrigation management policies for agro ecoregions, to reassess the way in which water is used in combination with the restoration of soils, terrestrial coverage and also the adoption of deficit irrigation. Altogether, this is to decrease the demand for water without significantly affecting yields—including some benefits, for example, an increase of the antioxidant contents in fruits under water stress (Ojeda et al. 2012; Patiño-Gómez and Reza-García 2012; Torres-Salcido 2012; Falagán et al. 2016; Lei et al. 2016; Nguyen et al. 2016; Santillán-Fernández et al. 2016; Zapata-Sierra and Manzano-Agugliaro 2017; Hernandez-Ochoa et al. 2018; Pokhrel et al. 2018; Salem et al. 2018).

12.2.3 Improving Irrigation Water Sustainability

The beginning of the rational and efficient use of water goes through an adequate balance, from the economic and technical point of view of the use of surface and underground water for irrigation—taking into account the preservation of the aquifers; the cost/benefits ratio of introducing new irrigation techniques in each specific scenario; the use of modern tools for decision making and policies implementation—also considering that the success of irrigation projects is determined by governance and socio-cultural contexts (Zetina-Espinosa et al. 2013; Arredondo-Ramirez et al. 2015; Alarcón et al. 2016; Lankford et al. 2016; Mastewal 2016; Singh et al. 2016; Varouchakis et al. 2016; Wang et al. 2016). Further, a good delivery of water to the crop fields and the accurate measurement and monitoring of the water distribution systems is essential in order to solve the problems of water efficiency and availability (Nam et al. 2016; Soler et al. 2016). Finally, the fact that with the actual patterns of consumption, a sustainable agriculture and its water use which can't be afforded without a smart food system, should be evaluated (Taylor 2018).

The increase of the efficiency of the use of water for irrigation is one of the most important measures to achieve for the better management of water, which is often based on the use of sophisticated systems. The sprinkler and drip irrigation systems have some recognized advantages on the irrigation by gravity. In any case, the choice of which to use should be based on technical studies in each specific case. A correct dosage of the water needed by the crop not only prevents seepage and deep percolation but also contributes to a better uptake of nitrogen by plants, reducing emissions of N_2O—a greenhouse gas.

A significant water saving is achieved with an appropriate irrigation schedule, using mathematical models and measurements of soil moisture contents. However, as stated above, it is necessary to fully evaluate the more technical irrigation systems because, if they are not well managed, a drip irrigation system can also lead to problems of secondary salinization, or a sprinkler irrigation system may not distribute evenly the water, thus inhibiting the productive potential in the irrigation area and causing the salinization of other regions. In some cases, technified irrigation may increase greenhouse gases emissions (Andrés et al. 2014; Wang et al. 2014; Hannam et al. 2016; Ibrahim et al. 2016; Balafoutis et al. 2017; Darouich et al. 2017; Chen et al. 2018; Li et al. 2018; Patle et al. 2018; Yan and Li 2018). Therefore, a stronger evaluation is required of the energy related to and economic issues in the modeling and simulation stages of the design of the agricultural production process. More specifically, in the selection of the irrigation system as well as the use of renewable energies, automation, remote sensing, and information technologies. With regards to the use of solar energy, it has been reported that the practice of appropriate irrigation scheduling and the adaption of photovoltaic pumping systems, eliminates intermittences and allows energy savings of approximately 45%, along with the diminishing of CO_2 emissions (Mérida García et al. 2018; Narvarte et al. 2018).

Ultimately, it is imperative to move to a scientific and technically supported agriculture, with a holistic approach, being able to find spaces of opportunity—even for the traditional methods of irrigation. For example, the use of aerated irrigation improves the soil root zone environment and increases crop water and fertilizer absorption, consequently increasing crop yields (Gutiérrez-Jagüey et al. 2012; Romero et al. 2012; Cruz-Blanco et al. 2014; Bekri et al. 2015; Du et al. 2018; Narvarte et al. 2018; Frisvold et al. 2018). However, given the future challenges of the shortage of water, it is necessary to preserve the volumes of "extra" water, that are achieved with the increase in the efficiency, and not destine them immediately to increase the area of irrigation, or for other uses, without a proper study of this scenario, which will contribute to the resilience of the basins (Scott et al. 2014). Along with the implementation measures of technified irrigation, its economic stimulation may have a more decisive role than the technology itself—for example, to stop the decrease (depletion) in the level of aquifers (Sainz-Santamaria and Martinez-Cruz 2019).

12.2.4 The Role of Local Actors

The development of capacities and links between the producers, the exchange and transfer of experience, as well as the preservation of the heritage of knowledge of the producers, are all important aspects to consider. The significance of a decentralized and non-bureaucratic self-government, in which there are horizontal agreements between irrigation users and, in whose context, practical knowledge can be taken advantage of in favor of efficient governance and management of water, has been highlighted (Palerm-Viqueira 2015). Occasionally, small changes at the tactical level (dates of sowing and fertilizing, etc.), lead to a better production (Holzkämper 2017; Ozturk et al. 2017; De Frutos Cachorro et al. 2018). It is a very important role that the associations of users of irrigation can play in the most effective and efficient use of the resource. Furthermore, they can contribute to the maintenance of the cultural landscape and ecological balance (Djumaboev et al. 2017; Su et al. 2018).

12.2.5 Irrigation in México

In Mexico, the largest consumptive use of water is the irrigation (77%), being vital to agricultural production, as two-thirds of its territory are arid or semi-arid regions. Additionally, the rainy season is concentrated in only a few months of the year (mainly in summer). Despite the ancestral experience of irrigation in Mexico, serious problems affect it and are like commonly observed negative aspects in Latin America and other countries. Some of these issues include:

(1) Prevalence of irrigation by gravity (surface) and persistence of the practice of uncontrolled flooding (Fig. 12.1), involving severe water losses by runoff, seepage, and deep percolation, as well as high soil sodicity and salinity, as it has been demonstrated in very similar climate conditions (Cox et al. 2018);
(2) Inadequate planning of irrigation—mainly based on the resource availability, without considering the characteristics of the soil, the needs of the crop, etc., and motivated by an insufficient extension of work with the farmers and poor dissemination of the best practices, derived from technical and scientific results;
(3) The poor state of the irrigation water delivery infrastructure, which leads to a bad delivery performance that, coupled with the low application efficiency, gives a considerable decrease in the total efficiency of irrigation;
(4) Insufficient infrastructure for the harvesting and conservation of rainwater, useful practice that increases the resilience of farming systems to the effects of drought;
(5) Lack of incentives for water saving and responsible use of irrigation, leading to little awareness in this regard; and
(6) Insufficient knowledge about irrigation water quality impairment (organic contaminants, pollution with nitrates, salinization, etc.).

Fig. 12.1 Uncontrolled flooding—an inefficient irrigation practice (photo of the authors)

As a consequence, the irrigation water withdrawal exceeds the irrigation water requirement due to significant losses in distribution and application, with a water requirement ratio of about 44% in 2009 (Frenken and Gillet 2012).

It is common practice to use municipal wastewater for irrigation. It is an economically proven fact that the use of wastewater can be beneficial and is also a source of water in places with water shortages. This practice entails serious risks to human health and to the quality of groundwater, for example, due to contamination with organic micropollutants—such as pharmaceutical and personal care products, which is why it is necessary to treat them as per acceptable limits, something of which requires investment. This is also related to the balance between taxes and costs for the use of treated or untreated wastewater. For instance, this is a common aspect between Colombia and Mexico regarding the cultivation of sugarcane. The excessive use of wastewater for irrigation has brought serious problems of groundwater contamination, as in the case of the Mezquital Valley. The mobility of pollutants, such as atrazine when irrigating with wastewater, can influence this. It should be mentioned, and notwithstanding what is known empirically, that irrigation with residual water can increase the organic matter in the soil (Contreras et al. 2017; Sánchez-González et al. 2017; Biel-Maeso et al. 2018; Galvis et al. 2018; Lesser et al. 2018; López-Morales and Rodríguez-Tapia 2019; Salazar-Ledesma et al. 2018).

The abovementioned suggests the need for sustainable management of the water used in Mexican agriculture. This includes, but is not limited to, the following actions:

the correct evaluation of the soil humidity, water demand of the crops and evapotranspiration; a proper scheduling of irrigation; the evaluation of the energy involved in the irrigation processes—which may be an incentive or a barrier for the introduction of more technified irrigation technologies; planting crops and varieties of low water consumption as demanded by the market; rainwater harvesting and conservation (Dile et al. 2013; Sun et al. 2016; Gutiérrez-Gómez et al. 2018).

12.3 Some Experiences from the Atlixco-Izúcar Valley

12.3.1 Experimental

An amount of 20 plots distributed in the study area were selected, according to their height above sea level, and classified within a high, medium or low zone, as is indicated in Table 12.1—which shows the geographic location of the studied sites that are illustrated in Fig. 12.2. The city of Atlixco is in the high region, whereas the

Table 12.1 Crops, surfaces and geographical location of the studied plots

Site	Zone	Crop	Surface, ha	Length	Latitude	h, masl
SNT	L	Sugar cane	1	98.507500	18.553500	1241
SLC		Sugar cane	1	98.477600	18.515000	1174
SSP		Sugar cane	1	98.476900	18.564800	1206
Ayu		Sugar cane	2	98.505800	18.536200	1173
Mat		Alfalfa	2	98.477000	18.576200	1246
BLA		Maize	2	98.482900	18.596700	1256
SNT	M	Sugar cane	1	98.459500	18.583600	1265
SLC		Maize	1	98.448300	18.615000	1282
Aml		Sugar cane	1.5	98.432200	18.700300	1379
Tep		Maize	1	98.431900	18.718300	1459
LG		Sugar cane	0.75	98.452500	18.638100	1326
Tat		Sugar cane	0.6	98.473500	18.635900	1362
Ter		Sugar cane	0.75	98.460700	18.716800	1463
Acc		Maize	1	98.486900	18.773100	1605
SAY	H	Alfalfa	0.4	98.393100	18.884800	1760
SDA		Alfalfa	0.5	98.359900	18.909800	1823
SBC		Maize	1	98.353200	18.944800	1850
SPA		Gladiola	0.5	98.380800	18.935817	1861
ER		Coriander	1	98.400433	18.859433	1734
SJH		Alfalfa	1	98.454200	18.798633	1687

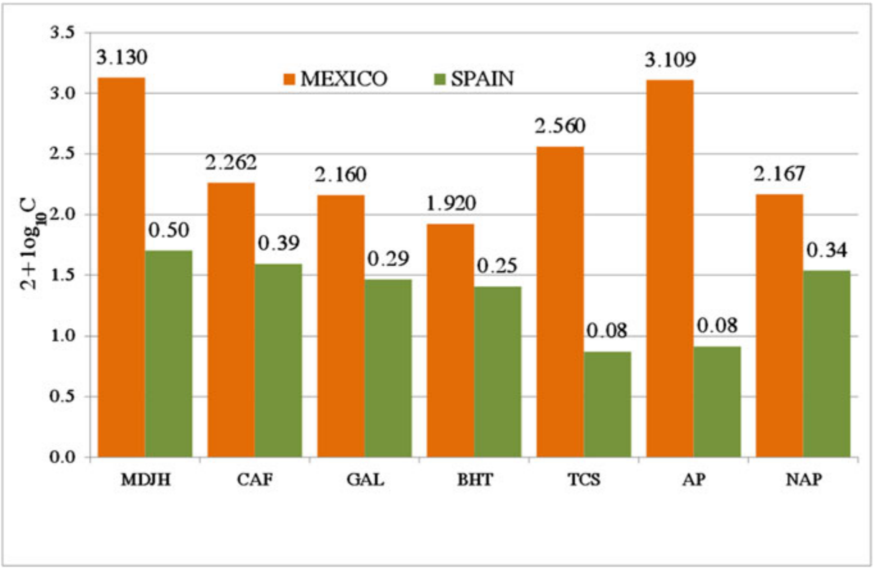

Fig. 12.2 Comparison of mean values of micropollutant levels (C, μg L^{-1})

city of Izucar de Matamoros is situated in the low region. The study campaign was conducted at the end of the drought season in April–May 2012. All the plots were georeferenced with a GPS and the delivering capacity of the main irrigation canal to each plot was determined. Flow measurements were conducted with a Gurley cup-current meter model 622 A, according to commonly accepted procedures. The results of previous intervention, with the participation of the University, were also considered.

To assess whether the volume of water that is needed by the crops was exceeded, a calculation of the supplied water to each plot, based on flow measurements, was compared with a semi-empirical estimate of the different crop requirements, considering the data of the soil texture, the crop agronomic parameters and evapotranspiration data available for the different zones. The soil texture and other water quality parameters were determined in the laboratory, according to Mexican standards.

For producers in training, the following three demonstration plots—of one hectare each, were enabled: (1) a plot with a sprinkler irrigation system, (2) another plot with a gated pipe surface irrigation system, whereby the water is distributed in the field by gravity to the furrows, and (3) the other plot with a drip irrigation system. Sugar cane was used as a model and the three plots were visited by farmers, their organizations and community leaders.

12.3.2 Water Use

Table 12.2 summarizes the quantitative evaluation of the use of irrigation water. It may be seen that 13 of the 20 studied plots use an excess of irrigation water, higher than 43%. For the 20 plots studied, the overall volume of water in excess for a cycle, amounted to 187,967 m^3, and based on the total volume used was 507,065 m^3, is equivalent to 37.1% of excess. To understand what this means, let's assume the proportionality of the 21 ha of the 20 plots to about 10,000 ha of crops in the Atlixco-Matamoros region, along with a flow of the Nexapa River of 7 m^3 s^{-1}, the amount of water that is used in the excess cycle is equivalent to 147 days of the river flow. These results confirm previous estimates of 40–60% of irrigation water used in excess (studies conducted by the authors in sugar cane plantations during 2006–2007), which is a potential source of water-saving (Vélez-Rodríguez et al. 2015).

Table 12.2 Irrigation water balance (volumes in m^3)

Site	V_U	V_{NC}	V_{PF}	V_M	V_N	V_E	V_{EC}	%Ex
SNT	2178.0	594.1	313.2	108.9	1070.5	1107.5	12182.4	50.8
SLC	2167.2	365.0	330.0	108.4	857.6	1309.6	14405.6	60.4
SSP	1890.0	891.2	407.7	94.5	1474.8	415.2	4567.4	22.0
Ayu	2217.6	1188.2	637.9	110.9	2031.2	186.4	2050.3	8.4
Mat	2448.0	1101.6	881.3	122.4	2199.5	248.5	11928.2	10.2
BLA	1497.6	790.1	381.9	74.9	1341.0	156.6	1878.8	10.5
Jrs	2034.0	594.1	292.5	101.7	1042.6	991.4	10905.5	48.7
SM	1926.0	443.5	216.7	96.3	827.2	1098.8	12087.3	57.1
Aml	2736.0	565.6	659.7	136.8	1416.4	1319.6	15835.6	48.2
Tep	633.6	467.3	76.0	31.7	622.1	11.5	137.9	1.8
LG	1080.0	375.2	102.8	54.0	572.7	507.3	5580.4	47.0
Tat	882.0	445.6	95.1	44.1	625.5	256.5	2821.4	29.1
Ter	1656.0	527.1	168.1	82.8	818.7	837.3	9210.2	50.6
Acc	1116.0	158.0	56.9	55.8	289.6	826.4	9917.2	74.1
SAY	1584.0	250.7	225.7	158.4	675.5	908.5	43606.4	57.4
SDA	576.0	167.2	54.7	57.6	306.6	269.4	12931.4	46.8
SBC	1699.2	413.1	229.4	169.9	859.5	839.7	9236.5	49.4
SPA	221.4	50.1	18.9	22.1	111.0	110.4	1656.3	49.9
ER	993.6	266.1	134.1	99.4	544.4	449.2	4492.0	45.2
SJH	1159.2	300.9	198.2	115.9	651.9	507.3	2536.5	43.8

Notes: V_U—volume of water used; V_{NC}—volume of water needed by the crop; V_{PF}—losses by deep percolation; V_M—handling losses; V_N—water needed by plot; V_E—volume of excess water; V_{EC}—volume of excess water per cycle; %Ex—percent of excess water. All volumes are in m^3. For sites locations and crops see Table 12.1

The obtained results represent only the application efficiency. The visual inspection of the plots and the irrigation network within this, as well as the previously mentioned intervention in the Irrigation District 2 of the Atencingo Sugar Mill, show a series of problems that contribute to the former, as well as to a poor delivery efficiency which, in the end, affect crop yields, specifically:

(1) The poor condition of most of the delivery and distribution network in addition to a lack of maintenance and hydrometric works causes high conveyance losses of water, roughly estimated in other regions of Mexico of at about 40–60%;
(2) The predominant use of surface irrigation, with inadequate management and inefficient exploitation of this technique, and very extended practice of land flooding. Watering at such long intervals that the plants are affected by water stress;
(3) The application of large volumes of water in fields with excessive slopes, which involves loss of soil and fertilizer by erosion;
(4) The absence of plot drainage; and
(5) Lack of an irrigation scheme made on a technical basis.

These results were analyzed with the producers in a regular session of the Association of Irrigation Users of Nexapa.

12.3.3 Technified Irrigation Results

Training considered the following three main irrigation techniques: (1) matching the irrigation method to crop—considering soil and field characteristics, (2) local climate conditions, and (3) reliability of water supply. Moreover, it is necessary to balance the trade-offs between saving water, reducing CO_2 emissions and intensifying food production. For example, surface irrigation may be inefficient under light sandy soils, as large volumes can be lost by deep percolation, although is well suited to large-scale extensive cropping. Sprinkler irrigation has the greatest potential on light soils and undulating fields and is a good match with high-value horticultural crops. Drip irrigation has the most capital cost and is used on high-value cropping (citrus and vineyards), where the benefits exceed cost and water is expensive and/or scarce. In addition, the experience in Mexico indicates that the perception and participation of producers are elements that must be considered in the process of automation and modernization of irrigation (Daccache et al., 2014; Olvera-Salgado et al. 2014; Flores-Gallardo et al. 2014).

The training was developed in several session practices. A total of 275 producers visited the demonstration plots and were able to see the benefits of the proven systems.

The results of the implementation of the demonstrated technologies clearly illustrate its potential for irrigation water saving.

The producer whose hectare was established with sprinklers, expanded the irrigated area by an additional four hectares (80% savings), with the same system of canyons getting a total yield of 878 t, 175.6 t ha^{-1}, surpassing the average yield in the region of about 120 ton ha^{-1} in the first cut, and for the second cycle, there is an estimated yield of 160 t ha^{-1}. Furthermore, with regards to irrigation, the producer states that when he used gravity irrigation it took 15 days of watering, whereas with canyons it only takes 10 days, with 6–7 h of watering per day.

In relation to the drip irrigation system, the producer extended it by two more hectares and, at the same time, watered two more hectares sharing with surface irrigation, as the pressure was very high and got a yield of 200 ton per hectare with drip irrigation, and over 160 tons with a well-used traditional system.

Concerning the gated pipe surface irrigation system, the producer enabled two sets of 10 furrows, but the used water quantity was enough for the irrigation of two more sets.

12.3.4 Organic Micropollutants in Irrigation Waters

In Fig. 12.2 are shown the mean values of the concentrations of three pharmaceuticals: caffeine (CAF), naproxen (NAP) triclosan (TCS); three personal care products: galaxolide (GAL), tonalide (TON), methyldihydrojasmonate (MDHJ); the antioxidant butylhidroxitoluene (BHT) and alkylphenols (AF) in the irrigation waters sampled in the 20 studied plots and its comparisons with those from an irrigation network in the province of Barcelona, Spain, a mixture of river and reclaimed water (Calderón-Preciado et al. 2011).

It may be seen that the levels in Mexico are very much higher than the observed values in Spain, which assume greater threats to human health and food security, within these areas. This reflects the problem of untreated wastewater disposal in Latin America. the nil or little attention of authorities and policymakers to the problem, and the need for more focus and research from the scientific community.

In general, the concentrations in the middle zone are the highest, with values like those of the river for the other OMP, which is illustrated by the APs in Fig. 12.3. The foregoing indicates that, in general, in the middle zone there are more contributions of these pollutants. This may be related to the location of the parcels studied, near these undrained populations, which may be discharging domestic wastewater to the irrigation ditches.

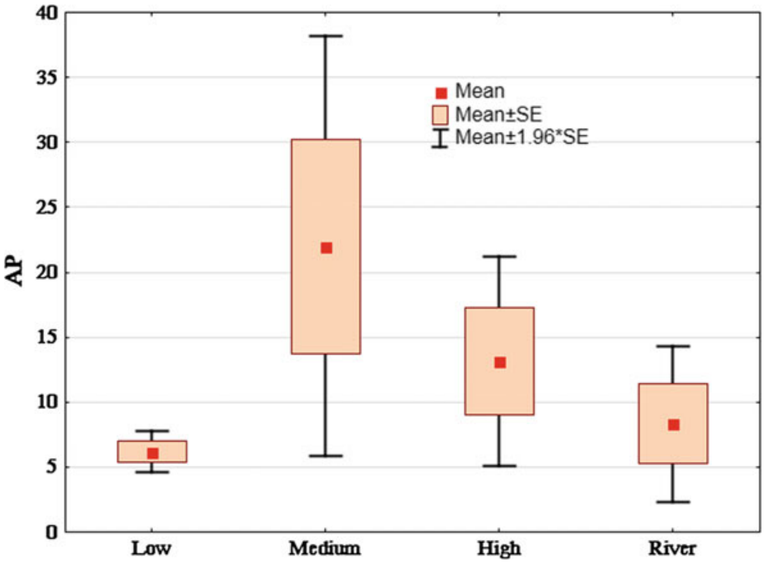

Fig. 12.3 Mean values, μg L^{-1} of the AP for the three zones and the river

12.4 Conclusions

The problems with the efficiency of the application of the irrigation water imply that nearly 40% of the irrigation water used is unnecessary. There are also delivery problems that are reflected in conveyancing losses.

More efficient irrigation techniques were demonstrated in three plots: sprinkling, drip, and gated pipe systems. The measured results of the use of these systems showed water savings of above 50%.

Among the suggested recommendations of a technical nature are as follows:

(1) Improve the water delivery conditions, especially the channels in poor condition.
(2) Perform leveling in the croplands to avoid soil and fertilizers drag off, as well as diminish water losses;
(3) Use of tillage techniques as the subsoiling to improve soil humidity conservation;
(4) The search for consensus between the producers to apply irrigation rules that are technically well-supported, and not by the number of hours of water availability, as is presently the case. Therefore, improve the practices of the traditional surface irrigation;
(5) Extend, according to the economic availability and considering of government support, the more technical irrigation systems, such as the gated pipes, sprinkler, and drip irrigation;
(6) Apply irrigation according to the physical and chemical characteristics of the water and the soil, especially the humidity of the latter. This includes the devel-

opment of irrigation schedules to implement watering to refit the roots moisture to the adequate levels;

(7) Use methods of conservation of the soil moisture, as the use of crop residues; and
(8) Handle composting techniques to take advantage of rational use and sustainable management, by means of organic fertilizers, to lessen the impact of the use of chemical fertilizers and nitrates.

The main requirement for future research is the evaluation of the crops' water footprint, according to ISO14046, in order to identify the involved water use, which is a useful decision tool for all the involved actors in irrigation water use (Rios-Flores et al. 2015; Lovarelli et al. 2016).

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Chapter 13
An Overview of Aquaculture Activity in Hidalgo State

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Abstract In recent years, Mexico uses 76.3% of the available water for food production. Aquaculture is an important animal protein production activity with an annual growth of 6.6%. Hidalgo is the second landlocked state in fish production. The national aquaculture official reports 967 production units, which are divided in intensive, semi-intensive, and extensive production levels. The main aquaculture resources produced in Hidalgo include Carpa (4606 tons), Mojarra (4015 tons), Trucha (173 tons), and Bagre (24 tons). The objective of this chapter is to present a broad vision of the water management sustainability of aquatic resources and its impact from various economic, social, and environmental points of view, in a short-term perspective.

Keywords Economy · Environment · Fisheries · Sustainability

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13.1 Introduction

Mexico owns around 0.1% of the total fresh water available worldwide, which determines that a large portion of the country is classified as desert area (CONAGUA 2016). The country receives about 1,449,471 hm^3 of rain annually, 67% of which falls between June and September, corresponding to summer and autumn. Water distribution across the country is uneven: Mexico has extremely arid areas (north, center, and northeast) and, to the south, humid regions (Chiapas, Oaxaca, Campeche, Quintana Roo, Yucatan, Veracruz, and Tabasco) that receive 49.6% of the precipitation (Fig. 13.1). According to the reports, 65% of the rainfall is evapotranspired and returned to the atmosphere while 24% flows through rivers or streams and 11% infiltrates into the subsoil naturally and recharges aquifers (CONAGUA 2016). Considering the export–import of water from the rivers Mexico shares with neighboring countries—USA to the north and Guatemala and Belize to the south—the country possesses 447,260 hm^3 of renewable fresh water annually and is considered a country with low water availability (CONAGUA 2016; Agua 2018).

According to the water statistics of 2016, Mexico was determined to use 76.3% of the water available for the agricultural sector, 14.6% for public supply, 4.8% for electricity generation, and 4.3% for industry. Most of the water resources of the country are used in food production: agriculture (58,450 hm^3/year), livestock (207 hm^3/year), and aquaculture (1136 hm^3/year), among others (CONAGUA 2016). Aquaculture is part of a productive chain that creates direct and indirect employment, added value, currency, and raw material for other industries and is an overall key factor

Concepto	Norte, centro y noroeste	Sureste
Población 2015	93 115 945	27 889 870
% Aportación al PIB	79.8%	20.2%
Número de municipios y delegaciones	1 383	1 074
Agua renovable (hm³/año)	147 408	299 370
Agua renovable per cápita (m³/hab./año)	1 583	10 374

Fig. 13.1 Map of water distribution in the 13 hydrological-administrative regions of Mexico (CONAGUA 2016)

to food security (FAO 2016). In particular, aquaculture has grown in the past decades; it is a source of income and means of livelihood for millions of people (Parrado 2016) and constitutes the animal protein production activity with the highest annual growth (9%). Internationally, Mexico is ranked 24 in aquaculture production, which generates over 16% of the national fish production (CONAPESCA 2018).

Fishery is commonly criticized due to its limited sustainability and the environmental impact it causes (Martínez 2018; Somer 2009; Rabassó and Hernández 2015). The most frequent environmental impact is the pollution of water bodies with nutrients and organic matter by discharges from untreated effluents (Oliveira et al. 2015; Pardo et al. 2006; Marinho-Soriano et al. 2009; Martínez-Córdova et al. 2009). However, it is hard to determine the isolated impact of aquaculture effluents in the environment given the interaction with environmental factors (Buschmann and Fortt 2005; Rabassó and Hernández 2015).

Several studies have proven that aquaculture affects the receiving bodies by adding nutrients and organic matter (Rabassó and Hernández 2015; Oliveira et al. 2015) and that the scale of the problem is related to the increase in farming, the amount of artificial food used, food handling, and feeding techniques (Tacon and Forster 2003; Crab et al. 2007; Deutsch et al. 2007). Therefore, it is necessary to estimate the nutrient discharge into receiving bodies and determine the real discharge of production units through environmental samplings (Velasco-Amaro 2012).

Hidalgo represents a power in fish farming among the states without coastline across the country and was the second place in aquaculture production in 2017; therefore, updated information on the sector is necessary, including production systems and normativity (SEDAGROH 2017). For these reasons the aim of this chapter is to show a comprehensive overview of aquaculture and its impact from short-term, economic, social, and environmental perspectives.

13.2 Materials and Methods

A search was carried out in various sources, to generate a database with information registered in the Secretary of Agriculture, Livestock and Rural Development, Fisheries and Food (SAGARPA 2018) of the State of Hidalgo; also included data from the Hidalguense Aquaculture Committee of Health A.C. and the State Fishing Sector, recording general production data and compliance with current regulations.

13.3 The Role of Aquaculture Around the World

Although it is a longtime tradition worldwide, fishery as a food production sector has increasingly grown for the past 50 years around the world (FAO 2016) since it provides food rich in proteins at a low cost (CONAPESCA 2018).

During the 29th session of the Committee on World Food Security that took place in Rome on May 2003, the participants discussed “The role of aquaculture in improving food security at community level,” underlining the contribution of aquaculture to food security, poverty alleviation, and improvement of the nutritional state of vulnerable and marginal groups (Magallón-Barajas et al. 2007).

In 2010, FAO conducted a detailed analysis on the world production of fish obtained from aquaculture and fishery. Currently, the annual production of fish for food from aquaculture has grown at an average annual rate of 8.8% and increased three times faster than the world meat production (2.7%) in the same period. The world aquaculture production reached a production peak in 2010 (7.5% higher than in 2009), corresponding to 60 million tons at an estimated value of USD 119 billion. In the same year, Asia contributed to 89% of world production, 62% of which came from China.

FAO (2016) has recently published a detailed analysis on the world fish production from fishery and aquaculture. Here, we describe the most relevant aspects of the reports to provide an overview of the sector and, particularly, aquaculture. The world aquaculture production, including aquatic plants, reached 110.2 million tons, at an estimated first sale value of USD 243.5 billion. The first sale value, recalculated using the latest information available from some of the producer countries, largely exceeds the previous estimations. In general, the data from FAO corresponding to the volume of aquaculture production are more precise and reliable than those related to value (FAO 2016).

The total production included 80 million tons of fish for food (USD 231.6 billion) and 30.1 million tons of aquatic plants (USD 11.7 billion), and 37,900 tons of non-food products (USD 214.6 million). The production of fish farmed for food is included in Table 13.1.

Among the farmed aquatic plants, they were seaweeds and a lower production volume of microalgae. Finally, non-food products included ornamental seashells and pearls (FAO 2018). Asia and South America are the main aquaculture producers around the world. China produces 49,244 tons, amounting to 61% of world production. Table 13.2 shows the most representative countries in aquaculture production per continent: Egypt in Africa, Chile in South America, China in Asia, Norway in Europe, and New Zealand in Oceania (FAO 2018).

Table 13.1 The Production of fish farmed for food

Production	Aquatic animal	Profits in billion
54.1 million tons	Finfish	USD 138.5
17.1 million tons	Mollusks	USD 29.2
7.9 million tons	Crustaceans	USD 57.1
938,500 tons	Turtles, sea cucumbers, sea urchins, frogs, and edible jellyfish	USD 6.8

Source FAO (2016)

Table 13.2 Most important countries in aquaculture production per continent and percentage of world production; data from 2017

Country	Ton (thousands)	Global percentage
Africa		
Egypt	1371	1.7
Nigeria	307	0.4
Sub-Saharan Africa	281	0.4
America		
Chile	1035	1.3
America Latina	1667	2.1
North America	645	0.8
Asia		
China	49,244	61.5
India	5700	7.1
Vietnam	3625	4.5
Indonesia	4950	6.2
Bangladesh	2204	2.8
Europe		
Norway	1326	1.7
UE-28	1292	1.6
Oceania		
New Zealand	210	0.3

*Compiled by the authors from data from the current state of aquaculture and fisheries (FAO 2018)

The report on the current state of fisheries and aquaculture by the FAO determined that nearly 81% (115 million tons) of the world fish production was destined for food and the rest (27 million tons) was not for human consumption. While 40.5% was traded live, fresh, or chilled, 45.9% was chilled, cured, or other for direct human consumption (FAO 2018). Nowadays, over 100 million people depend on the sector to make a living as employees or managers in the production and support areas. These job opportunities have often allowed young people to remain in their communities and have promoted the economic viability of isolated areas, improving the conditions of women living in developing countries where over 80% of the aquaculture takes place. In 2016, 85% of world population employed in the fisheries and aquaculture sectors was located in Asia, followed by Africa (10%) and Latin America and the Caribbean (4%).

More than 19 million people (32% of the people working in the sector) worked in aquaculture, mainly in Asia (96% of the total participation in aquaculture), Latin America and the Caribbean (2% of the total, 3.8 million people), and Africa (1.6% of the total, 3 million people). Europe, North America, and Oceania accounted each for less than 1% of world population working in the sectors (FAO 2018; Lopez-Sanchez et al. 2018).

13.4 Aquaculture Activity in Mexico

Fisheries and aquaculture in Mexico contribute to the domestic distribution with quality, healthy, and affordable seafood from seas, rivers, lagoons, and reservoirs. Together they ensure the production of innocuous and high-quality foods to satisfy the domestic demand and promote a greater offer for the international markets (SIAP-SAGARPA 2017). Mexico is ranked 24 in the worldwide list of countries with aquaculture production (SAGARPA 2018), producing over 16% of the national fishery, 4% more than in 2006 (FAO reports 12%) and is expected to grow by 40% in the next 10–15 years (FAO 2006–2013).

In the period 2013–2016 (Fig. 13.2), the domestic fishery and aquaculture production grew at an average annual rate of 1.6%, reaching historic volumes over 1.7 million tons (SAGARPA 2018; CONAPESCA & SAGARPA 2011).

The aquaculture production in Mexico is divided according to the coastline. The highest percentage is produced in the Pacific (79%), mostly in Sonora, Sinaloa, and Baja California Sur, followed by the Gulf and the Caribbean (18%), including Veracruz, Tamaulipas, and Campeche, and finally the states with inland water (3%), among which are Mexico State, Hidalgo, and Puebla (SAGARPA 2018).

The aquaculture production in Mexico, considering fishery and aquaculture, consists mostly of shrimp, with 109,800 tons. In 2018, SAGARPA operated and managed 29 aquaculture centers in 22 states. They produced 19.5 million freshwater organisms

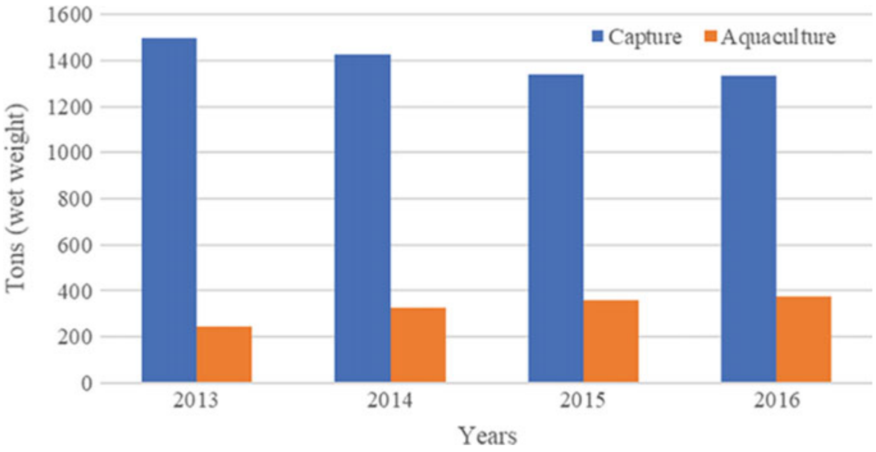


Fig. 13.2 Historical series of domestic fishery and aquaculture production by origin 2013–2016 in thousands of tons (SAGARPA 2018)

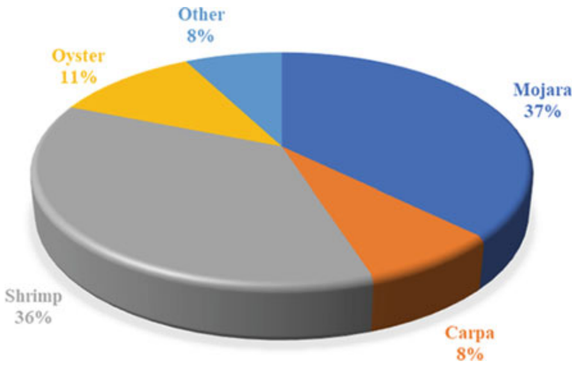


Fig. 13.3 Aquaculture production of the most economically relevant species in Mexico (SAGARPA 2018)

(Fig. 13.3), among which are: bream (37.4%), carp (7.69%), shrimp (36.1%), scallop (11.3%), and others as catfish, trout, bass, and longnose gar (7.6%), considering that shrimp and bream are included in the national production (CONAPESCA 2018).

13.5 Aquaculture Production in Hidalgo

Fishery and aquaculture in Hidalgo contribute consistently to the creation of direct employment and the production of high nutritional quality foods. They provide roots to the population in its place of origin and set the foundation to establish ecotourism projects (INAPESCA 2018). Fish farming in the state started in 1965 with the operation of "fish farming stations," and the first of which was the Fish Farming Center of Tezontepec de Aldama aimed at carp farming. In 1972, the Trust for de Development of Aquatic Wildlife (FIDEFA) boosted the production, trade schemes, and a deeper penetration in the rural areas. Therefore, a higher number of reservoirs were established for fish farming (CAP) than for aquaculture production units (UPAs). Since 1996, the number of UPAs has increased, reaching 544 units according to the fisheries and aquaculture chart of Hidalgo.

By 2016, 610 UPAs had been established and 538 professionals were certified in aquaculture. The most recent information shows that 73 out of the 84 municipalities (87%) carry out aquaculture or fishery activities. Tezontepec is the municipality with the most UPAs (72), followed by Ixmiquilpan (45), and Tecozautla (44). Regionally, aquaculture has been considerably reinforced since the SAGARPA regionalization proposal, which considered rural development districts (DDR). The 2010 Aquaculture chart of the state reported the following number of DDRs per municipality: Huejutla (060), Huichapan (061), Zacultipan (062), Mixquiahuala (063), Pachuca (064), and Tulancingo (065). Mixquiahuala holds the largest aquaculture and fishery infrastructure with 252 UPAs and 97 CAPs (SAGARPA 2018).

The fisheries sector of Hidalgo, through the official report of the aquaculture chart of the state, classifies fish farming in three different production levels: intensive, semi-

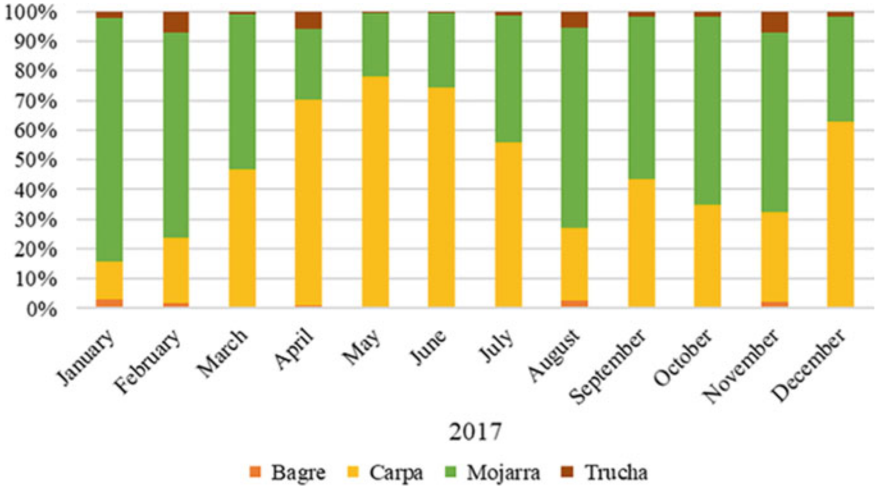


Fig. 13.4 Aquaculture production by species in Hidalgo during 2017 (CONAPESCA 2018)

intensive, and extensive. Intensive production takes place in 57 UPAs, while 519 units carry semi-intensive production, and 34, extensive one. Currently, 28 species are being farmed or managed, including carp (three species and two varieties), tilapia (three species), catfish, trout, bass, silverside, prawn, detritus worm, frog, ornamental fish (12), and white shrimp. They are effectively used because only one species per organism is farmed. Most of the UPAs focuses on polycultures, behind the main species as carp and tilapia (SAGARPA 2018).

Carp is farmed in 310 UPAs, especially in district 063 (Mixquiahuala). The species farmed include *Cyprinus carpio* (common carp, varieties *C. carpio specularis* and *C. carpio rubrofruscus*), *Ctenpharyngodon idellus* (grass carp), *Hypophthalmichthys molitrix* (silver carp), and *Aristichthys nobilis* (bighead carp). Three species (*Oreochromis niloticus*, *O. aureus*, and *O. mossambicus*) and six varieties (cherry snapper, rocky mountain, GIFT, Spring, Red Jumbo, and Sterling) of tilapia are farmed in Hidalgo (Fig. 13.4). Trout farming is mainly focused on *Oncorhynchus mykiss* (rainbow trout) in 95 UPAs, district 065 being the most important producer. Channel catfish (*Ictalurus punctatus*) has been well accepted in Valle de Mezquital and Huasteca Hidalguense. It is currently farmed in 19 UPAs and rural development district 063 is the largest producer (CONAPESCA 2018).

13.6 Environmental Policies and Aquaculture in Mexico

Thanks to works by CONAGUA, INEGI, and INE, experts have identified 1471 basins in the country, categorized in hydrological basins, according to surface water availability. Reports indicate the availability of 731 basins organized in 37 hydrological regions. Since 1997, Mexico has been divided in 13 hydrological-administrative regions (RHA), composed of groups of basins, the basic units of water resources management. Municipalities respect the boundaries of RHAs to promote the collection of socioeconomic information. For more information, see Fig. 13.1 (CONAGUA 2015).

CONAGUA manages 4008 station to measure weather and hydrometric variables. Climatological stations measure temperature, rainfall, evaporation, wind speed and direction. Hydrometric stations measure river flows and extraction by reservoir outlet. Hydroclimatologic stations measure some climatologic and hydrometric parameters (Cotler 2010).

Population growth and concentration in urban areas are a factor to consider regarding water availability. Estimations by the National Population Council (CONAPO) indicate that between 2012 and 2030 the population of the country will increase by 20.4 million. Additionally, by 2030 around 75% of the population will live in urban areas. The increase will lead to a drop in renewable water per capita in the nation (Arnell 2004). Malin Falkenmark coined the terms *hydric stress* and *water shortage* (1986), categories used by hydrologists to talk about the annual renewable freshwater supply in a region. Countries with hydric stress annually supply 1000–1700 m^3 of renewable freshwater per capita. If the supply is lower than 1000 m^3 per inhabitant, then the country suffers water shortage (Pardo et al. 2005).

The General Law of Sustainable Fishery and Aquaculture, published in June 2007, regulates the development of fishery and aquaculture in the state. It contributes to the enhancement of the legal framework of the fisheries and aquaculture sector, providing sustainability to fishery and aquaculture activities, complying with the necessary measures to benefit from aquatic plants and wildlife and ensure they are protected, fostered, and enhanced responsibly, integrally, and sustainably in the long term (CONAGUA 2016).

The sector is under the federal regulations in the General Law of Ecological Balance and Environment Protection, the Federal Law of National Waters, and the Federal Rights Law. Together, they determine the existence of mandatory documentation proving a favorable environmental impact, national fisheries and aquaculture registry, (aquaculture) water concession, water meter, and wastewater discharge concession (DOF 1994).

Article 223 of the Federal Rights Law establishes that water rights are to be paid for exploitation, use, or operation of national waters, according to the water availability area in which extraction occurs and the fees in the specific chart. Hidalgo has three availability areas (3, 4, 5, 6, 7, 8, and 9) in the XIII administrative hydrological region (Valley of Mexico) and availability areas 7, 8, and 9 in the IX administrative hydrological region (North Gulf).

Aquaculture pays the lowest water right fees per m^3. Fees are applied to water consumption when the daily volume used is lower or equal to 300 L per inhabitant, according to the population indicated in the previous year. This only refers to the population registered in the General Population and Housing Census published by the National Institute of Statistics and Geography (Table 13.3).

Table 13.3 Extraction fees for different uses according to the availability area for XIII hydrological-administrative area

Availability area	Surface water	Groundwater
1	$437.15	$456.33
2	$209.66	$210.41
3	$104.70	$118.62
4	$52.13	$55.30

Source Article 223-B of the Federal Law of Applicable Provisions Concerning National Waters 2016 (DOF 1992; DOF 2007; DOF 2010)

Table 13.4 Maximum allowable limits of pollutants established in the applicable provisions concerning national waters in the 2016 Federal Rights Law

	Receiving body type		
Parameters (mg/L)	Rivers, coastal waters, and soil	Rivers, reservoirs, coastal waters, estuaries, and natural wetlands	Rivers and reservoirs
	Monthly average		
DBO	0.00186	0.00275	0.00412
SST	0.00082	0.00121	0.00181

Source Article 278-B, section III, applicable provisions concerning national waters, Federal Rights Law, 2016 (DOF 1992; DOF 2007; DOF 2010)

Table 13.5 Fees to be paid when the maximum allowable limits of pollutants are exceeded, according to the applicable provisions concerning national waters in the 2016 Federal Rights Law

	Receiving body type		
Parameters (mg/L)	Rivers, coastal waters, and soil	Rivers, reservoirs, coastal waters, estuaries, and natural wetlands	Rivers and reservoirs
	Weights per kg of contaminants per quarter		
DBO	0.3137	0.3508	0.3691
SST	0.5388	0.6022	0.634

Source Article 278-C, applicable provisions concerning national waters, 2016 (DOF 1992; DOF 2007; DOF 2010)

The use or exploitation of public assets of the nation as receiving bodies of wastewater discharges creates the right with respect to the type of receiving body where the discharge takes place, according to the volume of water and pollutant discharged and when the maximum allowable limits determined by the Mexican Official Standards are exceeded (Table 13.4).

The volume of wastewater and the concentration of pollutants discharged in the receiving body are calculated quarterly. The fees charged for exceeding the allowable limits are in Table 13.5.

The Mexican Official Standard NOM-001-SEMARNAT-1996 establishes the maximum allowable limits of pollutants in wastewater discharges in national waters and assets, considering the type of receiving body as stated in the Federal Rights Law (Table 13.3). In 1994, a project for a new standard (NOM-089-ECOL-1994) to establish the maximum allowable limits of pollutants in wastewater discharges made into receiving bodies as a result of aquaculture, considering the categories of freshwater and sea brackish water. The limits established for basic pollutants are shown in Table 13.6.

13.7 Sustainability of Aquaculture

Worldwide aquaculture faces several challenges: supplying the market, providing alternatives to face hunger around the world, and meets the food demand generated by the growth of the world population (Magallón-Barajas et al. 2007). Production is sustainable and friendly with the environment, yielding highly nutritional products that are functional, healthy, innocuous, and biosecure (Magallón-Barajas et al. 2007; FAO 2017; FCEA 2015).

Although several factors are involved in a sustainable production, there are three essential aspects to consider: economic impact of the production, effect that industrial development has on the environment, and the ability to integrate different sectors of the society to the production (Avilés-Quevedo and Vázquez-Hurtado 2006; Magallón-Barajas et al. 2007).

13.7.1 Economic Approach to Aquaculture

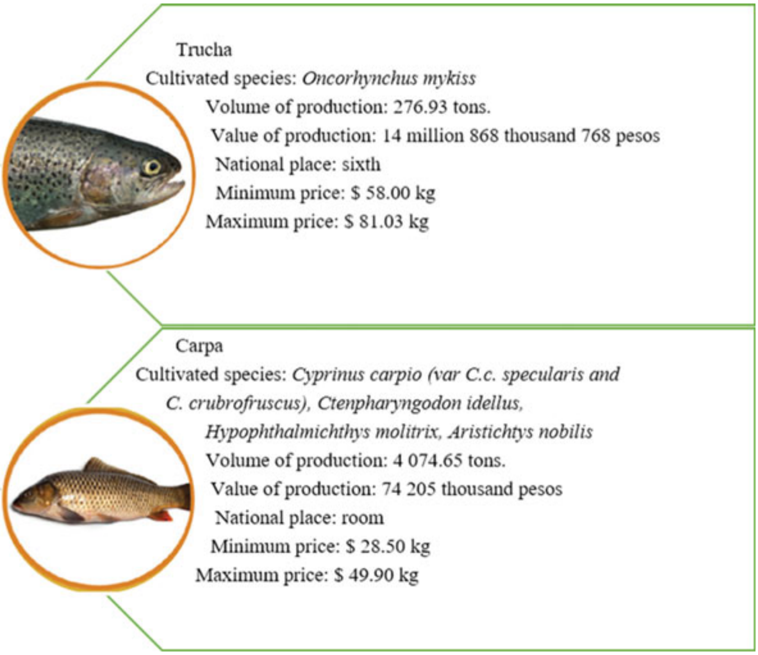
SIAP reported that, in 2018, Hidalgo produced 6418 tons of aquaculture products valued in MXP 69 million. The value of fisheries constituted 0.6% or the rural economy of the state. The four most important types of fish were bream, carp, trout, and catfish, which accounted for 98.9% of the total volume of fishery.

The farming and fishing of tilapia in Hidalgo during 2017 yielded a total MXP 32.5 million, equivalent to 47.1% of the fisheries value, at an average grow rate of 9.5% annually. The production of carp accounted for 28.3% of the fisheries value of the state: MXP 19.5 million, which represented 3757 tons obtained (Fig. 13.5). SAGARPA (2018) has stated that Hidalgo is the sixth producer of trout, the fourth of carp, the tenth of bream, and the 15th of catfish. The production levels in tons of live weight were: 276.93 tons of trout, 4074.65 tons of carp, 4580.57 tons of bream, and 91.98 tons of catfish. Indeed, the production of trout constitutes a greater income despite being one of the lowest productions in the state. This is because its value is five times that of other farmed fish. While trout is valued in MXP 61,260.60 per ton, bream reaches only MXP 13,303.04, carp MXP 889.09, and catfish MXP 3071.54 (Fig. 13.6).

Table 13.6 Maximum allowable limits in the current standard in Mexico

Parameter	NOM-001-SEMARNAT-1996					Federal Law on National Water Rights 2016			
	Rivers			Natural and artificial reservoirs		Use			
	A	B	C	B	C	1	2	3	4
Temperature (°C)	40	40	40	40	40				
pH						6–9	6–9	6–9	6–9
Dissolved oxygen (mg/L)						4		4	5
Settling solids (mg/L)	1	1	1	1	1				
SST (mg/L)	150	75	40	75	40	50	50	30	30
BOD (mg/L)	150	75	30	75	30				
Total nitrogen (mg/L)	40	40	15	40	15				
Total phosphorus (mg/L)	20	20	5	20	5	0.1		0.05	0.01
Fecal coliforms (NMP/100 ml)	1000	1000	1000	1000	1000	1000	1000	1000	240

Source NOM-001-SEMARNAT-1996



Trucha
Cultivated species: *Oncorhynchus mykiss*
Volume of production: 276.93 tons.
Value of production: 14 million 868 thousand 768 pesos
National place: sixth
Minimum price: $ 58.00 kg
Maximum price: $ 81.03 kg

Carpa
Cultivated species: *Cyprinus carpio (var C.c. specularis and C. crubrofruscus), Ctenpharyngodon idellus, Hypophthalmichthys molitrix, Aristichtys nobilis*
Volume of production: 4 074.65 tons.
Value of production: 74 205 thousand pesos
National place: room
Minimum price: $ 28.50 kg
Maximum price: $ 49.90 kg

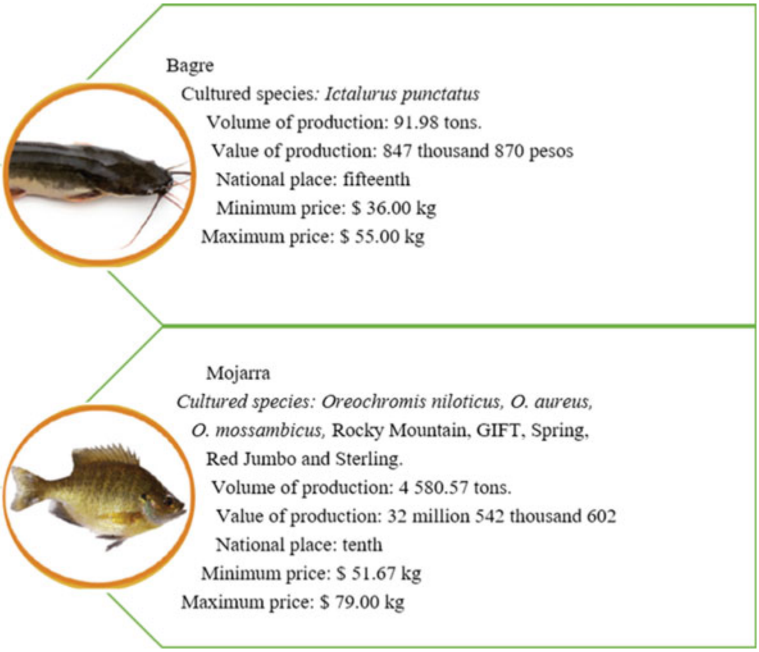
Fig. 13.5 Production data sheet of trout and carp farmed in Hidalgo. *Price in MXP (PROFECO 2018; SAGARPA 2018; SIAP 2018)

From the total 610 UPAs registered, 127 (21%) are not in operation for a number of causes; for example (a) infrastructure in bad state preventing water retention, (b) additional work needed, (c) lack of organization, and (e) discouragement because of the high fines established by the National Water Commission (CONAGUA 2016).

13.7.2 Impact of Aquaculture in Social Development

Aquaculture has a great development opportunity and provides jobs to millions of people worldwide. This activity is the source of income and means of living for many working class people. Recent estimations reveal that 56.6 million people worked in capture fisheries and aquaculture in 2014. From this number, 36% worked fulltime, 23% part time, and the rest only worked occasionally or in unspecified situations (FAO 2016; Gonzaga Añazco et al. 2017).

Aquaculture has effectively penetrated the rural environment: from the 610 UPAs registered in the aquaculture chart, 331 (54.3%) are in greatly marginalized areas, 147 (24.1%) in mildly marginalized communities, and 132 (21.7%) in areas of low marginalization. Fisheries and aquaculture have contributed to employment generation and high-quality foods. Furthermore, these activities directly benefit 39,828



Bagre
Cultured species: *Ictalurus punctatus*
Volume of production: 91.98 tons.
Value of production: 847 thousand 870 pesos
National place: fifteenth
Minimum price: $ 36.00 kg
Maximum price: $ 55.00 kg

Mojarra
Cultured species: Oreochromis niloticus, O. aureus,
O. mossambicus, Rocky Mountain, GIFT, Spring,
Red Jumbo and Sterling.
Volume of production: 4 580.57 tons.
Value of production: 32 million 542 thousand 602
National place: tenth
Minimum price: $ 51.67 kg
Maximum price: $ 79.00 kg

Fig. 13.6 Production data sheet of bream and catfish farmed in Hidalgo. *Price in MXP (PROFECO 2018; SAGARPA 2018; SIAP-SAGARPA 2017)

citizens in Hidalgo; for instance, UPAs benefit 7476 citizens (SAGARPA 2018). By 2010, these two activities were developed across 12,170 ha: 50 correspond to production surface of water mirror that 610 UPAs use; the rest correspond to the surface used by CAPs in the state where fishery activities take place (CONAPESCA 2018).

Most of the male workers in the sector are found in shrimp fishery (96.8%) while the minority is employed in animal aquaculture, which employs 77% of them. Fish farming and other aquaculture employ most of the female workers, with the exception of shrimp farming (22.9%). In contrast, shrimp fisheries provided jobs for 3.2% women. Female participation in fisheries activities is focused on developing fishing activities and farming in aquaculture farms; they also take part in administrative tasks (INEGI 2009). According to government information, 236 infrastructure works were announced between 2013 and 2017; over a billion pesos were invested in construction and infrastructure studies and around 169,000 people were benefited (CONAPESCA 2018).

13.7.3 Environmental Sustainability in Aquaculture

Aquaculture is socioeconomically relevant; therefore, it must achieve sustainability. To do so, FAO (2017) suggests (i) to adopt an ecosystemic aquaculture approach with fair and responsible tenure systems so that users of resources can manage them; (ii) to include aquaculture in management of basins and coastal areas; (iii) support development and investment in eco-friendly technology (for instance, fishery methods that have low impact due to low fuel consumption, innovative aquaculture production systems, and adequate waste management); and (iv) to create consumer and sector awareness concerning the importance of choosing sustainable fishery and aquaculture products (Ponce-Palafox et al. 2006).

The development of aquaculture in Hidalgo is considered in vertical 2 of the actions included in the 2016–2022 state development plan. The aim is to strengthen the aquaculture sector through programs and processes that increase financing and productive diversification, open new markets, bring technological innovation, and increase productive capacity and professionalization (state development plan of Hidalgo 2016; PED 2018). The lines of action include:

- Creating a state development program for aquaculture, based on a long-term approach, including the strengthening of the legal and institutional framework of aquaculture policies and harmonization of laws and regulations.
- Promoting financing schemes specific to productive diversification in aquaculture farms.
- Promoting the association of production units that allow for access to financing, consulting, and accompaniment.
- Enhancing commercialization and marketing strategies.
- Creating the necessary mechanisms for producers to access systematic consulting and accompaniment and obtain product certification.
- Promoting processes to enhance commercialization and growth in transformation and industrialization links.
- Promoting the creation of training schemes to professionalize the sector.

The plan also states that fisheries in the state has no official registry since most of the production is for self-consumption and only a few groups are organized; then, there is no National Fisheries Registry. In addition, inadequate trade channels, intermediaries, and the fact that producers face uncertainty to preserve their products limit the development of regional markets (Gonzaga Añazco et al. 2017).

13.7.4 Fish Innocuity

The development of healthy aquaculture demands adequate conditions of water recirculation, temperature, and oxygen as well as food that meet nutritional requirements of organisms in terms of quality and quantity, density adequate for the farmed species, and prophylactic measures at the end of each breeding cycle. Fish health is in charge of infectious diseases as those caused by parasites (Arispe and Tapia 2007).

We must stress the guidelines for the fish activity in Mexico, which consider the importance of having sustainable fishery. The guidelines are:

(a) High-quality and innocuous foods.
(b) Promotion of water management and recycling.
(c) National Biosecurity Program for continuous sanitary certification of breeding lines, eggs, and juveniles.
(d) Higher product quality standards to penetrate highly competitive foreign markets.
(e) Design of better culture systems that allow for lower operation costs.
(f) Improvement of production efficiency to offer products at competitive prices.
(g) Stimulation of trade to increase domestic and international consumption.
(h) Promotion of aquaculture management units (AMCs) and operation plans to achieve an orderly and sustainable aquaculture development.

13.8 Conclusion

Aquaculture in Hidalgo is developed in high and marginalized areas, becoming a food source for rural population (self-consumption aquaculture). Tilapia (*Oreochromiss* sp.) is the most commonly farmed fish because of the low farming requirements.

The study conducted allows us to conclude there is an unsatisfactory environmental performance given the UPAs' non-compliance with setup and operation requirements. This breach is a consequence of marginalization: 50% of the municipalities developing aquaculture are highly/very highly marginalized and governance does not address this sector of the population.

The foundation to create an effective regulation must consider the social factor as a line of action to achieve the environmental regulation objectives. The problems surrounding fisheries are the result of political, social, and environmental factors since most of the activity takes place in rural areas. Then, there is a lack of information flow toward the production sector as well as a disarticulation of the sectors involved.

The monitoring of effluents shows that the content of suspended solids is out of the limits allowed by the Mexican Standard, unlike the concentration of phosphorus and nitrogen. However, there is a potential impact of the activity by phosphorus and nitrogen discharges into receiving bodies because an increase in 1 mg phosphorus triggers the eutrophication process. Based on the bibliographical reviews, the current Mexican Standards is excessively permissive regarding discharges.

Self-consumption and rural aquaculture regularly lead to direct discharges of effluents into receiving bodies, creating nutritional contribution and eutrophication issues. We must consider that water bodies in many areas supply nearby communities with fresh water.

Aquaponics is a good alternative to prevent pollution in rural areas when integrated to pass systems. Aquaponics systems have been reported to be efficient and improve effluent quality by removing up to 90% of total solids in suspension, nitrogen and phosphorus varieties. The improvement of water quality by aquaponic systems is a consequence of the biofilm created in the support medium and roots, which create a mat when properly developed, and the increase in nutrient absorption efficiency in mature crops. However, this depends on the plant, support, and hydraulic residence times used. Most of the studies report varieties of lettuce, vegetables, and herbs are used. Nutritional requirements and nutrient absorption are characteristics to be considered. The needs depending on the area where she systems are located must also be considered to yield products locally demanded, whether they are vegetables, forage, or cut flowers. Conventional treatments of effluents in aquaculture come at an additional cost; therefore, aquaponics is an affordable and profitable alternative of treatment. Nevertheless, further research in this area is still needed to establish processes more accessible to small aquaculture producers.

13.9 Perspectives

As we have already seen in this chapter, aquaculture is a relevant activity worldwide, both economically and socially, and a source of food and employment for poor people. However, it must take good care of the environment to be considered as a sustainable activity. In the past, projects aiming for this objective were implemented; among them were good practices and environmental impact studies. The number of UPA producers interested in reducing water pollution is increasing. Primary treatments (filters and sedimentation tanks) are being replaced by compound treatments (oxidation ponds, biofilters, and artificial wetlands). Applying biotechnological treatments is a more effective alternative to remove pollutants without affecting the environment.

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Chapter 14
Water Resources Allocation with Uncertainties in Supply and Demand

Mo Li and Vijay P. Singh

Abstract Water shortage, exacerbated by increasing population and rapid economic development, causes conflicts when allocating water for exploration of natural resources, socioeconomic progress, and ecological environment, which reinforces the need for optimal water resources allocation in an efficient manner. However, owing to both natural variations and human activities, decision-makers find it challenging to cope with the complexity of fluctuating water supply and demand that are critical for water resources allocation. It consequently affects the variations of tradeoffs between conflicting economic benefits, associated penalties due to infeasibility, and constraint-violation risks. In response to these issues, this chapter discusses an optimization modeling approach for agricultural water allocation at a regional scale, considering the uncertainties of water supply and demand. The dual uncertainty of water supply and demand is quantified based on the concept of random boundary intervals (RBIs). The RBIs are incorporated into an inexact two-stage stochastic programming framework to allocate limited water resources to different crops in different time periods. The approach is applicable to most regions with limited water supplies to determine water strategies under changing the environment.

Keywords Water resources allocation · Supply and demand · Uncertainty · Irrigation district · Random boundary intervals · Inexact two-stage stochastic programming

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14.1 Introduction

Water scarcity is becoming a global-scale issue by shrinking water supplies, increasing climatic vagaries, and expansion of water demands. Climate change and complex topography have made uneven distribution of water resources in many countries (Wang et al. 2017). Therefore, water resources allocation is considered as the primary challenge to utilize water resources for satisfying multiple targets effectively. The growing population shifts cause a quick development in agricultural systems and thus cause continuous rise in food demand. The FAO analysis of 93 developing countries shows that most of the increase in agricultural production is in agricultural irrigation systems (Bruinsma 2003). As the largest water user, water resources initially used for agricultural irrigation are now being diverted to non-agricultural sectors (e.g., municipal, industrial, recreational, ecological and environmental activities) for increasing outputs, guaranteeing living quality, and promoting environmental protection (Jiang et al. 2016; Li et al. 2016a). It augurs for the requirement of an efficient method for water resources allocation, especially in agricultural irrigation systems.

Optimization is a necessary tool in water resources allocation and numerous mathematical optimization techniques have been developed, such as linear, nonlinear and dynamic programming; artificial intelligence search methods; and simulated annealing (Singh 2012; Davijani et al. 2016). In water resources allocation, decision-makers increasingly face challenges of uncertain conditions as, for example, fluctuating hydro-meteorological elements, varying socioeconomic policies, and errors in estimating modeling parameters. Hence, using inexact optimization methodologies for water resources allocation is necessary. Inexact two-stage stochastic programming (ITSP) is an effective approach for the analysis of problems which desires an examination of policy scenarios deal with uncertainties in the form of both interval numbers and distribution functions (Maqsood et al. 2005; Nematian 2016). However, this method has a limitation in handling complex uncertainties existing in water resources allocation.

In water resources allocation, water supply and water demand are two all-important components that would intensely dominate water allocation strategies. A high degree of uncertainty may exist in water supply and water demand. Water supply is sensitive to climate, technology selection, water utilization efficiency, and water-saving consciousness (Dong et al. 2014), while water demand significantly varies with meteorological conditions and land surface conditions and economic, social, and technical conditions (Guieysse et al. 2013). These cause high uncertainties in water supply and demand. They can rarely be simplified as crisp numbers, and even intervals or random variables can hardly tackle such complex uncertainties (Lu et al. 2015). The integration of random boundary intervals (RBIs) with ITSP is a potential way to address the complex uncertainties of both water supply and water demand in water resources allocation, which has been reported in limited cases.

This chapter, therefore, presents an optimization modeling approach for agricultural water allocation at a regional scale, considering the high uncertainties of water supply and water demand. We use RBIs to express water supply and water demand

and incorporate them into the ITSP framework. Thus, an RBIs-ITSP model is formulated to allocate limited water resources to different crops in different time periods. The advantage of the approach is that it can tackle the high degree of uncertainty of water supply and demand with the aim to obtain more accurate decision-making schemes under various flow levels considering the tradeoff between system economic benefits and penalties. Specifically, the randomness of the lower and upper bounds of water supply and demand is reflected, and the correlation existing between the lower and upper bounds is handled. We apply the developed approach to a real-world case study to demonstrate its feasibility and practicability.

14.2 Methodology

14.2.1 Random Boundary Intervals

In practical issues, the upper and lower bounds of the right-hand side of constraints can rarely be acquired as deterministic values. Instead, a data can be presented as a random boundary interval (RBI), and an RBI parameter can be expressed as $\left[\tilde{x}^-, \tilde{x}^+\right]$. In order to obtain $\left[\tilde{x}^-, \tilde{x}^+\right]$, samples of the possible values are collected in an interval form (r_1, s_1), (r_2, s_2), …, (r_n, s_n), with (r_i, s_i) representing the value of the ith sample. Based on the samples, the mean vector and covariance matrix can be calculated as (Cao et al. 2010):

$$\mu = \left(\frac{1}{n}\sum_{i=1}^{n} r_i, \frac{1}{n}\sum_{i=1}^{n} s_i\right) \tag{14.1a}$$

$$D = \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix} \tag{14.1b}$$

where $\sigma_1^2 = \frac{1}{n}\sum_{t=1}^{n}(r_t - \mu_1)^2$, $\sigma_2^2 = \frac{1}{n}\sum_{t=1}^{n}(s_t - \mu_2)^2$, and $\rho = \frac{\sum_t^n (r_t-\mu_1)(s_t-\mu_2)}{n\sigma_1\sigma_2}$.

Suppose that the inputs (e.g., water supply or water demand) follow a distribution based on the mean vector and covariance matrix through hypothesis-testing, a joint distribution function [i.e., $f(v, w)$] can be identified for $\left[\tilde{x}^-, \tilde{x}^+\right]$. Then, the probability distribution function (PDF) and cumulative distribution function (CDF) of the $\tilde{x}^-$ and $\tilde{x}^+$ can be obtained by calculating the marginal distributions of the joint distribution function $f(v, w)$. It will be of service to the solution of the RBIs-ITSP model.

Suppose $[a, b]$ is the range of $\tilde{x}^-$ and $[c, d]$ is the range of $\tilde{x}^+$. Then, we have:

$$\text{PDF of } \tilde{x}^- \qquad f_v(v) = \int_c^d f(v, w)\mathrm{d}w \tag{14.2a}$$

$$\text{CDF of } \tilde{x}^- \qquad F_v(v) = \int f_v(v)\mathrm{d}v \tag{14.2b}$$

$$\text{PDF of } \tilde{x}^{+} \qquad f_w(w) = \int_a^b f(v, w)\mathrm{d}v \tag{14.2c}$$

$$\text{CDF of } \tilde{x}^{+} \qquad F_w(w) = \int f_w(w)\mathrm{d}w \tag{14.2d}$$

14.2.2 *Inexact Two-Stage Stochastic Programming*

A general ITSP model with the maximum objective function value can be formulated as follows (Li et al. 2010):

$$\max f^{\pm} = \max\left\{c^{\pm}x^{\pm} - \sum_{h=1}^{H} p_h q\left(y_h^{\pm}, \xi_h^{\pm}\right)\right\} \tag{14.3a}$$

subject to

$$\alpha^{\pm}x^{\pm} \le \beta^{\pm} \tag{14.3b}$$

$$\chi^{\pm}x^{\pm} \ge \delta^{\pm} \tag{14.3c}$$

$$T\left(\xi_h^{\pm}\right)x^{\pm} + W\left(\xi_h^{\pm}\right)y_h^{\pm} = h\left(\xi_h^{\pm}\right) \quad \forall h = 1, 2, \ldots, H \tag{14.3d}$$

$$x^{\pm} \ge 0, y_h^{\pm} \ge 0 \tag{14.3e}$$

where $f^{\pm}$ is the objective function; $c^{\pm}$ is the vector of coefficients in the objective function; $\alpha^{\pm}$, $\beta^{\pm}$, $\chi^{\pm}$ and $\delta^{\pm}$ are the vectors of coefficients in the constraints; $x^{\pm}$ is the first-stage decision made before the random variable is observed; $q\left(y_h^{\pm}, \xi_h^{\pm}\right)$ is the second-stage cost function; $y_h^{\pm}$ is the second-stage adaptive decision that depends on the realization of the random variable; $\xi_h^{\pm}$ denotes the random variable (discrete value) with an occurrence probability level p_h ($\sum_{h=1}^{n} p_h = 1, p_h > 0$); and $T\left(\xi_h^{\pm}\right)$, $W\left(\xi_h^{\pm}\right)$ and $h\left(\xi_h^{\pm}\right)$ are random parameters with reasonable dimensions, and they are functions of $\xi_h^{\pm}$.

14.2.3 *RBIs-ITSP Model*

If the right-hand parameters in the constraints of the model (14.3a) are expressed as RBIs, model (14.3a) will become an RBIs-ITSP model. We formulate the RBIs-ITSP model as:

$$\max f^{\pm} = \max\left\{c^{\pm}x^{\pm} - \sum_{h=1}^{H} p_h q\left(y_h^{\pm}, \xi_h^{\pm}\right)\right\} \tag{14.4a}$$

$$\alpha^{\pm}x^{\pm} \leq \left[\tilde{\beta}^{-}, \tilde{\beta}^{+}\right] \tag{14.4b}$$

$$\chi^{\pm}x^{\pm} \geq \left[\tilde{\delta}^{-}, \tilde{\delta}^{+}\right] \tag{14.4c}$$

$$T\left(\xi_h^{\pm}\right)x^{\pm} + W\left(\xi_h^{\pm}\right)y_h^{\pm} = h\left(\xi_h^{\pm}\right) \quad \forall h = 1, 2, \ldots, H \tag{14.4d}$$

$$x^{\pm} \geq 0, y_h^{\pm} \geq 0 \tag{14.4e}$$

14.2.4 Solution Method for the RBIs-ITSP Model

The key to solving the RBIs-ITSP model is to transform the uncertain model into the deterministic model. Three steps should be undertaken: (1) Transform the RBIs with dual uncertainty into ordinary interval numbers using a chance-constrained programming (CCP) technique and two-boundary approach; (2) transform the ITSP model into two deterministic sub-models using an interactive algorithm; and (3) do coding and running the program of each transformed sub-model in an optimization software. The transformed sub-models are listed in Appendix. Detailed derivation procedure for step 1 is reported in relevant references (Huang and Loucks 2000; Cao et al. 2010).

14.3 Case Study

14.3.1 Study Area

Yingke irrigation district (YID) which is located in the middle oasis of Heihe River basin, northeast China, was chosen as the study area to test the RBIs-ITSP model. The latitude of YID is from 38° 50′ to 38° 58′ N, and the longitude is from 100° 17′ to 100° 34′ E, covering an area of 19,200 ha. The climate of YID is typically a cold, arid continental climate. YID is a semi-arid area with serious water scarcity problems. The annual average reference evapotranspiration (around 1200 mm) is nearly ten times the annual average precipitation (120 mm). More than 90% water supply for YID is used for agricultural irrigation. The other water is used for ecological irrigation and drinking. In order to ensure the ecological health in the lower reaches of Hiehe River basin, the surface water supply for YID is decreasing gradually. Hence, groundwater is also exploited as a supplemental water supply source. Affected by natural elements and human activities, water supply and water demand of YID fluctuate continuously. Further, the conventional water resources management method has led to unbalanced water distribution for various crops in different time periods, and thus causes the weak capacities to cope with risks attributed to no consideration of the effects of fluctuation of water supply-demand on water resources allocations. Therefore, it is necessary to apply the developed RBIs-ITSP model to YID.

14.3.2 Model Formulation

Considering the dual uncertainties of surface water supply and water demand, we formulated the RBIs-ITSP model for agricultural water allocation in YID. The aim of the model is to allocate limited surface water and groundwater supplies to four types of crops (grain crop, forage corn, spring wheat, and vegetables, accounting for more than 95% area of the total planting area) in each month during the whole crop growth period (from April to September) under three flow levels (high, middle, and low flow levels), in order to maximize system economic benefits.

Objective function

$$\max f^{\pm} = \max\left\{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\mathrm{MP}_i^{\pm}\cdot\mathrm{WP}_i^{\pm}\cdot\mathrm{WT}_{ijt}^{\pm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\sum_{h=1}^{H}p_h\cdot\mathrm{PC}_{it}^{\pm}\cdot\mathrm{WS}_{ijth}^{\pm}\right\} \tag{14.5a}$$

where $\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\mathrm{MP}_i^{\pm}\cdot\mathrm{WP}_i^{\pm}\cdot\mathrm{WT}_{ijt}^{\pm}$ represents the total benefit of the promised water resources (the first stage) and $\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\sum_{h=1}^{H}p_h\cdot\mathrm{PC}_{it}^{\pm}\cdot\mathrm{WS}_{ijth}^{\pm}$ represents the loss of the shortage of water resources (the second stage).

Subject to

(1) Surface water supply constraint. The surface water allocation in each time period under each flow level should not be larger than surface water supply for agricultural irrigation (equal to the total surface water supply minus ecological water use). As surface water supply is taken from Heihe River with high randomness, the value of surface water supply was, therefore, expressed as an RBI.

$$\sum_{i=1}^{I}\frac{\left(\mathrm{WT}_{ijt}^{\pm}-\mathrm{WS}_{ijth}^{\pm}\right)}{\delta^{\mathrm{sur}}} \le \left[\left(\tilde{Q}^{\mathrm{sur}}\right)_{th}^{-},\left(\tilde{Q}^{\mathrm{sur}}\right)_{th}^{+}\right]-\mathrm{EWU}\quad s=1,\forall t,h \tag{14.5b}$$

(2) Groundwater supply constraint. Similar to surface water supply constraint, the groundwater allocation for all crops in each time period should not be larger than groundwater supply.

$$\sum_{i=1}^{I} \frac{\left(\mathrm{WT}_{ijt}^{\pm} - \mathrm{WS}_{ijth}^{\pm}\right)}{\delta^{\mathrm{gro}}} \leq Q_{th}^{\mathrm{gro}} - \mathrm{DWU} \quad s = 2, \forall t, h \tag{14.5c}$$

(3) Water demand constraint. The water allocation amount for each crop in each time period should be larger than the minimum water demand to ensure crop growth. As water demand has a close relationship with meteorological factors with a high degree of uncertainty, water demand was expressed as an RBI.

$$\sum_{j=1}^{J}\left(\mathrm{WT}_{ijt}^{\pm} - \mathrm{WS}_{ijth}^{\pm}\right) \geq \mathrm{IA}_i \cdot \left[\tilde{D}_{it}^{-}, \tilde{D}_{it}^{+}\right] \quad \forall i, t, h \tag{14.5d}$$

(4) Maximum water allocation constraint. Water allocation, including both surface water and groundwater, to each crop under each flow level should not be larger than the maximum irrigation amount during the whole crop growth period in order to avoid water waste.

$$\sum_{j=1}^{J\sum}\sum_{t=1}^{T}\left(\mathrm{WT}_{ijt}^{\pm} - \mathrm{WS}_{ijth}^{\pm}\right) \leq \mathrm{IW}_i^{max} \tag{14.5e}$$

(5) Food security constraint. The production of grain crops should be guaranteed to ensure people's primary needs.

$$\sum_{j=1}^{J}\sum_{t=1}^{T}\mathrm{WP}_i \cdot \left(\mathrm{WT}_{ijt}^{\pm} - \mathrm{WS}_{ijth}^{\pm}\right) \leq \mathrm{PO} \cdot \mathrm{FD}_i \quad \forall i, h \tag{14.5f}$$

(6) Water allocation constraint. Water shortage amount should not be larger than the water target. In other words, water allocation amount to each crop with each water source in each time period under each flow level should be non-negative. This constraint can be expressed as follows:

$$\mathrm{WT}_{ijt}^{\pm} - \mathrm{WS}_{ijth}^{\pm} \geq 0 \quad \forall i, j, t, h \tag{14.5g}$$

(7) Non-negative constraint. The decision variables (water shortage) of the model should be non-negative.

$$\mathrm{WS}_{ijth}^{\pm} \geq 0 \quad \forall i, j, t, h \tag{14.5h}$$

Generally, $x^{\pm} = \left[x^{-}, x^{+}\right]$ is an interval number with known lower and upper bounds but unknown distribution and $\left[\tilde{x}^{-}, \tilde{x}^{+}\right]$ denotes an RBI number. The meanings of the symbols for the model are listed below. $f^{\pm}$ is the objective function (RMB, Chinese currency unit). i is the crop type, and I is the total number of crops ($I = 4$), with $i = 1$ means grain corn, $i = 2$ means forage corn, $i = 3$ means spring wheat and $i = 4$ means vegetables; j is the water source and J is the total number of water sources ($J = 2$), where $j = 1$ means surface water source and $j = 2$ means groundwater source; t is time period, and T is the total number of time period ($T = 6$), with $t = 1$, $t = 2$, $t = 3$, $t = 4$, $t = 5$ and $t = 6$ corresponding to April, May, June, July, August, and September, respectively; h is the flow level and H is the total number of flow levels, with $h = 1$, $h = 2$ and $h = 3$ denoting high, middle and low flow levels, respectively. $\mathrm{MP}_i^{\pm}$ is the market price per unit weight for crop i (RMB/kg); $\mathrm{WP}_i^{\pm}$ is the yield per unit water amount for crop i (kg/m^3); $\mathrm{WT}_{ijt}^{\pm}$ is the water target for crop i with water source j in time period t, being the first-stage decision variable; p_h is the occurrence probability of flow level h; $\mathrm{PC}_{it}^{\pm}$ (penalty coefficient) is the reduction of benefit per unit area for crop i in time period t if the water target is not achieved due to the shortage of water resources (RMB/m^3); $\mathrm{WS}_{ijth}^{\pm}$ is the water shortage when the water target is not met for crop i with water source j in time period t under flow level h, being the second-stage decision variable after the random variables are known; δ^{sur} is the water use efficiency factor of surface water; $\left[\left(\tilde{Q}^{\mathrm{sur}}\right)_{th}^{-}, \left(\tilde{Q}^{\mathrm{sur}}\right)_{th}^{+}\right]$ (expressed as an RBI) is the surface water supply amount in time period t under flow level h (m^3); EWU is the ecological water use amount (m^3); δ^{gro} is the water use efficiency factor of groundwater; Q_{th}^{gro} is the groundwater supply amount in time period t under flow level h (m^3); DWU is the domestic water use amount, including water for human and livestock drinking (m^3); $IW_i^{\max}$ is the maximum irrigation water amount for crop i (m^3); PO is the population of the whole irrigation district; and FD_i is the food demand for crop i (kg/capita).

14.3.3 Data Collection

The main parameters for the RBIs-ITSP model contain water supply, water demand, water target, and socioeconomic parameters, such as crop market price, penalty coefficient, irrigation area, maximum irrigation amount, and water use efficiency. Among them, water supply and water demand are two critical parameters with high randomness, and they were expressed as RBIs.

The surface water source of YID is from Heihe River. Hence, we used the runoff of Heihe River at Yingluoxia hydrographic station to generate the RBIs to express its high degree of uncertainty. Then, we obtained the surface water supply of YID, based on a diversion proportionality coefficient (8.7%). Based on the measured data of runoff volume from Heihe River for 70 years, we obtained the lower and the upper bounds of runoff at Yingluoxia hydrographic station, considering measurement and statistical errors. Based on these samples, we calculated the mean vector and covariance matrix. Assume the distribution of runoff follow approximately the normal distribution based on χ^2 hypothesis testing at 0.1 significance level (Li et al. 2016a). Therefore, we used two-dimension normal distribution to express the joint distribution of the lower and upper bounds of runoff volume. Based on the joint distribution, we obtained the marginal distribution of both lower and upper bounds of runoff volume. Then, we calculated the conditional distribution under different probabilities. In this study, we took a probability of 10% as an example to test the method. The specific process for obtaining the RBIs forms of surface water supply can be referred to the Appendix. The variations of interval values of runoff volume of Heihe River at Yingluoxia hydrographic station is depicted in Fig. 14.1. Then, we obtained the surface water supply. Monthly values were obtained based on the water use proportionality coefficient, and they were 0.05, 0.09, 0.16, 0.27, 0.25 and 0.18 for April, May, June, July, August, and September, respectively. The groundwater supply was taken as the average value from the local report (2010–2016). The groundwater supplies for April, May, June, July, August, and September are 961, 1001, 1031, 1049, 1005, and 949 × 10^4 m^3, respectively. The surface water supplies are listed in Table 14.1.

Water demand for each crop in each time period was derived from crop evapotranspiration, which was estimated by multiplying crop coefficient (K_c) with reference evapotranspiration (ET_0). We used the PM-ET_0 method to calculate ET_0 by meteorological data for 57 years. The basic data for calculating ET_0 can be referred to the previous reference (Li et al. 2016b). As both natural conditions (mainly meteorological factors) and social-economic policies (e.g., irrigation area) affected water demand, we used an RBI to express water demand, and the acquisition method of

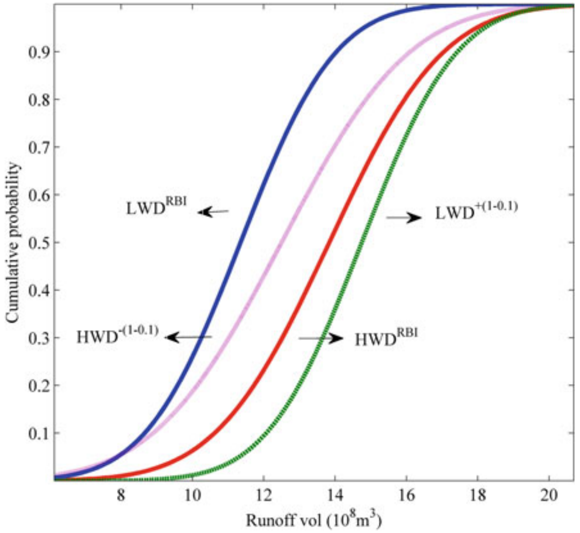


Fig. 14.1 Variations of interval values of runoff volume of Heihe River. *Note* LWD^{RBI}, HWD^{RBI}, $HWD^{-(1-0.1)}$, $LWD^{+(1-0.1)}$ indicate the lower bound of water demand (expressed as a random boundary interval parameter), the upper bound of water demand, the higher bound of water demand when the probability is 10%, and the lower bound of water demand when the probability is 10%, respectively

Table 14.1 Water supply

Mon	The lower bound of surface water supply is firstly considered (10^4 m^3)			The upper bound of surface water supply is firstly considered (10^4 m^3)		
	High	Middle	Low	High	Middle	Low
Apr.	[778, 957]	[670, 784]	[602, 741]	[892, 942]	[769, 772]	[691, 729]
May	[1287, 1583]	[1131, 1323]	[956, 1175]	[1476, 1558]	[1297, 1302]	[1096, 1157]
Jun.	[2187, 2675]	[2153, 2519]	[1392, 1712]	[2494, 2633]	[2469, 2479]	[1597, 1685]
Jul.	[4187, 5150]	[3503, 4099]	[2553, 3140]	[4802, 5070]	[4019, 4035]	[2929, 3091]
Aug.	[4131, 5081]	[2995, 3504]	[2471, 3039]	[4738, 5002]	[3435, 3449]	[2835, 2992]
Sep.	[2788, 3430]	[2144, 2508]	[1814, 2231]	[3198, 3376]	[2459, 2469]	[2081, 2196]

RBI was the same as that of surface water supply. The minimum water demand per unit area is listed in Table 14.2.

Other parameters are listed in Tables 14.3 and 14.4. Among them, we obtained the value of water target by multiplying a coefficient of water demand. This coefficient (i.e., 1.1) was determined by considering the temperature variation (Wang and Chen 2014). We got the maximum irrigation amount by calculating the extremum of the quadratic water production function (WPF), and the WPF for each crop was fitted

Table 14.2 Water demand

Parameters	Crops	Apr.	May	Jun.	Jul.	Aug.	Sep.
The lower bound of water demand is considered (m^3/ha)	Grain corn	[193, 219]	[537, 610]	[1286, 1460]	[1359, 1543]	[1272, 1444]	[483, 548]
	Forage corn	[175, 199]	[473, 537]	[587, 667]	[1654, 1878]	[1208, 1372]	[982, 1115]
	Wheat	[263, 299]	[1236, 1403]	[1275, 1448]	[1053, 1196]	0	0
	Vegetables	[386, 439]	[860, 976]	[1109, 1259]	[1121, 1273]	[599, 680]	[442, 502]
The upper bound of water demand is considered (m^3/ha)	Grain corn	[199, 204]	[555, 569]	[1329, 1362]	[1404, 1440]	[1314, 1347]	[499, 511]
	Forage corn	[181, 186]	[488, 501]	[607, 622]	[1709, 1752]	[1248, 1280]	[1015, 1040]
	Wheat	[272, 279]	[1277, 1309]	[1317, 1351]	[1088, 1116]	0	0
	Vegetables	[399, 409]	[888, 911]	[1146, 1174]	[1159, 1188]	[618, 634]	[457, 469]

Table 14.3 Data for different crops

Crops	Benefit coefficient	Water productivity	Maximum irrigation vol	Irrigation area
	(Yuan/kg)	(kg/m^3)	(10^4 m^3)	(10^4 ha)
Grain corn	[2.85, 3.15]	[1.75, 1.93]	4397	0.60
Forage corn	[2.19, 2.43]	[1.59, 1.75]	3719	0.44
Wheat	[2.17, 2.39]	[1.55, 1.71]	463	0.08
Vegetables	[3.28, 3.62]	[7.59, 8.39]	1302	0.21

Table 14.4 Data for different time periods

Items	Crops	Apr.	May	Jun.	Jul.	Aug.	Sep.
Water target (10^4 m^3)	Grain corn	[164, 174]	[458, 484]	[1096, 1159]	[1158, 1225]	[1084, 1146]	[411, 435]
	Forage corn	[110, 117]	[297, 314]	[369, 391]	[1041, 1101]	[760, 804]	[618, 653]
	Wheat	[31, 32]	[145, 153]	[150, 158]	[123, 131]	0	0
	Vegetables	[115, 122]	[257, 272]	[332, 351]	[336, 355]	[179, 189]	[132, 140]
Penalty coefficient (Yuan/m^3)	Grain corn	[5.77, 6.38]	[6.35, 7.01]	[7.5, 8.29]	[8.08, 8.29]	[8.08, 8.93]	[6.92, 7.65]
	Forage corn	[3.85, 4.25]	[4.23, 4.68]	[4.62, 5.1]	[5.77, 6.38]	[5,00, 5.39]	[5.39, 5.95]
	Wheat	[3.71, 4.10]	[4.45, 4.92]	[4.45, 4.92]	[4.08, 4.51]	0	0
	Vegetables	[30.11, 33.28]	[39.14, 43.26]	[45.16, 49.91]	[42.15, 46.59]	[36.13, 39.93]	[33.12, 36.6]

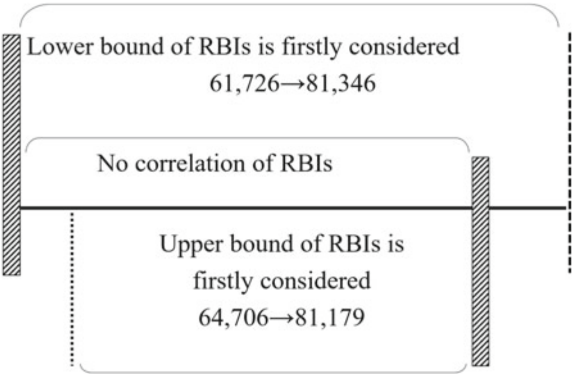
(Jiang et al. 2016). The population of YID was 16.44 × 10^4 people. The surface water and groundwater use efficiency were 0.68 and 0.8.

14.4 Results and Discussion

14.4.1 Economic Benefit

By solving the model, we obtained the results of both system economic benefit and water allocation. As the developed model was with high uncertainty, four submodels were transformed to reduce the complex uncertainties. Therefore, the system economic benefit varied within a dual interval as shown in Fig. 14.2, that was, from 61,726 to 81,346 × 10^4 RMB if the lower bound of RBIs (i.e., water supply and

Fig. 14.2 Variations of the system's economic benefit. *Note* The unit of the number is 10^4 RMB



water demand) was firstly considered (scenario 1) and from 64,706 to 81,179 × 10^4 RMB if the upper bound of RBIs was first considered (scenario 2). The variation range of economic benefit under scenario 1 was larger than that under scenario 2. The economic benefit value was the average level considering all the flow levels of water supply. The above variations were due to the correction between the lower and upper bounds of the surface water supply and demand. The conditional distributions and the original distributions of the lower and upper bounds of water supply and water demand contributed to the variations. If the high uncertainty of water supply and water demand was not considered, i.e., no correlation of the upper and lower bounds of water supply and water demand was considered, the system economic benefit would be just expressed as an interval number which was the result of ITSP model, rather than a dual interval number (see Fig. 14.2). The consideration of the high degree of water supply and water demand could help decision-makers gain insights into the possible variation range of economic benefit, and thus help the dynamic development of the regional agricultural economy.

14.4.2 Water Allocation Schemes

Water allocation schemes for the four crops during the whole crop growth period under different flow levels were obtained. Taking scenario 1 (the lower bound of RBIs was first considered) and middle flow level as an example, Fig. 14.3 shows the variation of total water allocation amount (the summation of surface water and groundwater) for different crops. It was clear that corn, including both grain corn and forage corn, occupied a large part of water supply, accounting for [81.3, 81.7%] of the total water allocation amount. It also indicates that there was a priority for planting corn. June and July were the months in which the peak of water demand was concentrated, accounting for 70–71% for the whole irrigation period. It can also be seen that for vegetables, the water allocation difference between the lower bound and upper bound was unremarkable. This was because vegetables produced higher benefit per unit water allocation amount and a higher penalty if water target was not

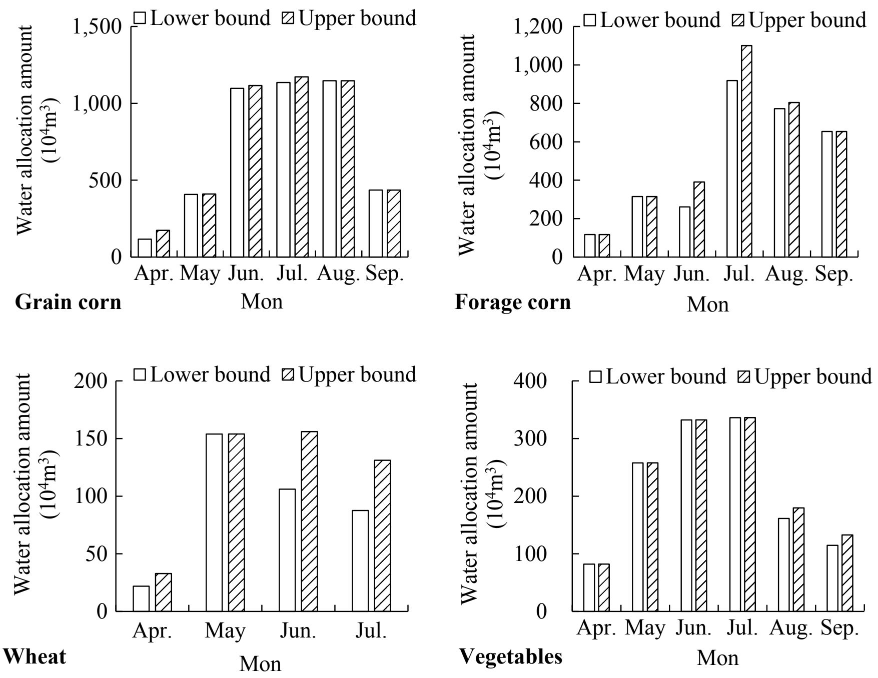


Fig. 14.3 Water allocation schemes for different crops

satisfied. Hence, water allocation priority was given to vegetables to improve the system's economic benefit. The water allocation amount for vegetables was [1.28, 1.32] × 10^7 m^3, while the water target for vegetables was [1.37, 1.47] × 10^7 m^3. The water allocation amount to vegetables did not achieve the corresponding water target, because food production should be guaranteed under limited water supply. In other words, if there were no food security constraint [Eq. (14.5f)], water allocation amount to vegetables would be as much as possible.

Figure 14.4 shows the water allocation amount for the total YID under different flow levels considering the two scenarios. For high flow level, as the water supply was sufficient to satisfy water demand, water allocation amounts nearly achieved their targets, while there was a gap between water allocation amount and water target under low flow level in both scenarios. The water allocation trend under the two scenarios was the same as the system's economic benefit. Taking low flow level as an example, water allocation amount was [7.85, 8.73] × 10^7 m^3 when the lower bound was first considered (larger variation), while water allocation amount was [8.43, 8.66] × 10^7 m^3 when the upper bound was first considered (smaller variation). In scenario 1 (the lower bound of RBI was considered), groundwater allocation amounts accounted for [27%, 29%], [28%, 30%] and [32%, 35%] under high, middle, and low flow levels, respectively. Similarly, in scenario 2, groundwater allocation amounts accounted for [27%, 28%], [28%, 29%], and [31%, 32%] under high, middle, and low flow

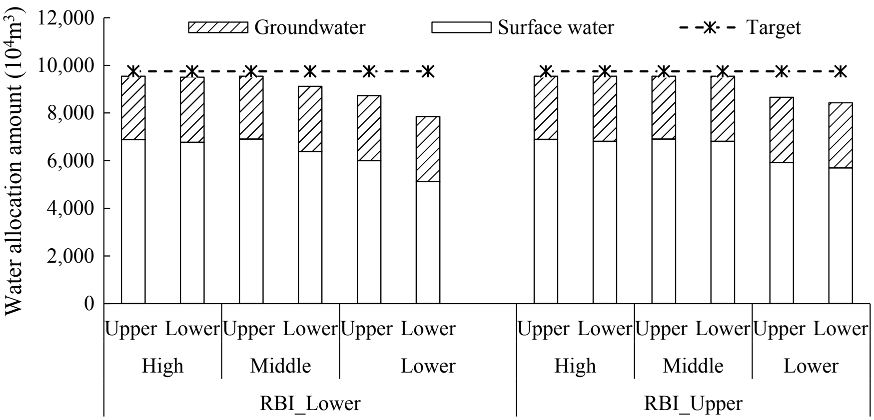


Fig. 14.4 Water allocation schemes for different crops. *Note* RBI_Lower indicates the lower bound of RBIs is firstly considered and RBI_Upper indicates the upper bound of RBIs is firstly considered

levels, respectively. From high flow level to low flow level, surface water allocation amount decreased, while groundwater allocation amount increased. This indicated that groundwater could be regarded as a regulating water source in a reasonable range to improve irrigation water allocation patterns in the YID.

14.4.3 Discussion

The optimal water allocation results were obtained based on the consideration of complex uncertainties of water supply and water demand, generating possible water resources allocation ranges that would provide decision-makers more alternatives for water resources allocation. However, in order to reduce computational burden, we made some simplifications. This study used three flow levels to present different degrees of water supply which significantly affected the final water allocation results. However, both water supply and water demand were random variables, and the water allocation schemes were also sensitive to the variation of water demand. This study did not divide water demand into different levels, which might not be conducive to generate more alternative schemes. This needs a future discussion on the joint effects of different levels of both water supply and water demand on water allocation schemes.

Besides, we used the CCP technique and two-boundary approach to transform the dual uncertainty (expressed as RBIs) of water supply and water demand into ordinary interval numbers. The violation probabilities were associated when using the CCP technique (Charnes and Cooper 1959). The choice of violation probabilities was greatly subjective (usually less than 20%). This study used the violation probability of 10% as an example to demonstrate the results. Different violation probabilities have a regular effect on system economic benefit and water allocation schemes. For example, both system's economic benefit and water allocation amounts would increase with the increase of violation probabilities. However, larger violation probabilities also meant larger risks for water supply. Therefore, selecting appropriate violation probabilities was worth considering.

14.5 Conclusion

In this chapter, a random-boundary interval-based inexact two-stage stochastic programming (RBIs-ITSP) approach is developed for water resources allocation. RBIs with the lower and upper bounds being random variables are introduced to account for the high uncertainty of water supply and water demand. Compared with the existing approaches for water resources allocation, the RBIs-ITSP approach is capable of reflecting complex uncertainties expressed as the integration of intervals, probability distributions, and random boundary intervals. Besides, the potential system-failure risks arising from the complex uncertainties can be quantified by means of violation levels (10% for this study).

The applicability of RBIs-ITSP approach is demonstrated in a real-world case study to allocate limited surface water and groundwater to main crops during the whole crop growth period under different flow levels in an irrigation district. The tradeoffs between system benefit and system failure risks were balanced. More alternatives to water allocation schemes were generated by considering the correlation existing between the lower and upper bounds of water supply and water demand.

The chapter attempts to integrate RBIs within the ITSP framework to reflect the high uncertainties of water resources allocation. The approach is applicable for most water resources management problems at different scales, such as watershed scale, regional scale, field-scale with water shortage problems and highly uncertain factors.

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Appendix

To solve the RBIs-ITSP model, the RBIs should be transformed into ordinary interval numbers using chance-constrained programming (CCP) technique. Then, the constraints with RBIs can be expressed as follows, taking Eq. (14.4b) as an example:

$$\Pr\left\{\alpha^{\pm}x^{\pm} \leq \left[\tilde{\beta}^{-}, \tilde{\beta}^{+}\right]\right\} \geq 1 - p \tag{14.6}$$

Equation (14.6) implies that the probability for constraint (14.4b) to be tenable is, $1 - p$, which p is the violation probability of constraint (14.6). Based on the two-boundary approach (Cao et al. 2010), Eq. (14.6) can be transformed into two constraints.

(1) When the lower bound of $\left[\tilde{\beta}^{-}, \tilde{\beta}^{+}\right]$ is first considered, Eq. (14.6) can be written as:

$$\Pr\left\{\alpha^{\pm}x^{\pm} \le \tilde{\beta}^{-}\right\} \ge 1 - p \Leftrightarrow \alpha^{\pm}x^{\pm} \le \tilde{\beta}^{-(p)} \tag{14.7}$$

where $\tilde{\beta}^{-(p)} = F_{v}^{-1}(p)$, given the CDF of $\tilde{\beta}^{-(p)}$ [i.e. $F_{v}(v)$]. Equation (14.7) can then be expressed as

$$\alpha^{\pm}x^{\pm} \le \left[\tilde{\beta}^{-(p)}, \tilde{\beta}'^{(p)}\right] \tag{14.8}$$

where $\tilde{\beta}'^{(p)}$ denotes a random variable whose CDF is $F_{w|v=\tilde{\beta}^{-(p)}}(w)$. $F_{w|v=\tilde{\beta}^{-(p)}}(w)$ is the conditional CDF of $\tilde{\beta}^{+}$ when $\tilde{\beta}^{-} = \tilde{\beta}^{-(p)}$ and

$$F_{w|v=\tilde{\beta}^{-(p)}}(w) = \int f_{w|v=\tilde{\beta}^{-(p)}}(w)\mathrm{d}w \tag{14.9}$$

It can present the correlation between $\tilde{\beta}^{-}$ and $\tilde{\beta}^{+}$.

(2) When the upper bound of $\left[\tilde{\beta}^{-}, \tilde{\beta}^{+}\right]$ is firstly considered, Eq. (14.6) can be written as:

$$Pr\left\{\alpha^{\pm}x^{\pm} \le \tilde{\beta}^{+}\right\} \ge 1 - p \Leftrightarrow \alpha^{\pm}x^{\pm} \le \tilde{\beta}^{+(p)} \tag{14.10}$$

where $\tilde{\beta}^{+(p)} = F_{w}^{-1}(p)$, given the CDF of $\tilde{\beta}^{+(p)}$ [i.e. $F_{w}(w)$]. Equation (14.7) can then be expressed as

$$\alpha^{\pm}x^{\pm} \le \left[\tilde{\beta}''^{(p)}, \tilde{\beta}^{+(p)}\right] \tag{14.11}$$

where $\tilde{\beta}''^{(p)}$ denotes a random variable whose CDF is $F_{v|w=\tilde{\beta}^{+(p)}}(v)$. $F_{v|w=\tilde{\beta}^{+(p)}}(v)$ is the conditional CDF of $\tilde{\beta}^{-}$ when $\tilde{\beta}^{+} = \tilde{\beta}^{+(p)}$ and

$$F_{v|w=\tilde{\beta}^{+(p)}}(v) = \int f_{v|w=\tilde{\beta}^{-(p)}}(v)\mathrm{d}v \tag{14.12}$$

The derivation process is also applied to $\left[\tilde{\delta}^{-}, \tilde{\delta}^{+}\right]$.

For the ITSP, it can be transformed into two deterministic sub-models (the lower and upper bounds of the desired objective function value) based on an interactive algorithm. A decision variable z is introduced to transform the target intervals into deterministic expressions. Let $x^{\pm} = x^{-} + \Delta x z$, where $\Delta x = x^{+} - x^{-}$ and $z \in [0, 1]$. Thus, the RBIs-ITSP model can be transformed into the following four sub-model.

When the lower bound of RBIs is considered, the RBIs $\left[\tilde{\beta}^{-}, \tilde{\beta}^{+}\right]$ and $\left[\tilde{\delta}^{-}, \tilde{\delta}^{+}\right]$ can be transformed into $\left[\tilde{\beta}^{-(p)}, \tilde{\beta}'^{(p)}\right]$ and $\left[\tilde{\delta}^{-(p)}, \tilde{\delta}'^{(p)}\right]$. Thus, we have

Sub-model 1–1

$$\max f^{+} = \max\left\{c^{+}\left(x^{-} + \Delta x z\right) - \sum_{h=1}^{H} p_h q\left(y_h^{-}, \xi_h^{-}\right)\right\} \tag{14.13a}$$

$$\text{subject to} \quad \alpha^{-}\left(x^{-} + \Delta x z\right) \le \tilde{\beta}'^{(p)} \tag{14.13b}$$

$$\chi^{+}\left(x^{-} + \Delta x z\right) \ge \tilde{\delta}^{-(p)} \tag{14.13c}$$

$$T\left(\xi_h^{-}\right)\left(x^{-} + \Delta x z\right) + W\left(\xi_h^{-}\right) y_h^{-} = h\left(\xi_h^{-}\right) \quad \forall h = 1, 2, \cdots, H \tag{14.13d}$$

$$y_h^{-} \ge 0 \tag{14.13e}$$

$$\Delta x = x^{+} - x^{-} \tag{14.13f}$$

$$0 \le z \le 1 \tag{14.13g}$$

where z and y_h^{-} are the decision variables. Let z_{opt}, $y_{h\text{opt}}^{-}$ and f_{opt}^{+} be the solutions of the sub-model 1–1. The optimized first-stage variable is $x_{\text{opt}}^{\pm} = x^{-} + \Delta x z_{\text{opt}}$, then, the sub-model corresponding to f^{-} can be formulated as follows:

Sub-model 1–2

$$\max f^{-} = \max\left\{c^{-}\left(x^{-} + \Delta x z_{\text{opt}}\right) - \sum_{h=1}^{H} p_h q\left(y_h^{+}, \xi_h^{+}\right)\right\} \tag{14.14a}$$

$$\text{subject to} \quad \alpha^{+}\left(x^{-} + \Delta x z\right) \le \tilde{\beta}^{-(p)} \tag{14.14b}$$

$$\chi^{-}\left(x^{-} + \Delta x z\right) \ge \tilde{\delta}'^{(p)} \tag{14.14c}$$

$$T\left(\xi_h^{+}\right)\left(x^{-} + \Delta x z_{\text{opt}}\right) + W\left(\xi_h^{+}\right) y_h^{+} = h\left(\xi_h^{+}\right) \quad \forall h = 1, 2, \ldots, H \tag{14.14d}$$

$$\left(x^{-} + \Delta x z_{\text{opt}}\right) \ge y_h^{+} \ge y_{h\text{opt}}^{-} \ge 0 \tag{14.14e}$$

where y_h^{+} are the decision variables. Suppose $y_{h\text{opt}}^{+}$ and f_{opt}^{-} are the solutions of the sub-model 1–2. Then, when the lower bound RBIs is considered, the final solution of sub-model 1 (including sub-model 1–1 and sub-model 1–2) of $f_{\text{opt}}^{\pm} = \left[f_{\text{opt}}^{-}, f_{\text{opt}}^{+}\right]$, $x_{\text{opt}}^{\pm} = x^{-} + \Delta x z_{\text{opt}}$ and $y_{h_{\text{opt}}}^{\pm} = \left[y_{h_{\text{opt}}}^{-}, y_{h_{\text{opt}}}^{+}\right]$ can be obtained.

When the upper bound of RBIs is considered, the RBIs $\left[\tilde{\beta}^{-}, \tilde{\beta}^{+}\right]$ and $\left[\tilde{\delta}^{-}, \tilde{\delta}^{+}\right]$ can be transformed into $\left[\tilde{\beta}^{\prime\prime(p)}, \tilde{\beta}^{+(p)}\right]$ and $\left[\tilde{\delta}^{\prime\prime(p)}, \tilde{\delta}^{+(p)}\right]$. Thus, we have

Sub-model 2–1

$$\max f^{+} = \max\left\{c^{+}\left(x^{-} + \Delta x z\right) - \sum_{h=1}^{H} p_h q\left(y_h^{-}, \xi_h^{-}\right)\right\} \tag{14.15a}$$

$$\text{subject to} \quad \alpha^{-}\left(x^{-} + \Delta x z\right) \le \tilde{\beta}^{+(p)} \tag{14.15b}$$

$$\chi^{+}\left(x^{-} + \Delta x z\right) \ge \tilde{\delta}^{\prime\prime(p)} \tag{14.15c}$$

$$T\left(\xi_h^{-}\right)\left(x^{-} + \Delta x z\right) + W\left(\xi_h^{-}\right)y_h^{-} = h\left(\xi_h^{-}\right) \quad \forall h = 1, 2, \ldots, H \tag{14.15d}$$

$$y_h^{-} \ge 0 \tag{14.15e}$$

$$\Delta x = x^{+} - x^{-} \tag{14.15f}$$

$$0 \le z \le 1 \tag{14.15g}$$

where z and y_h^{-} are the decision variables. Let z_{opt}, $y_{h\text{opt}}^{-}$ and f_{opt}^{+} be the solutions of the sub-model 2–1. The optimized first-stage variable is $x_{\text{opt}}^{\pm} = x^{-} + \Delta x z_{\text{opt}}$, then the sub-model corresponding to f^{-} can be formulated as follows:

Sub-model 2–2

$$\max f^{-} = \max\left\{c^{-}\left(x^{-} + \Delta x z_{\text{opt}}\right) - \sum_{h=1}^{H} p_h q\left(y_h^{+}, \xi_h^{+}\right)\right\} \tag{14.16a}$$

$$\text{subject to} \quad \alpha^{+}\left(x^{-} + \Delta x z\right) \le \tilde{\beta}^{\prime\prime(p)} \tag{14.16b}$$

$$\chi^{-}\left(x^{-} + \Delta x z\right) \ge \tilde{\delta}^{+(p)} \tag{14.16c}$$

$$T\left(\xi_h^{+}\right)\left(x^{-} + \Delta x z_{\text{opt}}\right) + W\left(\xi_h^{+}\right)y_h^{+} = h\left(\xi_h^{+}\right) \quad \forall h = 1, 2, \ldots, H \tag{14.16d}$$

$$\left(x^{-} + \Delta x z_{\text{opt}}\right) \ge y_h^{+} \ge y_{h\text{opt}}^{-} \ge 0 \tag{14.16e}$$

where y_h^{+} are the decision variables. Suppose $y_{h\text{opt}}^{+}$ and f_{opt}^{-} are the solutions of the sub-model 2–2. Thus, when the upper bound RBIs is considered, the final solution of sub-model 2 of $f_{\text{opt}}^{\pm} = \left[f_{\text{opt}}^{-}, f_{\text{opt}}^{+}\right]$, $x_{\text{opt}}^{\pm} = x^{-} + \Delta x z_{\text{opt}}$ and $y_{h_{\text{opt}}}^{\pm} = \left[y_{h_{\text{opt}}}^{-}, y_{h_{\text{opt}}}^{+}\right]$ can be obtained. It is noted that the solution of sub-model 2 is different from that of sub-model 1.

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Chapter 15
Population Dynamics and Tourism Effect on Future Water Demand. Case Study of Los Cabos, Baja California Sur

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Abstract In Mexico, tourism represents the third-highest source of foreign currency, whereby 2020 the number of visitors will be 45 million. The destination of Los Cabos Beach has become one of the most important sites due to the growing reception of tourists. However, as any enclave development presents a higher population growth, it places it as one of the coastal municipalities with the most considerable growth at the national level. As a result, there is an accelerated increase in the demand for water resources. This chapter analyzes the population and tourism dynamics, as well as their effect, on the future water demand in Los Cabos, BCS. The methodology is quantitative, based on the analysis of statistical data of representative variables (flow of visitors, length of stay, hotel rooms, total population, consumption, and average availability of water) through which future scenarios were projected. The results warn that the population growth of Los Cabos will cause enormous pressures on the availability of hydrological resources. This situation leads to reconsideration, on behalf of the authorities in charge of water management, to design policies and execute actions that lead to the rational use of the resource, as well as to think about alternative sources of supply. While some of the projections may be underestimated, they provide valuable quantitative information and a point of reference for decision-making. Also, the information generated contributes to a greater understanding of local challenges with respect to the sustainability of this vital resource.

Keywords Cape · Demand · Hotels · Scenarios · Water

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15.1 Introduction

Tourism has been established as one of the most dynamic, fastest-growing economic activities worldwide. For developed and undeveloped nations, it represents a way to diversify the economy and reinforce jobs to create value chains, generating and multiplying effects in all sectors.

Tourism is significant in economic terms, which can be expressed in different ways. For example, the World Tourism Organization (UNWTO 2017) indicates that tourism contribution to the Gross Domestic Product (GDP) is 10%, generates one out of every 11 jobs and also produces 30% of export services. The UNWTO has projected the expansion of tourism to continue by 2030, according to trends which indicate that 1.8 billion international tourists traveled around the world during 2017. Similarly, between 2010 and 2030, arrivals in emerging destinations (+4.4% per year) are expected to increase at a rate that will duplicate for developed economies (+2.2% per year) (UNWTO 2011).

Mexico is among the ten most-visited nations in the world (UNWTO 2018). Its mega-diversity has been used for several purposes (mostly tourism), based on the implementation of different programs and policies that place the country as the sixth economy with the main reception of visitors on the planet. Also, it is one of the 25 countries with the most significant tourism competitiveness in the world (World Economic Forum [WEF] 2017). Thus, the Fondo Nacional de Fomento al Turismo [National Fund for Tourism Promotion] (FONATUR 2000) has projected an amount of 48.5 million visitors will arrive in Mexico in 2020. The expansion of tourism is regularly considered as an economically positive aspect, however, without contemplating the distribution of resources and infrastructure that will be required to meet the demands of future visitors.

Regarding the management of the adverse impacts of tourism, Mexico has not generated the expected results. This situation is demonstrated in different reports of global competitiveness, issued by international organizations, where Mexico is ranked as one of the nations with the lowest performance regarding sustainability in the last ten years. According to the WEF (2017, 2018), a decline of 31 levels between 2008 and 2017 is indicated in that category (WEF 2008, 2017). The foregoing reveals the need to implement mechanisms to mitigate such tendencies.

Actions with emphasis must be implemented in the sun and beach destinations, given that the larger number of visitors and the highest hotel occupancy levels are centralized within them (Secretaria de Turismo) [Secretariat of Tourism] (SECTUR 2018).

In this research, Los Cabos, Baja California Sur (BCS) , Mexico, has been considered as a case study. In the 70's, Los Cabos was incorporated into the program of the Integrally Planned Centers (CIP). Since then, an intensification of the tourist inflow has been evident, for example, by 2017 the number of visitors was approximately 1.9 million people.

Nowadays, Los Cabos has been consolidated as one of the most significant locations for a diverse and luxurious offer of accommodation, increasing reception of tourists and employment generation. Relevancy is greatly expanding at a national level and according to Cruz et al. (2016), there is a stable, long-term relationship between tourist arrivals in Los Cabos and Mexico's GDP. Nevertheless, like any enclave development, Los Cabos presents issues, such as, a solid growth of resources to build and operate its lavish infrastructure and large resorts, fast population growth that places it as one of the coastal municipalities with the highest population growth at national level (Azuz and Rivera 2009) and, consequently, it experiences an accelerated demand for scarce water resources in the region. According to research conducted by Bunge (2011), the estimated demand for water per inhabitant daily is 250 L for domestic use, while the requirement of each hotel room is 1500 L per day.

Adversely, the National Institute of Statistics and Geography of Mexico (INEGI 2018a) highlights that the BCS[1] is the aridest entity in Mexico, with less rain and reduced accessibility to freshwater, per inhabitant within 785 m^3. In contrast, the average mean of precipitation is 200 L per square meter, of which 5.7 L reach the aquifers and the remainder evaporate or run towards the ocean.

The limited availability of water for human consumption results from the combination of several factors, some of which include: geographical and climatic conditions; population growth; intensive demand from activities such as tourism, agriculture, and livestock; as well as the old dysfunctional infrastructure that causes failures and waste in its distribution. Producing overexploitation of aquifers and saline intrusion (Avilés et al. 2015; Almendarez et al. 2013), contributes to water stress and is considered as the most significant vulnerability for all BCS municipalities (Gámez and Ivanova 2012).

In the situation of Los Cabos, there is a water supply deficit of 100 L per second in San Jose and 180 L per second in Cabo San Lucas (León 2017). If those conditions persist, the population wellbeing and development of tourism, which supports the economy, may experience obstacles, limitations and even pause their development. It goes without mentioning the occurring of construction that will damage the landscape and the environment (Bunge 2011).

Following this situation, the question that guided this research was the following: (1) By 2050, how much water consumption can be obtained for domestic purposes in the Municipality of Los Cabos, BCS? Taking the aforementioned considerations into account, the objective of this chapter was to analyze the dynamics of population and tourism, as well as their effect on the future demand for water in the Municipality of Los Cabos, BCS, Mexico.

To meet the stated purposes, quantitative methodology was used, based on the analysis of statistical data of the following representative variables: (i) visitor flow, stay, hotel rooms, and hotel occupancy from 2000 to 2015; (ii) total population, consumption and average availability of water for the period 1960–2015 and (iii) the projection of four future scenarios which correspond to the years 2020, 2030, 2040, and 2050.

This paper is organized into five sections. The first section is related to the description of the background, problem, and objectives of the investigation as well as the

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[1] Adscription state of the Municipality of Los Cabos.

organization of the work. The second part contains an exhaustive literature review presented to enhance the theoretical and conceptual references related to the research. In the third segment, a social and environmental characterization of the area of study is developed and the methodology is described. In the fourth area, findings are addressed, starting with the analysis of the evolution of population dynamics, followed by the description of the behavior of traditional tourism variables, tailed by the presentation of reflections on alternative indicators, and ending with the outline of results of the proposed scenarios.

Finally, in the fifth section, the results are discussed and as part of the conclusions, the authors underline the usefulness of this paper as a contribution of information that can potentially be considered as a reference by decision-makers in designing and enforcing strategies towards the more efficient management of this vital resource. Furthermore, in academic terms, this paper contributes to a better understanding of local challenges with regards to water sustainability.

15.2 Literature Review

A concept that must be considered is the water footprint, as it is an environmental indicator that acts as a reference to quantify the impact of human activity on water resources or, to put it differently, the volume of freshwater we consume in the development of any human activity. It can be calculated from a consumption or production point of view and focused on a specific consumer, producer, process, product or geographic area (Díaz et al. 2015).

The global average water footprint associated with consumption and estimated for the period 1996–2005, is 1385 m^3 per person per year. The annual value for the United States is 2842 m^3, for China 1071 m^3 and Mexico 1978 m^3 (Mekonnen and Hoekstra 2010; National Water Commission-CONAGUA 2016).

According to Díaz et al. (2015) in Cantabria, Spain, the extended water footprint of tourism decreased as of the year 2006 from 151 to 134 m^3 each year, per job. This situation is reflected in the decrease in water consumption, passing in 2006 from 0.447 to 0.366 hm^3. De Gispert et al. (2015) consider that water consumption in the higher-end hotels can reach 400 L per person per day, and 146 m^3 each year.

In Benidorm, Spain, the rising demand for water supply for urban use is caused by tourism growth. It is because agriculture is declining, and priority is given to the creation of policies to ensure the demand for water for the tourism sector is met (Hernández and Zizumbo 2017). Vera (2006) outlines the Spanish tourism development model, the water demand for resource management and planning in the future, including land-use planning.

In Guanacaste, Costa Rica, a study was conducted based on tourist activity, which refers to water footprint and the problem associated with the use of water for irrigation relating to its consumption by golf courses—a volume that is equal to the amount of water consumed by a community of 3000–7000 inhabitants. The study also compares the day-to-day water consumption of 200 L by a person at home, to that of 500 L of water used by a guest in a hotel (Hernández and Picón 2013).

In Taiwan, it was estimated that the growth in tourism from 2006 to 2011 was 48% and water consumption reflected in water footprint was 74% (Sun and Hsu 2018). The water footprint in some Croatian islands was estimated in order to determine the impact of the tourism sector on water demand to the local population. It is argued that this water footprint has been caused mostly by tourism and is closely related to the number of tourists and not to the residents (Grofelnik 2017).

On the Spanish coast of the Mediterranean Sea, an estimation of factors affecting domestic water consumption was performed using two ordinary minimum square models, as well as a geographically weighted regression. The study refers to residential tourism, which concludes that the most influential variables are the percentage of second homes or residential properties with swimming pools, at the municipal level (Villar and Pérez 2018).

On the coast of the Mediterranean Sea, it was established that tourism is an essential factor affecting water consumption—a factor that has been neglected in domestic water models. For the study, a panel data analysis and a nonlinear model of the monthly water consumption was used (Toth et al. 2018).

In Mexico, a study of the quality of freshwater was conducted due to the increasing coastal migration and tourism development in Holbox Island, Quintana Roo. It demonstrated that water quality problems exist, and that management is required to avoid deterioration in water quality of coastal ecosystem services (Rubio et al. 2018).

In China, the water footprint was calculated using the analysis to assess the direct and indirect water consumption, related to tourism, in the metropolitan region of Beijing, Tianjin, and Hebei (Jing-Jin-Jin). The consumption of food is a factor that impacts the water footprint of tourism (Li 2018).

In Ecuador, an analysis of the demographic pressure on water resources and its relation to the sustainability of the tourist destinations, concludes that intensification of demographic pressure influenced mainly the increase on residential migration, resulting in a series of problems with water availability. The method used a population pressure index, composed of five indicators, namely: (1) population distribution, (2) population in arid areas, (3) domestic water consumption, (4) population growth, and (5) hydric stress (Massa and Arteaga 2018).

Studies, such as the above mentioned, confirm that the impact of the tourism sector on the consumption of freshwater is relevant to Los Cabos, Baja California Sur, given the scarcity in the water region where the resource is located.

15.3 Study Area and Methodology

15.3.1 Socio-Environmental Characterization of the Municipality of Los Cabos, BCS, Mexico

Los Cabos is one of the five municipalities of BCS and has a territorial area of 3750.9 km^2 Ministry of the Interior (SEGOB 2018). It is bordered on the north by the Municipality of La Paz, south and east by the Gulf of California and west by the Pacific Ocean. Los Cabos is located within 23° 03′ north latitude and 109° 42′ west longitude of the Greenwich Meridian.

Information from SEGOB (2018), points out that the prevailing climates are of two types: warm-dry, north of San José del Cabo; and temperate-dry in the highest part of the Sierra de La Laguna and San Lazaro. Temperatures are associated with the desert conditions of the majority of Los Cabos territory, with the coldest month being January and the average annual temperature is 24 °C. About rain patterns, they occur in summer, with September having the highest rainfall. Despite the presence of tropical storms and hurricanes during May to October, the hydrological resources of the region are scarce and are represented by a stream of permanent flow, and others of rain flow, that run during certain times.

According to Ibáñez (Ibáñez 2015, 2017a), the natural conditions and strategic location allows an extensive coastline, certified beaches, marine diversity, terrestrial and marine natural areas, a variety of ecosystems, plants, and animals that, in many cases, are endemic species that only inhabit Mexico and the region.

In addition, among its main attractions are (Ibáñez et al. 2016; Ibáñez 2017b): (1) beaches—with the most frequently visited being Playa del Amor, Costa Azul, Solmar, El Tule, Las Viudas, El Médano, Palmilla, and Chileno, of which the last three mentioned acquired international certificates (CONAGUA 2018); (2) ecotourism and adventure activities in the following four Natural Protected Areas (ANP) (i) Sierra La Laguna Biosphere Reserve, (ii) Cabo Pulmo Marine Park, (iii) San José del Cabo Estuary and (iv) Area de Proteccion de Flora y Fauna Cabo San Lucas (APFFCSL); (3) bars, nightclubs and nightlife center; (4) sport fishing; (5) golf courses; (6) various lodging and tourist infrastructure that allows to rest and perform several social events, such as, weddings, celebrations, meetings, concerts, tournaments, congresses, international summits, among others, and (7) sites with high historical and ecological value, for example, Jesuit Missions, as well as unique cultural features that predominate in the way of life of the rancher Sudcalifornian who lives in rural areas.

Regarding the performance of the quality of life indexes, the Consejo Nacional de Población [National Population Council] (CONAPO 2015) indicates that the marginalization index reached a value of −1296, which is considered as a very low degree of marginalization.

Additional socio-demographic indicators show that the population reached 287,671 inhabitants in 2015; of which 1.96% are illiterate, 12.33% do not have water, 0.58% do not have electrical power in their home, and 74.3% receive more than two minimum wages (INEGI 2015). While the Human Development Index (HDI) in 2010 acquired a value of 0.8784 points—which is categorized as a high level, during that same period, 28.5% of its inhabitants lived in poverty (INEGI 2011).

The same source states that the most relevant productive activities are (INEGI 2015): commerce, administrative services, construction industry, commercial and sports fishing, agriculture, livestock and tourism (sun, beach and ecotourism), representing a pillar of the municipal, and state economy.

The latter has been possible due to the implementation of robust federal investments, contributing to the consolidation of Los Cabos as one of the most visited beach destinations in Mexico. Nevertheless, as in most of the country's CIP, tourism flows have also contributed to the severe socio-environmental and legal problems such as: exponential population growth, marginalization of fisherman and agriculture, increase in insecurity, exploitation of vital resources such as water, modification of the coastline, excess of visitors in beach areas, increase in poverty, migration and displacement of local labor, conflicts of land tenure, greater water stress, to name a few (Ibáñez 2017b; Montaño et al. 2014; Lopez and Sánchez 2002).

Although the impacts of tourism in the study area are diverse, such as those mentioned above, this study seeks to analyze and construct the elements related to the problems associated with the growing demand for water for domestic and tourist purposes.

15.3.2 Methodology

The projection of future water demand scenarios for urban public use and tourism were made for the years 2020, 2030, 2040, and 2050, corresponding to scenarios 1, 2, 3, and 4, respectively. The variables involved to generate projections for the first sector where the population of Los Cabos Municipality, information from CONAPO, and estimated water demand per inhabitant of CONAGUA. In the case of projections of the tourism sector, the variables used for its elaboration were the number of rooms, the rate of hotel occupancy (data from Secretaría de Turismo [Secretariat of Tourism]) and water consumption per hotel room. The descriptive statistics of the variables used in the analysis are shown in Table 15.1.

The information source of the population from 2010 to 2030 is from CONAPO and the year 2040 up to 2050 are estimates conducted in the study and presented in

Table 15.1 Descriptive statistics

Variable	Mean	Standard deviation	Minimum	Maximum
Population	358,387	67,465	243,268	464,157
Room	12,278	3445	5980	17,365
Hotel occupancy	59.07[a]	–	49.18	68.9

Note [a]Geometric mean
Source Own elaboration based on CONAPO (2015) and DATATUR (2018)

Table 15.2 Population growth of the municipality of Los Cabos

Year	Population	Period	Growth rate[a]
2010	243,268	–	–
2020	360,424	2010–2020	48.16%
2030	464,157	2020–2030	28.78%
2040[a]	564,732	2030–2040	21.68%
2050[a]	662,807	2040–2050	17.37%

Note [a]own estimates
Source CONAPO (2015)

Table 15.3 Evolution of hotel rooms of the tourist destination of Los Cabos

Year	Room number	Period	Growth Rate[a]
2010	14,344	–	–
2020[a]	18,771	2010–2020	30.87%
2030[a]	24,418	2020–2030	30.87%
2040[a]	30,064	2030–2040	23.12%
2050[a]	35,711	2040–2050	18.78%

Note [a]own estimates
Source Own elaboration based on DATATUR (2018)

Table 15.2. The population growth between decades, valued in Table 15.2, is observed as the years go from one decade to another and grows in a smaller proportion.

Tourism room projections are based on our estimates, as well as their growth rates, and are presented in Tables 15.2 and 15.3. It is important to mention that it was not possible to predict the hotel occupancy series due to the absence of data for some years. Therefore, a geometric mean was calculated (which was 59%) and this result is close to the figure taken by Bunge (2011), of the Hoteliers Association of Los Cabos, for the same year, to project scenarios of the tourist destination of Cabo Cortes.

15.4 Results

15.4.1 Evolution of Population Dynamics

The increase of the population in Los Cabos has reached exponential figures, and to such an extent that it is considered as one of the country's coastal municipalities with the highest demographic increase. Figure 15.1 shows the evolution of the number of inhabitants in the last 65 years.

As of the seventies, when it was declared as one of the first CIP in the country, a considerable increase is observed. The accumulated growth from that date until 2015

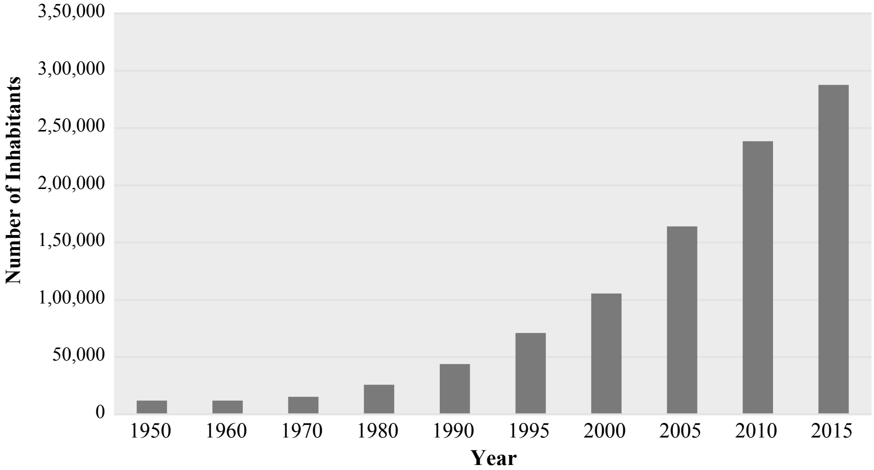

Fig. 15.1 Historical behavior of the total population in the municipality of Los Cabos, B.C.S., 1950–2015. *Source* Own elaboration based on data from INEGI (2018b) and CONAPO (2015)

reached 1.78% and the trends point to further expansion in the future. It is important to highlight that such behavior is influenced by migratory phenomena, which makes Los Cabos the BCS municipality with the largest non-native population.

The year 2015 represented 56.7% of the total population (Gobierno del Estado de Baja California Sur [State Government of Baja California Sur] 2017). It is mainly due to the amount of direct and indirect labor demand by tourism development, in addition to being the second place of residence for foreign visitors. Consequently, the population density has been radically modified, for example, the number of inhabitants per km^2 from 1950 to 2015 shifted from 3.2 to 76.7, respectively, observing an increase of 2.3%. Invariably, this situation will continuously generate high pressure on the environment (Ibáñez 2017a).

15.4.2 Growth in Tourist Variables

15.4.2.1 Approach Based on Traditional Indicators

The tourism development in Cabo San Lucas has experienced a strong expansion that is reflected in the behavior of common variables, such as the number of establishments, hotel rooms, the influx of visitors, length of stay of visitors, and the average percentage of rooms occupied in hotels. For example, the number of lodging establishments from the year 2000 to 2015 (Fig. 15.2), present an extension of 52 units, experiencing an increase of 63.4%. Whereas the number of rooms and lodging units surged from 6.7 in the year 2000 to 15.9 by the end of 2015 is reflected in the accumulated increase of 138.7%.

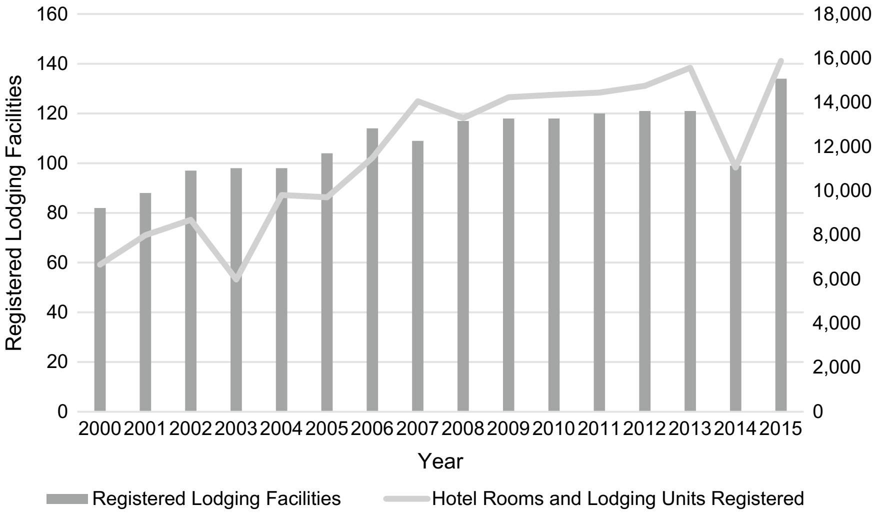

Fig. 15.2 Number of lodging establishments, accommodation and lodging Rooms registered in the municipality of Los Cabos, B.C.S., 2000–2015. *Source* Own elaboration based on data from DATATUR (2018)

It is important to highlight that during 2015, 77% of the hotel rooms had a five-star classification, and the number of visitors reached 1,231,415 people (INEGI 2016). From 2000 to 2015, it increased by 124.5% and by 5.6% in average annual terms (INEGI 2001, 2016). Additionally, a significant fact is that 74% of the visitors are non-residents, coming from the USA, who stay in the establishments that offer maximum luxury and comfort, thus indicating a preference for five-star accommodation units. In Cabo San Lucas, visitor stopovers reach 5 days per visitor, ranking it as the destination with the most extended average stay in BCS. Similarly, recent numbers point to increasing supply and tourist inflow.

15.4.2.2 Analysis Based on Alternative Indicators

In order to provide a more critical panorama of the impacts of tourism, the research developed by Ibáñez (2017a) has been considered as a reference, whereby the estimation of floating population quadruples as a result of tourism inflow. Also, in 2015, the ratio of overnight stays per inhabitant was 22. In the same way, the population density adjusted to the flow of tourists and their overnight stays, observing an exponential increase. Also, the density of rooms and accommodation units per km^2 display the same tendencies (see Table 15.4).

Therefore, in agreement with the same author, the aforementioned indicators provide a clearer picture of the impacts and implicit requirements of tourism development. Not only are residents considered, but also visitors who demand resources and infrastructure, and therefore generate an ecological footprint during their stay.

Table 15.4 Behavior of alternative indicators associated with Tourism in the municipality of Los Cabos, 2005–2015

Indicator name	Objective	Result municipality of Los Cabos		
		2000	2015	Variation
Tourist per inhabitant	Measure the proportion of visitors that visit a destination in relation to the number of inhabitants.	5	4	– 1
Overnight per inhabitant	Measure the proportion of visitors according to the average annual stay in a destination in relation to the number of inhabitants.	19	22	3
Population density adjusted to tourist flows	Estimate the population and visitors per square kilometer in a certain period of time.	174	405	231
Population density adjusted to the permanence of tourist	Estimate the population and overnight stays per square kilometer in a given year	567	1777	1210
Territorial density for units and accommodation bedrooms	Estimate the number of accommodations, hotel rooms per square kilometer in a certain period of time	1.77	4.23	2.5

Source Ibáñez (2017a)

15.4.3 Estimation of Future Water Demand Scenarios for Tourism and Domestic Purposes

According to de La Paz (2018), daily water consumption per inhabitant is 250 L. To estimate the urban public consumption, this amount was multiplied by the population of the Municipality of Los Cabos in 2010, as well as each of the scenarios, thus obtaining the daily water estimate, which was transformed into cubic hectometers (hm^3).

The volume was annualized and is presented, as per each of the scenarios, in Table 15.5. Similarly, the demand for water for tourist use was also estimated. However, in contrast to the urban public sector, according to Bunge (2011), each hotel room consumes 1500 L. The annualized volume is observed in Table 15.5. After the water volumes of both sectors were calculated, the total consumption was estimated and the results revealed: 26.84 hm^3 in 2010; 38.96 hm^3 for scenario 1; 50.25 hm^3 in scenario 2, 61.25 hm^3 for scenario 3, and 72.03 hm^3 in scenario 4.

Table 15.5 Water consumption projections of urban and tourist public uses

Variables	2010	Scenario 1 (2020)	Scenario 2 (2030)	Scenario 3 (2040)	Scenario 4 (2050)
Urban public water consumption (hm^3/year)	22.20	32.89	42.35	51.53	60.48
Hotel water consumption (hm^3/year)	4.64	6.07	7.90	9.72	11.55
Total, consumption	26.84	38.96	50.25	61.25	72.03

Source Own estimate based on data DATATUR (2018). Mexico and Bunge (2011)

15.5 Discussions and Conclusion

On one hand, the projections warn that population growth of the Municipality of Los Cabos will cause enormous and extraordinary pressures—aside from those already existing because it is one of the areas with the highest demand of water resources. It is based on the availability of the hydrological resources of the territory, such as the aquifers, that provide water to inhabitants. It is assumed that the low recharge capacity of the water bodies, caused by low rainfall and relief conditions that prevent filtration, will aggravate supply problems. This situation leads to the rethinking on the part of the entrusted authority of water management to design policies and implement actions that lead to the rational use of hydrological resources. Further, they ought to consider alternative sources of water supply, where research such as that from Almendarez et al. (2013) and Sánchez et al. (2013) developed in the state of Baja California Sur, has demonstrated with empirical evidence the possibility to raise financial resources to conduct programs that allow for the required quantity and quality of water supply, according to international standards.

Other research performed by Avilés et al. (2015); Almendarez et al. (2015) and Almendarez et al. (2016), in Baja California Sur, suggests that the objective of economic instruments is to encourage the rational use of water. On the other hand, in proportional terms, the tourism sector (including golf courses) presented a lower demand in relation to domestic use, where there was significant growth in future consumption. Given these scenarios, it is necessary that hotels continue to provide water to the lodge through the installation of desalination and treatment plants, as well as keep the use of the water supply via the aquifers to a minimum. One of the limitations of the study is that it does not include in the analysis the amount required for irrigation of the golf courses, the number of tourist residences and their daily water consumption, due to the unavailability of the information. Therefore, the projections may be underestimated, however, do provide valuable quantitative information and a point of reference for decision-making by those responsible for water management.

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Chapter 16
Status of Regional Drinking Water Services in Nuevo Leon, Mexico

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Abstract The water supply in Nuevo León, México varies significantly depending on the area or region in which the municipalities are located. The capital of the State, and its surrounding municipalities, indeed concentrate on a more significant number of citizens and therefore, has the most significant water supply. In contrast, the municipalities in the south of the State are the most disadvantaged given the less investment in the infrastructure for supply, deficiencies in the quality of service, etc. The objective of this work was to show the status of the water supply over the non-metropolitan municipalities of the State of Nuevo León in 2017, by analyzing the raw data provided by Water and Sewer Services of Monterrey. To carry out the analysis of the water supply service condition, based on the geographical location and the area of each of the non-metropolitan municipalities, a regionalization or discretization of the State of Nuevo León was carried out. Results showed that it is recommended to strengthen water supply sources, improve distribution efficiencies, implement a permanent program for the detection of visible and non-visible leaks, repair damaged pipes, and detect illegal outtakes. Likewise, the macro-metering should be increased at the sources of supply, storage tanks, and micro-metering, at every domestic water intake (users). Further, the need to build new infrastructure of water supply networks on rural communities by expanding systems, as well as promote the use of new alternative technologies, is indicated. Establishing a program of financial support for

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the preparation of dissemination and educational materials to strengthen the culture of water saving in the communities is also suggested.

Keywords Water supply · Water demand · Macro metering · Water distribution

16.1 Introduction

Water is a vital element of life. Its care and conservation allow us to ensure the growth and development of towns. According to the World Health Organization (OMS 2009), humans need 10 L of water supply—20 L of water for cooking and 30 L of water for personal hygiene, daily. This quantity is considered the minimum amount of water necessary for human survival in the short term. From the total volume of freshwater that can be used for human supply on earth, 0.61% is underground water, 0.009% is lake water, and 0.0001% is river water (USGS 2018). In Mexico's case, presently, there is a 348.1 m^3/s water production, of which 210.6 comes from underground water, and 137.5 comes from surface sources, such as rivers, lakes, and dams. Moreover, 14.2% of this total available water production is used for public supply (CONAGUA 2016a).

The combined supply of water for public use is made up of water that is distributed through the supply networks, providing for users, as well as diverse industries and services. Having access to water, in both quality and quantity suitable for human consumption, is one of the most basic needs as it directly impacts the health and general welfare of the population. Nationwide, 119.5 million inhabitants have water supply coverage in private homes, which represents 92.5% of the total population (CONAGUA 2016b). Objective 3 of the 2014–2018 National Water Program establishes that water supply, sewerage, and wastewater should be strengthened (CONAGUA 2014). In this regard, the water supply in Nuevo León is carried out through the operator organization, called Water and Sewage Services of Monterrey (by its Spanish acronym, SADM), which is a decentralized public institution. The primary challenge that SADM faces is "to guarantee water supply for the city of Monterrey, with the quantity, quality, opportunity and from the perspective of environmental sustainability of new sources. An associated challenge is maintaining a 24-h supply of water in the current systems and ensuring that this coverage is reached in those areas that do not have this level of supply yet" (Aguilar-Barajas et al. 2015). According to data provided by SADM (2017), water supply coverage in the Metropolitan Area of Monterrey has remained practically the same in recent years, since in 2000 it was 99.53% and in 2016, 99.69%. On the other hand, in non-metropolitan municipalities, the situation has been very different, in that coverage increased significantly from 76% in 2000 to 99.45% in 2016.

Although there are several studies related to water supply in Nuevo Leon (Lutz and Salazar 2011; Salazar and Lutz 2015; FAMM 2015; SEMARNAT 2017), these studies present the information considering the metropolitan area of Monterrey (MAM) and the non-metropolitan municipalities. This fact does not allow us to establish what the situation of water supply is in the non-metropolitan municipalities. Therefore, the objective of this paper is to show the situation of the water supply in the non-metropolitan municipalities of the State of Nuevo León in 2017, by analyzing the raw data provided by SADM.

16.2 Regionalization

Nuevo León is one of the 32 states of the Mexican Republic. It is in the northeast area of the country, has an area of 64,555 km^2 that represents 3.3% of the national territory, with a population density of 79.8 inhabitants per square kilometer. It is divided into 51 municipalities, and its capital is the City of Monterrey (INEGI 2018). Nuevo León is bordered to the north by the USA, to the west by Coahuila, Zacatecas, and San Luis Potosí, to the south by San Luis Potosí and to the east by Tamaulipas.

The Intercensal Survey 2015, conducted by the Instituto Nacional de Estadística y Geografía (the Mexican National Institute of Statistics and Geography, INEGI, 2015), shows that Nuevo León has a total population of 5,119,504 inhabitants, of which 49.7% are men and 50.3% are women. On average, 1,393,542 private homes are inhabited by 3.7 people. The availability of services in dwellings is 95.3% of piped water and 97.6% of sewage systems. With regard to the degree of marginalization, the municipalities with the highest index in the State are Aramberri, General Zaragoza, Mier y Noriega, and Rayones, while those with the lowest rate of marginalization are San Pedro Garza García, San Nicolás de Los Garza, Guadalupe, Apodaca, and Santa Catarina (CONAPO 2015).

The water supply in Nuevo León varies significantly depending on the area or region in which the municipalities are located. Indeed, the capital of the State and its surrounding municipalities, comprise the most significant number of citizens and, therefore, are those with the largest water supply. In contrast, the municipalities in the south of the State are the most disadvantaged.

To carry out the analysis of the water supply service situation, based on the geographical location and the area of each of the non-metropolitan municipalities, a regionalization or discretization of the State of Nuevo León was carried out. The non-metropolitan municipalities were grouped into five regions: Peripheral Center, Northeast, Northwest, South, and Valle de Pilón. The discretization of the 51 municipalities of Nuevo León in the proposed regions is shown in Fig. 16.1.

All this was conducted in order to individually analyze the water supply for each of these municipalities, establishing evaluation indicators and the corresponding improvement actions. The management of the information that was gathered, in both government agencies and their official Web sites, was carried out at the municipal level and grouped according to the regionalization shown in Table 16.1. It is important to note that the municipalities which were not considered in the analysis and formed part of the Metropolitan Area of Monterrey are: Apodaca, Cadereyta Jiménez, García, General Escobedo, Guadalupe, Benito Juárez, Monterrey, San Nicolás de Los Garza, Santa Catarina, and San Pedro Garza García.

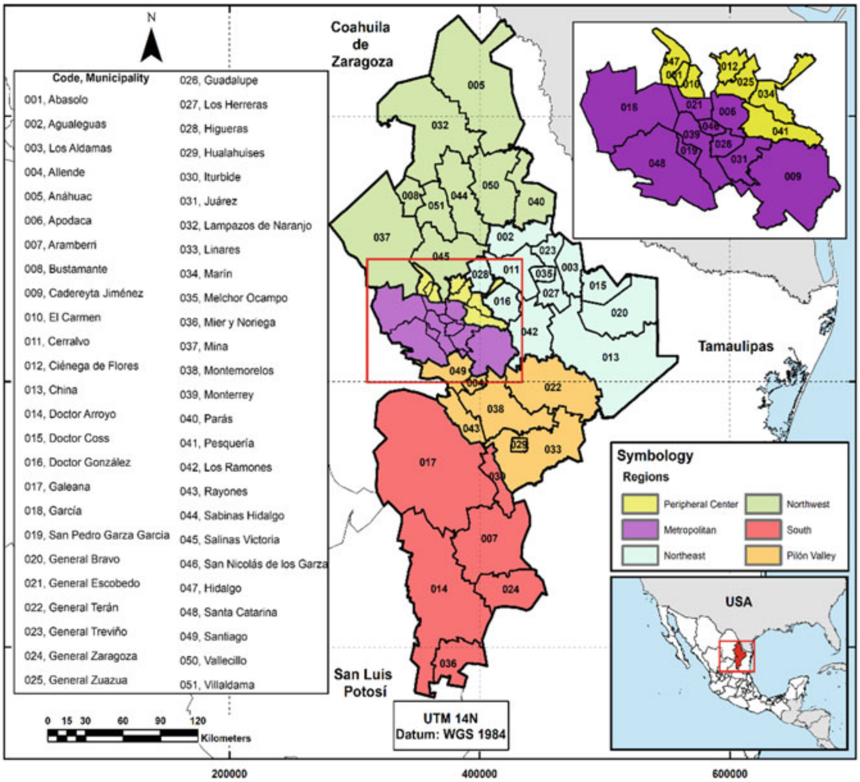

Fig. 16.1 Regions and municipalities in the current situation of the water supply (SADM 2017)

16.3 Water Supply by Region

16.3.1 Coverage of Water Supply Service

Water supply coverage refers to the number of dwellings in each municipality that have water supply service, either inside or outside the house, and whether they have a service contract in place. About this, SADM assigns a Service Identification Number (SIN, by its acronym in Spanish) to each dwelling that has water supply service and classifies it according to the type of fee it charges them—that is, either domestic, industrial, commercial or public use fees. To determine the water supply coverage in the non-metropolitan municipalities, SADM's commercial area provided all the SIN list and its corresponding fees (SADM 2017). Also, detailed information on consumption, billing, and collection for 2010, 2011, 2012, 2013, 2014, 2015, and 2016 was also obtained. Dwelling reports of the Population and Housing Census 2010, as well as from the Intercensal Survey 2015 were also obtained at the official Web site of the Mexican National Institute of Statistics and Geography (INEGI 2015).

Table 16.1 Types of water supply

Region	Underground			Surface			Total		
	No. of sources	Macro-metering working	Macro-metering not working	No. of sources	Macro-metering working	Macro-metering not working	No. of sources	Macro-metering working	Macro-metering not working
Peripheral Center	15	9	6	1		1	43	26	17
Northeast	18	15	3	3	3		33	24	9
Northwest	21	16	5	4	4		37	26	11
South	21	21		1	1		22	22	
Valle del Pilón	119	106	13	5	5		133	120	13
Total	194	167	27	14	13	1	268	218	50

Sources by Region (SADM 2017)

The following expression determined the percentage coverage “COSAP” (Eq. 16.1):

$$\text{COSAP} = \frac{\text{total of NIS}}{\text{total of dwellings}} * 100 \tag{16.1}$$

The information used to determine the coverage for 2016, along with the information from the 2010 Population and Housing Census, was provided by SADM. However, for the municipality of Ciénega de Flores, the registered numbers for 2010 considered both the SIN reported by SADM and the total number of houses reported by INEGI. That is because this municipality has registered accelerated growth in recent years. Likewise, the municipalities of El Carmen, General Zuazua, Hidalgo, Marín, Doctor Coss, Los Herreras, Melchor Ocampo, and Sabinas Hidalgo show an increase in SIN from 2015 to 2016. Therefore, the total SIN for 2015 was reported in comparison to the total housing reported by the Population and Housing Census 2010.

Similarly, the municipalities of Pesquería and Salinas Victoria presented a high increase in the total SIN from 2015 to 2016 and thus, were linked to the total number of inhabited dwellings reported by the Intercensal Survey 2015. Finally, in the case of the municipality Los Aldamas, some total dwellings, as well as inhabited dwellings lower than the total SIN, was reported by SADM. Therefore, its coverage is approximately 100%.

Regarding the analyzed information, in general, the regions have a 78.5% coverage of water supply (Fig. 16.2). Specifically, the Peripheral Center region has an 88.2% coverage (the highest), the Northeast region 86.1%, the Northwest region 82.8%, the Valle del Pilón region 75.3%, and the South region 60% (the lowest). As for the number of people who do not have water services in their dwellings, the calculation

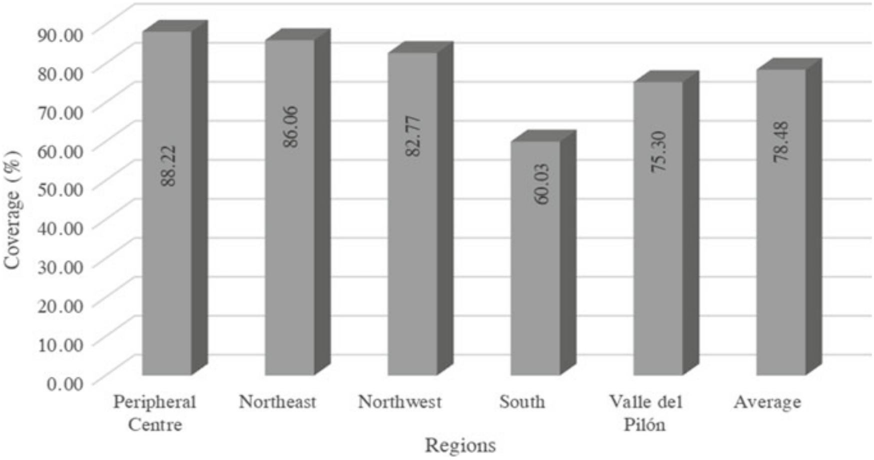

Fig. 16.2 Water supply coverage by region (SADM 2017)

was obtained from the coverage shown in the analysis and from the population and number of inhabited dwellings reported by INEGI.

It was found that, in the Peripheral Center region, within the municipality of Hidalgo, having the most extensive coverage in the region (97.2%), 389 people do not have water services. By contrast, the municipality of Pesquería has the lowest coverage (74.7%) in the region, and 22,097 people do not have water services. In total, 42,007 people in the region do not have water services. In the Northeast region, the municipalities of Higueras and Los Ramones showed the highest and the lowest coverage, being 96.5 and 63.5%, respectively. The number of people without water supply services in Higueras was 54 and in Los Ramones 1630. Overall, the total number of people without water supply services for the region was 4817.

In the Northwest region, the highest and lowest coverage corresponds to the municipalities of Salinas Victoria (97.4%) and Mina (52.9%), whereby 1409 people do not have water services in Salinas Victoria and 2509 people in Mina, with the total number of people without water services in the region being 13,274. In the Valle del Pilón region, the municipality of Hualahuises has a 98.2% coverage, and 109 people do not have water services. However, the municipality of Rayones has coverage of 30.3% (the lowest of all regions), and 1839 people do not have water services. In total, in the region, 42,326 people do not have water services.

The situation in the South region is the most unfavorable and, particularly, the municipality of Mier y Noriega, which has the highest coverage (91.3%) but has 606 people without water services. In contrast, the municipality of Galeana has the lowest coverage (44.2%) with 22,946 people without water services. In total, 48,377 people in the region do not have water services.

Finally, according to the calculation made, based on the data provided by SADM and on the numbers consulted at INEGI, the total number of people without water supply services in non-metropolitan municipalities is 150,800 (19.4% of the population in non-metropolitan municipalities). It should be noted that the coverage belongs to the service provided through public water networks.

16.3.2 Current Demand of Water Supply

Demand is determined by the sum of the consumption (based on the different types of fees and the physical losses of the system). Likewise, allocation refers to the amount of water that is assigned to each inhabitant, considering the different uses of water and the physical losses in an average annual day. It is reported as L/inhabitant/day (CONAGUA 2015b). To calculate the demand of water supply, SADM's Production Management submitted the monthly volume of water that was supplied in 2016 and reported the supply sources with which the water supply service was provided to each of the municipalities (Fig. 16.3). These volumes directly represent the total value of the consumptions and the physical losses of the system. It is important to mention that for the municipalities El Carmen, General Zuazua and Santiago, a part of the total volume of water supplied to them is taken from the supply network of the

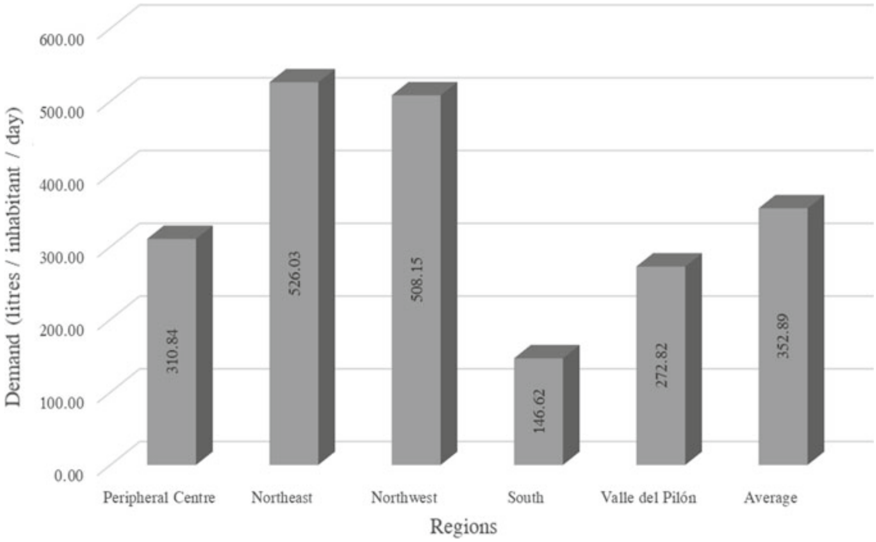

Fig. 16.3 Demand for water supply by region (SADM 2017)

metropolitan area of Monterrey, and the corresponding information is not available. Therefore, the reported demand for these municipalities is approximate. The value of the population considered in this section is the total population number that was reported by INEGI, according to the intercensal survey conducted in 2015.

According to the information presented, the average water demand in these regions is 352.89 L/inhabitant/day. The Northeast region stands out with an average demand of 526.03 L/inhabitant/day. Likewise, the South region reports the lowest water demand with 146.62 L/inhabitant/day, which is related to the coverage, as it also reports the lowest value. It is worth mentioning that the municipality of Mier y Noriega has the lowest demand of all non-metropolitan municipalities, with a value of 86.40 L/inhabitant/day.

16.3.3 Supply Sources

The sources of supply refer to the bodies of water from which this resource is obtained—whether surface or underground, for the supply to the populations through a water distribution system (CONAGUA 2015a). The information regarding the sources of supply was provided by the SADM's Production Management (Fig. 16.4). From these sources, water supply is delivered to the communities of each municipality to the municipal capitals. According to this information, the following are considered as the sources of supply: underground, surface, and aqueduct outlets.

The data that has been provided for the latter does not specify what the source of the water is and thus, it is simply reported as a source of supply.

The total number of sources of supply in 2016, as reported by SADM, is 267, of which supply 81.29 Mm^3 of water to 778,460 people in the non-metropolitan municipalities. From all these sources of supply, 72.3% is groundwater, and 17.3% is surface water. The Valle del Pilón region has the largest number of sources of supply (133), while the South region, with only 21 sources, has the lowest number of all. About the volumes of water supplied by these sources, the Valle del Pilón region provides an amount of 26.89 Mm^3 and represents 33.08% of the total of the regions.

The South region provides 6.69 Mm^3 of water, which represents 8.23% of the total volume. However, it should be noted that the Northeast region has the lowest volume of supply sources (6.33 Mm^3). Regarding the quantity of water available in the sources per inhabitant, the Peripheral Center region shows 87.70 m^3/inhabitant, the Northeast region 150.58 m^3/inhabitant, the Northwest region 145.58 m^3/inhabitant, the South region 61.96 m^3/inhabitant, and the Valle del Pilón has 111.21 m^3/inhabitant. It is important to mention that the municipalities of Abasolo, El Carmen, Doctor Coss, General Bravo, Los Aldamas, and Mina, only report a supply using aqueduct outlets. Such a situation could put these municipalities at a certain level of vulnerability, in the event of any failure within those sources. However, about the municipality of Mina, where a set of wells is located, from which the metropolitan area of Monterrey is supplied.

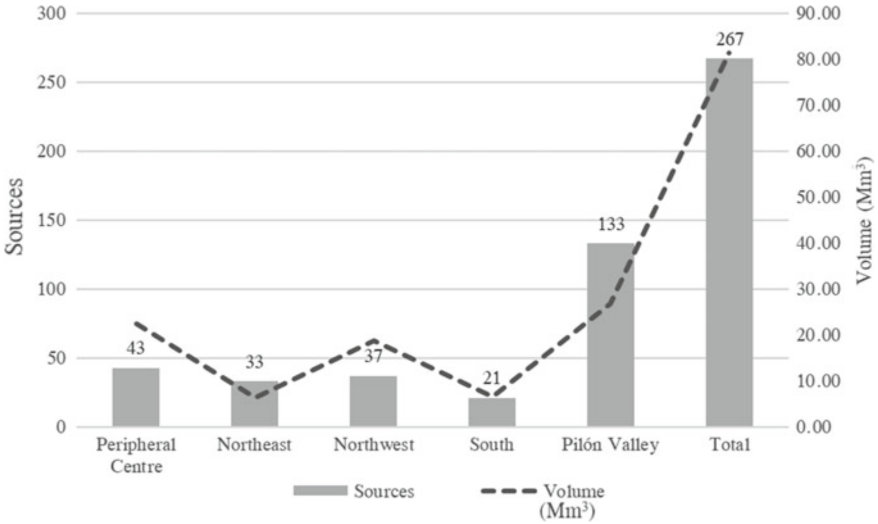

Fig. 16.4 Water supply. Sources by region (SADM 2017)

16.3.4 Macro-metering in Sources of Supply

For quantifying water volume obtained from sources of supply, it is vitally important to carry out macro-metering. That allows full knowledge of the extracted flows, which lead to determining the production of water. In conjunction with micro-metering, this permits the determining of the efficiency of the system (CONAGUA 2012). In this case, the SADM's Production Management provided the information regarding the sources of supply that were available in 2016 (Table 16.1).

The macro-metering in the sources of supply indicates that, on average, the regions have 79.17% of macro-metering working and 20.83% of it not working. In particular, the Peripheral Center region has 61.31% of it working and 38.69% not working, and the Northeast region has 71.53% of it working and 28.47% not working. On the other hand, the Northwest region shows 77.41% of it working and 22.59% not working, the South region has 100% of it working and the Valle del Pilón region, which has the highest number of macro-metering (133), has 94.56% of macro-metering working and 5.44% not working.

16.3.5 Purification

The process of water conditioning is carried out through purification, which means that, regarding water quality, the components that could be present in the water and pose health risks are eliminated through physical and chemical processes.

The water quality of the treatment plants effluent is regulated by official Mexican Standard NOM-127-SAA-1-1994 (DOF 2000). For a similar analysis, SADM's Operations Department provided the inventory of water treatment plants, updated to December 2016 (Fig. 16.5). On average, the regions use 23% of their installed capacity. In particular, the Peripheral Center region has 90% (the highest), the Northeast region 36%, the Northwest region 89%, the South region 89%, and the Valle del Pilón region 17% (the lowest).

Regarding the number of water treatment plants, there are 12 in all regions. Specifically, the Peripheral Center region has only one treatment plant, located in the municipality of Ciénega de Flores, which began its operations in 2007 with an initial installed capacity of 50 L/s.

The Northwest region has two plants located in the municipality of Anáhuac—the first plant started operation in 1990 and currently has 65% of its installed capacity (20 L/s), and the second plant commenced operations in 2006 and currently has 94% of its installed capacity (100 L/s).

The Northeast, South, and Valle del Pilón regions have three plants each. The Northeast region uses 36% of its installed capacity. Since the 250 L/s of installed capacity purify only 89.12 L/s, two of the plants are in the municipality of China and another in Los Ramones. The plants in China use 36 and 40% of their installed capacity, respectively, while the Los Ramones plant uses 32%. The plants located

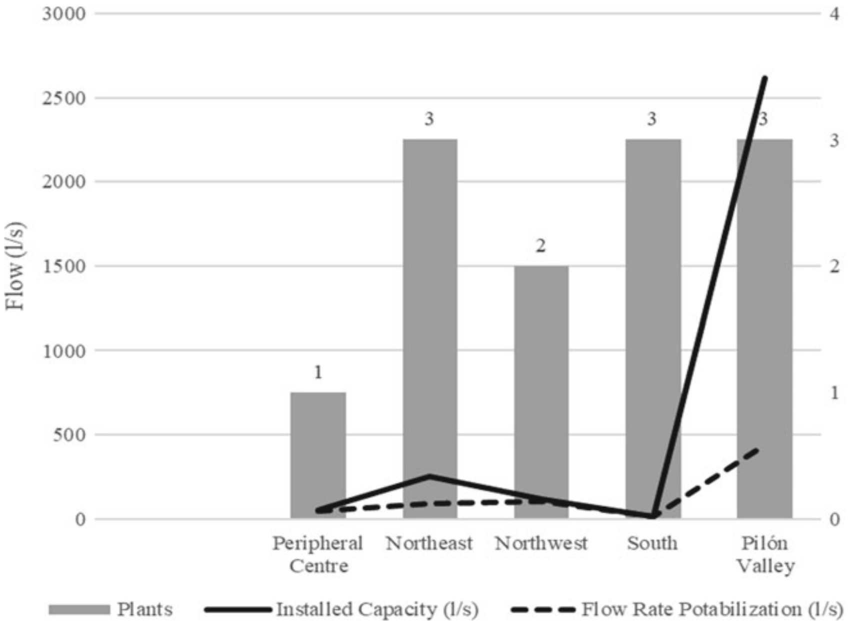

Fig. 16.5 Water treatment by region (SADM 2017)

in China were set up in 1992 with an installed capacity of 220 L/s, and in 2007 with 5 L/s, respectively. The Los Ramones plant is the most recent one as it started operations in 2013, with 25 L/s.

The southern region also has three water treatment plants (all three are located in the municipality of Doctor Arroyo). One of these plants began operations in 1975 and has an installed capacity of 0.2 L/s—however, SDAM reports it as currently "in reserve." The other two plants started operations in 2007 and 2013, having capacities of 12 and 2 L/s, respectively, and utilize 93 and 80% of their installed capacity, respectively.

Finally, the Valle del Pilón region has three plants located in the municipalities of Linares, Santiago, and Allende, with a percentage of installed capacity use of 65, 13, and 53%, respectively. Also, these three plants are the ones that have more years of use in the regions analyzed since beginning operations in 1932, 1964, and 1988.

16.3.6 Storage and Regulation Infrastructure

Water distribution systems are composed of different infrastructures that, together, must ensure the distribution of water with good quality and adequate water pressure for each network. As part of this infrastructure storage and regulation, tanks should be mentioned. Usually, these tanks must have water storage volume for three main

Table 16.2 Storage capacity in tanks (SADM 2017)

Region/municipality	Total		Active %
	No. of elements	Capacity (m^3)	
Peripheral Center	22	7635	66.7
Northeast	34	5140	39.5
Northwest	37	8551	64.9
South	75	8171	82.4
Valle del Pilón	115	13,948	79.3
General total	283	43,445	68.7

functions: regulating, storing (this volume is used in case of source failures), and fighting fires. According to the topography of the area where the construction of the tanks is intended, these can be designed as elevated tanks, for cases of very flat and surface lands, where high areas are available near the point of supply (CONAGUA 2015a).

Given this situation, the Department of Non-Metropolitan Municipalities of SADM provided the database whereby the inventory of storage tanks is shown (Table 16.2). It has all existing tanks, highlighting the storage capacity and the type of tank (elevated or on the surface). It is worth mentioning that the information provided considers both the infrastructure in use and the one that is not currently being used. However, the reason for which a part of this infrastructure is inactive is unknown because SADM did not provide this information.

Regarding the storage infrastructure, these regions have a storage capacity of 43,445 m^3 in 283 active elements, out of a total of 412, which represent 68.7% of the active elements. Specifically, they have 82.4% of active elements in the South region with a storage capacity of 8171 m^3 whereas the Northeast region has 39.5% of active elements with a storage capacity of 5140 m^3. These values represent the maximum and minimum of the regions, respectively. The Valle del Pilón region has the largest storage volume with 13,948 m^3. The Northeast region is the one with the lowest storage. The capacity shows 0.030 m^3/inhabitant in the Peripheral Center region, 0.122 m^3/inhabitant in the northeast, and 0.066 m^3/inhabitant in the northwest. The south has the lowest index with 0.007 m^3/inhabitant, and the Valle del Pilón has a ratio of 0.058 m^3/inhabitant. The stored capacity average ratio of the five regions was 0.056 m^3/inhabitant.

16.3.7 Piping Lines

The piping infrastructure for water supply to the non-metropolitan municipalities was grouped into three categories, or types, of elements that represent most of the total of pipes. These are aqueducts, supply lines, and home network lines. Aqueducts represent the pipelines of greater capacity that are used to direct water from the source of supply to the vicinity of urban or rural towns. Further, supply lines are connected to the aqueducts to distribute this resource to the main sectors of towns, and home network lines dispense the water at the finest level, waiting only for the individual connection of each outlet.

SADM's Engineering Department provided information regarding water piping through a geographic information system (GIS), which is continuously updated with information on hydraulic infrastructure or pipe network. Based on the information from the GIS, regarding the water supply piping lines in the State, a spatial overlap was made within the limits of the municipal political division, which is reported by INEGI in the Consultation System for 2010 Census Information. Subsequently, using geospatial functions of the GIS, the linear meters of pipelines in each of the regions were obtained.

The analysis showed that the Peripheral Center region has a total of 979.9 km of pipelines, from which more than 70% are domiciliary pipes. This region presents a little more than 90 km of aqueducts, which are responsible for the principal piping. The municipality of Hidalgo has the most considerable length of aqueducts in its territory. However, regarding lines of conduction at supply and domiciliary level, Ciénega de Flores, El Carmen, General Zuazua, and Pesquería stand out in the region. Regarding the total number of piping lines, General Zuazua and Pesquería have more than 200 km of pipeline, whereby Abasolo and Marín are the municipalities with the shortest length. In the Northeast region, 143.3 km of the aqueduct, 188.7 km of supply lines, and 390.3 km of domiciliary distribution lines have been installed. The municipalities with the longest pipe measured are China, Cerralvo, and Los Ramones, with 138.3 km, 94.2 km, and 85.5 km, respectively. The municipalities of Agualeguas, Doctor González, General Treviño, Higueras, Los Aldamas, Los Herreras, and Melchor Ocampo have an entire piping infrastructure ranging between 25 and 42 km. Out of the nine municipalities that make up the Northwest region, two do not have the aqueduct-type infrastructure, namely Anáhuac and Parás. The rest of them total a little over 54 km of aqueducts for transportation of water supply. From these municipalities, Mina stands out with almost 31 km of piping of this type, followed by Sabinas Hidalgo who has 13.9 km. Total piping infrastructure in the region is 712 km of pipelines, from which Sabinas Hidalgo, Salinas Victoria, and Anáhuac have the largest quantities, presenting 212.6, 168.4, and 125.1 km, respectively. The South region has 795.8 km of total pipelines, from which 124.8 km are aqueducts, 459.4 km are supply lines, and 211.6 km are lines in domiciliary networks. The municipality of General Zaragoza does not have aqueducts. Among the municipalities of the region, Doctor Arroyo stands out, with the most complex network of 55.6 km of aqueducts, 265.3 km of supply pipes and 119.5 km of domiciliary lines, representing more than 50% of the total piping infrastructure of the region. The Valle del Pilón region has the most significant number of piping lines, with 960 km distributed in 175 km of aqueducts, 172.9 km of supply lines, and 612 km of domiciliary supply lines. Linares and Montemorelos stand out in total pipelines with 234.9 and 212.9 km, respectively. In general, non-metropolitan municipalities have 4170 km of piping lines, with little more than 587 km of aqueducts, 1138 km of supply lines, and 2444 km of domiciliary distribution lines. The Peripheral Center and the Valle del Pilón region have the highest total values, with 979.9 and 960 km, respectively. The Northeast, Northwest, and South regions have pipelines which total more than 700 km. Among the values of aqueduct-type conduction infrastructure lengths, the Northwest region has the lowest, with a total of 54 km. Similarly, the Peripheral Center region has 90 km of the aqueduct, while the rest exceeds 100 km. As expected, the regions that have the largest populations have a more considerable amount of infrastructure for piping at the domiciliary level, with the maximum amount of just over 700 km found in the Peripheral Center region.

16.3.8 Age of the Distribution Network

There is a total of 4170 km of pipes in Nuevo León among aqueducts, supply lines and domiciliary lines (Table 16.3). Some of them are more than fifty years old or a little less than ten years old. Table 16.3 shows the age of the infrastructure at the State level, with detailed data at the regional level. There is an issue, due to lack of information in this area, in the catalog of SIG database, since approximately 58% of the elements do not show the information (that is 2420.3 of the 4170.6 km of the State pipeline). From those remaining and showing the installation date, 52.5% are less than ten years old, 42.4% are in the range of 10–20 years, and 2.36% are between 20 and 30 years. Of the pipes, 2.72% are older than 50 years. At the regional level, the Northwest and the Peripheral Center have a relatively more modern piping infrastructure—that is, 78.2 and 64.62% of their pipes were installed less than ten years ago. On the other hand, the Northeast, South, and Valle del Pilón regions present infrastructure that was mostly installed between 10 and 20 years ago.

16.3.9 Improvement of Efficiencies

According to CONAGUA (2012), the efficiency of water supply systems relates to "the ability to capture, conduct, regulate, purify and distribute water, from the natural source to all consumers, with total quality service." These indicators are measured in three areas for water supply service institutions: the physical production and distribution system, the commercial sphere, and the institutional administrative sphere. However, the most common indicators in these studies are physical, commercial, and overall efficiency.

Physical efficiency "Efis" (Eq. 16.2) refers to the conservation of water in the supply system, and it mainly shows the capacity of a supply system to deliver end users the water injected into the network and the magnitude of the volume of the actual leaks (CONAGUA 2012). It is obtained by percentage with the following expression:

Table 16.3 Age of piping infrastructure in Nuevo León (SADM 2017)

Region	Age of the piping infrastructure			
	<10 years %	10–20 years %	21–30 years %	>50 years %
Peripheral Center	64.62	30.36	1.60	3.42
Northeast	23.90	62.57	13.54	0.00
Northwest	78.20	20.02	0.00	1.78
South	45.58	54.42	0.00	0.00
Valle del Pilón	24.21	68.46	2.07	5.26
Regional average	52.49	42.43	2.36	2.72

$$\text{Efis} = \frac{\text{Billed volume}}{\text{Produced volume}} * 100 \tag{16.2}$$

The analysis of efficiency studies showed that, on average, the real efficiency rate in the analyzed regions is 36.81%. The Peripheral Center region has the highest physical efficiency at 52.89%, followed by the Valle del Pilón region at 34.54%, the Northeast region at 32.90%, the Northwest region at 32.40%, and finally the South region with a 31.32% rate.

It should be noted that, according to the analysis carried out by CONAGUA in the period from 2002 to 2008 (CONAGUA, 2012), the average physical efficiency in the country was 56.6%. In the Peripheral Center region, the municipality of Hidalgo has the highest efficiency at 71.84%, and the municipality of Ciénega de Flores has the lowest efficiency at 32.52%. In the Northeast region, the municipality of Cerralvo has the highest efficiency rate of 43.32%, and the municipality of Los Aldama has the lowest real efficiency rate at 16.77%. In the Northwest region, the municipality of Salinas Victoria shows the highest efficiency (of all non-metropolitan municipalities) with a 79.66% rate, and the municipality of Ciénega de Flores has the lowest physical efficiency rate at 32.52%. In the Northeast region, the municipality of Cerralvo has the highest efficiency rate of 43.32%, and the municipality of Los Aldama has the lowest efficiency at 16.77%. In the Northwest region, the municipality of Salinas Victoria has the highest efficiency (of all non-metropolitan municipalities) rate at 79.66%, and the municipality of Anáhuac has the lowest rate of 32.52%. Finally, in the South region, the Mier and Noriega municipality has the highest efficiency rate, at 57.75%, and the municipality of Galeana has the lowest efficiency rate in the region at 19.39%.

Unaccounted water "ANC" (Eq. 16.3) refers to the physical losses of water in the distribution systems, due to leaks in the pipes, or storage tanks, or connections, etc. It is the water portion that, having been produced in wells or treatment plants, is not commercialized. It is quantified as the difference between produced water and billed water, divided by the produced water, and is expressed as a percentage using the following equation:

$$\text{ANC} = \frac{\text{Produced volume} - \text{Billed volume}}{\text{Produced volume}} * 100 \tag{16.3}$$

The percentage of unaccounted water is 63.19% in all these regions. The analysis by the region shows that the Peripheral Center region has 47.11% of unaccounted water (the lowest rate in the regions), the Northeast region, 67.10%, the Northwest region, 67.60%, and the South region has the highest rate at 68.68%, followed by the Valle del Pilón region at 65.46%. It is highlighted that the percentage of non-revenue water for the City of Linares was 47.08% in 2011 (SEMARNAT 2017).

The fee assigned to a product or service depends on the process involved in it. In the case of water supply, an equitable and efficient monetary value has been assigned—in other words, having high and low figures should be avoided. It must be such a fee that users can gauge it and not exceed levels that may hinder the rest of the population from accessing water supply. The costs must reflect what is involved in the extraction, treatment, and distribution of water supply (CONAGUA 2015b). The cost of this resource not only depends on the factors mentioned above but also on other circumstances causing the value of the product to vary. This amount of consumption depends mainly on the location of the service if it is located in the vicinity of the metropolitan area, as it is in Monterrey, or if it comes from a foreign system, as in the case of non-metropolitan municipalities. In Nuevo León, collection depends on three types of fees that are assigned to consumers. This classification is in Fig. 16.6.

It should be noted that the type of user can be: domestic, commercial, industrial, or public. Among domestic users, there is a particular ranking, which generates a preferential collection system for people over 70 years of age, pensioners, retirees, widows, and people with disabilities. The initial cost of the fee is determined according to the degree of marginalization of the place. Likewise, the collection is divided in two different ways: (1) for those that only have water supply service and, (2) those that have both water supply and sanitary drainage services. Of the latter, about 25% more is added to the cost of the consumption volume. When the monthly consumption exceeds 200 m^3, users with only water service will pay what corresponds to the value of that consumption, plus the extra unit amount for each additional cubic meter. Users who have consumption from 0 m^3 up to 6 m^3 are charged an extra fixed fee; users who have 7 m^3 up to 10 m^3 of consumption are charged a higher fixed fee than the first rank; and from 11 m^3 upwards, they are charged an extra fixed fee that has an even higher cost than the first two ranks. On average, costs of consumption change monthly because a single rate has not been established throughout the year or period. The final consumption can be determined by calculating or diagnosing each of the situations in which they are immersed. According to the records, from the monthly consumption records of water supply for 2016, provided by the SADM's commercial area, an annual average of the amounts to be paid was made for each cubic meter of water. This data shows an increase of one unit, ranging from 0 to 200 m^3.

Users in the commercial, industrial, and public rankings have a higher amount, due to their higher water demand. Thus, a higher cost is established in their initial fee. It should be noted that the fees for these consumptions are grouped into a single category, creating the same general collection system.

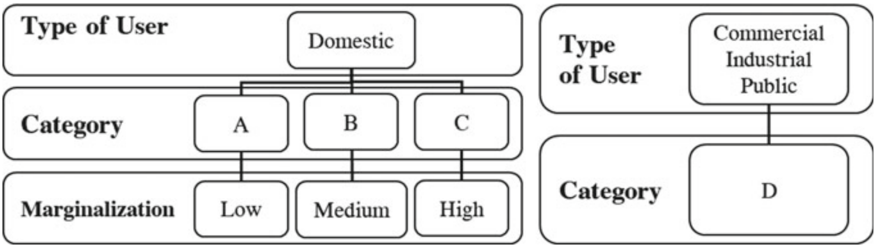

Fig. 16.6 Rate system for the water supply service in Nuevo León (SADM 2017)

The way to collect water supply service data in Nuevo León is through the individual measurement system. It was achieved through micro metering “MicTot” (Eq. 16.4), which is carried out to ensure that users pay only for the volume of water supply consumed and to ensure accurate and error-free invoicing. The coverage of micro-metering is made by dividing the number of outlets with working micrometers, by the total number of existing active outlets and, thus, the percentage is represented by the following equation:

$$\text{MicTot} = \frac{\text{Number of outlets with working micrometres}}{\text{Total number of existing active outlets}} * 100 \tag{16.4}$$

SADM’s Operations Department and Distribution Management provided a report containing the distribution of active services in Nuevo León, as of closing December 2016. This information shows the total number of installed micrometers. It is worth mentioning that, in order to determine the number of working and non-working meters, a percentage of reading anomalies is applied, considering a 2% average in Nuevo León. From the information provided, in total, the regions have 242,440 micrometers. Specifically, the Peripheral Center region has 36.07% of the total micro-metering system, the Northeast region 9.10%, the Northwest region 17.62%, the Valle del Pilón region 29.84%, and the South region 7.37%. In the case of the Peripheral Center region, in 2016, the municipality of El Carmen reported a total of 30,941 Water Service Control ID’s (SIN being its acronym in Spanish) for domestic use. Compared with the total micro-metering system (13,360) for this same use (domestic), this figure represents 42.54%, ranking this municipality as having the lowest percentage of micro metering. On the other hand, the municipality of Villa Aldama in the Northwest region has a total of 2034 SIN for domestic use and micro-metering of 2028 which represents 97.20%—the highest value.

It is necessary to implement a real rating system for the collection of water supply services, to manage this resource more adequately and efficiently, to achieve sustainable use. That is why it is essential to design fees based on technical criteria that are independent of political issues since they represent the main source of revenue for operating organizations to cover for their operation, management and maintenance costs, and to expand coverage and quality of services (CONAGUA 2015b). In Mexico, the most common rates are increasing rates, either continuous or staggered, in which there is a fixed charge, and the charge per cubic meter increases according to the user consumption. The fixed charge is the payment that the user has to make, regardless of their consumption, that allows covering the costs of measurement, billing, collection, and other administrative expenses, for providing the services to end users.

Commercial efficiency “Ecomer” (Eq. 16.5) is obtained by dividing the amounts collected by the amount billed; then it is reported as a percentage as follows:

$$\text{Ecomer} = \frac{\text{Amount collected (without considering late payments)}}{\text{Amount billed}} * 100 \tag{16.5}$$

The average commercial efficiency in the non-metropolitan municipalities is 70.25%, with the Peripheral Center region having 49.53%—being the lowest of all regions, Northeast region has 86.1% and Northwest region 60.73%. The region with the highest percentage efficiency is the South with 86.99%, and the Valle del Pilón having 67.9% efficiency. It is worth mentioning that, according to the analysis carried out by CONAGUA in the 2002–2008 term (CONAGUA 2012), the average commercial efficiency in the country was 73.5%. In the municipality of General Zuazua, within the Peripheral Center region, the lowest commercial efficiency is at 22.33%, whereas the municipality of Marín has the highest commercial efficiency in the region, at 84.23%. Generally, in the Northeast region, the efficiencies are above 75%. Specifically, the municipality of Los Herreras has the lowest commercial efficiency (75.63%), and Doctor Coss has the highest out of all the municipalities (89.87%). The Northwest region, in the municipality of Parás, has the highest commercial efficiency at 89.86%, and the municipality of Vallecillo has the lowest at 54.45%. For the South region, the results of the analysis of commercial efficiency show that the municipality of Galeana is at 71.27% (the lowest) and the municipality of Mier and Noriega has the highest, reaching 93.04%.

Overall efficiency "Eglob" (Eq. 16.6) refers to the volume of water that is charged to end users, according to the total amount of water that channeled into the supply system. This indicator is calculated by multiplying the physical efficiency and commercial efficiency, allowing us to obtain a general performance measurement that represents the percentage of produced water that is paid (CONAGUA 2012).

$$\mathrm{Eglob} = \mathrm{Efis} * \mathrm{Ecomer} \tag{16.6}$$

The average overall efficiency in non-metropolitan municipalities is at 24.63%. The Peripheral Center region has the highest overall efficiency at 30.60%, and at 16.86%, the Northwest region has the lowest overall efficiency of all the regions that were analyzed. These values are below the national average of 44.07% that was obtained from data as of 2002 to 2008 (Lutz and Salazar 2011). Regarding the value of the indicator in the regions, the Peripheral Center region in the municipalities of Marín and Hidalgo have values of 40.57% and 18.56%, being the maximum and minimum values, respectively. In the Northeast region, the municipality of Los Aldamas has the lowest value (13.80%), while the municipality of Cerralvo has the highest value (35.90%). The Northwest region has maximum and minimum values of 27.18 and 9.48% (the lowest of all non-metropolitan municipalities) and corresponds to the municipalities of Parás and Anáhuac, respectively. In the South region, the municipalities of Galeana and Mier y Noriega have overall efficiencies of 12.69 and 49.11%, respectively, being the minimum and maximum values of the region. Finally, in the Valle del Pilón region, the municipality of Linares has an overall efficiency of 15.05%, which is the lowest in the region, and the municipality of Montemorelos has the highest overall efficiency at 29.55%.

16.3.10 Projections

According to population data projections (INEGI 2015), for the Peripheral Center Region, the population projection by 2050 will be 518,396 inhabitants, with the Northeast region estimated as having a population of 51,634 inhabitants. On the other hand, in the Northwest region, the number of inhabitants is predicted at 188,792, while in the South region, 147,212 inhabitants, and finally, for the Valle del Pilón region, a population of 339,000 inhabitants is estimated by 2050.

The supply-water demand and supply projection for the year 2050, the estimated current demand was plot versus the total municipal population. The projected total demand for the year 2050 resulted in 95 Mm^3. For calculating supply and demand, a diagram of physical losses reduction was considered, forecasting 1.5% per year until 2020, 1% per year from 2021 to 2030, and finally, 0.5% from 2031 to 2050. The proposed diagram is a gradual reduction, considering that it is feasible. Figure 16.7 shows the demand projection, with the loss reduction diagram, of the total of the non-metropolitan municipalities.

The following figures show the breaches calculated from the volume of supply sources that was distributed in 2016 (supply), against the estimated demand from the projection to 2050. Note that the calculated supply is considered constant over time.

The analysis between supply and demand of the breaches shows that by 2050 in the Peripheral Center region, the supply would represent 27.78% of the total, with a demand of 34.73% (Fig. 16.8). The Northeast region would have the lowest percentage of regions with 7.79% of the total supply, and demand of 6.10% (Fig. 16.9). For its part, the Northwest region is estimated at 23.11% of the current supply and would be considered 21.56% of the demand by 2050 (Fig. 16.10). Likewise, the South region would represent a percentage of 8.23% with a demand of 7.31% (Fig. 16.11). Finally, Valle del Pilón region would have the highest supply at 33.08% and demand of 30.31% (Fig. 16.12). About the breaches, the Peripheral Center region would have

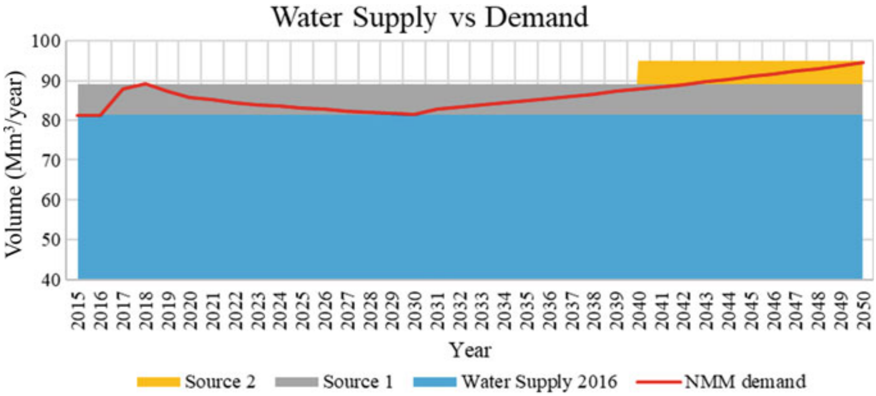

Fig. 16.7 Water supply versus demand by regions. *Source* This work

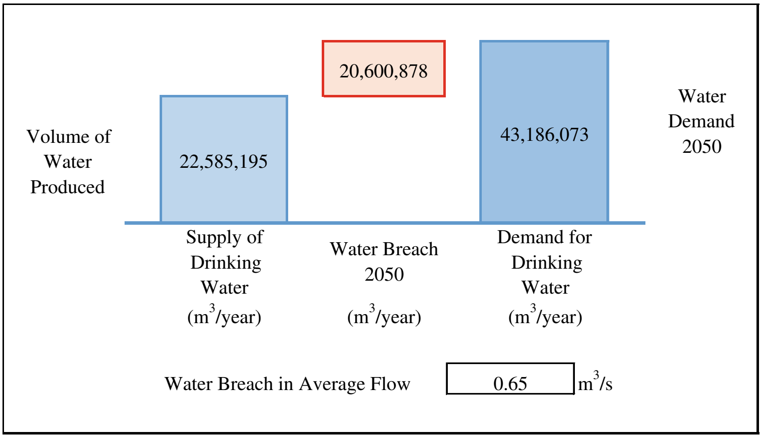

Fig. 16.8 Water breach to 2050 in the Peripheral Center region. *Source* This work

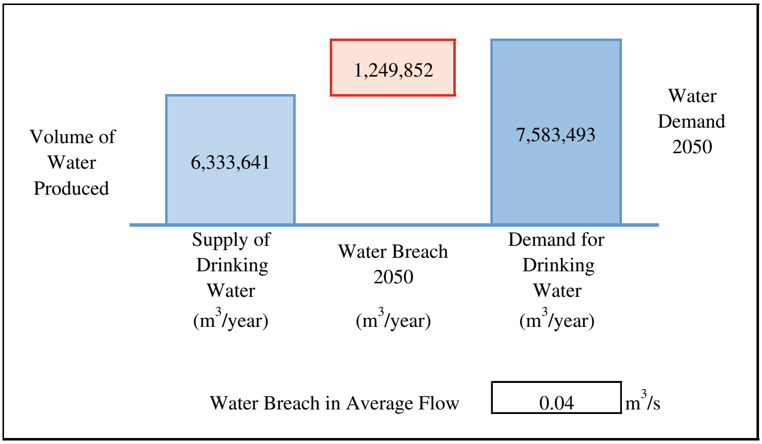

Fig. 16.9 Water breach to 2050 for the Northeast region. *Source* This work

the highest percentage of breaches to be filled, at 47.84%, and the Northeast region has the smallest breaches to fill, at 2.90%. The Northwest, South, and Valle del Pilón regions would have a breach of 18.63, 5.55, and 25.08%, respectively.

Finally, based on the results obtained, it is necessary to fill a breach of 43,062,894 m^3 per year, equivalent to the supply of 1.37 m^3 (Fig. 16.13), while if the reduction diagram proposed is considered, it would be a breach of 13,208,680 m3 per year, equivalent to 0.42 m^3/s.

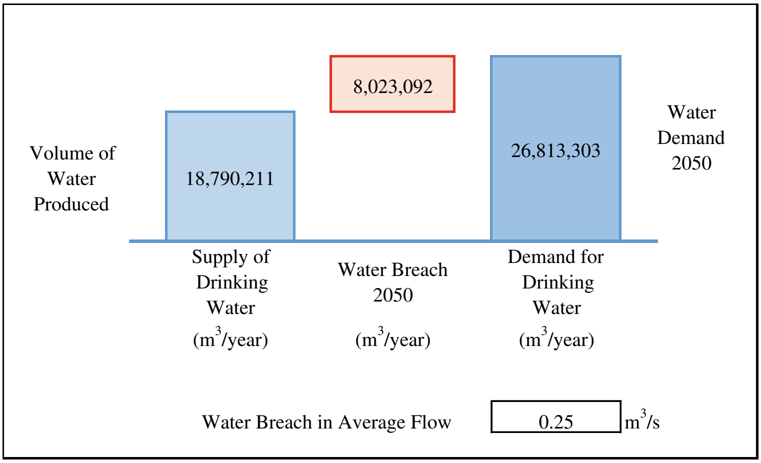

Fig. 16.10 Water breach to 2050 for the Northwest region. *Source* This work

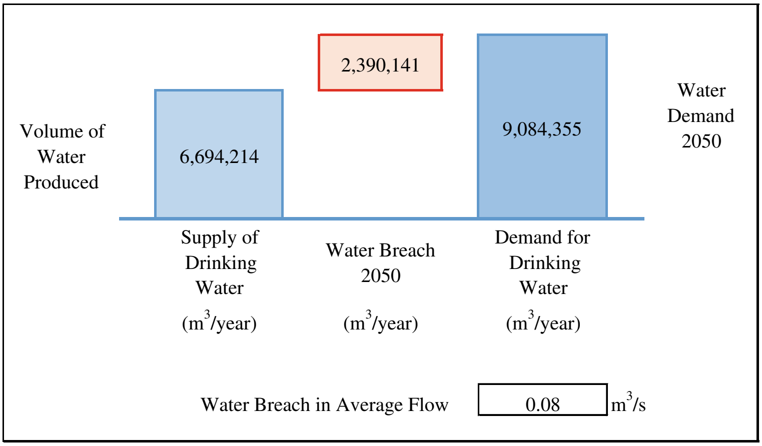

Fig. 16.11 Water breach to 2050 of the South region. *Source* This work

16.3.11 Situation of the Regional Water Supply Services

Table 16.4 shows the summary of the analysis of the information provided by SADM. It is observed that one of the areas of opportunity is about the low physical efficiencies that the service of water supply presents in most of the municipalities that make up the regions. The other area of opportunity pertains to the non-revenue water, since most of the municipalities have high levels of physical water losses in the distribution systems, either due to leaks in the pipes, storage tanks or connections.

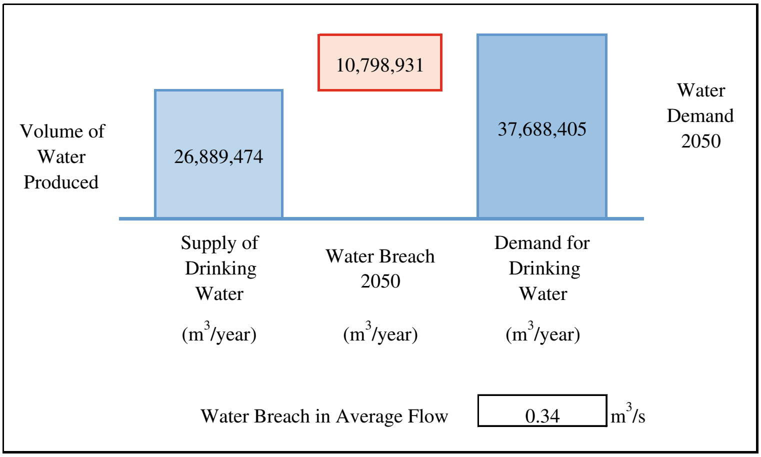

Fig. 16.12 Water breach to 2050 of the Valle del Pilón Region. *Source* This work

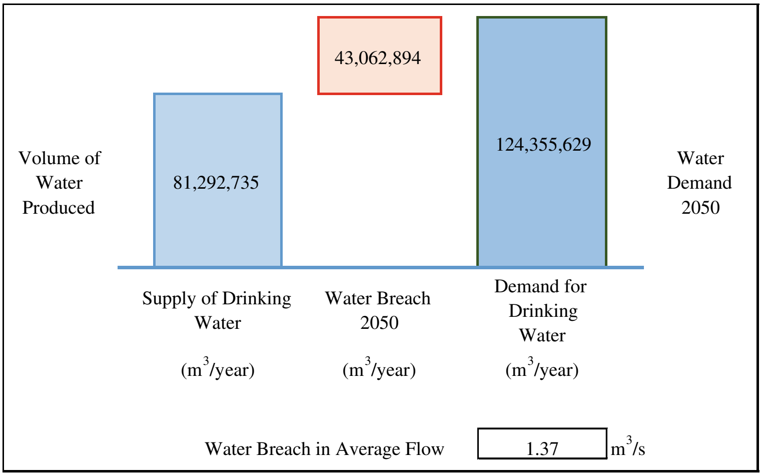

Fig. 16.13 Water breach to 2050 for non-metropolitan municipalities. *Source* This work

Table 16.4 Identified problems by regions (source: own contribution)

Identified problem	Region				
	Peripheral Center	Northeast	Northwest	South	Valle del Pilón
Low coverage of Water supply service	Pesquería	Dr. González Los Ramones	Anahuac Mina Vallecillo	Aramberri Dr. Arroyo Galeana General Zaragoza Iturbide	General Terán Rayones
Very low macro-metering coverage	El Carmen General Zuazua	Cerralvo	Parás Salinas Victoria Villaldama		Linares
No macro-metering present		General Bravo General Treviño			
Low physical efficiency of water supply service	Ciénega de Flores Marín	Agualeguas Cerralvo China Dr. Coss Dr. González General Bravo General Treviño Higueras Los Aldamas Los Herreras Los Ramones Melchor Ocampo	Anahuac Bustamante Lampazos de Naranjo Mina Parás Sabinas Hidalgo Vallecillo Villaldama	Aramberri Dr. Arroyo Galeana General Zaragoza Iturbide Mier y Noriega	Allende General Terán Hualahuises Linares Montemorelos Rayones

(continued)

Table 16.4 (continued)

Identified problem	Region				
	Peripheral Center	Northeast	Northwest	South	Valle del Pilón
Low commercial efficiency of Water supply service	Abasol Hidalgo		Anáhuac Sabinas Hidalgo Vallecillo		Linares Santiago
Non-revenue Water supply	Ciénega de Flores Marín	Agualeguas Cerralvo China Dr. Coss Dr. González General Bravo General Treviño Higueras Los Aldamas Los Herreras Los Ramones Melchor Ocampo	Anáhuac Bustamante Lampazos de Naranjo Mina Parás Sabinas Hidalgo Vallecillo Villaldama	Aramberri Dr. Arroyo Galeana General Zaragoza Iturbide Mier y Noriega	Allende General Terán Hualahuises Linares Montemorelos Rayones

16.4 Conclusions and Recommendations

The diagnosis revealed the areas of opportunity that the operator organization possesses. In general, non-metropolitan municipalities have areas for improvement, regarding water supply. Of the five regions analyzed, the Northwest and South regions presented the lowest indicators. Specifically, the areas of opportunity are about the coverage of the water supply service, the low efficiencies—both physical and commercial, and therefore the overall efficiency. Also, there is an area of opportunity related to macro-and micro-metering. The Peripheral Center, Northeast, and Valle del Pilón regions, although in general presented better values to the other two regions, are below the indicators at the national level. It is worth mentioning that, while the SADM staff was always friendly and accessible, there were many inconveniences regarding the flow and validation of the provided databases. There was a certain degree of disorganization concerning information, and a lack of communication between the different areas of SADM. It is recommended that supply sources be strengthened, distribution efficiencies improved, a permanent program for the detection of visible and non-visible leaks be implemented, damaged pipes be repaired, and clandestine outlets detected. Likewise, the macro-metering should be increased in the sources of supply, storage tanks, as well as micro metering in homes (users). New infrastructures of water supply networks should be built in rural communities by expanding systems. It is also recommended that new alternative technologies be promoted. There is a need for a program of financial support for the preparation and dissemination of educational materials to support the culture of water preservation in the communities. Itinerant campaigns for the installation and replacement of micrometers and billing and collection should be included to increase efficiency.

Finally, it is recommended to collect relevant information periodically and update the analysis of both physical and commercial losses. This information should include the variable costs related to such losses.

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Part IV
Water Management and Governance

Chapter 17

National Parks as Water Sources: Does Governance Contribute to Their Conservation?

Laura Celina Ruelas-Monjardín, Héctor Venancio Narave-Flores and Raymundo Dávalos-Sotelo

Abstract Natural protected areas (NPA) were enacted with the purpose of conserving the biodiversity they shed, and also for maintaining the environmental service related to aquifer recharge. Within the NPA, the emphasis has been given to the creation of national parks because most of them are located in high mountains whereas water sources originate. Within a region, mountains discharge can represent up to 95% of the basin total amount of runoff. The importance of high mountains as water sources manifested in the 1930s, most of them were declared as national parks, due to the pressure to land-use change. In a survey sent to directors of seventeen Mexican national parks, it was found out that water supply to the downstream towns, was one of the most valuable services national parks provide. Supply that ,however, is threatened by the pollution of the water sources, drought due to climate change, and overall, by the lack of coordination among the multiple levels of governance to allocate economic, political, and legal resources national parks demand to comply with the purposes they were decreed to.

Keywords National parks · Governance · Water sources · Conservation

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17.1 Introduction

At the international level, mountains were recognized as sources of water and fragile ecosystems, as per Chap. 13 of Agenda 21 Programme (United Nations Organization [UNO] 1992). Mountain regions, defined as areas more than 1000 m above sea level, make up only 27% of the Earth's continental surface (Ives et al. 1997). However, the share of the world's population of which mountain regions supply with water, largely surpasses this value. For this reason, mountains are often referred to as natural "water towers" because their disproportionately high discharge, compared to lowlands, is of significant hydrological importance (Viviroli and Weingartner 2008). About 10% of the world's population depends on mountain resources. A much larger percentage draws on other mountain resources, especially water (UNO, Agenda 21). Despite these enormous benefits, they are rapidly changing and being threatened by accelerated soil erosion, landslides, rapid loss of habitat, and genetic diversity. Also, human beings living there face widespread poverty and loss of indigenous knowledge.

In Mexico, mountain areas deserve the highest attention. In 2002, the National Forest Commission (CONAFOR) promoted the Sustainable Management Program of Mountain Ecosystems. The purpose of this program was to protect watersheds located in sixty priority mountains, which cover a surface of nearly 7.4 million of densely forested areas which supply water to more than 33 million people living close to 100 major cities. Forest in the headwaters of the basin plays an essential regulatory role since they control the quality, quantity, and timing of the water flow and also protect soil from water erosion. They also help to avoid the loss of soil fertility on the slopes and the siltation and degradation of rivers and estuaries.

Worthy forest cover is the most effective land awning for keeping the water as sediment-free as possible, along with the reducing factors affecting overland flow by increasing roughness of slopes, infiltration of water in the soil, etc. Forest is undoubtedly the best overlay for drinking-water-supply watersheds, as forestry activities do not involve the use of fertilizer, pesticide, and fossil fuel, nor outfalls from domestic sewage, animal waste or industrial processes (Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO] 2005).

In order to reduce land-use change in Mexican mountain watersheds, most of them were declared national parks in the 1930s (Ruelas et al. 2010). Currently, there are 67 national parks (NP) out of a total of 182 natural protected areas (NPA) (Comisión Nacional de Áreas Naturales Protegidas [CONANP] 2017). From these 67 national parks, 16 belong to the marine ecosystem and 51 to the terrestrial ecosystem. Most of them were created through a decree which provides them with legal standing. Most of them have management programs. Despite having such legal and management support, the parks face severe threats that put at risk important environmental services, such as water provision. In general, research on national parks pays little attention to water environmental services. The emphasis is on the biodiversity that they house. Accordingly, this chapter focused on terrestrial national parks, given their relation to mountain ecosystems. It has been organized based on three objectives: firstly, to analyze the relationship between national parks and hydric stress; secondly, to enhance the hydrologic importance of the services the parks provide in a mountain context, and thirdly, to analyze to what extent governance structures and processes—designed for conservation of national parks—have contributed to such an outcome. To reach these objectives, a survey was sent to the directors of forty terrestrial national parks, not including the other eleven land-based parks whose data was missing. The questionnaire, which was sent through the software SurveyMonkey, was answered by fourteen directors of the above-mentioned terrestrial national parks and adapted from the Management Effectiveness Tracking Tool (METT) (Stolton et al. 2007). The adaptation included aspects of governance that contribute, in a high, medium or low manner, to the conservation of the parks. To support the information given by the directors, documents related to the creation, such as the decrees of the parks (which mainly occurred in the period 1936–1962) were reviewed, except for two cases—one in 1860 and another in 1917.

Their management programs were also analyzed, due to their integral part of a planning process that establishes the directives, strategies, and actions to achieve the conservation of park ecosystems. This process is conducted via the ample participation of different key players in the definition of the management policy for the short, medium, and long periods.

The information gathered was organized in three sections: (1) places the fourteen national parks, in the context of the administrative hydrological regions, classified by degree of hydric stress; (2) pinpoints the ecosystemic services supplied by the national parks in a mountain context, and (3) discusses the governance processes and structures designed to achieve the objective of conserving the parks.

17.2 National Parks and Hydric Stress

National parks (NP) are an emblematic category due to the richness they contain. Further, they are pioneers in the protection of protected spaces, at a world scale, and also a referent for the process of declaration of the rest of NPA (Iniesta, 2001, in Prieto 2017). They constitute the better-known category—being national parks, and the one that has the strongest rooting (Gómez-Pompa and Dirzo 1995). The first national park created in the world was the famous Yellowstone Park in 1872 and, as a protectionist movement, it was soon adopted by other countries (González-Ocampo et al. 2015; Prieto 2017). In Mexico, NPs have played an important role in the history of governmental conservation efforts, which goes back a century with the creation of the National Park Desierto de los Leones in 1917 (Villalobos 2000; Tovar et al. 2006). In the period 1934–1940, under the presidency of Lazaro Cardenas, 38 NPs were created and represent over half of the 67 NPs existing today.

These parks were chosen in mountain ecosystems due to their significance in hydrologic environmental systems. The quantification of these services highlights their importance for the world's inhabitants (Table 17.1).

The constant decrease in per capita availability of renewable water in Mexico must be grounds for concern. In the period 1955–2016, per capita availability went from

Table 17.1 Hydrologic environmental services of the mountains of the world

Concept	Amount
Fresh water available in arid zones coming from the mountains	70–90%
Fresh water available in humid areas coming from the mountains	30–60%
Freshwater originating from the mountains	80%
Dense forests in mountain areas	28% of total
World's population dependent on water from the mountains	Over half
Important rivers that flow from the mountains	All of them
Earth surface on mountain zones	24%

Source Adapted from The Panos Institute (2002), Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO) (2000), Denniston (1996)

11,500 m^3/inhab/year to 3687 m^3/inhab/year, i.e., a 68% reduction in six decades (Breña and Breña 2007; Comisión Nacional del Agua [CONAGUA] 2017). According to Godinez et al. 2018: 2, based on CONAGUA (2014), the current gap in the national water balance amounts to 11,500 hm^3 $year^{-1}$, as the sustainable water supply (water use that does not compromise ecological flows nor comes from overexploited aquifers) is estimated to be 66,900 hm^3 $year^{-1}$. The water use of all water users is estimated to be 78,400 hm^3 $year^{-1}$, 36% of it is underground water. This gap is only destined to widen in the future, with an expected doubling figure of 23,000 hm^3 $year^{-1}$. All uses are expected to grow, including agriculture, public, and industrial. Thus, hydric environmental services provided by mountains must be re-evaluated. Two national parks, namely the Constitución de 1857 and Volcán Nevado de Colima, are within watersheds whose administrative hydrologic regions (RHA 1 and VIII) present moderate stress (CONAGUA 2017). Although the Constitution of 1857 is connected to another system of international mountains, such as the Rocky Mountains, there is also a national park with the same name, that is, they utilize between 10 and 20% of renewable water (RW) (more than 1000 and less than 1700 m^3/inhab/year). Two other national parks, Cumbres de Majalca and Cumbres de Monterrey, are in basins of the region RHA VI which present medium to high stress since they use between 20 and 30% of RW (over 500 and under 1000 m^3/inhab/year). Further, two national parks, El Tepeyac and Desierto de los Leones, are in basins of region RHA XIII which present high stress, that is, they utilize more than 40% of the RW available, and their inhabitants have less than 500 m^3/inhab/year. Paradoxically, in the administrative regions with higher stress, the greatest GNP percentage of the country is generated, based on the highest concentration of people.

For example, basins in region RHA XIII Aguas del Valle de México, VIII Lerma-Santiago, VI Río Bravo, and I Península de Baja California account for 33.01% of renewable water, provide 82.31% of GNP and contain 76.95% of the country's population (CONAGUA 2017), with data from (Consejo Nacional de Población [CONAPO] 2012, Instituto Nacional de Estadística y Geografía (INEGI) 2016a, b; CONAGUA 2016a). The remaining eight parks Cascada de Basaseachi, Sierra de Organos, Barranca de Cupatitzio, Gogorrón, El Chico, Cañón del Río Blanco, Cofre de Perote, and Pico de Orizaba are in regions RHA (II, III, IV, IX, and X) with low stress, that is, they use less than 10% of renewable water.

It is not predicted that this stress situation will improve in the future. The following figures illustrate this scenario. Mexico is among the top countries of groundwater consumption that exceeds its recharge (World Economic Forum 2011); six of its rivers are among the world's most depleted freshwater sources; it is number seven in the world for the most water extracted (Comisión Nacional del Agua y Secretaría de Medio Ambiente y Recursos Naturales (CONAGUA-SEMARNAT) 2016), and it is also the largest groundwater user in Latin America (Scott and Banister 2008). The general trend is that water availability per capita will decrease in time as population increases (Godinez et al. 2018).

Climate change will also affect the capacity of national parks to provide hydric environmental services. In 2020, El Chico National Park will experience a reduction of 70% in the amount of annual infiltration, according to a British prediction model, and a 15% reduction as per a North American predictive model, showing volumes of 0.4×10^6 m^3 and $1, 26 \times 10^6$ m^3 of water, respectively (Monterroso et al. 2008).

This stress condition, which affects the mountain basins of the administrative hydrological regions where the parks are located (Fig. 17.1), adds to the complex problem detected by Arriaga et al. (2009) for the 110 priority hydrological regions of the country, which are located in an area of 777,248 km^2 of the main hydrographic basins in Mexico.

The problems identified are:

- overexploitation of surface and subterranean water, which causes a significant reduction in the amount of water available;
- saline intrusion;
- desertification and decay of water systems;
- pollution of shallow and deep aquifers—mainly due to urban, industrial, agricultural, and mining outfalls that provoke diminished water quality and eutrophication;
- activities that modify the landscape, such as deforestation, basin alteration, dams, and channels construction;
- drying and filling out of flooded areas, and
- the introduction of exotic species to water bodies with the consequent displacement of native species and the reduction of biological diversity.

This varied problems that mountain basins face requires a precise analysis, which highlights the hydrological importance that national parks have regarding water availability—including an adequate amount and quality, not only for human beings but also for the ecosystems that depend on water supply. Next, the environmental services being provided by the parks, as mentioned by the park directors, are described.

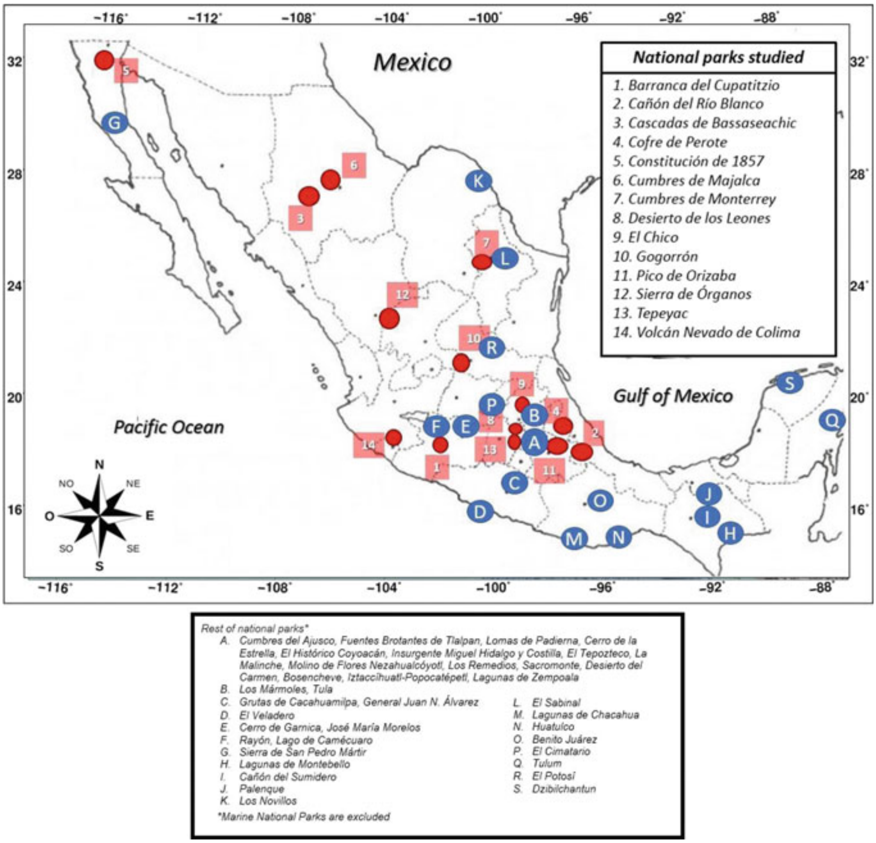

Fig. 17.1 Location of the terrestrial national parks. *Source* Designed with own data

17.3 Hydrologic Importance of National Parks Studied

In Mexico, mountains are considered as priority systems for conservation due to their biological value and water resources. As water towers, most of them have been protected to ensure their hydrologic services. Before defining how the national parks contribute to this purpose, a brief description of each of the 14 national parks is provided in Table 17.2. As can be seen in Table 17.2, parks exhibit a contrast regarding the surface they protect. They span from 458 ha to 177 395 ha. Also, most parks were decreed during the period 1934–1940. These protected mountains (Nevado de Colima, Tepeyac, Gogorron, Barranca de Cupatitzio, Cañón del Río Blanco, Cumbres de Majalca, Cofre de Perote, and Pico de Orizaba) are key to water capture and aquifer recharge. The Gogorron covers areas of the mountains of the Sierra San Miguelito, which is an essential area for capturing water for the recharge of the aquifer, which is shared between the states of Guanajuato and San Luis Potosí. In this park, the species *Quercus potosina* captures part of the water that

Table 17.2 General data of the national parks studied

Name	State of Mexico	Year of creation	Surface (ha)
Barranca del Cupatitzio	Michoacán	1938	458.21
Cañón del Río Blanco	Veracruz	1938	48,799
Cofre de Perote	Veracruz	1937	11,549
Constitución de 1857	Baja California	1962	5009.30
Cascada de Basaseachi	Chihuahua	1981	5802
Cumbres de Majalca	Chihuahua	1939	4701.27
Cumbres de Monterrey	Nuevo León	2000	177,395
Desierto de los Leones	Ciudad de México	1917	1529
El Chico	Hidalgo	1982	2739.22
El Tepeyac	Ciudad de México	1937	1500
Gogorrón	San Luis Potosí	1936	38,010
Sierra de Órganos	Zacatecas	2000	1124
Pico de Orizaba	Veracruz	1937	19,750
Volcán Nevado de Colima	Colima	1936	6554
			Total 324,920

Source Designed with authors' data

is percolated in rhyolite fractures, since it can penetrate these fissures and capture this water. Artesian wells have been built, whose waters are for medicinal use. The aquifer which contributes to its recharge is used for agriculture, livestock, and tourism activities. The Santa Ana Dam is part of the infrastructure that has been built. The Desert of the Lions National Park is located within two mountain ranges that enclose the eastern part of the Valley of Mexico, namely the Sierra de las Cruces and Sierra del Ajusco. Here are numerous streams and small dams that still feed two rivers of the Valley of Mexico—the Rio Mixcoac River and Rio Hondo River. Initially, Mexico City was supplied from the large number of springs which existed and which, to date, continue to supply a part of this city.

El Chico NP, although decreed with this name in 1982, functions as a protected area since 1960. It was created with the aim of protecting the area from the immoderate tree felling carried out by mining activity at the time. Within the area are several springs, such as, Los Otates, El Pescado, and El Salto, as well as several streams known as the La Sabanilla, Las Animas, Las Goteras, La Peña Sentada, and Gordolobos—all of which are tributaries of the river El Milagro which, in turn, flows into the river Amajac. El Chico NP plays a pivotal role in the water balance of the region with its contribution of water to the basin of the Valley of Mexico and the Panuco River.

The Cascada de Bassaseachic NP, located within the Sierra Tarahumara, which in turn is part of the high Sierra Madre Occidental, was created with the aim of preserving the forest and the use of the waters of the rivers Durazno and Bassaseachic. In the case of the NP Constitution of 1857, its ecosystems of conifer and chaparral forests allow the continuity of cycles and natural processes of great importance among others, the preventive action of erosion and soil drag. It is also an area of great value for water capture and recharge of the aquifers on which the region depends (Secretaría de Medio Ambiente y Recursos Naturales y Comisión Nacional de Áreas Naturales Protegidas (SEMARNAT-CONANP) 2011). The NP Barranca del Cupatitzio was declared in 1938 for its function of rainwater catchment, since their aquifers that give rise to the Cupatitzio River are recharged, which supplies drinking water to the city of Uruapan and generates electricity to irrigate cultivation fields. This river is born within the grounds of the park, in a spring known as "the knee of the devil."

The NP Cañón del Río Blanco is located in the foothills of the Pico de Orizaba in the central mountainous region of Veracruz. It covers the hills of Sierra de Agua, Tecamaluca, Ojo Zarco, Nacoxtla, Huiloapan, San Cristobal, Xochio, Encinal, and Nogales. The Río Blanco is the most important in the region, as it produces numerous waterfalls and flows in the municipalities of Ciudad Mendoza, Nogales, Rio Blanco, and Orizaba. The Cumbres de Majalca NP, located in the mountains topographic system of the Sierra Madre Occidental, is integrated by the valleys of Aluvión de Guerachic, Sacramento, and San Marcos that recharge the aquifers of the hydrological production systems of the lower part of Encinillas, General Trias, and the city of Chihuahua. That is one of the main goals that prompted its creation—the search for sustainability of their natural, scenic, and hydrological resources. Majalca houses two hydrological watersheds, and its vegetation is determinant in the processes of rainfall, runoff, and infiltration of water to recharge the aquifers. These waters feed rivers that support local agriculture and livestock and are taken partially to the city of Chihuahua. It constitutes the origin of several streams, which supply rivers and waters that are exploited for domestic, agricultural and industrial applications. It is considered by Conagua (The National Water Commission) as one of the 40 sites of vital importance for its vegetation cover, about the recharge of aquifers, especially of the rivers Chuviscar and Sacramento. The Cumbres de Monterrey NP, located in the northern part of the Sierra Madre Oriental, is fundamental for the region because it produces approximately 70% of the water consumed by the city of Monterrey, the third largest city of Mexico by population density. In it are the basins of Pesquería, Ramos, Santa Catarina, and San Juan rivers, of which stands the Santa Catarina, as it is the largest catchment area. Water is the most crucial environmental service provided by the park. Therefore, the lack of provision of liquid would mean dramatic changes in the well-being of the inhabitants of the metropolitan area of Monterrey. It supplies water to half of the population of Monterrey and its surroundings, which is four million inhabitants. The Tepeyac NP covers part of the mountain range of the Sierra de Guadalupe. It is one of the few pockets of green areas which are located in the north of Mexico City and does not have a nearby tributary. Formerly, the Lakes of Zumpango and Texcoco bordered part of the hills. Unfortunately, its slopes have been urbanized, so precipitation is lost in the urban drainage system.

The Pico de Orizaba NP is located on the highest mountain of Mexico, which is 5636 m above sea level. From the top of this volcano originate the Blanco, Cotaxtla, Jamapa, Metlac, and Orizaba Rivers, all of which form part of the Papaloapan basin. Further, the Balsas River and its tributaries form the basin of the Balsas and supply water to numerous populations of six municipalities within the state of Puebla and at least 25 municipalities of Veracruz.

The Cofre de Perote NP constitutes a receiving basin of streams that feed rivers, springs, and lakes. It has an important role in the climatology and hydrology for several cities in the region. In this mountain originate the watersheds of the La Antigua, Actopan, and Nautla Rivers. It supplies water to a population of approximately 770,000 people in the region. Finally, the National Park of El Nevado Colima houses the volcano of Colima and the Nevado de Colima, in the highest part of the mountain system—being the Sierra de los Volcanes and at the western end of the Neovolcani axis. The drainage system of the great massif empties into the Tuxpan River, which initially serves as a boundary between the states of Colima and Michoacán, and then between Colima and Jalisco, along with the tributary Rio Salado that goes 18 km from the city of Colima. Finally, the Río de la Lumbre serves as a limit to the States of Colima and Jalisco. The vegetation cover that it sustains plays a significant role in the infiltration of water from rain and thaw. It is also a key factor for the recharging the aquifers that make possible the agricultural, livestock, industrial, and urban activities of the valleys of both states in the lower parts of the orographic system.

17.4 Governance Structures in the National Parks

Governance refers to the interactions among structures, processes, and traditions that determine direction, how that power is exercised, and how the views of citizens or stakeholders are considered by those making decisions (Graham et al. 2003). Governance has been recognized as a determinant to the conservation of protected areas throughout the world (World Commission on Protected Areas (WCPA) 2003), within which national parks are included. In Mexico, the General Law of Ecological Balance and Protection of the Environment (LGEEPA for its Spanish acronym) establishe the structures and processes for the planning and management of the NPs. Within the structures of management, the management program and the Advisory Council remain as key components for the governance process at the national park level. The management programs are defined in the rules of the LGEEPA, art. 3 frac. XI, as the governing instrument of planning and regulation which establishes the activities, actions, and basic guidelines for the management and administration of the respective protected area. In this sense, the surveyed park directors responded that 79% of the NPs have a management program, 10.5% were in the process of being published at the time of the interviews and another 10.5% does not have one at all. In what measure, are MPs being implemented? An amount of 35% is being executed at a high level, and they are Constitucion de 1857, Gogorron, Sierra de Organos, Volcano Nevado de Colima, and Desierto de los Leones. In 43% of cases, it is being implemented at a middle level, namely: Cofre de Perote, Pico de Orizaba, Cumbres de Majalca, El Chico, Cascada de Basaseachi, and Barranca del Cupatitzio.

The Advisory Committee remains as the mechanism by which the views of citizens or stakeholders are considered by those making decisions. It has its legal standing in arts. Parts 19–30 of the LGEEPA regulation, establish which sectors of the government and society must be represented. Its function is to advise and support the directors of the NPs in aspects of management of these spaces. It was found that only 64% of NPs have this mechanism for participation that contributes to governance in national parks. It was also discovered that in the parks that have this mechanism, 33% is being carried out at a high level and 77% with an average level. The federal government has the largest level of participation on the boards through institutions such as The National Forest Commission (CONAFOR), Federal Attorney of Environmental Protection (Profepa), and Ministry of Environment and Natural Resources (SEMARNAT). Next in the level of participation is the academic sector, through research projects, organization, training, and environmental education. A third level is the social sector in reforestation, control, and combat of forest fires, monitoring, cleaning, and maintenance actions. In the final level are Civil Society Organizations (CSOs) in conservation, reforestation, organization, and training. If governance means a new way of governing, different from the old hierarchical model, in which government authorities exercise sovereign power over groups and citizens who constitute the civil society (Mayntz 1998), it could be said that the hierarchical model still predominates in national parks.

Despite this mode of governance, and if the percentage of forest cover that conserves the parks is taken as an indicator, it can be said that the structures of governance have been working, since about 75% of the NPs studied maintain a coverage between 75–100% and the remaining having coverage between 51–75%. With this, it can be shown that governance processes that occur via public participation, through the Advisory Committee, have also contributed to the levels of conservation of parks regarding vegetation cover (Beaumont 1997; Lane 2001; Stoll-Kleemann and O'Riordan 2002).

17.5 Concluding Remarks

National parks located in protected mountains have played a key role on the water supply to the downstream population. The provision of this environment service highlights the need to investigate mountain national parks as water towers, as well as hotspots of biodiversity. The diminishing per capita availability in six decades, from 1955 to 2016, which went from 11 500 m^3/inhab/y to 3687 m^3/inhab/y, proves that mountains must be re-evaluated. Although a hierarchical model of governance still predominates in national parks, this has had a key influence on the levels of conservation, measured as the percentage of forest cover. Perhaps the agency structure, represented by the federal government, has received important feedback from the advisory committees, which ultimately influence decision making.

From a century ago (on average), that parks were enacted, arguably, they play a strategic role in the conservation of mountain watersheds that are a source of water for basin users downstream. What should be reinforced in the management and operation of parks is the business of financing and capacity building at local levels, since there are already parks that are administered by state and local governments.

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Chapter 18
The Institutional Challenges in the Sanitation of the Municipalities in Mexico: The Case of Zacatecas

Patricia Rivera and Refugio Chávez

Abstract In the last decade, the State of Zacatecas has had significant progress in the construction of treatment plants. This progress comes from a state intervention that has centralized the treatment in urban areas with plants of advanced technology. As a result, this has allowed the state to pass from a national position, of one of the lowest levels of wastewater treatment, to an intermediate position, whereby approximately half of the treatment plants operate. Despite this progress, it is necessary to identify and analyze the limitations that municipalities face in the treatment of wastewater, from an institutional capacity perspective. This analysis is based on the state and official national inventories (and other sources) on treatment plants, a review of regulatory compliance and semi-structured interviews with officials involved in the matter. The importance of the urban factor in water treatment is highlighted, as well as the lack of a long-term action program. Methodologically, changes in official sources stand out, making evaluation difficult over time.

Keywords Treatment plants · Municipalities · Zacatecas

18.1 Introduction

Population growth demands increasing amounts of water. Since ancient times, rivers, lakes, and seas accumulate indiscriminate discharges derived from human activity. These discharges, together with over-extraction and low treatment capacity, have generated excessive pollution that has worsened over the years.

In general, there is an imbalance between the water extracted from the subsoil (aquifers) and the treated water. Untreated wastewater is an important pollutant vector when it infiltrates the groundwater, but also pollutes the air when it evaporates and

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causes odors or generates volatile particles. It is noted that the lack of treatment has three significant impacts: (1) water quality is modified and causes changes in the ecosystem, production activities and population dynamics; (2) the volume of water available for consumption is reduced; and, (3) in drought seasons, the pollution becomes more acute. Also, if these contaminated waters are used in agriculture, they indirectly lead to public health problems. Consequently, this presents a severe problem that must be analyzed and addressed.

In Mexico, wastewater discharges are divided into two sectors—municipal and industrial. The municipal areas are those unloaded by urban centers into the urban and rural sewerage systems (CONAGUA 2014). The industrial parts are discharged directly to the nationally-owned receiving water bodies (however, the industries that are inside the urban areas discharge their sewage into the urban sewage system, so they are accounted within the discharge of water for urban use).

For several decades now, following international regulations and attending to national needs and local contexts, Mexican governments and agencies in charge of water management have placed the wastewater treatment process as a priority. Furthermore, they have set it as a central strategy in the supply, preservation of water excellence, improvement of the quality of life, protection of public health and a way to advance towards sustainable development. The evolution of the service in Mexico has been remarkable during the last eight years. However, the challenges remain considerable, and the context in which the institutional treatment policy has been developed is far from being efficient or effective.

We clarify that although the sanitation of wastewater involves different interrelated phases—namely, collection, transport, treatment and adequate disposal to the receiving bodies (under conditions that the environment itself achieves the repeating process of assimilation and re-assimilation, without harming the ecosystem or the health of the population). This work will focus specifically on the treatment analysis as, we believe, it has greater lag.

This analysis aims to provide elements to identify institutional capacity constraints, faced by the municipalities in wastewater treatment, which can be useful in creating solutions to such issues. This vision of institutional capacity is made up of two components—the political capacity and administrative capacity. The first part is defined by Rosas (2015, p. 56) as “the political interaction that state actors and the political regime establish within the framework of certain rules, norms, and customs with the socioeconomic sectors and with those that operate in the international context.” This interaction generates complex cooperation networks, known as intergovernmental relations (IGR) (Rosas 2015, p. 58). The second part is understood as “the technical-bureaucratic skills of the organization to implement its official objectives” (Rosas 2015, p. 55). The central elements of administrative capacity are human resources and organization.

This analysis focuses on the State of Zacatecas, where a series of problems that reflect the national situation is pointed out. The work is divided into the following five sections: (1) introduction; (2) background and causes of wastewater treatment in the country; (3) current national regulations and political constraints that prevail in the provision of the service; (4) description of the treatment plants in the State of

Zacatecas, including a chronological analysis, the types of treatment used and the influence of urbanization; and (5) reflections on the progress and challenges of the national institutional process, through the example of the State of Zacatecas.

18.2 Relevant Background of Wastewater Treatment in Mexico

In general, water supply services (obtaining clean water to supply a population) have always had greater attention compared to sanitation. This logic, which prioritizes only one part of the water in the hydrological cycle, condemns untreated water to reincorporate into natural channels, creating many negative impacts on the cycle and ecosystems.

According to WHO data (2017, p. 10), 2.3 billion people lack any sanitation, and 6 out of 10 people, from of a total of 4.5 billion people, lack safe sanitation—the one that hygienically guarantees that the individual has no contact with fecal matter (>58% of the world population). According to the United Nations, about 2212 km^3 of wastewater per year are released to the environment as municipal and industrial water flows, as well as agricultural drainage (WHO 2017, p. 2). These waters represent the primary sources of organic pollution (measured as biochemical oxygen demand—BOD), which have significant impacts on freshwater and coastal marine ecosystems. Further, they have a direct impact on fishing in inland waters, whereby they can increase groundwater contamination and thus, compromise food security (agriculture and fisheries) and the subsistence of poor rural communities that depend on them (WWAP 2017, p. 14).

For the United Nations (2017), globally, more than 80% of wastewater is discharged without treatment. However, the level of treatment is generally a function of the level of wealth. On average, high-income countries treat about 70% of wastewater generated, while in middle-high income countries, it is only 38%. In low-income countries, 28% of wastewater is treated and, in developing countries only 8%.[1] In the case of Latin America, it is estimated that only 20% of municipal and industrial wastewater is treated. In the latter, the situation is distressing because the exposure and risk of diseases are particularly high. According to the agency, more than 800,000 people die every year from the consumption of contaminated water or because they cannot wash their hands properly. Likewise, water-related diseases cause 3.5 million deaths per year in Latin America, Africa and Asia (WWAP 2017, p. 10).

It is particularly alarming if we consider that: (a) 80% of the population lives in cities, and a large part of them live in settlements close to contaminated sources; and, (b) the region is one of the most biodiverse and houses a third of the world's water sources. According to the World Bank (2013), the disposal of wastewater

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[1] In poor countries, the volumes of treated wastewater are very low, and those that come from industry or services are much smaller (Lahera 2010).

carries a cost several times higher than the provision of drinking water. However, the socio-ecological cost of not treating them is even greater.

In Mexico, sewerage coverage (which alludes the population living in private homes with a drain connected to the public sewerage network, a septic tank, river, lake, sea, avine or crack) in 2005 reached 85.6%, and it went to 92.8% in 2016. In 2008, the 1833 plants in operation in the country treated 83.6 m^3/s, 40% of the 208 m^3/s collected in the sewage systems, and for the year 2016, there were 2536 plants in operation, which treated 123.6 m^3/s, that is, 58.3% of the 212.0 m^3/s collected through the drainage systems.

That means that existing plants have increased by just over 35%, although installed capacity has increased in higher proportion (from 113 m^3/s in 2008 to almost 181—a growth of more than 53%). However, the treated flow does not have the same proportion of increase, since it went from 83.6 m^3/s in 2008 to 123.6 m^3/s in 2016, growing only 43.32% (CONAGUA 2017). This means that there are plants with greater efficiency, but which are underutilized (Table 18.1).

Data on sanitation in Mexico are presented by region. It is visible that the number of plants in operation, documented in the three periods of 2008, 2013 and 2017, places the (VIII) Lerma Santiago region as the one with the most significant increase, followed by the (III) and (VI) to a much lesser extent. Succeeding these regional advances, concerning installed capacity and treated flow in the same years, the (VIII) region stands as the first one, followed by the (VI) Rio Bravo region and, to a lesser extent, number (XVII).

With the information presented, covering the last decade, there is evidence of an increase in the collection of wastewaters, including municipal and non-municipal discharges. There is a different trend in discharges—that is, an increase in industrial and a decrease in municipal, due to the monitoring of varying policies. Despite these variances, the treatment of wastewater has an increase in both sectors (Table 18.2 and Fig. 18.1) of more than 70%, going from 117.34 m^3/s in 2008 to 199.5 m^3/s in 2016.

Over the last years, the untreated waters still represent more than 60% of the total, and therefore, the tendency is negative regarding water treatment (CONAGUA 2010, 2014, 2017). This trend is mainly explained by the industry, which in 2016 treated only a third of the total discharged, while municipal waters were treated in just over 50%. It is necessary to clarify that in this article we focus on municipal treatment.

The data shows that the goals that the sanitation institutions have proposed have not been achieved. Therefore, an analysis of the institutional capacity is necessary. The institutional capacity is understood as the administrative and political elements in three levels: (1) macro, focusing on the intergovernmental relations (IGR); (2) normative aspects that fix that political framework; and (3) meso and micro which agglutinate the factors within the dependencies that condition the use and transformation of their own resources (organization and human resources) (Loera and Salazar 2017; Rosas 2015). It is worth mentioning that the levels above are developed interdependently and explain each other (Fig. 18.2).

The concept of institutional capacity is a changing theory that is redefined and reinterpreted (Loera 2015; Rosas 2015), according to time, place and who analyzes

Table 18.1 Wastewater treatment plants in operation, 2008, 2013 and 2016

Region	Number of plants in operation			Installed capacity (m^3/s)			Treated flow (m^3/s)		
	2008	2013	2018	2008	2013	2018	2008	2013	2018
I	45	63	72	8.19	9.25	9.55	6.11	6.52	6.98
II	90	102	123	4.54	5.54	8.13	3.18	3.75	4.83
III	249	339	444	8.38	9.92	10.7	6.6	7.72	8.55
IV	147	190	222	7.6	9.89	10.75	5.5	7.76	8.66
V	83	88	95	3.17	4.65	4.78	1.98	3.74	3.77
VI	188	227	238	28.32	33.86	32.81	22.23	23.02	24.3
VII	113	146	160	5.19	6.71	6.98	4.03	5.43	5.47
VIII	465	576	587	23.17	39.8	41.82	18.02	26.52	30.69
IX	91	94	107	2.91	5.63	5.3	2.31	4.27	4.17
X	127	147	161	5.35	7.2	7.53	3.14	5.59	5.37
XI	97	114	116	3.36	4.42	4.74	2.67	2.58	3.85
XII	55	83	78	2.26	3.06	3.16	1.73	1.98	2.11
XIII	83	118	133	10.6	12.27	34.32	6.14	7.05	14.84
Total	1833	2287	2536	113.04	152.2	180.57	83.64	105.93	123.59
% Progress		24.77	10.89		34.64	18.64		26.65	16.67

Source CONAGUA (2010, 2014, 2017)

Note The regions are: (I) Península de Baja California, (II) Noroeste, (III) Pacífico Norte, (IV) Balsas, (V) Pacífico Sur, (VI) Río Bravo, (VII) Cuencas Centrales del Norte, (VIII) Lerma-Santiago-Pacífico, (IX) Golfo, (X) Golfo Centro, (XI) Frontera Sur, (XII) Península de Yucatán, (XIII) Aguas del Valle de México

Table 18.2 National comparison of wastewater and treated water 2008, 2013, and 2016

	2008	2013	2016
Municipal wastewater discharges	235.8	230.2	228.9
Collected water	208	211.1	212.2
Treated water	83.64	105.9	123.6
Non-municipal discharges (industry)	190.4	210.26	217.4
Treated water	33.7	60.72	75.9
Total discharged water	426.20	440.46	446.3
Total treated water	117.34	166.62	199.5

Source CONAGUA (2010, 2014, 2017)

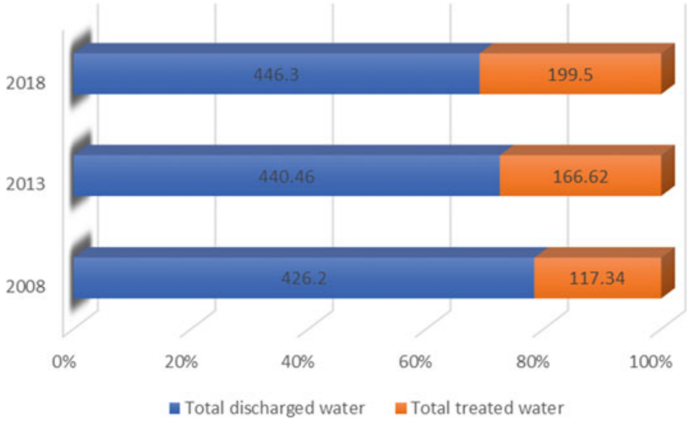

Fig. 18.1 National comparison of total wastewater and total treated water. *Source* CONAGUA (2010, 2014, 2017)

Fig. 18.2 Components and levels of institutional capacity. *Source* Prepared with information from Rosas (2015, p. 59)

it (Rosas 2015)—in other words, according to specific contexts. This concept brings together, as mentioned, the political and administrative capacity. The political capacity according to Rosas (2015, p. 56) is defined as "the political interaction that the actors of the State and the political regime establish within the framework of certain rules, norms, and customs with the socioeconomic sectors and with those that operate in the international context." Following the same author, this capacity is analyzed as a process where legal changes and complex networks of cooperation between the different levels of government and other institutions, operate to achieve compliance with wastewater sanitation, i.e., the intergovernmental relations that occur between actors.

For the emergence of these relationships, a framework of federal and state regulations that identify treatment as a priority is necessary, although, in practice, government action usually prioritizes political profitability. Due to insufficient budgetary resources, the provision of drinking water and the construction of the drainage network against sanitation measures is considered a priority, since the former represents a greater electoral capital and the expansion of the network of influence on the communities. Although there are undoubtedly regulatory advances (such as the recognition of elements, promotion of sustainable development, recognition of environmental functions, etc.), in practice, there is a sharp shock, because essential elements, such as the payment for treatment, are still incipient, and thus limiting the advance to mere speech.

Compliance with regulations also implies "the technical, bureaucratic ability of organizations to implement their objectives" (Rosas 2015, p. 55), that is, the administrative capacity. In the case of water sanitation, we talk about the management of its resources (planning), which is translated into the strengthening and professional development of municipal staff (professionalization, training, incentives), the management of financial resources (income-expenditure control, infrastructure and technology, maintenance, subsidies,), the establishment of rates based on cost-benefit analysis studies, in addition to limiting the interference of political authorities in decision making (autonomy), which allows for better performance (Loera 2015, p. 49).

About planning, the infrastructure available for water treatment does not meet the needs of the population and is inefficient in its operation. An essential part of the plants does not operate or work correctly because of the over and underutilization of resources. That is, some plants operate with deficiencies and treat a higher flow to their installed capacity, while others have an installed capacity greater than the flow of wastewater they capture. This ineffective planning implies high costs. According to CONAGUA (2017), the total installed capacity is 180 m^3/s, although the treated flow is only 123 m^3/s, which means a process efficiency of 68.3%. Further, although the regulations encourage inter-municipal grouping to save costs, many of them do not have the necessary solvency or, put simply, they do not prioritize the operation and handling of their plants so that most of the plants are assigned to municipalities individually.

Infrastructure and technology play a vital role. Treatment plants are inefficient in their operation, for example, inadequate maintenance and lack of training, misuse of treatment techniques and infrastructure lag. The treatment techniques and their degree of complexity equally play a critical part. According to CONAGUA (2014), most of the plants use activated sludge treatment (in 2013, 57.3% of the total used this method), which, remarks Lahera (2010), makes intensive use of chemical and energy products, generates emissions of air pollutants (ammonia) and large quantities of toxic sludge, whose final disposal is not guaranteed. Also, at a national level, according to an assessment of the CONAGUA to a group of treatment plants, most of those that were in operation corresponded to oversized designs in which there is also excessive mechanization, instrumentation, and automation. All this makes it more expensive and complicates the operation and maintenance, as well as the amortization of investments. On the other hand, during the rainy season, the treatment operations are hindered by the widespread existence of drainage systems, in which sewage and rainwater are combined, as well as the discharges of toxic industrial waste, without previous treatment (Romero, in Lahera 2010).

Loera (2015) points out the autonomy of the operating agencies as a critical management factor. The author states: that the higher the autonomy—the better the performance; the organisms must have the mechanisms that allow them to stipulate tariffs that cover or approach operating costs; as well as the possibility of establishing collection rules that guarantee the payment of these. Although the construction of plants has state or federal support, the operation and maintenance are an exclusively municipal cost, which diminishes its margin of action. Thus, the operating agencies become dependent on support from alternative programs, such as financial instruments granted mostly by the federation *Drinking Water, Sewage and Sanitation in Urban Zones* (APAZU); *Program for the Construction and Rehabilitation of Drinking Water Systems and Sanitation in Rural Areas* (PROSSAPYS), or Federal and State participation programs as *Wastewater Treatment Program* (PROTAR).

The treatment of the water does not have ecological recognition, and the benefits that could imply the entry of money in the use and sale of treated water in non-potable uses, are not considered either (Lahera 2010). In the State of Zacatecas, there are already significant advances in the agreements for the sale of treated water (as is the case of the Inter-municipal Water and Sewerage Board of Zacatecas (JIAPAZ)), and even a small percentage of this water is sold. However, there is no necessary infrastructure for the distribution of treated water and the implementation of agreements for the sale of water to larger companies.

As noted, the financial resources are a firm base in the sanitation of wastewater, but this must be complemented with human and professional resources. According to Salazar and Lutz (2016), professionalization is fundamental to improve the effectiveness of organizations, since they assume that meritocracy has better performance, unlike the personnel that entered as part of a payment of political or personal reasons. Also, continuous training and appropriate incentives are necessary to achieve the best development in the sanitation facilities (Rosas 2015; Loera 2015).

In short, for the institutional capacity of an operator in sanitation to have efficient management, it must have clear and precise planning, based on a common objective, where all the instances involved collaborate for its optimal functioning, in an adequate legal framework. Within the organism, it should be noted how to use their financial and human resources, as the autonomy of the body implies a complete mastery of technical criteria in the selection of staff, the provision of incentives to its operational staff, the effective use of their material resources, modern equipment and technology and, especially, the transparency in the finances.

18.3 Water Regulation, Policy, and Management

When analyzing the treatment plants, under various situations, the problems are not only linked to the needs of infrastructure and technical constraints but also the political-institutional role (government) and normative issues. Water treatment is an obligation that belongs to the municipalities. However, the delegation of powers (subject to the political will and a centralist power), in most cases, will not be coupled with technical and financial capabilities and thus, limiting much progress in the field (Vélez 2018).

At the regulatory level, according to Garduño et al. (2003), water administration must be based on a balanced combination of economic, regulatory, participatory, order and control instruments. The Mexican regulations on the subject are intended to be a reflection of this aggregate since the instruments it has been derived from (including the Constitution) the *National Water Law* (LAN) and the *Federal Rights Law* (LFD). They establish the payment for the use of national waters, as well as for the use or exploitation of public goods, belonging to the Mexican government (as receiving bodies of wastewater discharges). If we look at the management instruments in Mexico (Fig. 18.3), the economic item refers to the obligation to pay the charges foreseen in the LFD and, the possibility of transferring water rights. The instruments of order and control, included in the LAN, refer to the inspection and measurement of verification that users comply with the terms and conditions of their concessions, discharge permits, and sanctions, in case of non-compliance. The regulatory instruments mainly include the granting of concessions and discharge permits (for periods between 5 and 50 years). Finally, the participatory instruments envisage the organization of users—for example, to distribute water in an irrigation module and operate and maintain the infrastructure, as well as the establishment of basin councils, to reconcile the interests of federal, state and local governments, with those of the users and other interested groups.

The regulation of wastewater discharges to receiving bodies began in Mexico, with the enactment of the *General Law of Ecological Balance and Environmental Protection* (LGEEPA) in 1988, which allowed, in 1991, to incorporate the charge of the wastewater discharge in the LFD, and, subsequently, the emergence in 1992 of the LAN. These three initiatives established the need for the prevention and control of pollution in water resources.

This normative framework is given a binding character, with the *Official Mexican Standards* (NOM), that establishes the maximum permissible limits of discharges of wastewater in waters or national water bodies (1996), the limits in the discharge of wastewater to urban or municipal sewage systems (1998), the limits of pollutants for treated wastewater that are reused in public services (1998) and the limits of pollutants

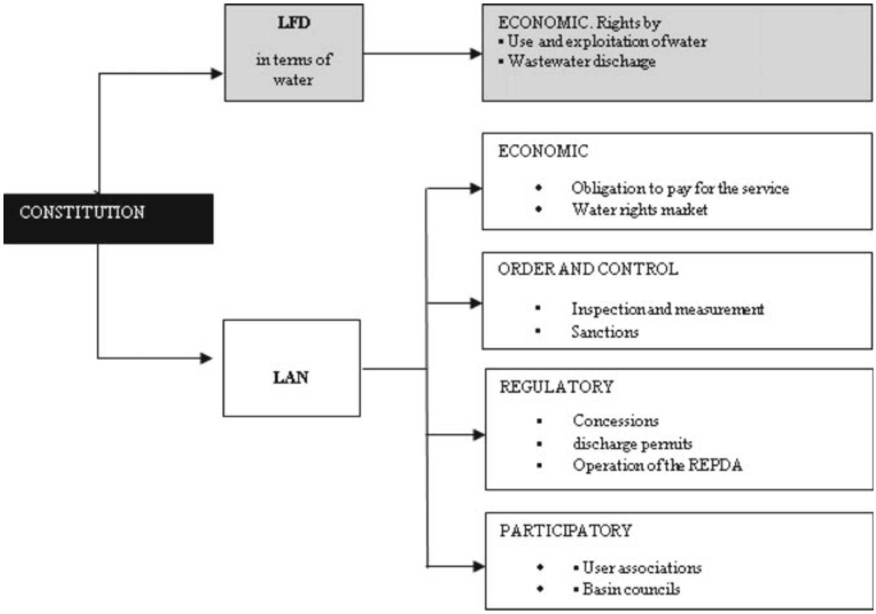

Fig. 18.3 Water management instruments in Mexico. *Source* Garduño et al. (2003)

in sludge and biosolids for their use and final disposal (2003) (SEMARNAT 2014; De La Pena et al. 2013).

With the expedition of the LAN (1992), the concession titles, allocation, and discharge permits are registered in the *Public Registry of Water Rights* (REPDA), in which the rights and obligations regarding wastewater appear. Further, it establishes the permit authorizing the discharge of wastewater to nationally owned receiving bodies, considering the quality determinants indicated in the NOM (Santés and Pombo 2013).

In addition, there are state frameworks that influence the use, management, and treatment of water. Each state has its protocol composed of laws, regulations, programs, and plans, which can be lax according to the economic, technical, and political resources available. In the State of Zacatecas, three important laws can be found:

(1) *Law of the Potable Water, Sewerage and Sanitation Systems of the State of Zacatecas* (Ley de los Sistemas de Agua Potable, Alcantarillado y Saneamiento del estado de Zacatecas 1994, last reformation POG-23-03-2013): regulates the potable water, sewage and sanitation systems of the State (Art. 1 and 4), puts these services in charge of the municipalities (Article 3) or the concessions (Article 3. IV); and it demands sustainable policies in the treatment to prevent and control pollution (Art. 4, VIII).
(2) The *Law of Ecological Equilibrium and Environmental Protection of the State of Zacatecas* (2007) commits municipalities (Art. 8. XI) and housing developments (Art. 55. VII) to carry out the treatment of wastewater from their pro-

cesses, together with an environmental impact assessment for its activities (Art. 58. V), and allows municipalities to grant and use concessions, permits, and authorizations for activities with effects on the hydrological cycle (Art. 89.I-II) (Poder Legislativo del Estado de Zacatecas 2007).

(3) Other state laws with some degree of influence on the matter are the Law *of Sustainable Forestry Development of the State of Zacatecas*, which limits the use of forestry when it puts at risk the socio-ecological balance (Article 81) and requires compliance with ecosystem management programs (Art. 133-V) (Congreso de Zacatecas-LVIII Legislatura 2006). The *Law of Planning Development of the State of Zacatecas* requires coordination between state development policies and legislation on ecology (Art. 4, 5 and 11), (Gobierno de Zacatecas 2003). Also, the *Urban Code for the State of Zacatecas* seeks to reduce pollution and protect the environment from urban growth (Art. 63.I-J) and the development of the real estate sector (Art. 213, 227.V, 228, 229, 236, 240, 325) (Gobierno de Zacatecas 1996).

Furthermore, in Zacatecas, as in most of the country's states, the *Hydric Regional Programs Vision 2030* have been integrated and applied into the 13 Hydrological-Administrative Regions, which establish the medium and long-term strategies for sustainable water use (SEMARNAT 2013).

At the political-institutional level, it is important to mention that each new Mexican government administration formulates, within the *National Plan of Development, the Hydric Nacional Programs* (PNH) (the last one was created in 2014, see Programa Nacional Hídrico (2014)), the *National Program of Infrastructure*, and others, orientated towards seeking the preservation and sustainable use of water resources. For example, the PNH 2001–2006, sought to increase to 65% of the coverage of sewage treatment collected, and restore the quality of national water (although, in the period 2000–2006, it barely reached 36.1%). However, legal, economic and technological instruments were created that stimulated the reuse of treated wastewater, specifically in activities whereby first-use water is not required.

Faced with the Millennium Development Goals, the Mexican government committed to raise the total volume of sewage collected in the country to 60% and placing it as a primary objective in the 2007–2012 PNH (De La Peña et al. 2013, p. 2), although only 47.5% (99.8 m^3/s). In the PNH 2014–2018, it was proposed to expand the coverage of sewerage and basic sanitation to 93 and 99% disinfection, respectively (which would imply the incorporation of approximately 8 million people to potable water service and 8.5 million to the water sanitation service). The increase in the technical, administrative and financial capacities of the organizations that provide these services, as well as the increase and improvement of municipal and industrial wastewater treatment (SEGOB 2014).

Despite the advances, there are still problems of various kinds that traditional management has not yet been able to solve, especially at the local level. The changes in the administration plans and programs, as well as the advances and regressions in the matter, show a permanent conflict in the allocation and use of water by all the stakeholders and administrators (public and private). If we add the critical factors, such as a decreasing supply, increasing demand and climate change—which all increase the pressure on water resources, then we can observe the necessity to strengthen institutional capacities, developing a long-range perspective that can cope with this complex and changing scenario. Therefore, we will analyze the institutional limitations of sanitation in the State of Zacatecas, to illustrate the common deficiencies of the management in the national territory, hoping that these findings can be useful to decision makers.

18.4 Zacatecas: The Results of Management Without a Defined Project

The State of Zacatecas has an extension of 74,502 km^2 and consists of 58 municipalities, which include a total of 4672 localities and 34 aquifers, listed as available (to be exploited). The State of Zacatecas is divided into three river basins: The North Pacific basin (III), the Central North basin (VII) and the Lerma-Santiago-Pacific Guadalajara basin (VIII). In principle, a basin is a territory enclosed by a series of vast mountain ranges, whereby the relief inside that basin can delimit smaller units through which the water drains. Within each basin, management plans are developed, and coordination is carried out by the three levels of government (Federation, State, and Municipalities). The agreement is developed together with users, civil society organizations and the academy.

In the State of Zacatecas, dry and desert climates predominate, and annual rainfall barely reaches 496 mm per year (CONAGUA 2017, p. 273). According to the SEMARNAT (2012), the state water situation—which is a reflection of the national panorama, is aggravated by: (a) the overexploitation of aquifers and groundwater; (b) the pollution of aquifers by mining activity; (c) low efficiency in irrigation; (d) recurrent droughts; (e) inefficient hydraulic infrastructure; and, (f) the intense pressure of the agricultural, urban and industrial sectors for first-use water.

By 2016, the total population was 1,588,418 inhabitants, estimating it at 1.73 million in 2030. It is the eighth largest state (representing 3.83% of the national territory) and, also, the eighth with the smallest number of inhabitants per km^2 (with 19.73 inhab/km^2). In 2015, the state GDP amounted to 130,885 billion pesos, which represented around 1% of the national GDP. The sectors that contributed most were mining (23.6%), trade (13.44%), real estate services (12.57%), manufacturing (9.79%), agriculture (8.4%) and construction (7.68%). In 2016, according to the CONAGUA (2017, p. 274), of the total water extracted by the 96 existing extraction plants, agriculture consumed 85% of the total available water (1475 of a total of 1671 hm^3/year), 11% of it was used by industry (including energy production) and 4% went to public consumption. It is a tendency similar to the national trend, whereby 76.3% is dedicated to agriculture, 9.1% to industry and energy as well as 14.6% to public supply.

The State of Zacatecas has an interesting population aspect—that is, the few growing urban areas are home to 60.78% of the population, with many modest municipalities having a small or decreasing population representing 39.22% of the total. Thus, this explains the lower levels of the provision of drinking water and, particularly in sewerage, as the difference between urban and rural areas reaches 14% (Tables 18.3 and 18.4). Although the percentage is smaller, compared to the 20% difference between the urban and rural national population (CONAGUA 2017, p. 97), it is believed to be the reason why population dynamics and public demands become key factors for the location of treatment plants, as it will be seen later.

Table 18.3 Rural and urban contrast of the state population of Zacatecas in drinking water and sewage services, 2016

Population	Habitants	Population with access to drinking water (%)	Population with access to sewage (%)
Urban	965,508	99.04	98.12
Rural	622,909	95.32	83.46
State total	1,588,418	97.6	93.14

Source Prepared with Information from CONAGUA (2017)

Table 18.4 Type of treatment used in plants

Classification	System	Subtype	Subtotal	Percentage
Primary	Lagoon	Simple	19.1	
		Biofilters	1.5	
		Wetland	1.5	
		Partly aerated	5.9	27.9
Secondary	Biological filters		1.5	
	Activated sludge	Simple	4.4	
		High rate	4.4	
		Thin bubble	1.5	
	RAFA	Simple	17.6	
		Static biofilter	4.4	
		Wetland	7.4	
		Dual	1.5	
	Dual			
		Lagoon with activated sludge	2.9	45.5
Tertiary	Bioenzymatic	Simple	23.5	
		Wetland	2.9	26.5
Total				100.0

Source Prepared with information from CONAGUA (2017)

The percentage that represents the water used in consumptive uses, for renewable water, is an indicator of the degree of pressure. Zacatecas is considered to have a high level of pressure (between 40 and 100%). In fact, in all three basins, the pressure is high enough (42.1% in zone III, 48.4 in zone VII and 44.8 in zone VIII), to represent a value twice the national average (19.2%, considered low, as it is between 10 and 20%) (CONAGUA 2017, p. 85). According to SEMARNAT (2012), the current water demand has exceeded the available supply in the state, generating a gap of 400 hm^3, which could increase to 528 hm^3 by 2030. The increasing water stress affects, especially the quality of water, consider this water management and its treatment as priority policies.

18.4.1 Treatment Plants in the State

About the most recent information on treatment plants, the CONAGUA (2017) had registered in 2016 a total of 70 plants. These were built with state resources and four of private origin,[2] distributed over a total of 42 municipalities, 22 of which had only one plant, 13 had two, four had three plants, and three had more than four, meaning that 19 municipalities did not have wastewater treatment (31% of the total).

Thus, three municipalities had more than four plants, with an average population of 150,000 inhabitants (including Fresnillo and Guadalupe), while four municipalities had three plants and an average of 42,000 inhabitants, (including Pinos, Sain Alto, and Villanueva). Finally, thirteen municipalities had two plants, and its average population was approximately 26,000 inhabitants (Fig. 18.4).

Of the 74 plants, 36 operate satisfactorily—that is, 49%, a further 26 plants have deficiencies, and 12 are out of operation (Castro 2013). According to their degree of functioning, there are four types of plants: First, the plants that operate satisfactorily comply with NOM-001 (and some are close to compliance with NOM-003), have good cleaning and maintenance conditions and represent 35% of the total. Second, are those plants whose main characteristic is to operate acceptably, however, not at their optimum level, representing 14% of the total. Third, plants that operate with deficiencies and considered as having major difficulties—such as, lack of maintenance and repair, a need to build certain areas, flooding areas, financial problems and even some small plants having difficulties incorporating users into their network. Finally, are those plants that are out of operation, mostly due to the infrastructure being already in a deplorable condition. These last two groups constitute 50% of the state total (Rivera et al. 2018) (Fig. 18.5).

It is necessary to describe the situations experienced by organisms to explain the degree of functioning. First, agencies face high costs for the consumption of

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[2] It is necessary to specify that the data for 2016 are variable, the data of the INEGI and the CONAGUA differ among themselves, in our case, and the data comes from the second source and is complemented with the diagnosis Program of wastewater treatment (*Programa de tratamiento de aguas residuales*—Ptar). In addition, it should be mentioned that the state press refers to other data regarding the state treatment plants.

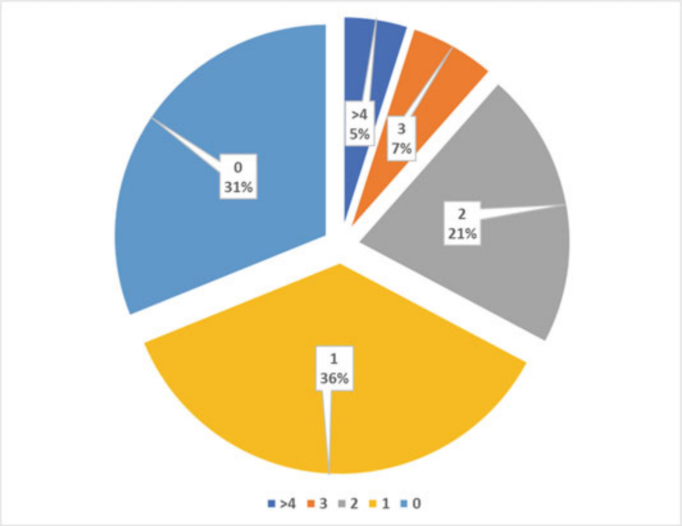
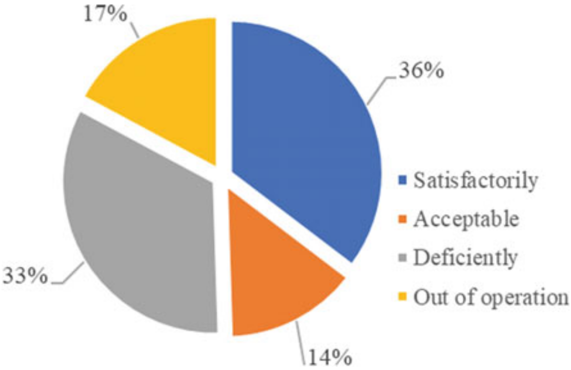


Fig. 18.4 Number of treatment plants in municipalities. *Source* Prepared with information from CONAGUA (2017)

Fig. 18.5 Percentage of treatment plants according to their operation. *Source* Prepared with information from CONAGUA (2017)



electricity. This factor is wholly related to the available income that organisms have (meager in most cases). A second limitation is the lack of payment for the concept of sanitation service in water fees. In most of the organisms of the state, this is not an integrated cost, although it is highlighted that in January 2017, the JIAPAZ was the first agency to incorporate the costs of sanitation services. This initiative is the result of a cut in the federal financial subsidies received for its operation, which forced it to search for an alternative measure to collect resources (Vélez 2018). It should be noted that this insertion of the sanitation in the tariff is valuable because it sets a precedent for the rest of the municipalities of the state.

A third element is a disparity in the location of the treatment plants, within the municipalities of the state, which entails a very low collection of residual water. This situation occurs, especially in small municipalities, and away from the state economic and political centers, which use the plants seasonally and do not provide a regular service. Between 15 and 20% of the plants expel water without treating the lacustrine vessels of the entity, becoming creditors to an economic sanction, and generating an additional expense to the municipality (Regalado and Alonzo 2012).

Derived from these financial difficulties, most of the operating agencies do not have the necessary resources for its operation (including maintenance), which leads to financial dependence and subjection to political will, mainly of the federal sphere, thus reducing the autonomy of the agencies.

Furthermore, not all agencies have the ability to obtain federal incentives. Therefore, the size and management capacity are decisive, resulting in smaller agencies depending mostly on municipal interest and financial support.

In addition to the financial resources that give certainty to the operation, the human resources of the operating agencies are fundamental (micro-level). According to the Federal Delegation of the SEMARNAT in Zacatecas and the CEAPA, "in some municipalities, there is no adequate staff in order for the plants to work or simply the existing staff does not attend the treatment plants." Further, "some plants in operation violate the regulation since they do not comply with the efficiency of the process, which will represent a waste of money for the infrastructure is generally very expensive and does not fulfill its purpose" (Martínez 2011).

On the other hand, the Vélez (2018) analysis of the Osiris treatment plant demonstrates that human resources are essential in the investigation of institutional capacity. It describes a scenario where there is a strong need for more personnel to deal with sanitation, a high turnover of managers that make management more complicated than it actually is, a mix of highly-qualified staff with vast experience and staff that have been transferred from an office position to a physically grueling job—outdoors with long hours per day. Although this change of employee allocation may simply be a result of staff rotation, it is often viewed as a form of punishment within the JIAPAZ.

For the authorities, the underlying problem of the treatment plants is "that there is not something that can allow a blunt infringement on any community, due to the lack of municipal capacity and because the search for a possible solution to the problem would be further hindered" (Martínez 2011). The CEAPA has ruled out that the solution to this problem is only to increase the consumption fee. Even when "the fair price is not paid, as in other services" the solution is broader and more complex, requiring the user to know all the costs of water, from its extraction to returning it to nature, either through receiving bodies or through agriculture. Thus, the problem of treatment plants is not only a political, legal or economic (tariffs) issue, but one that also requires environmental education programs, a rational use, efficient administration and coordination (Regalado and Alonzo 2012) between all the stakeholders involved, the staff training and even the modernization of municipal management.

18.4.2 Chronology of the Wastewater Treatment in Zacatecas: Or Absence of Responsible Planning

If the history of the construction of the plants is reviewed, it can be said that they began to be installed in 2004 until 2007, constituting the period in which 50% of the plants in the state were fitted. Of these, a third of the total is currently out of service or operating with deficiencies. It means that it is necessary to integrate maintenance and clarify the years in which the infrastructure is useful and functional in state planning. Also, there is no pattern of growth, or constant maintenance, in the establishment of treatment plants that indicates a plan to reverse the steady growth of wastewater in the state, not even now when management and treatment are priorities due to the critical situation.

Concerning compliance with its regulations, the existing information does not allow an in-depth analysis of the plants. However, the plants in operation comply mostly with NOM-001—maximum limits for discharging water—and some are closer to NOM-003—maximum limits that allow reuse. Of the NOM-002—discharges to the urban and municipal sewage, and NOM-004—maximum limits for the contamination of sludge and biosolids for its use and final disposal, no information was available.

The technical improvement actions analyzed by PTAR (2014) indicate that the most recurring problem is maintenance, due to corrosion of the material, which must be integrated into urgent planning. Although in more modern plants, another type of deficiency was found, such as the low incorporation of the population into the network and low budgets for operational payments—especially for the electricity services to the Commission Federal de Electricidad (CFE), which denote the low municipal capacities. The prioritization of water treatment in urban centers is visible, neglecting rural areas.

18.4.3 Municipal Wastewater Treatment Processes in the State of Zacatecas

In addition to the operation of the plants, the various processes of treatment used to treat the water, in the State of Zacatecas, are equally as important in order to achieve efficiency in wastewater treatment. According to the CONAGUA (2007), the types of water treatment processes are, namely, the: primary process—to remove suspended solids by physical means and reduce BOD of a certain percentage (sedimentation and flotation processes in lagoons); secondary process—remove colloidal and dissolved organic materials through natural and chemical processes (biological filter system, anaerobic reactors, stabilization ponds and activated sludge); and, tertiary process—remove dissolved materials, such as gases, natural and synthetic organic substances, ions, bacteria, and viruses (ion exchange, reverse osmosis, advanced oxidation, electro-disinfection, etc.) (Bioingeniería Sanitaria 2015). Around 46% of the plants in Zacatecas use processes from the second group (nationally this percentage exceeds 70%).

According to the zone (urban/rural), we can observe that the method of activated sludge (mainly the high rate) is used in the most urbanized areas. It is followed by the natural lagoon type, which deals with small urban areas. Another method applied in urbanized and semi-urbanized populations is the Anaerobic Reactor of Ascending Flow (RAFA).

Some precisions about the methods used include: the simple lagoon—the most used and insufficiently treating water since it is limited to an initial physical separation of large, untied solids (separation of small very dense solids such as sand, remove between 60 and 65% of the total) and sedimentations that separate the existing suspended solids (30–35%); and the RAFA method—the second most used, conditions water treatment because its useful life is closely linked to the maintenance of infrastructure (Mansur 2000) (one of the main problems of plants in the state).

While tertiary-type treatments (bio-enzymes), being more expensive than the previous ones, are scarce and limited to purify industrial waste, the predominant methods seem to be selected for their operation and maintenance ease. That is because they use fewer resources in the treatment (not only the land used, but also electrical energy), chemical substances and, to a lesser extent, the generation of leftovers or remnants in the process. In other words, the less expensive systems to build and operate are sought, but they eventually fail and have a higher cost than those of more advanced technologies (Table 18.4).

In this sense, it is possible to affirm that the most important factor to consider in the types of treatment is the total cost of operation, both the initial investment (usually considerable regardless of the type of treatment, although quite variable) and the maintenance, as well as the cost of the technology used.

This factor can generate that the proposed system (no matter how simple it is) becomes inoperative. It is necessary to pay attention to this aspect since it conditions multiple socio-ecological aspects, such as the contamination of waters and basins—to the detriment of the species that coexist in them, the water supply to rural localities and urban areas, the best use of resources by the industry, among others.

18.4.4 Urbanization: A Key Factor in Explaining the Operation of Treatment Plants

It has been seen that a large part of the plants is in urbanized areas and that these are the ones that work best. Therefore, it can be sustained that the treatment of wastewater privileges in urban areas. Based on the classification made by the INEGI, an urban town is one that has a population greater than or equal to 2500 inhabitants or, is a municipal seat regardless of the number of inhabitants. Of the plants, 42.7% serve urban populations (26.5% are located in municipalities with populations between 2500 and 10,000 inhabitants, and 16.2% with over 10,000 residents). The balance

Table 18.5 Distribution of plants according to rural/urban areas

Population served	Total plants (%)
<1,000	23.5
1,000–2,500	33.8
2,500–10,000	26.5
>10,000	16.2
	100.0

Source Prepared with information from CONAGUA (2017)

serves populations of less than 2500 people, 23.5% of the total serving populations with less than one thousand inhabitants (Table 18.5).

These data indicate that there is a tendency to prioritize the establishment of plants in rural areas and to equip them with the treatment service. However, when analyzing the operation of the plants, we are witnessing a reverse trend, whereby urban state growth, and the needs arising from it, concentrate on water treatment (not only visible in the establishment of plants with a higher capacity for treatment, but also for maintenance and operation over the years).

If the data in Table 18.5 is analyzed, it is found that in the group of plants that operate satisfactorily (a total of 24 plants), 79.9% of them are located in urbanized populations, of these more than 50% serve urbanizations greater than 10,000 residents. The remaining 20.1% is in populations of less than 2,500 inhabitants. In the group of plants that operate, 60% serve urban populations, while the rest serve rural populations. In the collection of plants that operate with deficiencies, this trend is reversed, and we discover that only 17.4% are found in urbanized populations.

The last batch, comprising of plants out of operation, fully accentuates this trend and we see how 91.7% of these non-operative plants are located in rural areas. These data make it possible to corroborate how rural communities have been experiencing a greater lag in the coverage of this service. It might be the result of one of the objectives of the PNH 2007–2012, is to prioritize the "satisfaction of the water and sanitation services of the regions, with the greatest dynamics and population growth" (De la Peña et al. 2013). That is not without forgetting that 19 municipalities lack treatment plants.

It is true that there are geographic, demographic, political, social and economic restrictions in the operation of the treatment plants, and it is necessary to know and solve them to operate correctly and follow the regulations. However, as noted, one of the main factors that explain the installation and operation of treatment plants in Zacatecas is the demographic—particularly the urbanization of space. Rivera and Vázquez (2014) illustrate how the provision of services (drinking water supply, sewerage, and disinfection) in well-urbanized areas such as the Municipality of Zacatecas, Guadalupe and Fresnillo, are practically covered. Although these plants have deficiencies, due to the type of treatment used, advances in the matter are visible and almost exclusive to urbanized areas. Therefore, it can be stated that the population and urban growth have laid down the foundation for the location of the treatment plants.

18.5 Concluding Thoughts

It is expected that renewable water will continue to decrease, mainly due to the increase in population, causing a situation of water stress in northern and central Mexico. This is also evident in the southeast, where the forecasts point to increasing imbalances due to global warming. To guarantee total access to drinking water and the treatment of wastewater, they are consolidated as priority policies in the environmental agenda of most Mexican states. Of these two, the challenge is even greater in water treatment. On the one hand, there have been significant advances in the last eight years, since access to drinking water has been practically guaranteed, and the country has been provided with an essential infrastructure for water treatment. However, on the other hand, there are a series of urgent problems (abandonment, high costs, and misuse) that must urgently be addressed, given that the construction of treatment plants infrastructure is characterized by a centralist designation that does not take into account the local context.

So far, although there is an initiative to reinforce traditional management, through the strengthening of institutional capacities regarding water, the articulation of the stakeholders continues to be of low intensity, mainly due to administrations, policies and multilevel programs that make it difficult to combine all the objectives. As a final reflection, we consider that there are two axes, with multiple interrelated factors, that jointly explain the operation and efficiency of treatment plants in the State of Zacatecas, but that, given the conditions at the national level, can explain part of what happens in the country. These two axes are as follows:

(1) A macro axis focused on intergovernmental policy and relations (IGR), which evidences the greater attention to large advanced technology plants (this means giving priority to the most specialized plants). Although the problems of urban areas are urgent, due to population concentration, it should not be forgotten that sanitation in small communities entails higher costs, which according to some authors could exceed values of 15 to 1 (Pombo 2004). This privilege to the centers of higher population, while disregarding the small municipalities with low population density, presents a failure in the processes of decentralization of public policies in the different levels of government. The threads move from a central level (the Federation), which conditions the work of municipalities, allowing the larger municipalities to become stronger and the smaller ones weaker—left behind in the water treatment processes, resulting in an unequal dependence on federal financial subsidies for their operation and maintenance that leads to (an even more) mined autonomy. However, the stakeholders are not only the government and institutions but also society, with each having an important role in sanitation. It has not been possible to articulate the participation of water committees with the ejidos and municipalities, and, therefore, do not manage to enter the central agenda of water management. Although it is said that social participation has been promoted, it has not been possible to consolidate a space (or various spaces) from which the work and needs of the communities are included, interacting and discussing with government stake-

holders and specialized water technicians. In many cases, the plants acquire a nuance of political capital that is often used as a vote conditioner in elections.

(2) A second axis that integrates the administrative part of the operators, both their organization (meso) and their human resources (micro). Within the agencies themselves, the diminished priority of the sanitation issue stands out, the water supply and the sewage system are privileged, and the percentages of progress in these two areas are always higher. However, agencies should not forget the strong links in all services, because it is the same water, the one distributed (potable water) must be collected through the sewage, partially sanitized in the treatment plants and, finally, ready to be reused. Therefore, the need to advance in the phases of sanitation and reuse becomes a priority to integrate the entire water cycle.

About the organization of the technical functioning of the plants, the most recurrent limitation is their maintenance and the need for a permanent updating of information. In practice, 48% of plants in operation is a changing number due to some small and/or large aspects of maintenance. In other words, not all of the plants are continuously working. Also noteworthy is the low consideration of the periods of life of each plant—that is, the time necessary to redevelop a new project. Medium and long-term planning becomes mandatory, including the replacement of plants (all the technical details about the useful life of a plant must be specified from the beginning), to avoid the corrosion of materials and their abandonment. Other problems found are the sediments deposited in some plants that block the filters and the exits, mainly in the primary treatment, and other local problems such as floods.

The economic axis is fundamental and can be analyzed in two parts. First, a certain tendency (perhaps more frequent in small municipalities) in the municipal administrative-financial cuts, due to unfavorable conditions when facing operating costs (payment of electricity, the availability of resources for construction, rehabilitation, and maintenance of the infrastructure, acquire the chemical reagents for the operation, cover the lack of training of operational personnel, and others). Second, the difficulty of being able to incorporate in the payment of drinking water the cost of sanitation services, either due to the financial incapacity of the communities or the low political profitability of the measure. Both are linked in a decisive way to key political factors such as decentralization. Furthermore, at the level of human resources (micro-level), there is inefficient hiring of over or under-qualified staff to operate and maintain the plants (in many of the Mexican municipalities the jobs are modified almost entirely with a change of government). The small plants alter their staff with the arrival of a new municipal administration and the more significant organizations, such as the Osiris plant in Guadalupe-Zacatecas conurbated zone, with the change of a state government, which implies the rotation of its management and operational positions.

Finally, an aspect that should be highlighted is the limitation of information, which is essential for social participation, as it is necessary to be aware of the problems we have on sanitation. This restriction results in methodological limitations, which do not allow a detailed analysis because the information provided by each plant is different from each other. Even in the dependencies, the information generated is not always the same, such as the case of INEGI and CONAGUA. The information is incomplete, and sometimes it does not exist, such as in the case of compliance with the regulations.

In theory, the plants in operation should satisfactorily cover the NOM-001—which are the maximum limits of pollutants discharged, and (at least) be close to achieving NOM-003—indicates the maximum permissible limits of pollutants for treated wastewater that are reused in services to the public. The latter is vital because it allows us to advance in reuse of an area with water shortages, such as the State of Zacatecas. Another dominate fact is that there is no information or reference to the NOM-002 and the NOM-004 in the reports of the plants. On this aspect, we must also highlight the variability with which the information is presented in each report and many of the statistical compilations of the country. The methodologies are changing, and the variables worked tend to change with each edition, which makes it difficult for any analysis, comparison or assessment of public policies in the area. Long-term plans must also include the obligation of clear public information; otherwise, all social and academic inclusion will be limited.

Collaboratively, these problems and their interrelations show a state inability in the provision of services, and a crisis of institutional capacity, where municipalities have responsibilities that they cannot cope with (due to lack of capabilities and/or resources), denoting a deficient decentralization of functions, where discourses are advancing, and realities are always lagging. Proof of this is that, in the case of Zacatecas, less than 50% of the treatment plants are functioning.

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Chapter 19
Mining, Water and Society: Recycling of Mining Effluents as a Social Solution to the Use of Water in Mexico

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Abstract According to a Ghana thesis written in 2008: "Mining is viewed as one of the important economic activities which have the potential of contributing to the development of economies. At the same time, the environmental and health

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impacts of mining on surrounding communities have been a major concern to governments, the general public and stakeholder organizations, and individuals. While the contributions of mining activities to the economic development of Ghana is well acknowledged, others contend that the gains from the mining sector to the economy are achieved at significant environmental, health and social costs to the country." Mexico has lived in the last five years some experiences similar to the following: "on August 6, 2014, nearly 40 million liters of a copper sulfate acid solution poured into the Bacanuchi and Sonora Rivers from the Buenavista del Cobre copper mine, which is owned by Grupo México. The spill impacted an area almost 200 miles along the Sonora River Basin, which is home to more than 22,000 people. It has been more than a year since the spill and officials from both the mine and Mexican government claim the river is now safe. An environmental remediation plan was submitted by the mine and approved by Mexican environmental officials. However, cleanup efforts have reached about 19 miles from the site of the spill, which only encompasses land owned by Grupo México." These facts emphasize the need for research on the recycling of treated water in the mines in order to provide the neighboring communities with clean sources of water and to reduce the probability of spills from the tailings dams, known in Mexico as "*presas de jales*" due to overfilling and/or combinations of climatic change impacts, such as cyclones or hurricanes. In this chapter, some approaches to the recycling of treated water are presented taking as an example a cooperating mine located in Central Mexico.

Keywords Flotation process · Mining effluents · Sulfate-reducing consortia · Upflow anaerobic sludge blanket reactors · Artificial wetlands

19.1 Introduction

One definition of mining may be considered "the process of extracting useful minerals from the surface of the Earth, including the seas. A mineral, with a few exceptions, is an inorganic substance occurring in nature that has a definite chemical composition and distinctive physical properties or molecular structure. One organic substance, coal, is often discussed as a mineral as well. Ore is a metalliferous mineral, or an aggregate of metalliferous minerals and gangue (associated rock of no economic value), that can be mined at a profit. *Mineral deposit* designates a natural occurrence of a useful minerals, while *ore deposit* denotes a mineral deposit of sufficient extent and concentration to invite exploitation. When evaluating mineral deposits, it is extremely important to keep the profit in mind. The total quantity of mineral in a

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given deposit is referred to as the mineral inventory, but only that quantity which can be mined at a profit is termed the *ore reserve*. As the selling price of the mineral rises or the extraction costs fall, the proportion of the mineral inventory classified as ore increases. The opposite is also true, and a mine may cease production because (1) the mineral is exhausted or (2) the prices have dropped, or costs have risen so much that what was once ore is now only mineral" (EB 2017).

According to Yeboah (2008): "Mining is viewed as one of the important economic activities which have the potential of contributing to the development of economies. At the same time, environmental and health impacts of mining on surrounding communities have been a major concern to governments, the general public and stakeholder organizations, and individuals. While the contributions of mining activities to the economic development of Ghana is well acknowledged, others contend that the gains from the mining sector to the economy are achieved at significant environmental, health and social costs to the country".

19.2 Social Impacts of Mining in Mexico

As mentioned in the paragraphs above, the mining industry provides many of the raw materials for social development. Metal mining has steadily increased over the centuries, with occasional "rushes" for several minerals (gold, silver, radium, titanium, etc.) which occurred in connection with booms in demand. The common mining practice could be summarized in a few steps: obtaining a license, digging the ore, selling the metal and, once the deposit is exhausted, abandonment and starting another mine elsewhere. Not surprisingly, mining is among human activities with widest environmental and social impacts (Carvalho 2017).

The situation in Mexico is worrisome. A recent book details "four cycles of the mining dispossession in Mexico" that go from the conquest in the sixteenth century to the present. In just 15 years, from 2000 to 2015, 63,934,736 hectares of Mexico's territory, 31% of it, has been concessioned to foreign companies and a handful of Mexican enterprises (López-Bárcenas 2017).

In Mexico, the mining industry has increased the generation of foreign currency since 2016, reaching 17 thousand 489 million dollars, which falls under the profit levels of the automotive, oil and electronic industries, workers abroad remittances, tourism, and only surpasses agroindustrial activity. However, in Mexico, the mining industry has not yet regained its position as the fourth most important currency generator (CAMIMEX 2018).

This generation of foreign currency previously mentioned could occur as a consequence of several factors, such as social and environmental conflicts. Tetreault (2015), among others, mentions that this conflict is the result of neoliberal reforms that have facilitated "accumulation by dispossession." First, by transferring public resources in the form of mineral rights and state-run mining companies to the private sector, and second, by dispossessing small farmers and indigenous communities of their land, water, and cultural landscapes in order to allow mining companies to carry out their activities. The resistance movements that have emerged to confront this dispossession are led on the local level by people whose livelihoods, health, and cultures are threatened by large-scale mining projects. They reflect "the environmentalism of the poor" in that they seek to keep natural resources outside of the sphere of the capitalist mode of production (Tetreault 2015). The technological developments in the mining industry have facilitated exploration and made the exploitation of previously inaccessible mineral reserves economically feasible. For example, in Mexico, mining companies are going back to areas that had been exhausted by conventional mining methods by the mid-twentieth century to extract dispersed mineral deposits with state-of-the-art technologies, including open-pit mining, hydrometallurgy, electrometallurgy and, pyrometallurgy. As the name suggests, hydrometallurgy as an extractive metallurgy discipline involves the recovery of metals by wet methods, i.e., from aqueous solutions. The third contributor to the extractive metallurgy—electrometallurgy—can also be regarded as a subset of hydrometallurgy, if electrowinning and/or electrorefining of metals are performed from aqueous solutions. If, however, these two electrometallurgical operations use molten salts that require high processing temperatures, then electrometallurgy may also be classified as pyrometallurgy (Peši 2005; Tetreault 2015). These technologies are currently being used by international companies in the southern part of Mexico, where the largest number of indigenous people are concentrated. Large-scale modern mining projects have multiple environmental and social consequences. Open-pit mining destroys the land that contains the minerals, leaving behind gigantic craters and heaps of contaminated rubble that emit toxins into the environment. Aside from aesthetic considerations, this implies the loss of habitat for wildlife and, deprives local communities of the use of the land to produce essential foods. What is more, powerful explosives are used in open-pit mining, meaning not only that communities located near mining sites must put up with much noise, but also that their dwellings may suffer structural damage. These are just some of the problems facing people, for example, the Nahua farmers who live close to *Peña Colorada*'s iron-ore mine in the Sierra de Manantlán and the inhabitants of Cerro de San Pedro, located right next to the mine operated by New Gold Inc. in San Luis Potosí. These indigenous groups have long defended their territory and natural resources. They document a process that deprives the local indigenous population of natural resources and the cultural landscapes that sustain their livelihood, social welfare and worldview, and that the political tactics of the Benito Juárez-Peña Colorada Mining Consortium reflect "negative reciprocity", since they are oriented to extract the minerals in exchange for nothing or very little for the local population (Tetreault 2013, 2015).

It is difficult to separate the economic and social impacts of mining activities because the closer the countries are to the sources of mineral wealth, the farther they seem to be from obtaining a good part of the benefits. If the income from mining is not properly distributed, inequalities within the communities will be aggravated, generating poverty, malnutrition, illiteracy and poor health conditions, as well as the displacement of established communities, that can constitute a significant cause of resentment and social conflict. On the other hand, mining activity can generate economic effects, for example, the pollution of rivers and therefore the deterioration of fish populations, as well as the appropriation of grazing lands and forest resources for such activity (MMSD 2002).

The people most directly affected by this environmental destruction are those who live in communities located close to mining sites. In Mexico, these communities tend to be inhabited by poor rural families with diversified economic strategies that include small-scale farming and ranching as well as temporary and permanent low scale activities. Indigenous communities are increasingly affected as mining operations expand into the relatively isolated areas that they have inhabited even before the conquest, the so-called refuge regions, where subsistence agriculture predominates. As in other parts of Latin America, the arrival of companies like the Canadian mining companies inevitably gives rise to "conflicts over the production of territories." That includes not just conflicts between local farmers and mining companies but also internal conflicts between community members who oppose mining activities and those who support them. For example, the activist Miguel Angel Mijangos-Leal highlighted the tensest conflicts from the over 15,000 that have been reported. One of them involves the Canadian mining company, Torex Gold, and its Media Luna gold mine in the state of Guerrero. Workers there started a strike in November 2017, and so far three workers having been killed by the so-called *guardias blancas* (white guards) hired by mine owners. Another case involving a Canadian mining company, Canadian Esperanza Silver, sought to destroy the Xochicalco archaeological site, as well as communal lands located on El Jumil hill in Tetlama, Morelos. Finally, there is the ongoing case in Chicomuselo, Chiapas, which led to the murder of anti-mining activist Mariano Abarca in 2009, who was fighting against the impacts of Canadian mining company Blackfire Exploration (TeleSur 2018; Tetreault 2015).

Mexico has lived in the last five years experiences such as the fact that "on August 6, 2014, nearly 40 million liters of a copper sulfate acid solution poured into the Bacanuchi and Sonora Rivers from the Buenavista del Cobre copper mine, which is owned by Grupo México. The spill impacted an area almost 200 miles along the Sonora River Basin, which is home to more than 22,000 people. More than a year after the spill, officials from both the mine and Mexican government claim the rivers are now safe. An environmental remediation plan was submitted by the mine and approved by Mexican environmental officials. However, cleanup efforts have reached about 19 miles from the site of the spill, which only encompasses land owned by Grupo México" (Fernández 2015). "Grupo México initially blamed the toxic spill on higher than usual rainfall, but environmental authorities firmly point to faulty company equipment. Grupo México subsequently said in a statement to the Mexican Stock Exchange that 'one relevant factor of the accident was a construction defect in the seal of the pipe' where the leak occurred. The Mexican government agency PROFEPA said in an official report: 'The pipe was open, without a control valve, such that the [waste water] flowed uncontrollably towards the stream.' The toxic materials traveled almost 90 km downstream…." According to Rojas Rueda from Greenpeace Mexico, mine sites across the country would benefit from improved regulation and supervision. He argues that if the Mexican government wants to prevent such toxic disasters in the future, 'it should strengthen environmental laws and provide [PROFEPA] with more and better inspectors to make random inspections, particularly at the [tailings] dams associated with mines.' As soon as you can hold members of a company the size of *Grupo México* responsible for contamination like this, you can be sure they will stop doing those things,' Rojas Rueda says. 'Today, because economic sanctions are for very small amounts, [the companies] do not care if they cause contamination' …" (Wilton 2015).

These facts encourage the research towards the recycling of treated water in the mines in order to provide this vital resource to the neighboring communities' sources of clean water and to reduce the probability of spills from tailings dams, known in Mexico as "presas de jales". The word jal or jales comes from the Náhuatl or Aztec language "xalli" meaning very fine sands or particles (Cabrera 2002). The mining industry in Mexico is concentrated in twelve entities: Chihuahua, Michoacán, Zacatecas, Durango, Sonora, Coahuila, Guanajuato, San Luis Potosí, Hidalgo, Sinaloa, Colima, and Jalisco. For decades they have generated a large amount of waste and have contaminated sites throughout the country. Due to the development and modernization of extraction and processing of mineral resources, several stages are considered (INECC 2007). The first is exploration, which consists of works and drilling, the impact of this stage causes the generation of noise, vibration, and emission of dust. The second is exploitation, which is the realization of different works such as shots, tunnels, and yards for mineral deposits and material discharges; the effects on the environment of this stage are the construction and operation of tailings dams. The third is mining works (*beneficio* in Spanish), which include concentration, crushing, and milling, as well as the generation of noise, vibrations, and emission of dust, and the treatment of water effluents. Smelting for obtaining metals and their alloys, industrial furnaces are used in this activity producing emissions to the atmosphere. Finally, refining which helps the elimination of impurities in metals to increase the content of valuable elements, producing hazardous waste and wastewater. In general, the stages of a mining process, except prospecting, involve preliminary studies and generate high impact environmental problems. To separate the ore from waste, basically, two methods are used: flotation and hydrometallurgy (Pacheco-Gutiérrez 2006). The mining industry in Mexico has contributed greatly to the economic development of the country (Sheoran et al. 2010). However, it has generated 65% of industrial waste and contaminated sites throughout the country (SEDESOL 1993). Approximately 95–98% of the processed material is discarded, along with the remains of the additives used the generation of tailings dams (Ojeda-Berra 2008; Pacheco-Gutiérrez and Durán-Domínguez-de-Bazúa 2007). The number of mining sites is unknown, but it is estimated that there are 10,000–50,000 abandoned or inactive sites (Carrillo-Chávez et al. 2003). The other major environmental problem that this industry generates is the high consumption of water. Although water consumption by the mining industry is only 3% of the total water consumption in the industrial sector, several factors require water recycling due to the locations of this industrial branch. The volume of water used may represent a significant portion of local sources. Sometimes water must be pumped from distant sources or deep wells. Thus, its availability implies an increase in costs for the industry (Pacheco-Gutiérrez and Durán-de-Bazúa 2006). Therefore, some mining companies have installed systems to recover the wastewater after separating the solid sedimentary material in the tailings dam, it is pumping it back into the process and, with this, in addition to reducing the costs of obtaining single-use water, it decreases the discharge volume of mining operations (Lizárraga-Mendiola et al. 2009). In the case of the cooperating mine that uses the flotation process to concentrate the mineral, the recycling of the treated water and its subsequent mixing with single-use water is called internal recycling. That involves a separation of the solid concentrate as a foam, leaving the glues or gangue. Water comes out with the rest of the solids and the dissolved substances used for creating the foam. This solid-liquid mixture is sent to a slag heap where, through solid-liquid separation, the fine solids are allowed to settle for relatively long periods, generally known in the mining jargon as tailings dam, in order to recover the water found in the top, this is called external recycling (Nedved and Jansz 2006). However, the physical separation by sedimentation in the tailings dam has not been seen in all cases as a sufficient step to guarantee the desired degree of quality for the waters associated with the flotation process and particularly for its reuse in the process (Erten-Unal and Wixson 1999; García et al. 2014). Both recycling systems affect the composition of the feed stream of the water. This procedure gradually gives rise to disturbances in the metallurgical results, due to the presence of carbonaceous organic materials dissolved in the water returned without treatment. These carbonaceous organic materials, such as residual xanthates and its oxidation products (dixanthogens) selectively absorb most sulfates and residual sulfides that cause undesirable technical problems (known generically in the mining jargon as "unwanted depression"). The presence of dissolved metal ions such as Cu^{2+}, Fe^{2+}, Pb^{2+} and, finally, alkaline ions activate the not sulfurous gangue, causing negative effects on the efficiency of the flotation process of valuable minerals. This phenomenon is due to the degree and percentage of dissolved species (organic and inorganic) that accumulate during the operation. Also, changes occur in the salinity of the water increasing the amount of the so-called sludge (Coetzer et al., 2003; Deo and Natarajan 1998; García et al. 2014; Levay et al. 2001; Muzenda 2010; Pacheco-Gutiérrez and Durán-Domínguez-de-Bazúa 2007; Rao and Finch 1989; Sandenbergh and Wei 2007; Shengo et al. 2014).

In response to above, numerous research groups are studying the effects of water recycling schemes, which inevitably are reflected in the sustainability of the use of water resources in the affected areas (Coetzer et al. 2003; Levay et al. 2001; Mudd 2008; Sandenbergh and Wei 2007). Thus, to reduce the consumption of water from a single use of this industry, it is necessary to develop a train for processing water and water accumulated in the tailings dam. One of the methods for treating water from the flotation process is to add flocculants, but it is necessary to have an infrastructure and significant residence times, which is often not feasible from a practical and economic point of view. On the other hand, inorganic and organic impurities or chemical species that can be generated in ionic forms or as complexes cannot be eliminated by simple gravity or precipitation. Studies have shown that water effluents from the flotation process contain significant concentrations of surfactants and their degradation products are physical-chemically stable in the form of emulsions or as colloids that are difficult to separate by sedimentation or filtration (García et al., 2014; Rubio et al. 2002). Also, chemical treatments, such as the chemical neutralization of the treated waters, make use of reagents with specific action such as CaO, $Ca(OH)_2$,

Na_2CO_3, Na_2S, etc., which are dosed in a single basis or as mixtures (Fu and Wang, 2011). The electrical charges of the suspensions are destabilized by the neutralization and production of the precipitates (Dobson and Burgess 2007). This approach represents a long-established practice, and it is still in use today. The main disadvantage of this chemical treatment is the generation of large quantities of sludge that require elimination and sometimes additional processing (Obreque-Contreras et al. 2015). Moreover, if large volumes of wastewater must be treated, the relatively high cost of associated reagents might impede its application.

The implementation of biological treatments such as bioreactors or biofilters can overcome one of the main drawbacks of chemical treatment: The generation of large amounts of solids, although biological treatment requires regular monitoring, is economically and environmentally acceptable (Dobson and Burgess 2007; Mulligan and Gibbs 2003). Such is the case of anaerobic upflow sludge bed reactors where bacteria such as *Desulfovibrio* and *Desulfotomaculum* proliferate, which can transform sulfides to sulfates, precipitating the metal ions found in the water effluent of the flotation process (Dobson and Burgess 2007; Espinosa-González 2015; Obreque-Contreras et al. 2015). For this reason, the proposal for a water treatment methodology using an upflow anaerobic sludge blanket (UASB) reactor, is seen as a viable solution without generating undesirable wastes. In addition, microorganisms take advantage of the ability to assimilate organic matter and nutrients dissolved in the aqueous phase (carbon, nitrogen, and phosphorus) for their own development (Salgado-Bernal et al. 2012a, b).

In this chapter, an example based on the biological treatment of the effluent that comes from the flotation process of a mining plant, where zinc, copper, and lead sulfide concentrates are generated, is presented. This research has been carried out since 1995 through the cooperation between the mine owners and the technical staff with the group denominated Program for Environmental Chemical Engineering and Chemistry belonging to the Facultad de Química of the Universidad Nacional Autónoma de México (FQ, UNAM). Numerous theses and research papers, some of them confidential, have been the scientific products from this cooperation and some of the results have been applied to improve the operation of the mine in order to protect the environment.

The example is presented as a general strategy since the technical and scientific data are in the theses cited along. It deals with the efficient use of water to concentrate the ores using the flotation process through its treatment using a UASB reactor coupled with an artificial wetland system that might be in the banks of the tailings dams. The use of water in this flotation process is fundamental to the overall efficiency of the separation desired. As it requires large quantities of water with particular physicochemical conditions to perform the concentration of sulfides with maximum productivity, it should not contain residual chemicals from previous separations. However, if treated water is used that has the presence of soluble sulfates of metals and metalloids, as well as residues of chemical agents, the process may be affected. Therefore, to minimize the demand for freshwater from the surroundings of the site, a biological treatment should be implemented. Taking advantage of the capacity of the sulfate-reducing bacteria (SRB) present in a UASB reactor, it is possible to convert sulfates into sulfides, precipitating these salts as sulfides again. Thus, the management of water recycling would make better use of the carbonaceous compounds present as energy sources for these sulfate-reducing microorganisms. That will contribute to reduce their impact on the environment as well as to promote the transfer of technology to the cooperating mine improving the recycling of the process water already treated. The subsequent mixing of treated flotation water with single-use water would be true internal recycling. Finally, the use of artificial wetlands as a final step to remove the metals that still were present would improve the process water recycling, leaving the streams and springs to the neighboring communities in a pristine form (Ruiz-López et al. 2010).

In sum, this chapter presents an approach to the recycling of treated water in a cooperating mine located in Central Mexico. The final goal is to preserve and keep the streams and springs for direct human use by the neighbouring communities.

19.3 Example: A Mining Industry in the State of Mexico

19.3.1 Location of Cooperating Mine

The State of Mexico[1] is located in the central part of the country (Fig. 19.1). Most of the rock and soil formations in the state are volcanic in origin (Medio Físico 2005).

Fig. 19.1 The state of Mexico and cooperating mine locations (Espanol.mapsofworld.com): UTM 2106098 North, 370389 East, 2105227 South, 369539 West, Zacazonapan municipality (LFTAIPG 2018: Google Maps, retrieved from http://sinat.semarnat.gob.mx/dgiraDocs/documentos/mex/estudios/2008/15EM2008M0033.pdf)

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[1] There are two possible origins for the name of Mexico. The first is that it derives from *metztli* (moon goddess) and *xictli* (navel) to mean from the navel of the moon goddess. This comes from the old Aztec idea that the craters on the moon form a rabbit figure with one crater imitating a navel. The other possible origin is that it is derived from "*Mextictli*" an alternate name for the god *Huitzilopochtli* ("*Origen y fundación del Estado de México*" [Origin and foundation of the State of Mexico] (in Spanish). Club Planeta. Retrieved July 8, 2010).

It is bordered by the states of Querétaro and Hidalgo to the north, Morelos, and Guerrero to the south, Michoacán to the west, Tlaxcala and Puebla to the east, and surrounded on three sides by Mexico City, formerly known as the Federal District (Medio Físico 2005).

There are three river basins in the state: the Lerma, the Balsas, and the Pánuco. There are rivers dams such as José Antonio Alzate in Temoaya, Ignacio Ramirez in Almoloya, Guadalupe in Cuautitlán Izcalli, Madín in Naucalpan, Vicente Guerrero in Tlatlaya, Tepetitlan in San Felipe del Progreso as well as those in Valle de Bravo and Villa Victoria (Medio Físico 2005). The cooperating mine for studying the effluents and disposed solids is located in the southern portion of the Valle de Bravo municipality. A complete study on the cooperating mine concerning natural sources of water, water use, wastewaters produced, a possible solution to reduce acid mine drainages, and solutions to the efficient use of process water is presented elsewhere (Goslinga-Arenas 2015; Neri-Oliva 2014; Pacheco-Gutiérrez 2006). The conservation of the water sources is an important aspect of the mine owners and technical staff since the operations carried out to recover the valuable metals from ores require relatively important amounts of water (Pacheco-Gutiérrez 2006).

19.3.2 Cooperating Efforts Between Mine Owners and Universities

The main issue for the UNAM research group and the owners of the mine in the study is the conservation of the water sources. That is because the operations carried out to recover the valuable copper, lead, and zinc rich minerals require relatively important amounts of water. Very few owners of mines, either Mexicans or foreigners, have been genuinely interested in solving their technical problems by cooperating with university research groups as is commonly done in Europe, especially in Germany. Thus, cooperation is not common in Mexico. Only a few mines' operating staff, with the agreement of the owners, relies on academic points of view to improve their technical activities. For this reason, the authors considered the important to write about it in order to promote this beneficial cooperation, particularly in Mexico where many problems are being encountered due to the negligence of the governmental authorities and the lack of environmental concern by the owners.

In the following paragraphs, key issues are discussed about the reduction of the amount of water from springs, streams, and wells used for the mine processing step known as flotation. As mentioned before, this chapter is not a scientific or technical report but presents a socially beneficial strategy that the authors consider convenient for all parties, the researchers from the UNAM and other universities and institutes, as well as nonprofit organizations and the cooperating mines.

19.4 Example: Recycling of Mining Flotation Effluents to the Process

19.4.1 UASB Reactor Used for Flotation Water Recycling

In the cooperative mine and most of the mines located in the center of Mexico, the flotation process effluents have been characterized, containing lead, copper and zinc sulfates (in orders of magnitude of g L^{-1}), with pH values between 2.8 and 3.9 units, which makes a highly stable sulfates and bioavailable metals (Chen et al. 2015; Lizárraga-Mendiola et al. 2008; Ríos-Vázquez et al. 2008; Ruiz-López et al. 2010).

Sulfates add to the risk of acid mine drainage already mentioned in previous sections. In the next diagrams, some key issues are considered to reduce the amount of water from springs, streams, and wells for the mine processing. Figures 19.2a, b present the overall water use mass balances considering the real data given by the technical personnel of the cooperating mine and the data calculated and proposed in a previous study by Pacheco-Gutiérrez (2006). Table 19.1 presents the water balance, calculated versus mine personnel provided data.

The example described in this chapter shows several research results that indicate the technical feasibility to treat the effluents efficiently from the flotation process by using UASB reactors for stabilizing sulfates. The process converts them in sulfides allowing the reuse of treated water in the same process, which is a mitigation measure for both cases, "*presas de jales*" effect and water supply to the mining company. Organic pollutants as a carbon source for the sulfate-reducing bacteria, allow the transfer of dissolved heavy metals sulfates from the aqueous phase to the solid phase as sulfides (Nkemka and Murto 2010; Ríos-Vázquez 2009; Rodriguez et al. 2012). These physicochemical changes between aqueous medium and reactor biosolids or sludge are mostly regulated by the pH and Eh values (Manahan 2017). As is well known, pH has ranged from 0 to 14 and Eh from -1000 to $+1000$ mV. In UASB systems pH ranges are reduced from 0.5 to 7.5 units and Eh from -150 to 10 mV. These intervals are extremely high at the level of heavy metals chemical speciation. That is, precipitation, solubility, toxicity, and adsorption of any heavy metal depend on the combination of pH and Eh values (Amabilis-Sosa et al. 2015).

The results suggest that chemical species study of heavy metals contained in UASB influent (effluent of flotation process) and effluent, together with biosolids contents will allow the establishment of the processes and following operation parameters for the recovery and/or final disposal of heavy metals, in this case, lead, copper, and zinc.

The UASB evaluated in this chapter have demonstrated around 80% of heavy metal and sulfates removal efficiencies. For this reason, it is important to study metals chemical species in UASB biosolids, which is the place where they are retained. Also, these sludges are characterized by having good settling capability and lack of clogging (Khan et al. 2011; Papirio et al. 2013).

One of the main characteristics of biosolids is their water content higher than 98% (Lu et al. 2012; Tchobanoglous et al. 2003). Nevertheless, the water content is

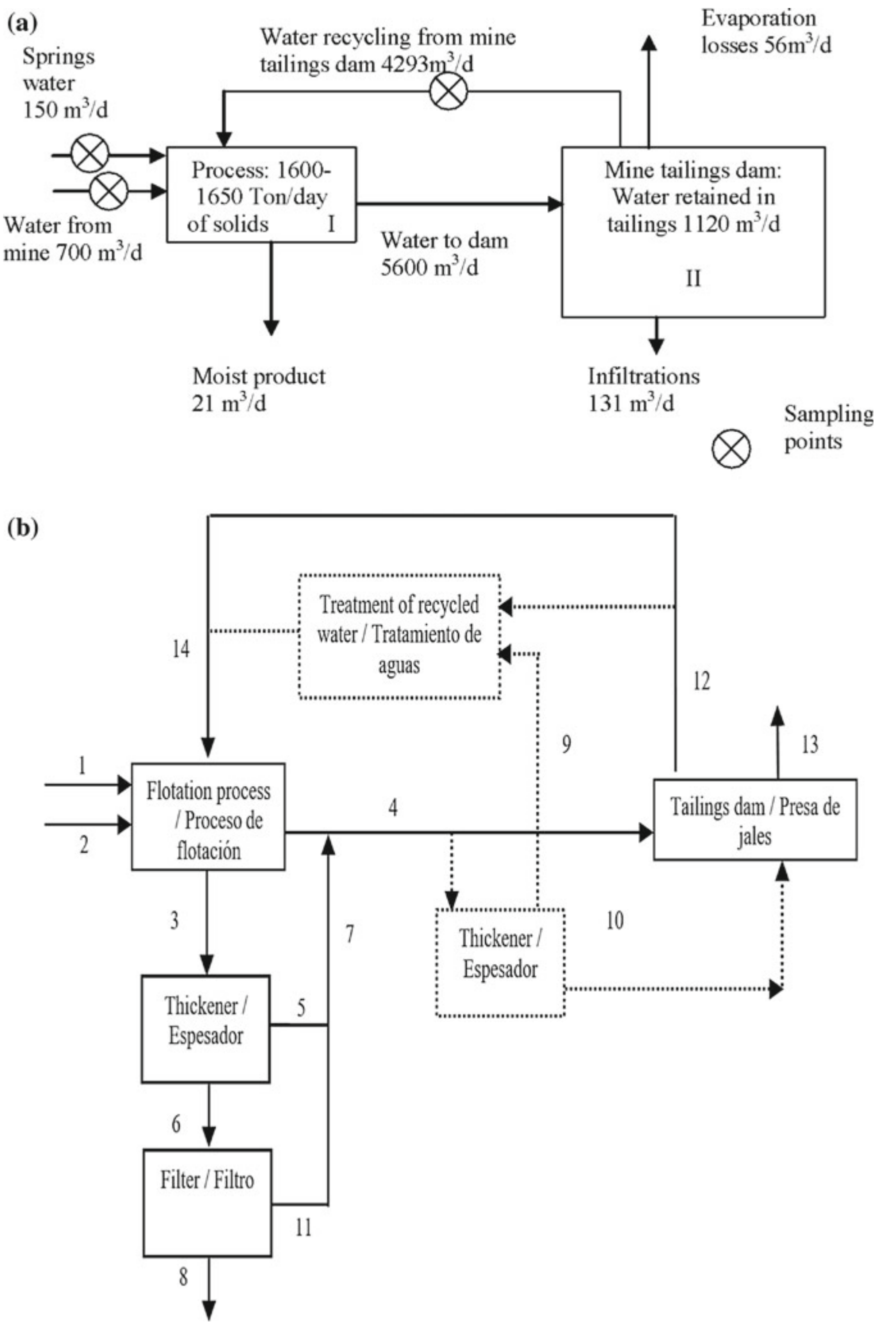


Fig. 19.2 **a** Data on total water balance based on data provided by the cooperating mine considering 1650 Tons per day of solids recovered (Pacheco-Gutiérrez 2006). **b** Diagram of the process of the cooperating mine based on data provided by the mine's technical personnel and calculated according to Table 19.1 (Pacheco-Gutiérrez 2006)

Table 19.1 Water balance: Calculated data versus the provided data

		Data given by personnel	Calculated data	Proposed data
Stream	Description	$m^3\ d^{-1}$	$m^3\ d^{-1}$	$m^3\ d^{-1}$
1[a]	Water of the mine	700[a]	700	302
2[a]	Spring water	150[a]	1316	150
3	Concentrated solids, 20% solids	1000	1000	1000
4	Tailings, 20% solids	5600	5600	5600
5	Recovered water in the thickener (concentrate)	833	833	833
6	Concentrate, 60% solids	166	166	166
7	Recovered water from thickener and filter	978	978	978
8	Concentrate, 92% solids	21	21	21
9	Recovered water in the thickener of tails (concentrate)	0	0	4846
10	Water to dam[b]	5600	5600	754
11	Water recovered in filter of concentrated solids	145	145	145
12	Water recovered from dam	4293	3584	301
13	Losses of water in dam	1307	2016	452
14	Recycled water	4293	3584	5148

Proposed data based on the study of Pacheco-Gutiérrez (2006)

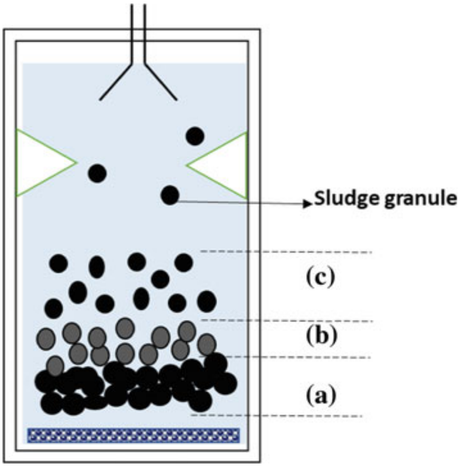
[a] These data do not allow to complete the water balance

[b] 20% solids is the given information by personnel as well as calculated and 65% solids is the proposed value

not homogeneous among the visible layers. These layers are a function of the depth due to the natural sedimentation process, which also influences the cellular residence time (Rastegar et al. 2011). In this sense, bacterial consortium, pH and Eh values may be different depending on the water content and sludge blanket compaction, so the methodology for measuring these physicochemical parameters must consider the degrees of compaction differentiation. In Fig. 19.3 biosolids subdivisions were suggested during UASB operation.

Depending on the sludge density, four grades of compaction were proposed, compacted, semi-compacted, in disintegration sludge blanket, and as granules sludge. So, in each compaction degrees, a pH and Eh characterization at the beginning must be

Fig. 19.3 Different biosolid compaction areas within a UASB. **a** Compacted sludge blanket, **b** semi-compacted sludge blanket, **c** in disintegration sludge blanket



done. Knowing that the UASB reactor operates with an ascendant flow, the sludge layers are semi-separated. When the UASB reactor is not in operation, it will not have that upward current," so the sludge will tend to settle (one layer on top of another) and visually it will be a little complicated to differentiate the layers, but the water content will be well differentiated between the sections. As well to pH and Eh values, the metals chemical species can be influenced by other medium components. In this case, carbon is the main one, whose concentration is easy to determine in biosolids, only using the water content and the density that is around 1.15 g cm^{-3} in sludges of UASB reactors (Henze et al. 2008) or by determining the organic matter content in the laboratory.

In addition to the above, the introduction of the sulfur amount contained in the aqueous solution it is required, which is a common practice in water characterization. With all this information, it becomes necessary to construct an Eh-pH equilibrium diagram, but that considers the chemical species in function of other chemical elements concentration, in this case of carbon and sulfur. These characteristics are fulfilled by the Pourbaix diagrams (de Carvalho Filho et al. 2016; Gow et al. 2016; Huang 2016). The main features of these diagrams are shown in Fig. 19.4a and the three main types of pH and Eh lines in Fig. 19.4b. The Pourbaix diagrams construction is not an easy task to carry out due to the corrosion and leaching issues which may occur. Although specialists in this area are the hydro-metallurgists, for environmental purposes it is possible to use software called HSC Chemistry to show the ionic and non-ionic species graphically in water based on the Gibbs energy.

These reducing metal sulfates are equivalent to knowing the metallic species and therefore their toxicity and disposal options (Kim and Osseo-Asare 2012; Tolonen et al. 2016). All this could be done after the centrifugation of each of the strata of the biosolids (Fig. 19.3) to measure pH and Eh in the supernatant. In Fig. 19.5, a lead-sulfur-carbon Pourbaix diagram is shown as an example, which it was generated with the HSC Chemistry 5.11 software.

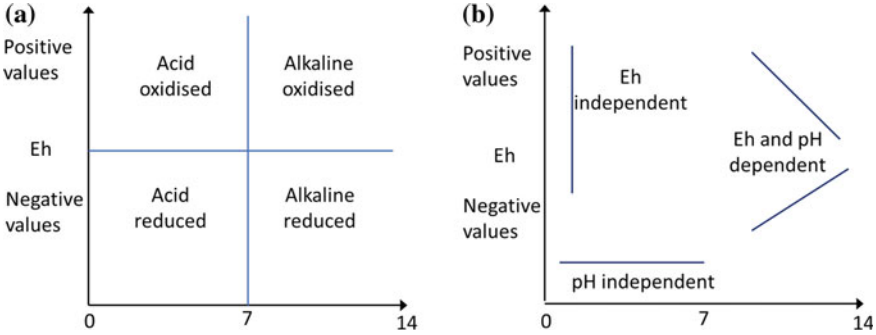


Fig. 19.4 **a** Main chemical characterization of metals in Pourbaix diagram. **b** The three main types of lines resultants between Eh and pH. Modified of Wright (2005)

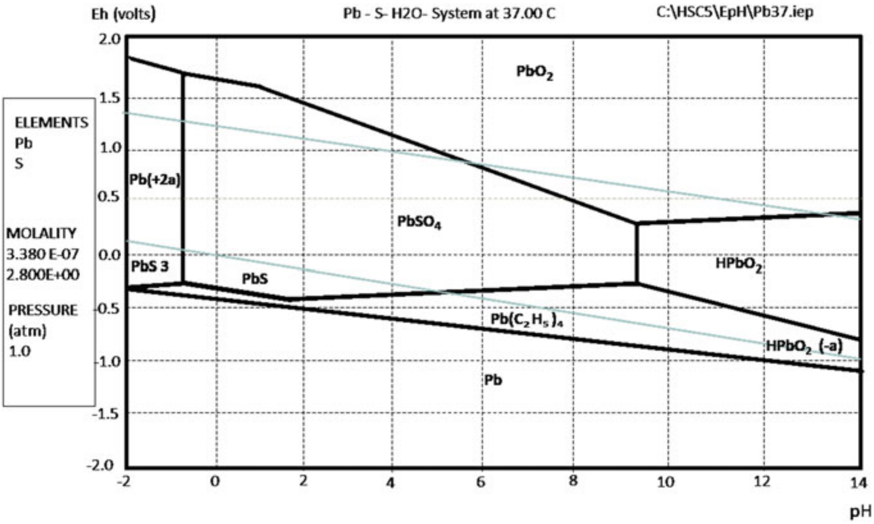


Fig. 19.5 Construction of an Eh–pH Pourbaix diagram of lead, sulfur, and carbon in a typical concentration of UASB biosolids

In the first instance, it is observed that dominant species are PbO_2, solid elemental lead (Pb), $PbSO_4$, liquid $HPbO_2$, liquid elemental lead (Pb^{+2a}) and organic lead $(C_2H_5)_4$. Of these species, due to the UASB anaerobic characteristics, the only species which were deduced to occur is the organic lead, usually as lead acetate and solid-state elemental Pb, that rapidly precipitates (Hoa et al. 2007). Both chemical forms of lead can be analyzed since they have a Chemical Abstract Service Registry Number (CASRN), and are described in the open scientific literature. Thus, the CAS provides information on toxicity, risks of exposure, transport, special precautions, physical-chemical characteristics, among others, recognized at an international level.

The above-raised concepts would allow proposing methods of neutralization, reuse/recycling, final disposal and even recovery of heavy metals contained in the biosolids in a technically efficient way, all based on the knowledge of the samples chemical properties. Precisely these properties will be established by Eh–pH diagrams described above.

19.4.2 Artificial Wetlands for Water Polishing

19.4.2.1 Horizontal Subsurface Flow Artificial Wetlands, HSFAW

These types of systems work quite readily for stabilizing heavy metals (Amábilis-Sosa et al. 2015; Soto-Esquivel et al. 2013a, b; Salgado-Bernal et al. 2012a, 2017; Ruiz-López et al. 2010). The interesting matter is that artificial wetlands not only stabilize dissolved metals but also contain the presence of very fine particles for being dispersed by wind when climatic conditions favor these phenomena (Lizárraga-Mendiola et al. 2008, 2009). It has been proposed to seed hydrophytes surrounding the tailings dam, along with its banks, in order to create an artificial wetland in the area that eventually will cover the site stabilizing the very fine particles deposited there (Fig. 19.6).

Also, when dry hydrophytes leaves have to be removed, as well as the excess growth, this biomass material can be used as fuel for a heating system to preheat the influent of the UASB reactor. Since archaea and sulfate-reducing bacteria are thermophilic microorganisms, and the resulting ashes can be recycled to the metal recovery process together with the ores extracted from the mine tunnels. Considering

Fig. 19.6 Photographs of one of the cooperating mine tailing dams (Pacheco-Gutiérrez 2006)

that the tailings dams banks are the suitable places to plant the hydrophytes, its management can be carried out without much effort particularly in the entrance of the UASB effluents to the tailings dams (Fig. 19.6).

19.4.2.2 Impact of the UASB Reactor-HSFAW System on the Neighbouring Communities

First of all, the communities may corroborate that the enterprises are looking into the matter of possible runoffs of their tailing's dams establishing a biological barrier formed by hydrophytes. This issue implies that communities should have some insight into what is going on the neighbouring mine. Unfortunately, most mine owners keep this vital information for the security of the communities hidden with the positive support of the governmental authorities (LFTAIPG 2018). For this reason, it is important to remember the ecocide caused in 2014 in northern Mexico with a spill that impacted an area almost 200 miles along the Sonora River Basin, home to more than 22,000 people (Fernández 2015; Wilton 2015).

Second, the mine's neighbouring communities might benefit from learning about the combined system UASB-*HSFAW* for its use in their sanitation facilities. If the community does not have sanitation installations, they can build them with the mine's technical and economic support, since the system is environmentally friendly and can be built at a moderate cost, even using community support. Thirdly, the springs, wells, and surface water sources will be available for them since the enterprise would be recycling its processing water.

19.5 Concluding Remarks

The approach followed by the owners of the cooperating mine to maintain an academic collaboration with universities, as well as the active relationship with the mineworkers, their families, and the neighbouring communities have been not only profitable for them but also for the image they have before society, a rare case in Mexico.

If all the mines' owners followed this trend, the cases mentioned at the introduction would not occur.

Naturally, communities should be aware of these possible solutions, such as the use of environmentally friendly technical systems like the UASB reactors and the artificial wetlands, in order to protect their children's present and future sources of water.

Creating this awareness should be one of the tasks of university academic staff and students.

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Chapter 20
Assessing Socio-hydrological Resilience in Urban Metropolitan Environments: A Mexican Perspective

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Abstract Growing population and the increasing global trend of human migration from rural to urban environments are leading to an expansion of metropolitan landscapes, which threatens water security and hydrological environments within cities. Often water security and metropolitan hydrology are approached as two separate issues. Subsequently, social aspects of infrastructure inclusiveness and the social registers of hydrological landscapes are left behind. The disconnect between water management and society, and their resulting impacts, such as drought, flood or poor water quality, are exacerbated by climate change and demand the introduction of new water management strategies. We present the socio-hydrological resilience (SHR) concept as an interdisciplinary, holistic vision, which integrates socio-ecological methodologies with resilient water management practices. We examine traditional

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practices and present three novel approaches to water management in Mexico. On this basis, we define a set of socio-hydrological indicators that may be used to assess the resilience of urban environments to future change. We propose qualitative SHR indicators based on water security, social, and hydrological aspects. Finally, we propose a coupled method to evaluate the integration and interdependencies of these indicators. To gauge the potentially wide-ranging impacts of these alternative approaches and to assess future approaches, a quantitative set of multidisciplinary indicators is required. They are discussed but requires further research.

Keywords Socio-hydrological resilience · Metropolitan · Water security

20.1 Introduction and Key Terms

Growing population and the increasing global trend of human migration from rural to urban environments are leading to an expansion of metropolitan landscapes, which threatens water security and hydrological environments within cities. Often water security and metropolitan hydrology are approached as two separate issues. Subsequently, social aspects of infrastructure inclusiveness and the social registers of hydrological landscapes are left behind. The disconnect between water management and society, and their resulting impacts, such as drought, flood or poor water quality, are exacerbated by climate change and demand the introduction of new water management strategies. Using case studies from around Mexico we examine traditional practices and novel approaches to water management and define a set of socio-hydrological indicators that may be used to assess the resilience of urban environments to future change.

In this chapter, we give a brief outline of widely used key terms such as water security, climate change, metropolitan design, and socio-hydrological resilience as these definitions underpin both traditional and innovative water management practices. We provide a brief review of existing practices in Mexico, highlighting the limitations of traditional water management approaches and how they often disregard social aspects and ignore the broader hydrological systems in which they sit. To address these limitations, we present the *socio-hydrological resilience* (SHR) concept as an interdisciplinary, holistic vision, which integrates socio-ecological methodologies with resilient water management practices. Novel approaches towards water management are presented at three scales: metropolitan (10^1 km), urban (10^0 km) and architectural (10^{-1} km). These approaches are discussed retrospectively within the proposed SHR interdisciplinary framework. To gauge the potential impacts of these alternative approaches and to assess those of future approaches, a quantitative set of multidisciplinary indicators is required. We propose a set of qualitative SHR indicators based on water security, social, and hydrological aspects related to the novel initiatives described in study cases. Finally, we propose a method to evaluate the integration and interdependencies of these aspects. Refining these indicators and their weighting is discussed, but ultimately left open for future research where they could be further developed into quantitative indicators and weighting formulas for evaluation of water management proposals.

20.1.1 Security, Climate Change and Metropolitan Design

About water management, socio-hydrological resilience standards can be built on the notion of water security, which is severely threatened by a changing climate and rapid urbanization of the metropolitan environment and its surrounding rural regions. Here, we provide a brief definition of these terms in order to frame the discussion for this chapter.

The ‘dynamic and continuously evolving dimensions of water and water-related issues’ have led to various definitions of water security over the past decade (Grey and Sadoff 2007; Houdret et al. 2010; UNESCO-IHP 2012). The United Nations (UN) and UNESCO use a working-definition, developed by a broad range of organizations, agencies, programmes, and institutions to describe water security and provide an outlook for addressing current and perceived future water challenges (UN 2013; UNESCO-IHP 2012). Under the UN and UNESCO definition, water security is ‘the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability’ (UNESCO-IHP 2012). A holistic, interdisciplinary approach to sustainable water management is required to achieve water security. It is imperative that any approach contributes not only to social-economic development, but also ‘reinforces societal resilience to environmental impacts and water-borne diseases without compromising the present or future health of populations and ecosystems’ (UN 2013). The concept of water security and its attainment applies to multiple scales: from an individual, household, and community through urban and metropolitan to national and international. Water availability plays a key role in the water security concept and is affected by changes in climate, population, and land-use.

Water availability, quality, and disasters are conditioned by climate change. A warming climate will likely lead to greater evaporation and precipitation at the global scale, with a highly uneven distribution of precipitation. Runoff is expected to increase in high latitudes and a decrease in mid-latitudes and subtropical regions (Arnell 1999). Episodes of flood and drought are forecast to be greater in frequency and intensity, which will undoubtedly increase stress on water resources and security. ‘Climate change over the twenty-first century is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions, intensifying competition for water among sectors’ (Jiménez Cisneros et al. 2014). Global climate changes may be intensified by the concentration of urbanized zones in metropolitan areas via microclimate changes. Local variations cause microclimate changes in population (urban, peri-urban, and rural), land-use (percent area of pasture, crops, urban land, etc.), and land cover (percent area of trees and bare earth) (Ellis and

Ramankutty 2008). For example, urban heat islands result from the modification of land cover, where reduced vegetation cover, increased impervious cover and complex cityscape surfaces lead to lowered evaporative cooling, augmented heat storage, and sensible heat flux (Patz et al. 2005). Compiling these local changes can lead to substantial impacts at the regional scale. Beyond exacerbating global climate change, microclimate changes such as the urban heat-island effect can exert the most significant impact on local climatic conditions. 'Dark surfaces, such as asphalt roads or rooftops, can reach temperatures 30–40 °C higher than the surrounding air.' Consequently, most cities have shown to be 5–11 °C warmer than their surrounding rural areas (Aniello et al. 1995; Frumkin 2002).

Human-induced local or regional modifications to ecosystems range from considering humans merely agents of ecosystem transformation (ecosystem engineers) or a force rivaling climatic and geologic processes, able to irreversibly alter an ecosystem's form, process, and biodiversity. The latter relates to the urban environment, where the human population can be dense enough that local resource consumption and waste production become a significant component of local biogeochemical cycles and other ecosystem processes (Ellis and Ramankutty 2008). Rapid urbanization has exacerbated the impact that climate change poses to water security. Urban growth has amalgamated cities and towns into *agglomerations* with several urban areas and cores. Highly attractive for economic and industrial activities, as well as employment, these agglomerations are known as conurbations, city-regions, urban regions, metropolitan regions or global city-regions (Brenner and Schmid 2011) depending on their configuration, size, scale or genesis. These agglomerations demand new sustainable approaches towards urban management that are, in many cases, not evolving at the same pace as population growth, especially about water security. These new forms of management pose significant governance challenges leading to social inequality and affecting the way agglomerations are spatially configured while requiring design strategies that offer alternatives.

Migration to rapid growth areas generates social and economic inequality, especially in the suburbs. 'Many peri-urban areas in developing regions are associated with poverty. The poor peri-urban resident may have moved-in and established residence in precarious conditions or may have resided in the area before the urban encroachment and so have a rural background. Poor, ex-rural residents living on the fringes of cities are considered to be very vulnerable since they are subjected to a livelihood transmutation while they try to escape poverty' (Méndez-Lemus and Vieyra 2014). Legal and administrative delimitation of these conurbations is often complex. The merging of urban areas and towns is independent of their administrative boundaries, which results in fragmented management and a lack of systemic and integrated visions. Attempting to define the spatial impact of metropolitan resource requirements adds further complexity. To fuel rapid urbanization, resources are imported at national and global scales. In the case of water, resources are often extracted from remote sources and wastewater disposed of outside urban centres in a linear consumption-waste (take, make, and dispose) model. The inability to define physical boundaries poses further administrative challenges, due to metropolitan impacts surpassing official limits. To overcome these two challenges, a paradigm shift in water management that includes circular, systemic, and multiscale approaches is required. New approaches must be flexible enough to be incorporated within larger design strategies that can explore other modes of multi-scalar administrative delimitations while maintaining the ability to address social inequality.

20.1.2 Socio-hydrological Resilience (SHR)

To build a holistic, interdisciplinary approach that integrates social and hydrological aspects under rapid urbanization and climate change challenges, we explore the emerging notion of SHR. SHR departs from a more consolidated model of social resilience (SR), which is recognized as an interdisciplinary concept (from engineering, ecology, economics, psychology, sociology, urbanism, and architecture), a multifaceted phenomenon (social, spatial, and economic), and as an aspect to consider in recent decision-making and governance mechanisms, and implies a way of collaborative and transdisciplinary work.

SR is defined as 'the ability of groups or communities to avoid, cope with, learn, adapt, and recover from external tensions and disturbances as a result of social, political, and environmental change' (Adger 2000; de Kraker 2017; Saja et al. 2018; Shaw et al. 2014). SR has been approached from different system thinking perspectives that seek to include social aspects of resilience, based on a framework of sub-categories (social structure, social capital, social mechanisms, social equity, and social belief) (Saja et al. 2018). SR may also consider elements of social learning, social memory, mental models, and knowledge-system integration, vision and 'scenario building, leadership, agents and actor groups, social networks, institutional and organizational inertia and change, adaptive capacity, transformability, and systems of adaptive governance' (Folke 2006). Investigations have emphasized SR as a way to understand the effects and dynamics of the socio-ecological system on the human system. However, there is no defined method to measure it in a socio-hydrological context.

To assess linkages with water security, SR has been 'linked to a community's ability to: access critical resources (Langridge et al. n.d.); deal with disasters' (droughts or floods) (Saja et al. 2018); cope with changes in water availability or quality (Wurl et al. 2018); or with sustainability (Milman and Short 2008). Hence, managers, scientists, and communities must decide between working with 'individual system processes or viewing the system from a more abstracted level' (Blair and Buytaert 2016). In this sense, it is important to investigate concepts and indicators to measure urban processes involving the social and hydrological domains for the design of future metropolitan infrastructure and sustainable water management. Mao et al. (2017) proposed the SHR concept. SHR implies 'understanding and assessing resilience in a coupled socio-hydrological context', considering inter-connections between socio-hydrology and resilience. They also 'identify three existing framings of resilience for different types of human–water systems and subsystems (1) the water subsystem, which highlights hydrological resilience to anthropogenic hazards; (2) the human subsystem, foregrounding social resilience to hydrological hazards, and (3) the coupled human–water system, which exhibits socio-hydrological resilience.' Using the SHR concept, Wurl et al. (2018) 'argue that the coupled human-water system is the most appropriate tool to design strategies for resilient management of hydrological resources.' Ciullo et al. (2017) use the SHR concept to integrate two different types of socio-hydrological systems in human–flood interactions and feedback mechanisms: green systems, whereby societies deal with risk via non-structural measures and technological systems, whereby risk is dealt with also by structural measures such as levees.

The SHR concept represents a potential for a transdisciplinary framework to assess local study cases in urban environments where water security and management, social resilience, micro, and global climate change, and traditional and metropolitan design can be integrated and measured to create resilient models of urban space.

20.2 Existing Practices in Mexico

20.2.1 Review of Mexico's Water Availability and Demand

Since 2012, the Mexican Constitution established the access, disposal and sanitation of water as a human right. However, the provision of rights has had severe limitations throughout the nation. Mexico is a country under severe water stress. It has approximately 0.1% of the total freshwater globally available while being among the top 10 consumers of water in the world (197,425 million m^3/year), with principal users being: agriculture, 76%; general public, 15%; thermoelectric plants, 5%, and industry in general, 4%. Consumption rates are not uniform in time or space, for example, in Mexico City the Tlalpan borough has a water provision of less than 40 m^3/cap/year, while the Miguel Hidalgo borough has a consumption rate estimated at 190 m^3/cap/year. This difference in water use, demand and availability are characteristic of the country's water issues (PUEC UNAM 2010; Rosalva Landa 2014).

The availability of usable water is a complex problem that includes geographical distribution, pollution, and overexploitation. Mexico has a significant percentage of its territory under the desert and semi-arid climates, primarily in the central and northern parts of the country. In several areas of the center and north, water availability levels are currently lower than 2500 m^3/cap/year. In the Baja California peninsula, Rio Grande region and northern basins it is estimated that water availability will be less than 1000 m^3/cap/year by 2020, considered by the WMO as the minimum threshold to satisfy basic needs. At the same time, south–southeast Mexico, which has a more humid climate, has almost seven times more water than the rest of the country per capita, with water availability more than 23,000 m^3/cap/year in the south. Regional population and wealth exacerbate the impacts of non-uniform water distribution. Central and northern regions have 77% of the national population and generate 82% of the GDP, while they only have on average 33% of the water resource. Nationally, this places central Mexico (State of Mexico, Puebla, Tlaxcala, Morelos, Hidalgo, and Mexico City) with the highest level of pressure on its water resources (CONAGUA 2017; Rosalva Landa 2014).

Water availability is further limited due to widespread contamination of natural water bodies with municipal and industrial wastewaters. Nationally, 42.5% (±11.5%) of municipal wastewater is treated, introducing an estimated 191.5 (±84) m^3/s of raw wastewater into nature. Also contributing to the degradation of water quality are informal effluents introduced in areas that lack centralized sanitation services. Nationally, 11% of the population lack these services. However, there are regions, such as the states of Oaxaca and Guerrero, where up to 30% of the population lacks formal sanitation. On the industrial side, 216 m^3/s of raw wastewater are emitted. Surface water contamination is causing epidemiological problems in communities living near the riverbeds in Central Mexico, such as the Atoyac, Santiago, Lerma, Tula, and Coatzacoalcos rivers. The implications related to the lack of municipal and industrial wastewater treatment in Mexico are serious. In 2017, 32% of all the tested water bodies had water quality issues, while in central Mexico 49% of sites were found to be contaminated (CONAGUA 2017).

Water scarcity combined with the threat of pollution has led to the overexploitation of groundwater resources. In 1975, there were 32 aquifers defined as overexploited by CONAGUA (National water commission). They increased to 80 by 1985 and 106 in 2006. In contrast, the per capita availability of water in Mexico has decreased significantly since the middle of the last century: in 1950 it was 18,035 m^3/cap/year, and in 2013 it was 3982 m^3/cap/year, a rate determined as low by the United Nations Development Program (CONAGUA 2017).

20.2.2 Conventional Technologies and Their Limitations in Mexico

20.2.2.1 Conventional Technologies and Centralized Systems Under Stress

The nature of high-infrastructure water and sewage systems (force mains, treatment plants, pumping stations, etc.) does not allow sufficient flexibility or resiliency to deal with the expected impacts of population and climate changes this century. Centralized urban water and wastewater systems consume large amounts of energy in their 'processing phases, including purification, distribution, and sewage conveyance and treatment' (Cheng 2002; Jothiprakash and Sathe 2009). Due to the stress currently placed on energy systems, water, and sanitation systems need to be redesigned in order to remain effective. Water purification and sanitation technologies have reached their technological limits to treat recalcitrant contaminants (pharmaceuticals, microplastics, pesticides, etc.) (Garcia-Becerra and Ortiz 2018). Furthermore, high-infrastructure systems tend to require a close asset management approach. So far, centralized systems tend to lack stable financing across the globe (Panebianco and Pahl-Wostl 2006). In Mexico, municipal water management has been decentralized, going from the federal to the state and the municipal level. As a result, the majority of municipalities have foregone paying the operation and maintenance costs associated with sanitation services.

20.2.2.2 Linear Urban Water Metabolism

Linear material flows of take-dispose are in direct conflict with our planet's cyclical system (Zaman 2015). Usage of natural resources, including water, implies almost directly they are discarded as waste and our current water consumption habits do not consider its direct reuse, for example, lost cost-saving opportunities from reusing greywater and runoff in agriculture and landscaping. As we move closer to the limits of urban ecosystems' carrying capacities, the need to manage water and wastewater in closed production cycles becomes critical. New water and sanitation systems should include diverse water reuse applications, less water-intensive urban and industrial designs and long-term sustainability concepts, such as circular economies and production schemes (Connett 2013; Zaman 2015). It is noteworthy that beyond solving critical environmental problems, cyclical sustainable water, and sanitation approaches can be instrumental in achieving sustainable urbanism and activating their local economy (Lee et al. 2014; Puppim De Oliveira et al. 2013).

In the conventional framework of city growth, recovery of resources (particularly water resources) is not considered. To achieve sustainability, it is necessary to transform the linear approach to one that is circular-partially-closed, allowing water (and other resources) be recovered, reused and recycled (3R approach). A closed cycle in which waste and all wastewater are recycled is unrealistic. However, a partially closed-cycle allows improved water management that incorporates wastewater. A circular approach prioritizes the restoration and regeneration of resources to maintain its greater usefulness and value, separating the overall development of the inefficient consumption of finite resources, based on the assumption of large amounts of easily accessible resources (Ellen MacArthur Foundation 2015).

A clear indicator of the linear approach to urban water management in Mexico is the investment plan for the so-called strategic projects, which focus on Mexico City and traditional infrastructure. The Valley of Mexico (which contains the city of Mexico) concentrates 47% of the total investment in *strategic* projects. These projects are developed in the great cities of the urban system: Mexico City, Guadalajara, Monterrey, Leon, Guanajuato, San Luis Potosí; Acapulco, Ixtapa, Zihuatanejo, among others. Conventional infrastructure such as dams, aqueducts and sewage treatment plants absorb half of the budget. Long-distance aqueducts that supply large cities are often employed in these projects: Cutzamala system, Stage IV (827 km); Tecolutla-Necaxa Aqueduct (131 km); third line of the Cutzamala system (77.6 km); Monterrey VI (372 km); the Chapultepec Aqueduct (33 km); are some examples. Projects to remove wastewater from large cities are also given priority under these projects. Despite a national program targeting the reuse of all wastewater (Objective 1.2.1.), neither maintenance or rehabilitation of water supply sources appear in these strategic projects.

The current situation of scarcity and greater uncertainty in future water resources demands a new perspective in which wastewater is seen as a potential potable resource with the added benefits of energy production and nutrient recovery. However, in Mexico, almost all water treated in the urban environment is discharged into the surrounding area, while sludge is usually disposed of in landfills.

20.2.3 Urban Growth in Mexico

Worldwide, rapid population growth and urbanization are posing new water and sanitation engineering and infrastructure challenges. Water is vital in metropolitan design and growth processes. As stated by Meinzen-Dick and Appasamy (2002), 'of all the challenges posed by the dramatic growth of cities, none will continue to have a greater impact on the quality of human life or the environment than the provision of water, and the treatment of water-borne wastes.' Urban growth increases both water demand and impairment of water sources.

By 2050, it is expected that almost 70% of the global population will live in cities (settlements between 1000 and 19,999 inhabitants, depending on the country) (Satterthwaite 2000; WWAP 2018). Current energy-intensive, high-infrastructure water and centralized sanitation systems will be impractical for dense and high-growth megacities (Chiu et al. 2015). Mexico has, according to the 2015 intercensal survey, 119,530,753 inhabitants with 85% of the population residing in metropolitan areas and conurbations (137 in total). In 2015, 78.8% of the population lived in towns of 2500 or more inhabitants and it is expected that by 2030 almost 125 million people will live in cities.

In summary, rapid urban growth and increases in population density combined with inequalities in water availability and consumption, contamination, lack of treatment and access to formal sanitation, and resource overexploitation demand a change from conventional centralized and linear take-dispose approaches to water resources in Mexico. Current strategies towards water management react slowly and rigidly to demographic challenges and rapid population change, often demanding high investment infrastructure and long inception times. Current urban growth outpaces the time required to design and build current infrastructure (WWAP 2018). In the following section, we use three examples to describe manageable, decentralized, on-site and circular water strategies that tackle issues of water security from a socio-hydrological perspective and offer greater potential for resilience to population change.

20.3 New Approaches and Tools: Metropolitan, Urban and Architectural Scale

Based on water management and demographic challenges in Mexico, the following projects highlight water management approaches in Mexico that build SHR. These localized examples propose on-site multidisciplinary solutions, ecological integration, architecture, engineering, and permaculture design features. Unlike conventional strategies, that use natural resources under a centralized and linear material economy regime, these approaches aim to utilize a local circular economy. They minimize environmental and social impacts while maximizing the benefits to the socio-ecological systems in which they are implemented. Local-scale interventions can build resilience through the non-reliance on large-scale infrastructure (investment, governability, management, and understanding through time) and through their ability to quickly adapt to climate and population change. The projects in this section are used in subsequent sections as a basis to develop a series of qualitative indicators, feedback, and coupling for future policy design.

20.3.1 Oaxaca Potential Runoff Catchment Cartography

The metropolitan area of Oaxaca, located in the Central Valleys, Mexico, has changed dramatically over the past couple of centuries. Paintings and maps from the 19th Century (for example, Jose Maria Velasco—Vista de la Ciudad y Valle Grande de Oaxaca) show Oaxaca had clearly defined limits, whereas today the city limits are sprawling. During this time several geographical features have been transformed: the river Atoyac no longer meanders, the hills are covered by the city and agricultural areas have disappeared. Comparison of past maps and paintings with today's city highlights how the relationship between society and the environment has changed. It also provides an opportunity to examine how a metropolis may evolve in the future.

To generate a future vision, it is crucial to understand the landscape we inhabit. From an architectural perspective, the landscape can be defined as comprising the built environment and society, and their interactions with nature, both in the form of resource exploitation and enjoyment (equivalent to the natural capital concept). The landscape is seen as the materialization of complex structures that link nature and society, built throughout history. The importance of integrating landscape as a concept in the construction of future visions is crucial, especially if we consider challenges that society faces now and in the future. This ethos was the basis for an integrated future vision developed for the Central Valleys of Oaxaca. The vision used cartographic design to communicate the potential for sustainable, decentralized and resilient water management in the Metropolitan Oaxaca.

The Pedregal ravine project (Instituto de la Naturaleza y la Sociedad de Oaxaca; Foro Oaxaqueño del Agua; WWF 2014) is a local example of a sustainable, societally focused water management programme. It is an environmental centre that aims to

Fig. 20.1 Permaculture techniques in El Pedregal include dry toilets, treatment of grey waters, improved wood stoves, rainwater harvesting systems, composting, bioconstruction, regeneration of soils, terracing, and groundwater recharge

change the culture of water management in Oaxaca with local communities. Using permaculture methods, the project attempts to recover eroded soil using terracing and planting strategies, as well as slowing rainfall runoff through various techniques such as water infiltration, collection, and distribution (Fig. 20.1). The intention is to use the project as a replicable model for other ravines of the Central Valleys. This strategy highlights the potential for recovering eroded soil and sustainably manage rainwater with a realistic and governable model while providing an alternative to water importation. The latter process is unsuitable as it relies heavily on centralized infrastructures, such as the case of Presa Paso Ancho (Instituto de la Naturaleza y la Sociedad de Oaxaca; Foro Oaxaqueño del Agua; WWF 2014), and is based on a model of linear, intensive and competing use of water, mainly for urban and agricultural purposes.

Cartographic techniques were used to create the vision for Oaxaca (Fig. 20.2), which summarize the water collection potential of sub-catchments in the Central Valleys. The vision proposes the construction of a small dam in each of the upland sub-catchments to collect rainwater. According to official calculations, the city of Oaxaca needs approximately 95,000 m^3/day of water to meet societal needs. This need is not currently met, and future vision offers a sustainable alternative to large infrastructure projects (with high associated costs). The combined potential amount of water available is 864,000 m^3/day, based on observed rainfall and surface runoff, which suggests, at the annual-scale, there is no need for water scarcity the Central Valleys calculated with the hydrology toolset of geographic information systems (GIS) software. To ascertain the potential of each sub-catchment for water collection, rainfall was combined with a digital elevation model (DEM) to determine surface water Using the DEM as a base for the hydrology model, then Flow direction was calculated, flow accumulation and then with a defined threshold, stream order stream to feature and stream link. The stream link was converted into a vector to intersect runoff with the agricultural boundaries to locate the micro-dams above the agriculture level. Then, the watershed was calculated as the upslope area from these points, also

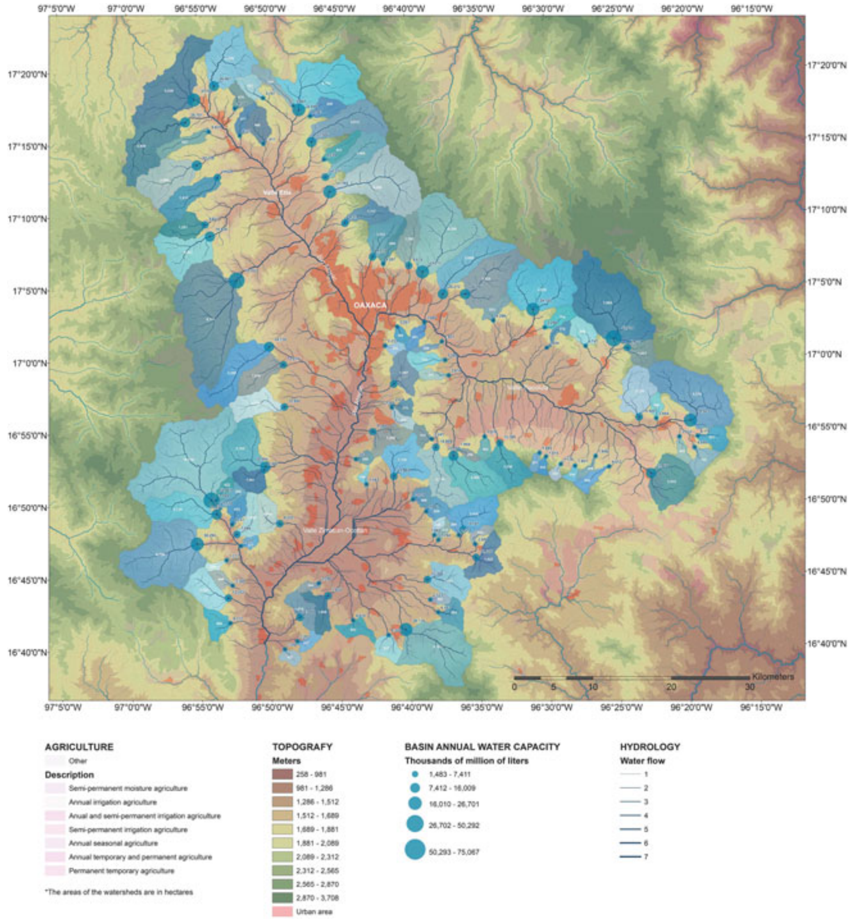

Fig. 20.2 Deployment of micro-dam catchment strategy in the metropolitan area of Oaxaca in the Central Valleys

using the watershed tool from GIS and the water accumulation with the annual rainfall from data provided by INSO. This basic calculation suggests that there is no water scarcity; on the contrary, the Central Valleys have water abundance, and for a fraction of the cost, and through smaller, easier to finance and resilient projects such as micro-dams, it would be possible to have a constant supply of water for the entire metropolitan area. It would reduce the competition with agricultural uses and achieve a more equitable distribution. At the metropolitan scale, the aggregation of these micro water catchments of blue infrastructure would build flooding resilience for the lower urban areas.

As previously stated, water availability is a key factor in water security. From a societal perspective, a region with true water scarcity is very different from one with poorly managed, but abundant water resources. The latter mindset shifts the problem from one of supply to one of distribution and decentralization, which involves civil society and the communities where water is collected, managed and distributed.

20.3.2 Mexico City Ravines

Recovering Waterscapes is a ravine landscape management programme designed to restore the remaining primal regions of the former valley and lake ecology in Mexico City. The project encompasses transdisciplinary research to recover ravines on the western side of the city. Developed under close collaboration between private and public entities through a public consultation process and meetings with the local authorities and experts, it provides a spectrum of data, knowledge, and expertise.

The programme was proposed as an aggregative and multiscale approach that understands the natural performance of ravines as part of a broader ecological network, fostering local and punctual interventions with metropolitan impacts. To ensure the citizens' right to live in suitable and agreeable environments, the project proposed dynamic, regulatory and prototypical interventions to rescue the ravines, both as infrastructural facilities and social spaces. It sought to re-integrate ravines into the urban fabric through the participatory engagement of agencies, communities, and neighbors, building awareness and combining responsibility and ownership.

The underlying concept was the recovery of the former waterscapes in Mexico City, yet the concept was not triggered by the nostalgia of lost landscapes, but by the undergoing water crisis in Mexico City at multiple levels. The primary source of water is from boreholes, which have been linked to subsidence at a regional level as groundwater levels are lowered. The city's secondary source of water supply is imported from lower river basins located hundreds of kilometers away (Tortajada and Castelán 2003). The city also pumps wastewater out into neighboring river systems. These unsustainable practices, together with the scarcity of water suffered by the broader metropolitan population, calls for an urgent rethink and re-understanding of the water provision and storage capabilities of the valley. Unfortunately, the potential for using ravines as green infrastructures are currently limited as they are polluted, used as sewage outlets and illegal landfill, and are invaded by informal settlements built at the risk of collapsing. Due to the informal growth of metropolitan areas, the settlements around the ravines use them as informal sanitation infrastructure, provoking ecological and soil degradation. This lack of infrastructural planning also includes lack of open and green spaces and social facilities.

The Recovering Waterscapes project uses small interventions, a hybrid of structural and non-structural micro-measures, at local scales that have a cumulative impact at the wider metropolitan scale. The interventions are grounded on basic principles: reinforcement of slopes; collection, filtering, and management of water; pedestrian accessibility; and the insertion of a variety of social, commercial and community programmes, thus engaging the local community. The project understands ravines as a type of landform with specific environmental qualities (flora and fauna) and intrinsic geographical and geomorphological properties. By analyzing surface water runoff and slope properties, the potential for capturing, channeling and infiltrating water into the aquifer and the lower areas of the valley may be derived. The project challenges the traditional idea of developing single projects in isolation, reinforcing the intrinsic relations between all interventions. With this mentality, phasing becomes crucial, for example, hydrological performance is considered together with pedestrian accessibility and existing facilities in the neighboring areas.

The gradual aggregation of small, local-scale interventions within a more comprehensive regional vision implies a flexible strategy that adjusts to specific budgets and local contexts instead of monumental and unrealizable interventions. It generates community awareness of potential futures by the establishment of concrete projects with visible impacts at various scales. Accessibility and slope management within the ravine network gives access to local landscapes and architectonic interventions: wetland systems, planting strategies and accessibility, to catalyze the recovering of waterscapes. The architecture of proposed buildings within the project is integrated with terracing systems for soil retention and water collection, circulation, wetland treatment, filtering and storage and terraces to overview and enjoy the landscape. This landscape works as both green and blue infrastructure that recovers resilient ecology and hydrologic functions of the ravine. It also improves the capacity of these neighborhoods to adapt to climate change. By managing and cleaning the illegal disposal and landfill of the ravine, the project prevents water-borne diseases and the filtering of pollution into groundwater resources.

At the architectural scale, buildings can form part of the ravine regeneration. For example, a community and environmental center were designed to have commercial facilities and provide easy access to the upper part of the ravine. The building generates a viewing terrace from which a water treatment itinerary starts, finishing in a rainwater collection pond and urban agricultural allotments. The terraces and access paths work as retaining structures to prevent landslides. At the metropolitan scale of Mexico City, the gradual reintegration of ravines into the valley’s water cycle allows groundwater recharge, bringing to life other hydrological features (ravines, rivers, lakes, etc.), improving the quality of the air by increasing the humidity levels, and providing inhabitants natural access to water and the opportunity to engage with the new socio-hydrological landscape. If we scale-up the impacts of these local interventions to the metropolitan scale, we can see a feedback effect at the larger

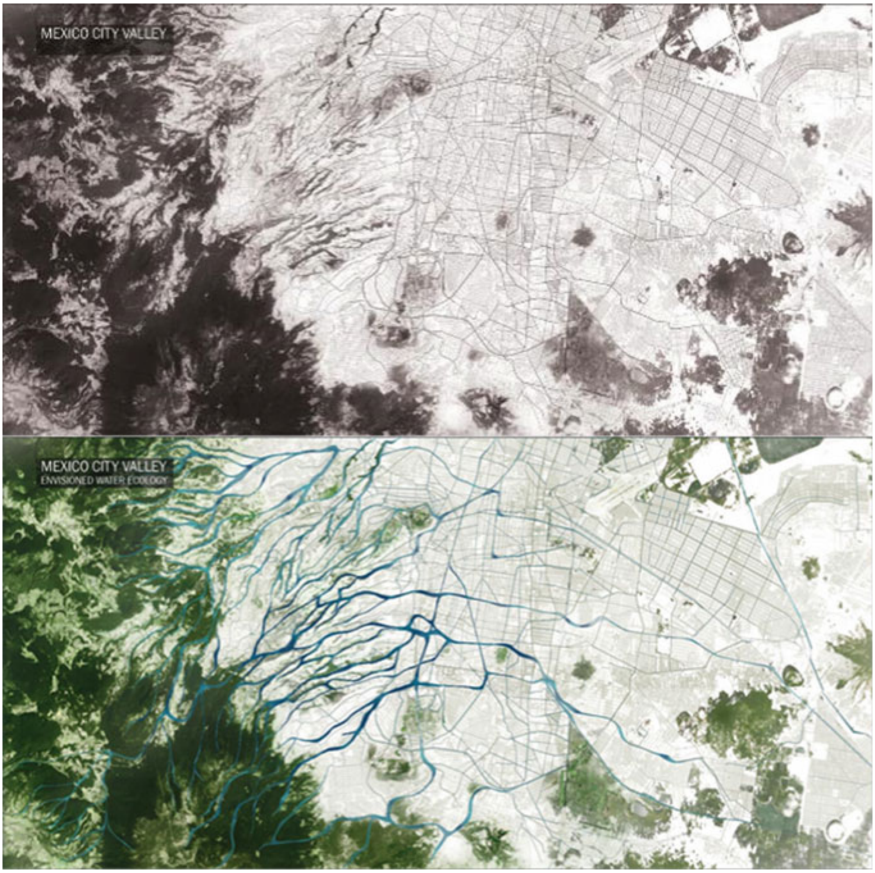

Fig. 20.3 Envisioning Mexico City's future: asphalted city (**a**) versus systemic ravine regeneration, green and blue infrastructure and quality open spaces (**b**)

scale (Fig. 20.3). The production of maps and other media allow a radically different strategy for Mexico City to be shared with the local communities for educational and participatory purposes.

20.3.3 Sanitation Ecotechnologies in Urban Communities

As previously mentioned, water availability in Mexico is significantly compromised by chronic pollution of its natural water bodies. Once the problem of water provision is addressed, the methods for managing and treating wastewater have the potential to compromise the benefits of making water accessible. In this case study, we describe the sanitation component of an urban, community-based project at the Metropolitan Autonomous University, Cuajimalpa Campus (UAM-C), in Mexico City. To satisfy human needs in the context of a local circular economy, an ecotechnology was implemented that minimizes the environmental impact and generation of waste while maximizing the benefits to socio-ecological systems.

Current sustainable sanitation trends include on-site technologies, such as composting dry toilets. So far, decentralized sanitation ecotechnologies have been developed for mostly rural or marginalized peri-urban areas. The need to urbanize these ecotechnologies is urgent, however, multiple studies show that the general public has a negative perception of on-site systems, since centralized sewer systems are equated with better social status and seen as the responsibility of the State, rather than self-management activities (Roma et al. 2013). In addition to the negative perception, they are also highly sophisticated bio-based technologies, which require the users, who are also operators, to have the adequate technical know-how to use efficiently, monitor, operate, maintain, and manage these solutions.

A programme was developed specifically for informing an urban population about the benefits of ecotechnological sanitation solutions, as well as supporting the transformation of its culture and habits through participatory and face-to-face methodologies for the co-design, implementation, and operation of an urban urine-diversion dry toilet (UDDT) prototype. Two different disciplines were coupled for this purpose: Social Studies for the adoption of sustainable sanitation values and technologies via participatory methods and Biological Engineering for the sizing, operation, monitoring and maintenance of an urban UDDT. It is fundamental that both disciplines are involved to guarantee the actual adoption of UDDTs. The programme was divided into three phases: diagnosis and promotion; design and prototype; and evaluation of its adoption. The first phase included conducting qualitative research via participatory methodologies to diagnose community perception of sanitation in general and UDDTs specifically. This fieldwork was carried out by a workgroup comprised of approximately 35 members of the university's community, mostly students from different bachelor programmes, a few professors and campus workers. The diverse makeup of the group was such as to improve the range of impact on all sectors of the university. This group was trained in ecotechnologies, participatory methodologies and promotional skills needed to reach out to the rest of the university.

The second and third phases took place during the second year of the programme. The second phase included establishing the social, cultural and technological design objectives with students of different bachelor programmes: Biological Engineering, Molecular Biology, Design, and Socioterritorial Studies. Also, using Social Innovation and Design Thinking approaches, the technological sanitation solution was jointly selected. Moreover, the architectural layout of the built space to house the UDDT, the Laboratory of Dry Toilets (LABS) was co-designed with these students in collaboration with an expert who specializes in bioconstruction and ecotechnologies. The UDDT's technological conceptual and final design, standardized operating procedures (SOPs) for the operation, maintenance and monitoring, as well as the scale-up plans were developed by biological engineering and molecular biology undergraduate students. The second phase also included building the LABS out of cob and ferrocement by the community to foster its connection to the UDDT prototype (Fig. 20.4). The permaculture features of the co-designed LABS and UDDT include Vietnamese-style chambers, greywater treatment biofilters, rainwater harvesting, solar-aided humanure composting, and air extraction with solar heating.

In the final phase, the degree of sociotechnological transformation (UDDT adoption) in the project's workgroup (35 students) was measured via an anonymous survey. The survey had three objectives: Firstly, to establish the level of knowledge obtained regarding the project's main themes (waste and wastewater source separation, waste biomass valorisation and the selected ecotechnologies); secondly, the change in values with respect to waste biomass and wastewater, and their perception as resources; and finally, the change in actions due to a change in values. Based on the survey results, this study achieved a significant socio-technological transformation within the community involved in the project (see Table 20.1).

Fig. 20.4 UDTT prototype

Table 20.1 Evaluation of the degree of adoption of the decentralized sanitation solution by an urban university community (socio-technological transformation)

Reported transformation and change in perceptions	Surveyed population (%)
Change every-day waste biomass management habits (incorporated source separation, reusing or composting, waste/wastewater reduction)	83
Inform of and influence waste biomass management habits in close social circles	70
Consider participatory methodologies effective to enhance adoption of sustainable sanitation solutions	80

20.4 A Novel Approach to Assessing Resilience Through Socio-hydrological Indicators

If the three previous case studies are to serve as a model for future approaches to water management, a set of multidisciplinary indicators are required to guide their implementation and maintenance, and to assess their impacts. In this section, we outline a set of integrated qualitative indicators with the potential to gauge SHR. The indicators go beyond the efficient management of the quantity and quality of hydrological resources to include impacts on society. SHR implies the integration of diverse viewpoints, from ethical and cultural perspectives to the long-term goals and needs of present and future generations. Currently, there are tools in economics, management, and engineering that aid the administration of multiple resources over time. However, due to the systemic and comprehensive nature of resilience, it is essential to identify, incorporate and evaluate parameters from a range of disciplines. This cross-discipline approach allows simultaneous correlation over extended periods of time and impacts economic growth, community social development, productivity, preservation and protection of the environment.

In determining the linkage between social resilience (SR) and water security for the design of sustainable urban metropolitan infrastructure, and considering the SHR concept, potential SR indicators are considered. We use SHR to guide the exploration of SR indicators where climate and population change, water security and management are contemplated for the design of urban metropolitan contexts. Establishing the right parameters, and their corresponding indicators are necessary to develop effective, resilient, strategic planning. It is because indicators act as vectors, notifying the magnitude and the direction of a parameter, which in turn can illustrate how close it is from the destination point and how quickly it is reaching or distancing away from that point. To move from novel approaches to a socio-hydrological resilience diagnosis, policies, plans, programs, and projects must include indicators in order to measure their efficiency. Resilience indicators give rise to information and documentation systems, which can then be used for fact-based decision-making, strategic planning, and management of a region, community or company. In addition to this, looking at projects from a common indicator framework fosters knowledge exchange based on various experiences and strengthens national socio-hydrological resilience.

20.4.1 Formulation of Socio-hydrological Resilience Indicators: Recommendations

Considering SHR is a nascent discipline, both as a research field and as a professional activity in municipalities and industry, resilience indicators are only beginning to be developed and understood. Nonetheless, we can extrapolate the theoretical frameworks from related fields like environmental, sustainability, energy and eco-efficiency indicators to formulate SHR indicators. Here we summarize recommendations on indicator construction and, in the rest of this section, we outline qualitative indicators that could be further developed as quantitative indexes in the near future.

In the case of eco-efficiency, indicators are constructed as rates that integrate engineering and financial parameters, where the numerator includes an impact, such as the resource consumption or polluting emissions, and the denominator represents the resulting level of production or benefit, in physical (product unit) or financial (value-added, profit) terms. The calculation of indicators can be furthered normalized (e.g., per one kilo of a product or one dollar of value) and following a rule that the lower the metric, the more effective the process is. A low value indicates greater benefit or productivity, that the impact of the process is lower (the numerator is smaller) or that the output of the process is greater (the denominator is greater) (Schwarz et al. 2002). In this manner, resilience indicators as rates could combine parameters from different fields (social, cultural, environmental, economic, scales of time and space, etc.) while establishing what the magnitude and direction of change mean for the resilience of a given system. In addition, indicators should be designed to be: (a) simple, so as not requiring a significant amount of time and resources to be produced; (b) useful, whereby they can convey sufficient information for adequate decision-making and planning; (c) understandable, where they can be appropriately interpreted by a range of sectors and stakeholders (neighbors, municipality and industry professionals, etc.); (d) cost-effective (in terms of data collection); (e) reproducible, incorporating standards to produce consistent and comparable results; robust, so as to indicate the progress towards resilience in multiples scenarios; and (f) stackable (across processes and time), so that they may be useful beyond the process or time for which the calculation was made.

20.4.2 Multiscale SHR Qualitative Indicators and Their Weighting

We use an alphabetically-based taxonomy system to describe the weighting method applied to the qualitative indicators. A is an essential indicator to achieve SHR, B is a required field that can only be discarded exceptionally if it does not apply to the nature of the project, C are recommended aspects when pursuing SHR, D are preferable aspects for SHR and E are part of good practices that give extra dimensions to SHR. Table 20.2 summarizes the proposed multiscale SHR indicators and their weighting. At the smaller scales of intervention, it is important to consider the possible feedback impacts at the larger scales and vice versa, the possibility of decentralizing large-scale proposals to build resilience across scales.

20.4.3 Socio-hydrological Resilience Coupling

The list of qualitative indicators (Table 20.2) is divided into three main sections: hydrological environment, water security, and social aspects. In order to achieve a balance between the socio-hydrological indicators, we propose a scatter-chart-based method to evaluate the interdependencies between coupled parameters (Wurl et al. 2018). To assess this integration, we have selected the main parameters weighted as 'I' in Table 20.1. On the X-axis are parameters related to water security and environments and on the Y-axis those related to social resilience (see Table 20.3). As an example of usage: in pair 'IV', water quality improvement projects cannot be proposed isolated from projects related to social habits or consumption reduction; in pair 'VI', socio-economic development cannot be planned in isolation from circular metabolism; in pair 'II', decentralized governance has to be co-related to multi-scalar water systems; governance needs to have the capacity to comprehend and act on entire hydrological systems such as ravines, basins, valleys, etc. In the case of the pair 'I,' climate change cannot be addressed without community involvement or constant supply in the 'III' case, must go hand in hand with a fair distribution of that constant supply.

With X and Y quantified, a scatter chart may be used to locate points A to F, according to their X (water resilience) and Y (social resilience) coordinates (Fig. 20.5a). This process allows a balanced coupling area of a 20% deviation to be defined from a 50–50 socio-hydrological relationship. Distribution of points outside the balanced coupling area would mean a disproportion between the social and water resilience. For example, a huge infrastructural dam for water supply that does not encompass a fair distribution strategy. A concentration of points in the diagonal area of the chart means the proposal is balanced and its low or high evaluation depends on the (left or right, respectively) tendency of the points as shown in Fig. 20.5.

Table 20.2 Qualitative indicators for SHR from multi-scalar case studies

			Metropol	Urban	Archit.	
			Oaxaca	Mexico ravine	LABS UDDT. Mex.	Weight
Social (economy and governance)	Governance[a]	Decentralized, adaptive governance	✓	✓	✓	A
		Prototypical, summative interventions	✓	✓	✓	B
		Legal framework	✓	✓	✓	C
		Delineated responsibility and authority (inc autonomy)	✓	✓	✓	C
		Phasing strategies and short to long-term management and contingency		✓		C
	Resource	Fair distribution of resources	✓	✓		A
		On-site water resources rather than off-site exploitation	✓	✓	✓	B
		Agricultural production resource sharing	✓			E
	Community[b]	NGOs, civil society integration	✓			D
		Self-building, on-site tech, micro-infrastructure, leadership and community initiatives	✓	✓	✓	C
		Social participation		✓	✓	A

(continued)

Table 20.2 (continued)

			Metropol	Urban	Archit.	
			Oaxaca	Mexico ravine	LABS UDDT. Mex.	Weight
		Address economic, social, and professional resistances and motivations			✓	B
		Educational (socio-ecosystem, local economy, conventional and innovative solutions)			✓	B
		Values and habit changing (reduction in water/wastewater demand, circular local water management)			✓	A
		User feedback, ability to cope with changes			✓	C
	Maintenance	Data and information gathering and management about the system follow up and maintenance	✓	✓		B
	Health	Health benefits, pollution reduction	✓	✓	✓	C
	Economy	Generation of new economies		✓		A
		Water savings		✓	✓	B

(continued)

Table 20.2 (continued)

			Metropol	Urban	Archit.	
			Oaxaca	Mexico ravine	LABS UDDT. Mex.	Weight
	Urban	Accessible ecosystem open and green spaces	✓	✓		A
		Community facilities		✓	✓	D
Water security (supply and waste)		Constant supply during draughts	✓			A
		Circular metabolism			✓	A
		Water quality	✓	✓	✓	A
		Multiscalar basin management	✓	✓		A
		Wastewater treatment and recycling		✓	✓	B
		Rainwater harvesting	✓	✓	✓	B
		Green space maintenance		✓	✓	C
		Pressure reduction of wastewater infrastructure		✓	✓	C
		Hybrid micro-scale structural and non-structural measures		✓		D
		Micro-scale structural measures (risk reduction and adaptability)	✓			C
		Non-structural measures (Biofilters)			✓	B

(continued)

Table 20.2 (continued)

			Metropol	Urban	Archit.	
			Oaxaca	Mexico ravine	LABS UDDT. Mex.	Weight
		Green and blue infrastructure	✓	✓	✓	A
		Operational and maintenance capacity	✓	✓	✓	B
Hydrology (ecology and environment)	Climatic events	Climate change adaptation	✓	✓	✓	A
		Soil retention	✓	✓		C
		Flooding prevention	✓	✓		B
	Pollution	Filtering and aquifer recharge	✓	✓		C
		Ecosystem restoration and decontamination		✓		B
		Water-borne disease prevention		✓	✓	B
	Human impact	Mitigation of human-induced microclimate changes (e.g., heat-island effect)		✓	✓	B
≪≫Multiscalar feedback integration system≪≫			✓	✓	✓	B

[a] Milman and Short (2008), [b] Cordova and Knuth (2005)

Table 20.3 Socio-hydrological coupling of ‘A’ indicators

Socio-economic development						VI
Ecosystem accessibility					V	
Habit/Econ. reduction				IV		
Equal distribution of resources			III			
Decentralized government		II				
Social participation	I					
	Climate change adaptation (flooding, droughts, soil)	Multiscalar basin management	Constant supply during draughts	Water quality	Green and blue infrastructure (aquifer recharge, soil retention, ecosystem restoration)	Circular metabolism

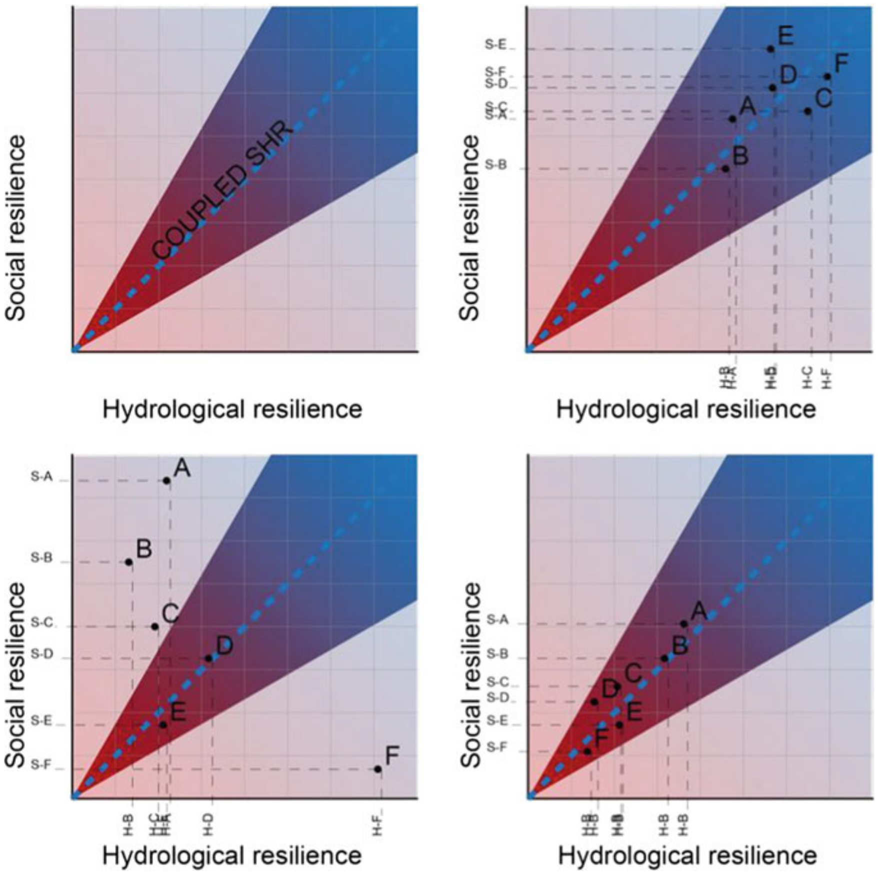

Fig. 20.5 **a** SHR coupling area definition in scatter chart scenarios, **b** well balanced and high SHR, **c** an unbalanced SHR, **d** well balanced but low SHR

20.5 Conclusions: Potential for Socio-hydrological Resilience in Transdisciplinary and Collaborative Approaches

This manuscript has set the basis for larger multi-disciplinary research into methods of assessing the incipient notion of SHR. Metropolitan landscapes are inescapably socio-hydrological. Contemporary conditions of rapid urbanization and climate change threaten water security which we, and the referred literature, propose must be addressed from the integrated, decentralized and circular perspective of SHR. Existing practices in Mexico, water availability, pollution combined with the rapid growth pace of urban populations requires a paradigm shift in water management practices and their social implications. The inherently dynamic, complex, and extensive human interactions with ecosystems demand a transformation to sustainable ecosystem management. 'Developing and maintaining beneficial interactions between managed and natural systems' is necessary and 'avoiding these interactions is no longer a practical option' (Ellis and Ramankutty 2008).

We propose the concept of socio-hydrological resilience as a new approach to analyze water management in urban areas of Mexico. This approach contributes to the usual management of water, which currently focuses on the administration of physical infrastructure for urban systems and the collection, treatment, distribution, and collection of wastewaters in cities. We provide a novel perspective to understand the problems related to water access, quality of water, water demand and water governance in urban spaces as issues intrinsically related. Due to an intense urbanization process in Mexico, identifying the components of the human-water system that enable the socio-hydrological resilience of cities to address uncertainty and changes in water availability is crucial.

We provide a theoretical, qualitative and retrospective analysis of traditional practices and emerging approaches, such as socio-hydrological resilience, which allows analyzing human-water systems and subsystems, and thereby offer evidence to support management and water security in specific cases. To this end, we build a series of indicators that will allow resilience assessments for urban environments in different scenarios in the future, regarding water use (supply and demand), access to water, natural disasters (droughts, floods) and climate change in the cases described. The socio-hydrological resilience approach is a theoretical and practical framework under construction since there is not enough evidence reported in the literature and each author evaluates different elements of human-water systems and subsystems. Unlike previous socio-hydrological resilience research, we consider water security objectives in the combined water-human system as an appropriate approach to design strategies for integrated and resilient management of water resources. Likewise, we develop a method that highlights the interrelationships between communities and natural resources, which tend to be uncertain, complex and subjective when the plurality of perspectives of interested groups, governments, and individual stakeholders is involved.

Addressing these complex interactions requires input from various disciplines, combining metropolitan design and decision-making with the engagement of local communities, civil society, and governmental bodies. Communication, transparency, education, and change of habits are social aspects that ensure the involvement of local communities. Therefore, we propose an outline for three groups of qualitative indicators, social resilience, water security, and hydrological environments, to ensure social participation and transdisciplinary integrated evaluation of water management proposals in metropolitan environments. To ensure the integrated relationship of these three groups, we propose a coupling scatter that assesses the balance of the social and the hydrological aspects of future projects. This manuscript forms the basis for a potential new branch of transdisciplinary research.

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Chapter 21
Vegetated Drainage Ditches in Mexico. A Case Study in Mazatlan, Sinaloa

Otoniel Carranza-Díaz and Iliana Hetzabet Zazueta-Ojeda

Abstract Urban and agricultural drainage ditches (DD) are important structures for the drainage of runoff. While agricultural DD remove the excess of irrigation water to lowlands areas, urban DD prevent the damage of civilian infrastructure caused by stormwater runoff. The drainage ditches in Mexico are generally unattended sites, where all type of waste is deposited. Moreover, they can be receiving bodies of clandestine domestic or industrial wastewater, which could contaminate the adjacent environment. The abandonment of urban and agricultural DD deteriorates the landscape and cause water contamination which could be derived in public health problems. This chapter presents a review of the current scenario of agricultural and urban DD in Mexico. The importance of these sites, as well as the associated environmental problems, is described. Finally, the vegetated urban and agricultural drainage ditches are presented, and their potential in the mitigation of environmental pollution and the improvement of the agricultural and urban landscape are discussed.

Keywords Drainage ditches · Runoff · Pollution · Mazatlan

21.1 Introduction

The urban drainage system in Mexico has been built to prevent flooding derived from rain as well as from agricultural and rural runoff. In urban and rural zones, the urban drainage is often constructed in the form of open-air channels that transport the rainwater as well as domestic discharges and urban runoff. The abandonment of many of the urban drains in Mexico has caused water contamination and detriment of the adjacent environment. Wastewater, both agricultural and urban, contains pollutants such as heavy metals, organic compounds, pathogenic organisms, and nutrients

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such as nitrogen and phosphorus that contaminate the environment. Furthermore, the pollution of the coastal zone in Mexico both on the Pacific coast and in the Gulf of Mexico is mostly due to the discharges of these drains putting at risk of losing the balance of the aquatic ecosystem.

An ecological option to mitigate the environmental impact of wastewaters transported through urban drainage ditches is the use of vegetated drainage ditches. They are environmental biotechnology little studied in Mexico, but it can be implemented for the control of pollutants from industrial effluents, agricultural, domestic discharges, as well as agricultural and urban runoff. The vegetated drainage ditches represent a low-cost bioremediation strategy that also allows revaluing the already existing urban drainage infrastructure. In this chapter, a review of the vegetated urban and agricultural drainage ditches in Mexico is presented. Moreover, the main pollution problems regarded with these ditches and the risks to public health are addressed. Also, a literature review was done in order to elucidate the number of publications in this field in Mexico. Furthermore, the selected results of the case study in the vegetated urban drainage ditch are located in the City of Mazatlan, Sinaloa is presented. The perspectives on the potential of this type of ecotechnology, as well as the challenges and difficulties associated with the management of vegetated drainage ditches are discussed in this chapter.

21.2 Agricultural and Urban Drainage System in Mexico

The urban drainage system in Mexico has the function of protecting urban infrastructure, industry, and the health and integrity of the population during rainwater events. Unfortunately, the current situation of many of these urban drains in Mexico is worrisome given the abandonment, lack of maintenance and the poor ecological culture on the part of the authorities and the inhabitants that surround them (García Hernández et al. 2011; Hernández-Antonio and Hansen 2011). Most of the drains in Mexico have thus become waste dumps and clandestine wastewater discharges. This situation is related to water pollution which causes environmental problems and the risk of human contamination. Also, in rainy seasons, the waste is transported to low areas where surface water bodies are found contaminating the adjacent environment.

Wastewater discharges are point sources of pollution and are characterized by variable flow rates and contaminant concentrations (Chin 2006; Ort et al. 2010). The control of these discharges to urban drains is a rather a complicated issue since they generally increase as the surrounding population grows. The lack of permanent environmental monitoring in rural areas makes it difficult to know the quality of the water transported by the urban drains, as well as its impact on natural water bodies such as rivers, coastal waters and natural reservoirs. In this way, there is a high probability of contaminating both surface and groundwater, with potential risk to public health and impacts on the ecosystem. Additionally, the agricultural industry in Mexico makes use of chemical products such as fertilizers, pesticides, herbicides, fungicides, hormones, antibiotics, and other plant protection products

(Moeder et al. 2017; Tasho and Cho 2016). These substances are used throughout hectares of crops representing a source of diffuse contamination (Nsenga Kumwimba et al. 2018). Due to its nature, the control of diffuse contamination represents a significant challenge since the origin of the pollutants is sometimes unknown or difficult to trace. Generally, these agricultural residues reach the drainage ditches through runoff or atmospheric transport and subsequent deposition (Sanchez-Osorio et al. 2017) exposing the population to diseases. Figure 21.1 shows an agricultural drain located in Navolato Mexico nearby the rural community "La Michoacana" (Ahumada-Santos et al. 2014). This drain has the function of collecting agricultural runoff derived from irrigation and avoiding floods during rain events. As shown in the figure, the drain has a constant trapezoidal cross-section, runs linearly several kilometers and collects agricultural, urban and other domestic waste runoff.

On the other hand, the urban drainage system is a fundamental part of the urban infrastructure in cities. Urban drains can be rustic, or concrete-lined, vary in geometry depending on their design, can have regular, linear cross-section or depend on the place form meanders (Vermonden et al. 2009). Thus, urban drains cross, parks, avenues, alleys and pedestrian paths within many of the cities in Mexico. The ignorance of the population about the importance and functioning of these structures has resulted in the abandonment of many of the urban drains in Mexico. Eventually, some drains are cleaned by the authorities before the rainy season begins. However, these urban structures are generally abandoned the rest of the year accumulating

Fig. 21.1 Agricultural drainage ditch in Navolato, México (*picture* Otoniel Carranza)

Fig. 21.2 The urban drainage ditch is carrying several types of waste (*picture* Otoniel Carranza)

both garbage and wastewater. Hence, bad appearance, odors and the proliferation of vectors such as mosquitoes, cockroaches, and flies can be developed threatening the public health (Ahumada-Santos et al. 2014).

The proximity between some urban drains and the housing areas reveals a poor regulation regarding sanitation. The pollution of urban drains is accompanied by a severe problem of environmental education and neglect by the authorities. The waste thrown into many of the urban drains include household garbage, empty containers, dead animals, expired medicines, batteries, organic waste, personal hygiene products paints, paints, detergents, and insecticides which can release toxic substances to aquatic organisms and risks to public health (Jimenez-Cisneros 2005; Ternes and Joss 2006). Also, some of these products are made up of chemicals that may be persistent in the environment or have a biocidal effect such as antibiotics and pesticides (Schwarzenbach et al. 2006). Figure 21.2 shows an urban drain that transports trash and wastewater. The drain may be a source of contamination for the surrounding housing area.

21.3 Public Health Risks

The poor sanitation system mostly in developing countries has caused that millions of people around the world are affected by contact with wastewater. According to WHO reports, six out of ten people in the world (approximately 4500 million) lack of sanitation (World Health Organization 2017). Mexico is the eleventh most populous country in the world with 112,336,358 inhabitants registered until 2015 (National Institute of Statistic and Geography 2015). Moreover, in Mexico 25.8% of rural communities do not have sanitary facilities while 2.6% of urban communities lack services of sewage and basic sanitation (National Water Commission, 2016). On the other hand, data from the World Health Organization indicate that diseases transmitted by contaminated water such as diarrhea, cholera, dysentery, typhoid fever cause more than 502,000 deaths per year (World Health Organization 2018). Currently, in Mexico, infectious and parasitic diseases of the digestive system reach some 6,123,428 cases in week 32, according to the epidemiological bulletin 2018 (Secretary of Health 2018). Risk factors such as poor management or inadequate sanitation services, ingesting contaminated food by wastewater increase the risk of contamination (Chin 2006). Disease-causing pathogens associated with water pollution can be caused by bacteria, parasites, and viruses (Diáz Delgado et al. 2003; Hernández Cortez et al. 2011). However, chemical pollutants can also put public health at risk. Infections related to water pollution do not distinguish age, sex or socioeconomic status. There are vulnerable groups such as children, older adults, pregnant women, and immunosuppressed people. Thus, the consequences of infection by organisms that cause diseases related to water pollution include dehydration, malnutrition, and even death.

Mexico lacks a drainage system that separates municipal wastewater from rainwater (Jimenez-Cisneros 2005). Consequently, rainwater can get mixed with raw wastewater during rain events. When the design capacity of the sewers is overcome, they expel the wastewater that eventually reaches low areas as shown in Fig. 21.3. Thus, the risk to the local population of acquiring diseases through contact with wastewater increases, since these waters are carriers of infectious agents and other pollutants (Gaffield et al. 2003; Henry and Heinke 1999).

Fig. 21.3 Urban sewer is throwing wastewater and discharging into an urban drain (*picture* Otoniel Carranza)

In the next paragraphs, some concepts on contamination agents that affect human health present in wastewater are described.

21.3.1 Bacteria

Intestinal bacteria are found in wastewater and are indicative of fecal contamination by humans or warm-blooded animals (Madigan et al. 2003). These bacteria are known as coliforms and are classified into total and fecal coliforms (Camacho et al. 2009). The total coliforms are non-pathogenic microorganisms that can survive and proliferate in water. The characteristic species of this group are *Escherichia*, *Citrobacter*, *Klebsiella, Enterobacteria*, and *Shigella,* all those belonging to the *Enterobacteriaceae* family (Guentzel 1996). Within total coliforms, fecal coliforms are considered pathogenic for humans (Madigan et al. 2003). The coliforms are found in various types of wastewater, including municipal, industrial, and agricultural wastewater (Ahumada-Santos et al. 2014). The presence of coliforms indicates the microbiological contamination of water and is a parameter present in Mexican environmental regulations.

Consequently, a high concentration of coliforms in wastewater that exceeds the maximum permissible limits established in NOM-001-SEMARNAT-1996 indicates a poor water quality and represents a risk to public health. On the other hand, the absence of coliforms is considered a good indicator of water quality from the microbiological point of view (NOM-001-SEMARNAT-1996) . The identification of *Escherichia coli* in the analysis of total and fecal coliforms indicates fecal contamination (Madigan et al. 2003). The diseases caused by bacteria that are transmitted through contaminated water include cholera, typhoid, paratyphoid fever, shigellosis and another salmonellosis (Secretary of Health 2018).

21.3.2 Parasites

The protozoan parasites and helminths are organisms with complex biology that is reflected in their diverse species, strains and hosts (Kilpatrick and Altizer 2010). The parasites that cause public health problems acquired by the ingestion of contaminated water or food are intestinal, and the most studied are those two, protozoa and helminths (Von Sperling 2007). For instance, the protozoa *Giardia intestinalis* and *Cryptosporidium* spp. are the most common diarrhea-causing intestinal parasites in the world (Quihui-Cota et al. 2017). In order to know the risk of their infection as well as to take control measures, their life cycles and infectious phases must be understood (García Dávila and Rivera Fernández 2017). The infecting phases of parasites in water are, respectively, cysts and oocysts. Regarding intestinal helminths, eggs are considered the infectious phase transmitting water-related diseases (Von Sperling 2007). The most common intestinal helminths transmitted by wastewater include

Taenia spp., *Ascaris* spp. and *Trichuris trichiura* (Menocal-Heredia and Caraballo-Sánchez 2014). The concern in the public health of these parasites and heminths is because of their persistence in the environment, resistance to chlorine disinfection processes and low infectious dose (Amoah et al. 2018). The control of parasitosis is of importance, mainly for children, due to the main consequences of these infections which are malnutrition, stunting and weight loss (World Health Organization 2011). These symptoms occur because one of the mechanisms of colonization lies in the shortening of the intestinal microvilli, limiting a proper metabolism and absorption of nutrients from the host (Quihui-Cota et al. 2017). Despite the efforts made by the authorities when carrying out massive deworming campaigns, still, the number of cases of protozoan and helminth infections in Mexico reaches 143,728 (Secretary of Health 2018). These data show that the Mexican population is still in contact with sources of infection, which causes the diseases to persist.

21.3.3 Virus

Viruses are the smallest infectious agents that are known today. Viruses transfer nucleic acid from one cell to another, multiply and cause diseases to microorganisms, plants, animals, and humans (World Health Organization 2011). Viruses can be found in wastewater and cause diseases for humans such as gastroenteritis, hepatitis A and poliomyelitis (Peláez et al. 2016). Some viruses that cause gastrointestinal diseases are rotavirus, enterovirus, and adenovirus (Secretary of Health, 2017). The main problem regarding viral diseases is the lack of specific treatments for their elimination and control (Sánchez 2016). The concentration of the virus eliminated by one person can be up to 10^{11} viral particles per gram of faeces which are an essential indicator of water pollution (Saavedra et al. 2012). There are about 140 serotypes of enteric viruses in wastewater (Gantzer et al. 1998). The most common are the viruses that cause gastroenteritis and the hepatitis virus (Von Sperling 2007). These microorganisms are an essential problem for water quality because they resist more in the environment than bacteria. Moreover, viruses are more resistant to disinfection processes due to the protective effect that occurs when interacting with solid particles suspended in the water (World Health Organization 2011). The virus detection has the disadvantage of requiring more specialized analytical techniques and is often difficult to detect them due to its low concentration in environmental samples (World Health Organization 2011).

21.3.4 Chemicals

Several chemicals can be found in wastewater and have a harmful effect on the health of the population. These contaminants are dissolved in wastewater and vary according to their origin and chemical composition (Dickin et al. 2016). The presence of agrochemicals such as pesticides and fertilizers in wastewater has great relevance in Mexico as it is one of the countries with the highest rates of agricultural production worldwide (Secretary of Agriculture 2017). Reports from Mexico's Secretary of Agriculture, Livestock, Rural Development, Fisheries, and Food registered that in 2017 the planting area in Mexico was 21.6 million hectares (Secretary of Agriculture 2017) which implies the use of a large number of chemicals for the crops (Bennett et al. 2005). The incorrect use of pesticides and the inadequate disposal of containers can cause residues of these substances to reach natural waters (Orta Arrazcaeta 2002). The contact with water contaminated with agrochemicals can cause serious health problems in the population. Pesticide poisoning can be acute (Ternes and Joss 2006). However, in most cases, they have long-term silent harmful effects (Maroni et al. 2006). The consequences include carcinogenic effects, DNA mutations, neurotoxic associations of high level of prenatal exposure, as well as problems in human behavior such as predisposition to suicide, autism, developmental delays, and learning problems, among others (Burns et al. 2013; Faria et al. 2014; Warren et al. 2003).

On the other hand, the excessive use of fertilizers contaminates natural waters such as aquifers and surface waters with nitrates (Pacheco Ávila and Cabrera Sansores 2003). The extraction and consumption of water contaminated with nitrates can have an impact on human health (Henry and Heinke 1999). The most worrisome effect for humans is the reduction of nitrates to nitrites in the intestine that subsequently reaches the bloodstream. The most susceptible people are those with gastric problems or children under three months in whom nitrite is absorbed in erythrocytes, oxidizing iron from hemoglobin to methemoglobin which is unable to transport oxygen in the blood, finally causing cyanosis problems.

The mining industry in Mexico is one of the most important ones from the economic point of view (Secretary of Economy 2018). However, the inadequate management of waste from this industry has caused some heavy metals to contaminate water and food, putting public health at risk. Wastewater contaminated with waste from the mining industry generally reaches the drains through runoff (Abu Bakar et al. 2013). Thus, the presence of heavy metals in shrimp and fish tissues has been documented, suggesting a possible entry of these contaminants into the trophic chain through bioaccumulation and biomagnification processes (Rajeshkumar and Li 2018). Additionally, heavy metals such as lead, copper, cobalt, and cadmium have been found in natural bodies of water. Among the sufferings and documented diseases that have been related to the contamination of water by heavy metals are mutagenic effects in DNA, oxidative stress, lung disorders, changes in hemoglobin, among others (Junaid et al. 2017). Ecological disasters such as the pollution of rivers and surface and groundwater sources of water provoked by enterprises without control are also huge problems (Fernandez-González et al. 2009; López Bárcenas 2014; Wilton 2015).

Another group of chemical contaminants that can cause damage to public health is the so-called organic micropollutants (Ternes and Joss 2006). These compounds have been found in wastewater in low concentrations, in the order of μg/L or ng/L. Organic micropollutants include drug residues, personal care products, plastic residues, flame retardants as well as polycyclic aromatic hydrocarbons (PHA) (Ternes and Joss

2006). Also, the emission of fossil fuels by industries and automobiles as well as the combustion of hydrocarbons generates PHAs (Edokpayi et al. 2016). These compounds have been documented to be potentially carcinogenic, genotoxic and mutagenic for humans (Mastandrea et al. 2005).

On the other hand, drug residues such as antibiotics represent a great challenge for public health. The indiscriminate use of antibiotics for the treatment and prevention of animal and human diseases has caused one of the most significant risks to global human health, multiresistant bacteria to antibiotics (Lien et al. 2016). This resistance is acquired through a natural process known as horizontal gene transfer, which involves the transfer of genetic material from one cell to another that is not descended in response to a selective pressure stimulus (Ternes and Joss 2006). Thus, the irresponsible use of drugs that are discharged into wastewater exerts selective pressure on the bacteria found in these bodies of water to obtain antibiotic resistance genes from already resistant bacteria that are also found in the environment. The consequence of multiresistant bacteria to antibiotics can be chronic diseases or even incurable diseases (Nuñez et al. 2012).

21.4 Vegetated Drainage Ditches

An ecological tool to reduce pollution in urban or agricultural drains is the use of aquatic plants in drainage systems (Nsenga Kumwimba et al. 2018). The aquatic plants that inhabit drainage ditches serve as biological filters which retain in their roots, stems and leaves, contaminants such as heavy metals, agrochemicals, nutrients and microorganisms (Flora and Kröger 2014; Vymazal and Dvořáková Březinová 2018). The use of plants in agricultural and urban drainage ditches offers multiple benefits for the improvement of water quality such as oxygen production, sanitation, absorption of contaminants, and elimination of pathogenic organisms (Ahumada-Santos et al. 2014; Flora and Kröger 2014). Also, vegetated drainage ditches serve as habitat for various organisms such as birds, reptiles and mammals, which find refuge and food in these sites (Herzon and Helenius 2008). The vegetation also improves the urban landscape creating a green infrastructure (Li et al. 2017). *Typha angustifolia* and *Typha domingensis* (Moeder et al. 2017; Vymazal and Dvořáková Březinová 2018) are among the plant species that inhabit the drains and has been most documented for environmental bioremediation purposes. The plant *Typha* spp. Is a macrophyte and have the characteristic of growing in fresh or brackish water (Fernandez-González et al. 2009). This plant has qualities that make it ideal for its establishment in drainage ditches. The plant *Typha* spp. Also tolerates wide ranges of salinity and total dissolved solids (Kadlec and Wallace 2009). This feature allows it to establish in transition zones between fresh and marine water (Vymazal and Dvořáková Březinová 2018). This plant can absorb and degrade organic and inorganic chemical contaminants (Imfeld et al. 2009; Kadlec and Wallace 2009).

An example of the use of *Typha* spp. in bioremediation is the study carried out by Blattel et al. (2009). The authors showed that the structure of the leaf (porosity and surface area per unit mass) of *Typha* spp. makes it propitious for the removal of pesticides, in comparison with other filtering plants such as *Triticum aestivum*, *Lolium* sp., *Medicago sativa*, and *Juncus patens*. Likewise, its effectiveness as a biological filter has been proven in natural and artificial wetland systems (Vymazal and Dvořáková Březinová 2018).

The plants in the drains are established naturally and contribute to controlling soil erosion (Herzon and Helenius 2008). The vegetation manages to adapt to the space, pollution and environmental conditions of the site until achieving homeostasis or steady state. Thus, vegetated drainage ditches create a complex ecosystem that is integrated into the urban landscape by providing an environmental service, generally ignored. Figure 21.4 shows a vegetated urban drainage ditch located between the main avenue and a parking lot.

In the rural environment, vegetated drainage ditches are frequently found. Only in the state of Sinaloa, 8548.5 km of agricultural drainage ditches have been documented (Ahumada-Santos et al. 2014). Due to the geometrical characteristics of these drains, generally without reinforced concrete lining, the plants tend to root at the bottom of the drain. Also, there may be interactions between surface water and groundwater, converting them into complex systems from an ecological and hydraulic perspective.

Figure 21.5 shows a vegetated agricultural drain ditch located in the municipality of Navolato, Sinaloa, Mexico. In this drain, the vegetation is well established and covers almost the whole water surface. The geometrical characteristics of this drain, such as constant cross-section and water flow are favorable to conceptualize it as a plug flow reactor (Chin 2006).

The functioning of vegetated drainage ditches lies in their maintenance (Nsenga Kumwimba et al. 2018). The vegetation that grows in the drains needs to be harvested in order to remove contaminants from the water. The plants should be harvested

Fig. 21.4 Vegetated urban drainage ditch in Mazatlán, Mexico (*picture* Otoniel Carranza)

Fig. 21.5 Vegetated agricultural drainage ditch in Navolato Mexico (*picture* Otoniel Carranza)

and extracted from the drain in order to allow the young plants to grow. Improper vegetation management can lead to problems such as obstruction of the hydraulic functioning of the drain. Frequently, after a harvesting event in vegetated drainage ditches, it occurs that the plants are partially removed from the drain. Thus, after a rain event, the plant biomass can accumulate downstream obstructing the water flow as shown in Fig. 21.6. Eventually, the organic matter decomposes and dissolves in the water column raising the content of biochemical oxygen demand (Kadlec and Wallace 2009).

In order to identify the research carried out on vegetated drainage ditches in Mexico, a search was done in three selected databases. The selected platforms were Science direct, Google academics as well as the scientific database CONRICYT which is widely used by academics in Mexico. In order to investigate whether there are case studies conducted in Mexico on the subject of vegetated drains used for environmental bioremediation, the search was made using a selection of keywords which were (i) Vegetated urban drainage, Mexico; (ii) Planted agricultural drainage, Mexico and (iii) Vegetated drainage ditch, Mexico. These keywords were investigated in the selected databases in both English and Spanish languages. Additionally, a comparison was made between the number of publications carried out in Mexico and those documented for other countries.

The results obtained from the literature review indicated few studies conducted in Mexico on vegetated drainage ditches. Only two documented works were found.

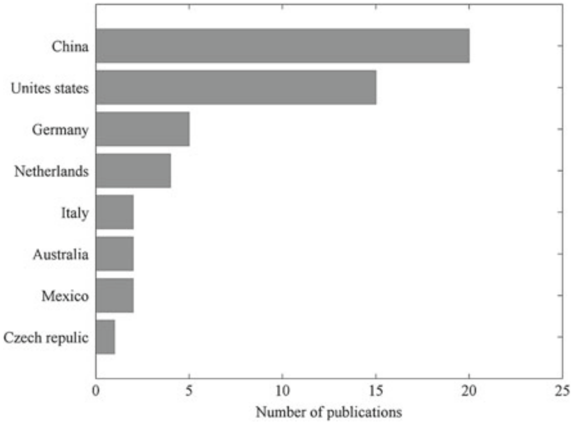
Fig. 21.6 Problems associated with inappropriate vegetation management (*picture* Otoniel Carranza)

These are the studies carried out by Ahumada-Santos et al. (2014) and Moeder et al. (2017). Both studies were conducted in the agricultural drainage ditch La Michoacana in northwestern Mexico (Navolato, Sinaloa).

The studied drain used the plant *Typha dominguensis* and transported agricultural runoff and domestic wastewater. In the first study, 38 organic contaminants were found, including pesticides, polycyclic aromatic hydrocarbons (HAP), artificial sweeteners and pharmaceutical waste at five selected sampling points along the drain. The *Typha dominguensis* plant demonstrated the capacity to absorb and accumulate organic micropollutants in its tissues (Moeder et al. 2017). In this same drain, Ahumada-Santos et al. (2014) studied the removal of total and fecal coliforms along the flow path.

The authors demonstrated that the plants help to reduce total and fecal coliforms in the drain. It was also found that the bacterial concentration increased in the punctual entries, as well as in June and July where the temperature is usually higher than the rest of the year (Ahumada-Santos et al. 2014). Although there are studies that have documented the state of contamination of some drains in Mexico (García Hernández et al. 2011; Menjarrez and de Cosfo 1976), the few studies with vegetated drainage ditches reflect the lack of knowledge that exists in the Mexican society concerning low-cost environmental bioremediation topics. However, in comparison with other countries, Mexico is among the eight countries in the world that have documented case studies in vegetated drainage ditches. Figure 21.7 shows a comparative graph among the countries where research has been documented in vegetated drainage ditches. Surprisingly, the number of publications made worldwide in drains with vegetation for bioremediation purposes reaches the limited number of 51 publications. It should be noted that China is the country that has the most documented

Fig. 21.7 Number of publications in the field of vegetated drainage ditches (modified from Nsenga Kumwimba et al. 2018)



cases of study on this subject. Mexico is the only country in Latin America that has documented studies concerning a vegetated drainage ditch.

21.5 A Case Study in Mazatlán, Mexico

The vegetated urban drainage ditch named “Atl$\underline{\acute{a}}$ntico” is part of the urban drainage system of “La Marina” residential zone in the city of Mazatl$\underline{\acute{a}}$n, Sinaloa, Mexico (Fig. 21.8). This drain collects urban runoff, as well as a permanent point discharge

Fig. 21.8 Vegetated urban drainage ditch “Atl$\underline{\acute{a}}$ntico” in Mazatlán, Mexico (*picture* Otoniel Carranza)

possibly coming from domestic wastewater. The “Atlántico” drain has the characteristic of ending in the dock of La Marina Mazatlán which connects with the coastal zone of the city of Mazatlán. Historically, the city of Mazatlán was built on a natural flooding area. Therefore, the “Atlántico” drain has an important function in the drainage of stormwater during the rain periods between June and November. The rest of the year, the “Atlántico” drain only transports the water from the permanent point discharge. The studied section of the “Atlántico” drain has a length of 800 meters and is located at Latitude 23.26421997 and Longitude −106.44388797 (Fig. 21.8).

The drain “Atlántico” was constructed with reinforced concrete on the slopes in order to facilitate the drainage of the water. Along the drain, there are plants which are regularly pruned by the cleaning service of the company La Marina. The natural conditions of the site, such as temperature, light, and the permanent source of water, allowed aquatic plants to establish in the urban drain (Fig. 21.8). The vegetation is of the vascular type where *Typha* spp. Predominating in approximately 90 percent of the surface area of the drain. In 2015 García-Pazos (2016) investigated this drain which aimed at establishing the presence of the nutrients NH_3–N, NO_2^-–N, NO_3^-–N and PO_4^{3-} and evaluated the removal of these contaminants along the flow path. The results of this work were presented at the 15th IWA International Conference on Wetland Systems for Water Pollution Control in Gdansk, Poland. Here, selected results of this investigation are presented.

The authors conducted eight sampling campaigns during 32 days of investigation between November and December 2015 (García-Pazos 2016). Four sampling sites were selected at equidistant distances along the drain whereas water samples were taken on both sides of the drain. Composite samples were constructed per site and per sampling campaign by mixing the water samples taken on both sides of the drain. The sampling campaigns began just after the plants were harvested by the cleaning service of La Marina. Consequently, the vegetation grew as the investigation went on. The water samples were taken using a sampling device that allowed to disturb as little as possible the water column during the sampling. The water samples were transported to the Marine Science Faculty of the Autonomous University of Sinaloa for further analysis. The ammonia nitrogen, nitrite, nitrate, and phosphate parameters were determined using a Hanna HI 83203 photometer, and a PreSens® Microx TX3 instrument was used to determine the dissolved oxygen concentrations in the water samples. Likewise, the temperature of the water was recorded in situ using a thermometer.

The water flowed from site 4 to site 1 (Table 21.1). The average water temperature in the first sampling campaign was 30.5 °C whereas in the last sampling campaign (after 32 days) the average temperature in the drain was recorded at 27.4 °C. The difference of 3.1 °C in the water column was attributed to the plant coverage in the drain. Consequently, an increase in dissolved oxygen in the water was found during the study period. In the first sampling campaign, dissolved oxygen remained in a range of 5–6 mg/L in the drain. By the last sampling campaign, the dissolved oxygen reached a range of 7.5–8.5 mg/L. These increases in the concentration of dissolved oxygen were attributed to the solubility of oxygen. Plants growing in the drain create a shadow that gradually covers the water surface. Thus, the temperature

Table 21.1 Nutrient concentrations (average value ± standard deviation) at the selected sampling points in the "Atlántico" drainage ditch

Nutrients	Sampling sites			
	1	2	3	4
NH_3–N	13.84 ± 6.61	15.07 ± 5.24	15.07 ± 5.81	17.30 ± 5.17
NO_2^-–N	<LOD	<LOD	<LOD	<LOD
NO_3^-–N	5.21 ± 6.06	4.15 ± 6.51	2.02 ± 4.12	8.14 ± 16.96
PO_4^{3-}	38.47 ± 30.17	20.47 ± 8.45	61.52 ± 75.71	17.97 ± 13.06

LOD, limit of detection

of the water decreases increasing the dissolved oxygen concentration. Table 21.1 shows the concentrations of the nutrients found in the water during this study.

A decrease in NH_3–N concentration was found along the flow path (from point 4 to point 1). Regarding removal, a decrease of 20% in ammonia nitrogen was found (Table 21.1).

The nitrite values were below the limit of detection of the instrument used (0.01 mg/L). A reduction of 36% in nitrate concentrations was found between point 4 and 1. Both, nitrate and ammonia nitrogen removal was attributed to the presence of vegetation. The phosphate concentrations showed an increase along the flow path, which was attributed to the contribution of nutrients possibly due to the urban runoff or wastewater discharging into the drain.

The nutrient removal observed in this investigation demonstrated the potential of the vegetated urban drainage ditch to be implemented as a strategy to water pollution control in coastal areas.

21.6 Perspectives

The use of vegetated drainage ditches as natural wastewater treatment systems is a little-studied system in Mexico. At the global level, this issue has gained acceptance in recent years, and the potential for water pollution control is promising (Nsenga Kumwimba et al. 2018). Vegetated drains are equivalent in operation to a constructed wetland (Vymazal and Dvořáková Březinová 2018). However, it is still necessary to document more study cases worldwide in order to understand their functioning.

The vegetation management in drainage ditches is a topic that needs to be studied. There is no methodology based on scientific criteria that suggest the harvesting periods of the plants. Frequently the plant harvest is carried out following empirical facts such as carrying out the harvest just before the rainy season. The absence of a harvest methodology regarding "how much" and "when" the plants should be harvested, shows the scarce effort made in scientific research for this purpose. In order to look for strategies to establish a program for vegetation management, some studies point to the optimum plant density (Reddy and Debusk 1984). The optimum plant density is that amount of plants in a given water surface where vegetation grows at a maximum rate. This concept has been used to determine the potential of plant biomass production for energy purposes (Reddy and Debusk 1984). However, no studies have been carried out to determine the relationship between optimal vegetation density and water quality in vegetated drainage ditches.

On the other hand, the plant biomass after harvesting is usually disposed in sanitary landfills which were not designed for this purpose. An exciting strategy may be the use of plant biomass for the generation of biogas or other biofuels (Nsenga Kumwimba et al. 2018). Laboratory-scale experiments using vascular plants can be the first step towards a strategy of recycling nutrients from the plant biomass that develops in the drainage ditches.

Drainage ditches are a fundamental part of urban and rural infrastructure worldwide. If these structures fail, cities, rural areas, and industry could suffer severe losses caused by floods, soil salinity, environmental pollution, and public health problems. Also, in the current context of global climate change, extreme weather events will be increasing. Thus, it is necessary to study the functioning of the drainage system further. Moreover, the drainage infrastructure should be designed to function not only as hydraulic structures but also as systems capable of providing environmental services such as rainwater harvesting, aquifer recharge, greenhouse gas mitigation, water improvement, and air quality. Future efforts should be devoted to understanding the environmental services provided by vegetated drainage ditches.

The lack of sanitation services in many rural areas in Mexico has led to use drainage ditches as garbage dumps. It is necessary to improve the municipal garbage collection system in order to reduce solid waste in the drainage ditches, mainly in rural areas of Mexico. This action will be possible by the high mobility of resources oriented to the sanitation of rural communities, as well as the implementation of environmental education campaigns. Inappropriate management of solid waste and wastewater discharged into drains exposes the population to preventable diseases. For this reason, it is necessary to include in the political and regulatory scenario the revaluation of the urban drainage system in Mexico. Also, to educate the population towards the culture of recycling and solid waste management. In other words, we need to stop seeing the drainage system as deposits of all kinds of waste and move towards the social appropriation of the urban drainage system.

The clandestine discharges of wastewater into the drains represent a significant challenge in terms of environmental regulation. However, some experiences have documented the benefit regarding environmental and social aspects when appropriate management of point sources of contamination is carried out. The recent study published by Reusch et al. (2017) showed that a legal framework for the protection of the environment could be implemented as wastewater treatment strategies, as it was possible to reduce the nutrient load to the coastal area of the Baltic Sea. In Mexico, it is necessary to modernize the current environmental legislation, so that communities with less than 2500 inhabitants have wastewater treatment. By this, the number of clandestine discharges discharged to the drains could be reduced. It also requires the political will of the 17 coastal states of Mexico in order to establish agreements to regulate loads of pollutants to the sea caused by drains. A fundamental element to achieve this objective is to make a diagnosis of the current state of drainage contamination in Mexico.

The complexity of the vegetated drainage ditches requires to be studied from an interdisciplinary perspective. The physical, chemical and biological processes that occur in the drains require the “expertise” of various areas of knowledge, such as biology, microbiology, public health, engineering, physics, and materials, as well as the social and institutional aspects. Although the conversion of the current urban and rural drainage system in Mexico to a vegetated drainage system implies a major challenge, there are experiences where green infrastructure has been chosen instead of promoting so-called gray systems, based on concrete structures and whose operation is predominantly mechanized. For example.

The city of New York implemented in 2010 a program called “NYC Green infrastructure program.” The objective of this program was to improve water quality in New York City by managing natural resources through the implementation of 30 urban green infrastructure projects: “Blue roofs and green roofs for rooftop stormwater detention and retention; porous pavement for parking lots; tree pits, streetside swales, and porous pavement for roadways; greenstreets, medians, and curbside extensions for roads; constructed wetlands and swales for parks and rain barrels for low-density single family housing” (Bloomberg 2017). Some benefits expected from this program are “Reducing combined sewer overflow (CSO) volume by an additional 3.8 billion gallons per year (bgy), or approximately 2 bgy more than the all-Gray Strategy; capturing rainfall from 10% of impervious surfaces in CSO areas through green infrastructure and other source controls; and providing substantial, quantifiable sustainability benefits—cooling the city, reducing energy use, increasing property values, and cleaning the air—that the current all-Gray Strategy does not provide” (Bloomberg 2017).

Although there are few examples of green infrastructure in Mexico (e.g., García-Pazos 2016), generally this type of ecotechnology is implemented based on empiricism. In this sense, a first step consists in the socialization of the benefits that the green infrastructure has, as well as the implementation of demonstration projects in selected sites.

The presence of organic micropollutants and pathogenic organisms in drainage ditches represents an environmental challenge. In order to remove these contaminants from water, it is necessary to know the physicochemical characteristics of the compounds (Ternes and Joss 2006) and understand the biology of the pathogenic microorganisms. A possible strategy to favor the removal of these contaminants in drains can be through the proper management of the vegetation. The use of vegetation blocks located at strategic sites along an agricultural or urban drainage ditch may favor the removal of some pollutants. Figure 21.9 shows a section of an agricultural drain in which only a part is covered by plants (right part). In the zone with vegetation, lipophilic compounds such as galaxolide and tonalide can be removed by adsorption (Matamoros and Bayona 2006).

On the contrary, in the zone without plants (left part of Fig. 21.9) compounds such as ketoprofen and some pathogenic organisms can be inactivated via photodegradation and photoinactivation (Matamoros et al. 2008; Von Sperling 2007). This man-

Fig. 21.9 Block of plants in an agricultural drainage ditch with potential for bioremediation (*picture* Otoniel Carranza)

agement strategy of the plants is complex and requires understanding the role of vegetation in drainage ditches. However, considering the risk of these substances for public health, it is necessary to advance further and consider strategies for water pollution control such as vegetated drainage ditches.

21.7 Conclusions

The vegetated drainage ditches have been little studied in Mexico, despite their potential as remediation strategy for urban water runoff discharging into coastal areas. Furthermore, vegetated drainage ditches also provide environmental services often overlooked. Here we highlight the need for further research about the role of plants as well as plant management in order to better understand the functioning of vegetated drainage ditches.

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Chapter 22
Water Quality Management in San Luis Potosi, Mexico

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Abstract Several countries have adopted water as a human right which implies access to safe water sources for human consumption, among other conditions. Mexico has adopted this human right as well; however, there are still many actions that must be implemented before achieving drinking water and sanitation coverage as stated in the sustainable development objectives. In this paper, the situation related to access to safe water sources for human use and consumption was analyzed for the state of San Luis Potosi in its four geographic regions: Altiplano, Center, Media, and Huasteca. Each of these regions has unique characteristics, for example, the Altiplano region is arid and its water sources are mostly groundwater, while Huasteca is a humid region and its sources are mostly surface water. For this work, each municipality of the state was visited, users and authorities were interviewed, documentary information was collected, and an analysis of this information was carried out to identify the problems most frequently encountered in each region, which are highlighted in this document. It was concluded that it is necessary to encourage a regionalized management plan in the state of San Luis Potosi for this resource in order to minimize the main problems related to the quality of water supply to protect the health of the population.

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Keywords Water quality management · Water management plan · Water supply

22.1 Introduction

Water is an essential resource that plays a central part in all economic activities; therefore, its use must be sustainable (Kunz and Moran 2014). The provision of safe drinking water is a crucial component for the world to eradicate poverty and improve public health services.

Around 3 out of 10 people worldwide, or 2.1 billion people, lack access to safe drinking water at home, more than twice as many lack safe sanitation. The WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene (JMP) estimated that in 2015, 29% of the global population (2.1 billion people) lacked "safely managed to drink water"—meaning water at home, available, and safe. 61% of the global population (4.5 billion people) lacked "safely managed sanitation"—meaning access to a toilet or latrine that leads to a treatment or safe disposal of excreta. The world remains off track in meeting the sanitation target, which requires reducing the proportion of people without access to drinking water (WHO, JMP, UNICEF 2017).

Mexico is considered a regional economic and political powerhouse because of the size of its economy. However, due to its growth, management and governance failures are causing several water crises across the country (Godinez Madrigal et al. 2018).

Deforestation and the lack of a land-use plan are the main problems in the state of San Luis Potosi and in watersheds that supply water to the State. In addition to that, incomplete infrastructure of rural and urban sanitation, resulting in environmental pollution that affects mainly underground and surface sources, and mostly affects the population and water quality.

In this chapter, a diagnosis of water problems was carried out in the four geographical regions of the state of San Luis Potosi in México. For this, the main municipalities of the state were visited to obtain information and register the current situation of the access to drinking water of quality. Case studies highlight the problematic and possible solutions in these regions.

22.2 Organizations Responsible for Water Supply and Treatment in Mexico

In Mexico, the supply of drinking water to the population is primarily the responsibility of the municipal authority. Although the administration of water, as a national resource, is in charge of the Ministry of the Environment through the Secretariat of Natural Resources and Environment (SEMARNAT) through the National Water Commission (CONAGUA). The latter is in charge of the administration of water resources and is responsible for authorizing the municipalities to use water sources for their purification and supply to the population. Nonetheless, the municipality is the state entity that has the fewest resources to meet all the demand for drinking water in its jurisdiction and frequently faces a problematic of drinking water availability that has several origins and different consequences.

CONAGUA is also in charge of operating federal government financing programs for the construction of the necessary infrastructure for water provision and sanitation; among them, the Program for the Sustainability of the Drinking Water and Sanitation Services in Rural Zones (PROSSAPYS). This program partially supports the states by financing the infrastructure needed for water and sanitation services in rural communities. Funding is distributed to the states through their State Water and Sanitation Commissions (CEA) based on the necessities manifested by the municipalities, or their water committees in the rural communities. Funds are provided to the Mexican Government by the Inter-American Development Bank (IDB) to promote the sustainability of water resources in the countries. PROSSAPYS provides funds to those communities considered in the range of high and very high marginalization levels. CONAGUA (2009) through the CEA in San Luis Potosi funded twelve projects for drinking water supply (new or rehabilitated systems) in communities of rural or peri-urban characteristics in all the regions of the State (Altiplano, Center, Media, and Huasteca) in the period 2008–2011.

22.3 Geopolitics of San Luis Potosi

22.3.1 Land Productivity

In recent years, the agricultural sector has shown a downward trend in their contribution of the national and state domestic gross product, due to the obsolete production systems, lack of phytosanitary controls, inefficient marketing systems, the absence of schemes for producers' organization and integration of manufacturing processes. Those factors should be amended to add value to production and develop the productive potential of each region of the state. Today, agricultural activities employ 29.3% of the employed population of the state, mostly in rural areas. The state has a total agricultural area of 682.382 ha, of which 84% are rainfed agriculture areas with low productivity.

There are 104 water storage dams and 30 diversion dams in the state of San Luis Potosi. However, this infrastructure is inadequate to meet the demand for the development of agricultural activities. This situation has forced the State workforce to migrate to urban areas, where there are industrial and commercial activities, in search of better opportunities for productive employment and income.

It is essential to address agricultural and forestry development of the state with responsibility and commitment under the principle of sustainability, preserving and taking care of natural resources. It is of utmost importance to get the training and technology in two ways, one aimed at enhancing the level of productivity and competitiveness of the agricultural sector—the other intended to raise the standard of living and income of the employed population in agriculture, mainly in municipalities with high levels of marginalization, where agriculture currently represents more than an economic activity, a subsistence work (INEGI 2015).

22.3.2 San Luis Potosi State Population

In 2008, the country had a population of 107.1 million inhabitants. From 1950 to 2005, the country's population quadrupled and went from being predominantly rural (57.4%) to mostly urban (76.5%). The metropolitan area of San Luis Potosi is classified as a place with a population of 2,717,820 inhabitants, and it is considered that by 2030, over 70% of the population will be concentrated mainly in urban areas, having, therefore, the problem of water supply and design of new hydraulic infrastructure (INEGI 2015).

22.3.3 General Relevant Issues

The discharge of municipal and industrial sewage represents a source of pollution in many of the municipalities; only 10 of the 58 municipalities in the state have water treatment plants. Even though in some municipalities new water treatment plans have been constructed, some of these plants are not operating due to a lack of funds and trained staff. As a result, other treatment plants do not have vigilance or supervision.

The information on water, which each municipality has, depends mostly on the legal status of each operating agency. Around 70.7% of the municipalities visited, Matehuala, Cedral, San Luis Potosi capital, Rioverde, San Fernando, Ciudad del Maiz, and Ciudad Valles, have decentralized agencies, i.e., 12.1% of the municipalities in the state, and 87.9% of the municipalities have agencies that cooperate for the public administration without being part of it.

It is important to note that operating agencies provide safe drinking water mainly to the head-city of the municipality and the surrounding communities. However, the most remote communities do not receive drinking water of quality, and they are supplied with alternative or intermittent sources that sometimes do not receive any chemical treatment. All the municipalities visited, have minimal water coverage to their communities, being 25% for the Altiplano region (the arid region of the state), 15% for the Center region, 18% for the Media region and 10% for the Huasteca region.

22.4 General Situations of Each Region of the State of San Luis Potosi

San Luis Potosi is divided into 58 municipalities grouped into four regions. Each municipality has inequalities in population composition that result in essential restrictions for their development. Of all the state municipalities, 22 are predominantly rural with 596.009 inhabitants; 17 are rural with 223.833 inhabitants, 12 are semi-urban with 227.990 inhabitants, and seven are urban with 1,362.582 inhabitants. The geographical location of San Luis Potosi State is shown in Fig. 22.1.

In rural and predominantly rural municipalities, the infrastructure of services like electricity and water supply is limited, roads still show significant lags, and the economically active population works in agricultural activities. In semi-urban and urban municipalities, employment structure is more diversified, as well as labor offer, and consumption possibilities. In the majority, industrial and manufacturing development is present, reflecting further diversification of employment in the tertiary sector, with the presence of micro-businesses, mainly shops, and informal employment. The main economic activities depend on each geographical region (agriculture, mining, tourism, industry, etc.).

It was necessary to compile existing information on quality, quantity, extraction, recharge, and primary uses of water, identified by watersheds, using the various reports, studies, and dissertations, in the Secretary of State, in the municipalities

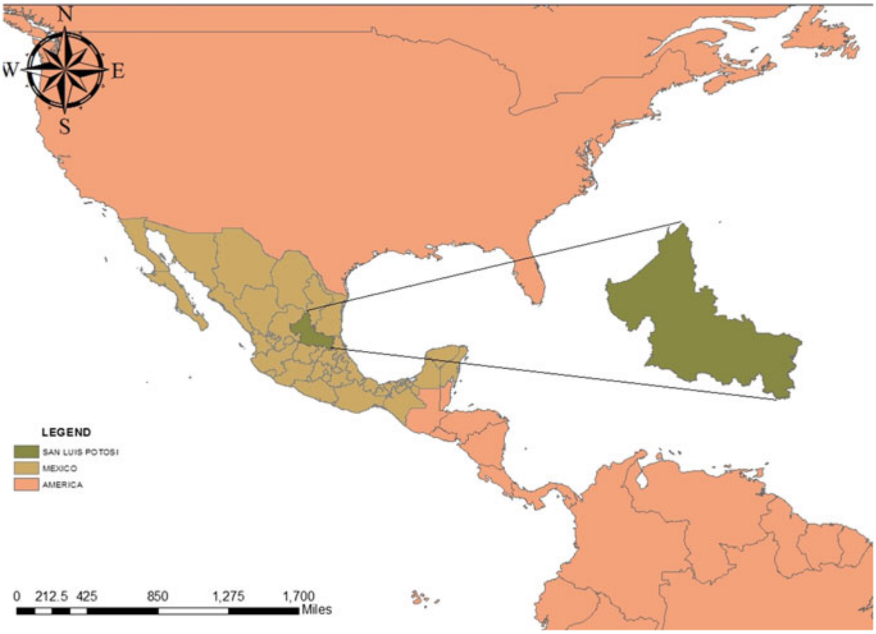

Fig. 22.1 Geographical location of San Luis Potosi State

and institutions of education. Also, focus groups were organized to review, analyze, discuss, and compile the information obtained in fundamental aspects.

The sample size was determined using a standard normal distribution. Before beginning the interviews, consent was obtained to collect the information. Interviews were conducted using a semi-structured questionnaire.

22.4.1 Altiplano Region

Observations on water held in the municipalities of the Altiplano region pointed out that the municipalities in this region have adequate organization and management of the resource. Culturally, the inhabitants take care of the resource because it is scarce, and people are prepared for times of drought. Rural communities have an adequate water management program, and even some communities have alternative energy sources to extract water at a low cost, as is the case of the municipality of Charcas. This municipality has a program to improve renewable energy, both for the extraction of water through the use of extraction mills, as for domestic use with solar cells.

The problems identified in the Altiplano region (Fig. 22.2) are represented by importing water from other municipalities as in the case of Matehuala, lack of geological studies for the opening of new wells, and the presence of pollution sources (municipal waste) near wells as in the case of Real de Catorce. About infrastructure, the problems are very similar in all municipalities of this region; the pipeline is obsolete, the pumping system is weak, a lack of automatic hypochlorinators equipment, and a lack of storage stacks of distribution and replacement material for contingency situations. In some communities, the deficiencies are even more substantial, as in the case of the community of Guadalupe Victoria in Charcas, where it was found that the primary deficiency is the design of efficient and economical construction works for the extraction of water. To date, it has not been put into operation due to the lack of financial resources for infrastructure projects of this type. Another frequent problem is the flooding in the rainy season due to the lack of adequate storm sewers, which results in flooding of agricultural and livestock land, and therefore, infiltration to groundwater wells.

Therefore, the supply of drinking water does not have a cost, because most of the time the resource is deficient for the population. Sometimes people go directly to the storage stack with buckets to carry water to their homes and cover their basic need. Regarding water quality, in some municipalities, storage stacks do not have adequate facilities for maintaining the resource under appropriate conditions, especially lack of staff and financial resources to clean them. The main quality issues in other municipalities are the high concentration of salts where water has high hardness and an unpleasant taste and even causes pipeline rupture. In addition, studies by Ortíz-Pérez (2011) indicated concentrations of fluoride above 1.5 mg/L which is the maximum permissible value specified in the Official Mexican Standard (Diario Oficial de la Federacion 2000), in most of the wells and distribution cells of the municipalities in this area, and in some cases arsenic was also detected. Among the

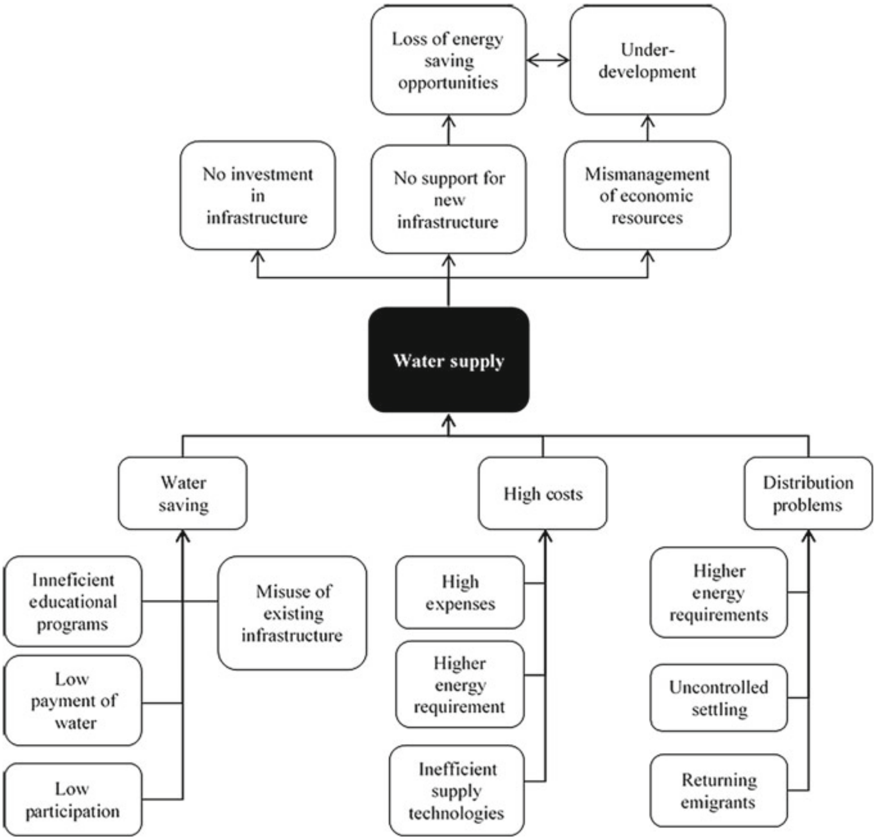

Fig. 22.2 Main problems and consequences of water supply in the Altiplano and Center regions

most common diseases in this region because of the intake of poor quality water is the dental fluorosis and often, allergies and hepatitis, although the source of the last one is not precisely known. The problems are summarized in Fig. 22.2.

22.4.2 Center Region

The situation of the municipalities in the Center region is very different from that observed in the rest of the state. Except for the metropolitan area of San Luis Potosi, Soledad de Graciano Sanchez, and other neighboring municipalities, there is a considerable backlog in infrastructure and information management. In the municipality of Villa de Arriaga, for example, water was not chlorinated because of the low availability of water (0.5–1.0 L/s), and they receive few economic resources for these requirements. These actions will further limit the development of new infrastructure in this municipality. As a result of water shortages, residents of some communities of the municipalities of the Center region consume water from troughs and ponds which also supply brick factories in the region. Consequently, mass poisonings have occurred in the population.

Also, municipalities have an enormous backlog in works to the distribution network system and water coverage. In these municipalities, there is no drinking water in the downtown area, or higher areas. The executives of the operating agencies of most municipalities in the Center region agree that there is inattention because resources are generally concentrated in the capital and other regions of the state. Regarding water quality, all the municipalities surrounding the capital only have bacteriological, and chlorine residual studies and they are unaware of other studies in their area. The study by Ortíz-Pérez (2011), reflects in detail the concentration of fluoride and arsenic in some wells of the municipalities in this area. In Fig. 22.3, a problem tree graph constructed with the analysis performed on the main problems of distribution, use, and accessibility of water is shown.

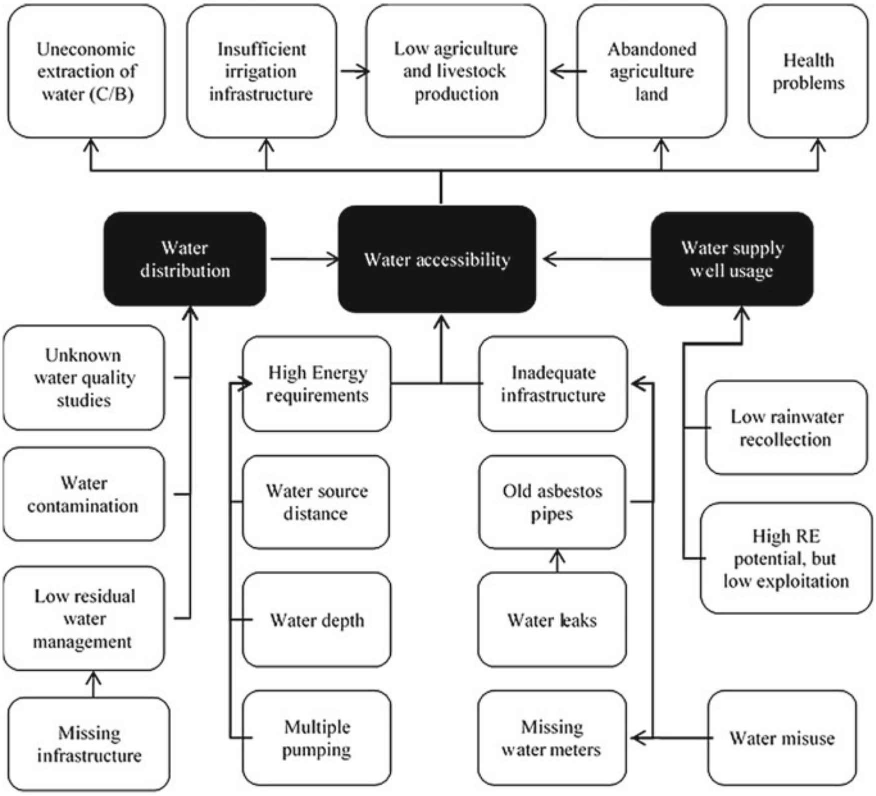

Fig. 22.3 Main problems of distribution, access, and use of water in the Center region

The existence of a regulatory framework that applies state-wide is of utmost importance for the prevention and control of pollution. At the state level, each municipal entity should have their Ecological Balance Law or equivalent, which clearly defines the tasks involved in prevention and control of pollution, integrated waste management, regulations and laws of water and wastewater. They would provide authority and power to the drinking water operating agencies. In turn, the policy could be implemented by the relevant government departments. It is also necessary, as demonstrated in the other three regions of the state, to work on the decentralization of the granting and management of water bodies of the state.

22.4.3 Media Region

In the Media region of the state, the scenario is similar in the topic of infrastructure. However, municipalities such as Rioverde, San Fernando, San Ciro de Acosta, Rayon, and Ciudad del Maiz present significant advances in the management and allocation of the resource. The water distribution system is efficient for the public, and executives of operating agencies are better informed of the current water situation and the problems of the region. Currently, these municipalities are developing executive projects to apply to state and federal support. However, due to the increase and concentration of population in urban areas in recent years, a scheduled supply system had to be implemented where water is only supplied to specific areas of the cities two or three days a week and other areas on the remaining days. The schedule cares the sectors located in the highest part of the municipality would not receive water otherwise due to the deficiency in the pumping system. Therefore, the requirements regarding the acquisition of larger pumping equipment, pipes for water distribution and pipe change, have become a primary necessity.

Regarding water quality, the municipalities of Rioverde, Ciudad Fernandez, and the community of Refugio in San Fernando perform routine studies with the Universidad Autonoma de San Luis Potosi (UASLP), in order to monitor the physicochemical characteristics and the presence of fluoride in the main wells. One of the main problems is the location of the wells supplying water to the population in agricultural areas, especially between maize and tomato. Regarding infrastructure, the greatest need is the lack of technical support to find other sources of safe water supply, since the pursuit of this resource is still performed by the traditional method of shaking. Also, automatic hypochlorinators equipment and more efficient pumping systems are required. The problems observed are presented in Fig. 22.4.

22.4.4 Huasteca Region

The water situation in the Huasteca of San Luis Potosi highly contrasts with the other three areas of the state. The municipalities of this region are supplied by surface

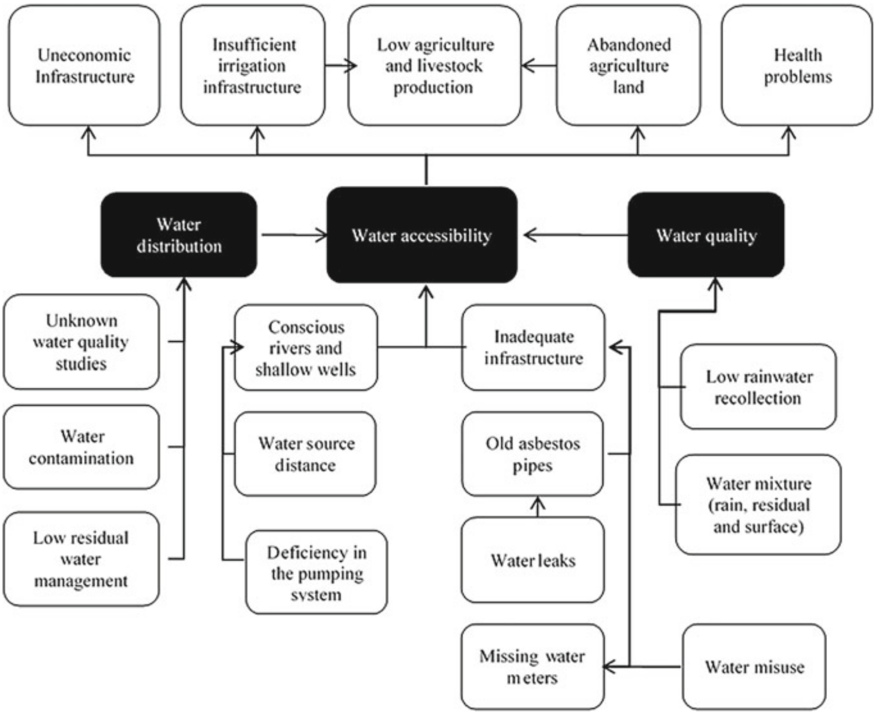

Fig. 22.4 Main problems of water in the Media and Huasteca regions

water, including rivers and permanent or intermittent streams. However, some rural communities do not receive drinking water, and their water supply is from treadmills that receive no treatment. Although rivers cross most municipalities, communities do not have access to it, even if the people live across the river shorelines, as is the case of the communities surrounding the Pujal Coy. In other municipalities such as Xilitla, the water shortage is so prominent in hot weather, that people must cover their daily needs with water bottles, which dramatically affects their economy because of the cost of each bottle. Besides this, it is widespread to find the distribution of water in trucks, especially in Ciudad Valles and Tamuin, which is the result of the lack of planning and unsuitable land organization for population growth.

The municipality of Ciudad Valles is the only one with a decentralized operating agency that works efficiently, and has the entire infrastructure for routine analysis, and addresses all matters relating to the management and resource management. This agency called the Department of Drinking Water, and Sewerage (DAPA) has a database of all the volumes of water extracted and chlorinated monthly and analyzes other organic and inorganic pollutants in certified laboratories.

Regarding water quality, pollution of surface waters by various factors is a severe problem, especially for the municipalities of the Huasteca region, where rivers are the only source of supply. The problem of river pollution is the result of the lack of land organization for the development of population centers, both structurally and functionally. As a consequence, there is a lack of drainage, sewers, and treatment plants designed for population growth. Also, although some municipalities have treatment plants, they are not operating correctly, as in the case of Tamuin and plant Birmania in Ciudad Valles. The financial resources provided by the state and the federation do not cover all the design (power supply, transmission, purification, water treatment, sewage treatment) so that it is sometimes only available for a given stage without fully considering the whole design. In addition, there is not a proper record of downloads which can be reliable or updated.

Figure 22.4 shows an overview of the current situation regarding infrastructure and water quality in the Huasteca region. There are two critical aspects that affect the quality of surface water in the Huasteca region: (1) the combination of wastewater and stormwater, which often affect the efficiency of wastewater treatment plants, and untreated overflow is discharged into rivers; (2) diffuse pollution, urban runoff flowing without any quality control, dragging the sediment, trash, grease and oils to streams, impacting them severely. It is, therefore, necessary to implement and create regulations on urban development when it comes to express the environmental impact in any municipality in the present or future. Although there are environmental laws, in most cases there is a lack of regulations to facilitate their implementation.

22.5 General Considerations

The diagnostic of the quality and availability of water for different uses in the major watersheds in the state of San Luis Potosi is necessary to achieve sustainable management and identify priority areas of study for the rehabilitation, operation, management and distribution, water disposal, and reuse.

These studies should go parallel to a concurrent understanding of the patterns and geohydrological processes in each area of the state. The water flowing into the aquifers and the one used on the surface depends on the quality and quantity attributes of watershed health. This perspective of study, because of its inherent complexity, necessarily requires the establishment of a multidisciplinary team.

22.5.1 The Public Management of Water

As mentioned above, being water an essential resource central to all economic activities, its use must be sustainable (Kunz and Moran 2014). Water management strategies are required to be effective despite variability in climate and geography conditions. To make better-informed management strategies, managers need to understand the dynamics of heterogeneous water systems under extreme climatic variability (Barrett et al. 2014) and understand those factors within a system which are most influential on system behavior. Managers also need to understand how these influential factors change under different climatic conditions and between sites (Giordano and Shah 2014).

Water management reforms can fail for multiple broader socioeconomic factors like lack of funding, political instability or the interference of global drivers like trade policies or droughts (Warner et al. 2015). The provision of safe drinking water is a crucial component for the world to eradicate poverty and improve public health. As part of the Millennium Development Goal (MDG) 7, halving the proportion of people without sustainable access to safe drinking water, and basic sanitation by 2015 was one of the targets (United Nations 2011, 2013). Although it was declared that the drinking water part of the goal was met (WHO and UNICEF 2014), this is not true globally as some regions still lag (WHO and UNICEF 2015).

Despite disparities in water access, it is also worthwhile to note that the declaration of success ignores two critical components of water supply, which are the provision of safe water and maintaining sustainable supply systems (Alexander et al. 2015). It was noted that development practitioners in the sector were paying more attention to building new facilities to meet the drinking water as part of the goal than ensuring their sustainability, (Kunz and Moran 2014).

In this way, the Management of Water Resources was established as an alternative solution to this problem. Due to this, it is essential to start from a socio-environmental and holistic analysis, considering the values that are attributed to water. This management is based on three pillars: economic efficiency, equity, and environmental sustainability. To achieve adequate management of water, managerial instruments which allow evaluating it are required. An enabling environment is needed through the creation of policies and legislation, and the institutional framework at different levels so that that water can be had for both human being activities as for the environment (Gil Antonio and Reyes Hernández 2015).

Many methods and techniques can be used to water management, including water conservation, reuse and wastewater management. Likewise, it is necessary to create a legal and institutional framework that establishes principles accompanied by work tools and methodologies for its application (Sánchez and Sánchez 2004).

The transversality of public policies is an essential issue of water management, defined as the combined efforts of the federal, state, and municipal public administration agencies to exert joint actions for solving problems linked to the same area and contribute to solving others (Vargas et al. 2004).

One of the principles of water management is the participatory approach of all the actors involved in water management. In San Luis Potosi, despite the efforts made so far, water management has not been achieved due to the lack of mechanisms that facilitate the participation of all the actors involved in the water distribution and use, especially in rural communities where the inhabitants have to manage and provide themselves with poor quality water.

22.5.2 Water Management in San Luis Potosi

Due to the excessive use of water for different human activities, in Mexico its use was regulated through several regulatory instruments, the main one being the National Water Law (NWL) of 1992. The NWL establishes that state governments are granted a more active role in water management, and they are invited to adopt their drinking water, sanitation, and sewerage management laws, and set their rates. It seems that in the legal field there is no clear definition of the instances that are responsible for defining water quality for a specific use to support those who must make decisions. However, there are legal instruments that allow monitoring of its quality. Among them, we mention "The Law of Health" which states in Article 119, that it is up to the Ministry of Health and the governments of the states in their respective areas of responsibility: to monitor and certify the quality of water for human use and consumption (CONAGUA 2009).

Also, the Water Law for the State of San Luis Potosi, in Chapter III relating to the State Water Commission (CEA) says that its assignment is to gather and update information on state waters related to the different uses, availability, and quality. Article 14 states that the CEO attributions are to command the practice on a regular and periodic basis, to perform control water sampling and analysis, to keep statistics, and take action needed to optimize water quality for the population supply as well as the sewage poured, in accordance with the applicable law (Ley de Aguas 2016; Peña 2006).

In the visits made to the different municipalities of San Luis Potosi, it was found that there is inadequate water management, which has been generated by the complexity of the associated problems and the lack of organization of water managers. Rural communities lack an adequate management program, and the inhabitants of those places are the most affected regarding access to quality water. In this sense, community management can lead to participatory sanitation; the active community can generate a process to develop waterworks, follow up, manage it, and make it work. Figure 22.5 summarizes a plan to achieve water management.

22.6 Case Studies

22.6.1 Water Supply Problems in the Altiplano Region

Recently, the Autonomous University of San Luis Potosi undertook an analysis of the water supply problem in communities between 500 and 2500 inhabitants considered as rural, in the Altiplano Region of San Luis Potosi, which is the aridest region of the state and its resources of water depend entirely on groundwater (Tejeda-González 2017). A total of 77 communities and the head-town of each one of the 15 municipalities of the Altiplano were visited. Information was obtained on the water sources available to the population, the water treatment processes used, and

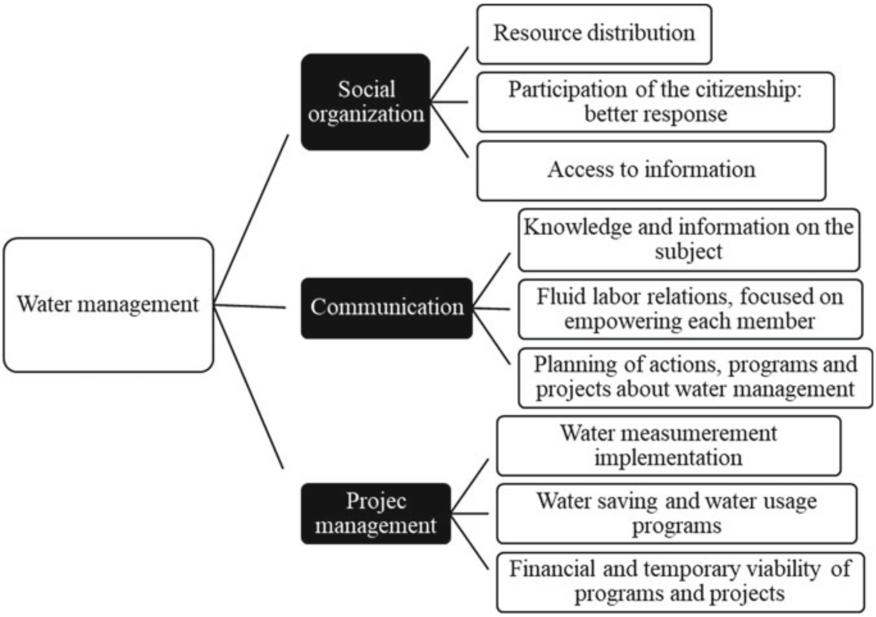

Fig. 22.5 Water management plan

on how local authorities and the population manage the water distribution to the communities. Analysis of problems was done according to the principles of the Strategic Environmental Assessment (SEA) (Fischer 2007). Evidence to support the analysis was documented through fieldwork, interviews to users and authorities for the water supply. Also, reports, governmental programs, and other documents obtained were considered in the SEA Analysis.

The following problems were documented.

1. The degree of social marginalization in the region is considered of mid-level, and it considers, among others, the access to the basic water and sanitation services in the house.
2. The drinking water services are the responsibility of the municipality that serves the head-town and the closest rural communities fundamentally; the others make their water demand assisted by several official instances.
3. In rural localities, farmers participate in "ejidal organizations" represented by a commissary and a supervisory council. The "ejidal organizations" are established in Article 27 of the Mexican Constitution. There are also "water committees" with a president, a secretary, a treasurer, and a person responsible for the operation of the water well on which the town depends. In this way, the ejido organization and the water committees make a request to the official authorities for the water resource needed in their locality.
4. The rural localities are responsible for paying the electricity needed to operate the wells pump. The electric power consumption is paid by the locality, and

the water committee oversees establishing the rates for the water services to the population based on the amount of the electricity receipt.

5. At the head-town of the municipalities, drinking water services are administrated by operating organizations, water boards, municipal water departments, or the ecology department. Their budget is often insufficient, so the water supply is mainly granted to the host city of the municipal government and nearby towns. In these cases, the State and the municipality are supported with Federal Grants as those obtained by the Mexican Government from the Inter-American Bank for Development (BID) and administrated by CONAGUA. Unfortunately, funds are only allocated to those localities considered as having very high marginalization.
6. The people responsible for the water supply can change with each municipal administration and do not always have the necessary knowledge and training to operate the water service.

These situations that have been highlighted for the Altiplano region of San Luis Potosi are practically identical in the other regions of the state and other states of the country located in the central-northern region, mostly arid.

22.6.1.1 Water Quality and Treatment in the Altiplano Region

The Altiplano region of the state of San Luis Potosi is located within the Hydrological-Administrative Region of the Northern Basins (Cuencas Centrales del Norte), a region of the country mostly semi-arid in which groundwater is the primary water resource for all sectors. In this region of the country, it is well known that water has a quality problem due to the presence of arsenic and fluorides (Bocanegra-Salazar 2006; Cardona et al. 2018), two pollutants from geological origin that cause health problems through the continuous consumption of this water (Rocha-Amador et al. 2011; González-Horta et al. 2015).

Water samples were collected from all sources of water supply used by the population in the 15 municipalities of the region. These sources included wells, water pots, storage tanks, and even small reservoirs. The samples were collected in seventy-seven sources of supply; eight rural populations with less than 500 inhabitants were visited by request of the municipal authorities. At each site, water samples were collected for microbiological analysis (sterilized bags), metals (HDPE bottles with HNO_3 trace grade), and physicochemical analysis (HDPE bottles). Some parameters were measured in the field (pH, ORP, conductivity, residual chlorine). The physicochemical and bacteriological parameters established by the National Legislation for drinking waters (Diario Oficial de la Federación 2000) were determined. For the analysis of arsenic and metals, the samples were filtered (0.2 μm membrane filter, PC-Nuclepore) and acidified to pH 2 with nitric acid grade trace analysis. Spectrophotometry of Atomic Absorption did the determinations with flame or graphite furnace (Varian SpectrAA 220FS and 220Z). The results obtained allowed to determine that the contamination with fluorides and arsenic in samples from deep wells represented 19% of the analyzed supplies. The determined concentrations varied in the range of 0.1–4.7 mg/L for fluorides (determined by the Ion Selective Method); in the case of arsenic, the concentrations varied between 0.5 and 141 μg/L (Tejeda González, 2017).

In addition to fluorides and arsenic, water showed a high content of salts (sulfates, chlorides, sodium) in nine municipalities, and presence of lead and other metals in many water sources, at concentrations higher to those recommended by the NOM-127-SSA1-1994. These results show that the problem of the quality of the water sources to which the population has access, at least in the Altiplano region is complex and requires urgent and concrete actions aimed to provide treatment even in rural areas depending on well water. Bacteriological contamination was detected only in samples from shallow wells and storage basins. For this, the responsible authorities of health (Ministry of Health) support with a permanent campaign of water disinfection, so that the population in the rural localities at least disinfects the water. Where possible, the water is made safe by using reverse osmosis systems (head-town in the municipalities and two rural localities in the Altiplano region) and disinfection, in most of the rural localities the necessary products are provided for the water disinfection of storage tanks and cisterns. In several localities, water is distributed to the population after being disinfected in the storage tanks, or there is a community water tap. Unfortunately, not all inhabitants disinfect the water because they indicate that it acquires an unpleasant taste. Also, an important sector of the population has adopted as a measure, the consumption of purified water to drink, even if they cook with untreated water.

22.6.2 Diagnosis of Water Quality and Treatment Alternative in Central Region

In this case study, a diagnosis of water quality was carried out to evaluate the contamination by fluoride and arsenic in well water for human consumption in the Center region of the state of San Luis Potosi (Torres Rodriguez 2016), based on previous work carried out by Ortíz-Pérez et al. (2006). First, the localities of each municipality were classified as urban (higher than 5000 inhabitants) and rural (less than 5000 inhabitants). Then, the percentage of the localities that have or do not have water quality studies was determined. Finally, the data was plotted to visualize the information (Fig. 22.6). With the above information, the percentages of the localities of the municipalities whose fluoride levels in the well water exceed the maximum permissible limits according to NOM-127-SSA1-1994 were determined (Fig. 22.7).

The wells chosen for this study correspond to the well in Laborcilla located in the municipality of Villa de Arriaga and the well Las Rusias located in the municipal seat of Villa de Reyes. Also, it was found in the diagnosis that in the study conducted by Ortíz-Perez et al. (2006) a fluoride concentration was reported in the Laborcilla and Villa de Reyes wells of 4.82 and 2.61 mg/L, respectively, which are higher than

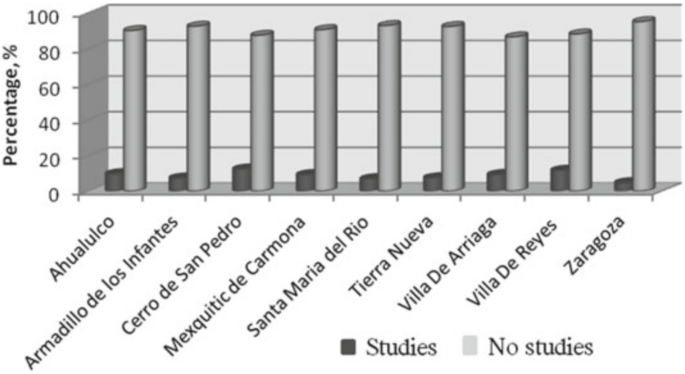

Fig. 22.6 Localities of some municipalities of the Center region of San Luis Potosi that have or do not have water quality studies

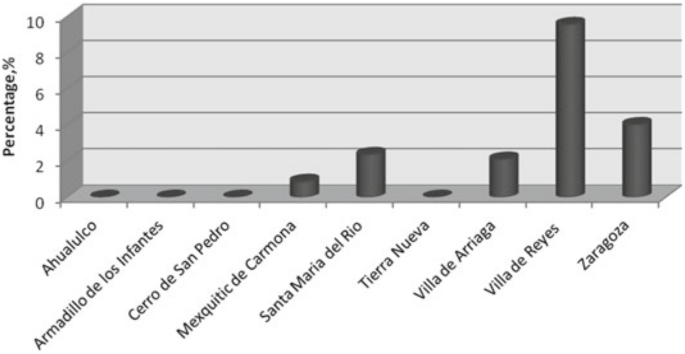

Fig. 22.7 Communities of municipalities that have water quality studies and where the maximum allowable limit of fluoride in water is exceeded

the maximum permissible limits. The water from these wells was selected to perform adsorption tests using bone char because of the high level of fluoride present in them.

The results of this study, shown in Fig. 22.6, revealed that approximately 90% of the localities in the municipalities analyzed in the diagnosis do not have water quality studies for their wells. Also, Fig. 22.7 shows the percentages of the communities that exceed the maximum permissible limits of fluoride which varied in the interval from 1 to 10%.

22.7 Conclusions

In the state of San Luis Potosi, the infrastructure to provide safe quality water for the population is not enough. In some cases, both the infrastructure to provide drinking water and that related to sanitation are obsolete or inexistent in rural and urban areas resulting in environmental pollution affecting the groundwater, surface water resources, the population, and water quality. The wastewater discharges from industries and municipalities represent the most significant source of pollution in the state.

Water management in the different regions of the state of San Luis Potosi depends substantially on the interests of the municipal authorities and the involvement of the inhabitants. Water quality is affected by both anthropogenic activities and nature, though there is not an adequate treatment process to generate water of quality for human consumption.

In the state of San Luis Potosi, it is necessary to encourage a regionalized management plan for this resource, with the intention of minimizing the main problems related to the water quality supply in order to protect the health of the population.

This work will contribute to developing other studies about water management, infrastructure development, quality and quantity water monitoring, water distribution and the issuing of water rights.

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Chapter 23
Ravines of "*Eternal Spring*," the Second Drainage System of Cuernavaca

Giovanni Marlon Montes-Mata and Rafael Monroy-Ortiz

Abstract Due to the city functioning and the urban expansion itself, water consumption and also pollution patterns have particularly intensified and diversified their damages, in such a way that they represent a serious risk to society and environment. Since 1900, it is estimated that, 248,000 km^3 have been extracted, an equivalent volume to 198 times the water of the world's rivers (FAO 2016; U.S. Geological Survey 1984); in addition, 80% of sewage water has not received any treatment before being discharged into the natural sources reaching 95% in some underdeveloped countries (UNWATER 2017). For example, the effects that of wastewater represent for public health, equal the death of 1 person every 20 s (OMS 2017a). The aim of this paper is to analyze the economic and social impacts caused by sewage spills out on Cuernavaca flow of ravines, identifying discharges points registered by the Cuernavaca Drinking Water and Sewerage System (SAPAC), with a statistical sample selection according to land uses. Sewage volume is estimated experimentally, which means that the flow rate can be calculated in the selected points, using the volumetric method; with this all information, a geographic information system is elaborated in order to identify total volume and contaminants for land use, the total urban contribution to water pollution, and finally economic treatment cost related to total sewage volume.

Keywords Ravines · Urban wastewater · Irregular dwelling · Treatment system · Economic cost

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23.1 Introduction

Water conditions are projected in the coming decades with serious difficulties for their availability, but at the same time, with high levels of contamination. In this case, the underdeveloped societies demonstrate a greater social vulnerability due to the lack of treatment of the residual effluents caused by a low budget provision and even, due to the lack of knowledge of the scale and dimension of the problem. At the same time, it is a common practice to pour the waters without any treatment to the nearest natural sources, including rivers, ravines, lakes, and sea. In the case of the city of Cuernavaca, the lack of availability of water and residual water treatment coincides; the flow of these is channeled through the public network, but to be poured into 311 discharge points in ravines, which become the second drainage of the city. The consequences of this are multidimensional but include mainly odor, visual perception, generation of vectors, and, importantly, social costs associated with the health of the population, whose morbidity is increased. In this paper, it is estimated the flow of the discharge points based on a representative sample in situ, to rethink treatment technologies according to the volume generated by the type of land use, demonstrating a possibility of development, economically and socially feasible mitigation strategies.

23.2 Water Use and Its Respective Pollution

Throughout the history of humankind, there have been different patterns use of natural resources, mainly related to the evolution of technical means in production modes; it is due to this that productive capacity of pre-capitalist stage presents large differences with the increasingly negative impacts observed in contemporary society. Elements such as tools, clothing, or housing are signs of development; however, when the processes of extraction, transformation, and disposal of natural resources are higher than human physiological needs, this characteristic of capitalism can be described as “human progress, inevitably destructive” (Tanuro 2013).

In this sense, the advent of the capitalist mode of production entails an exponential use of natural resources, achieving as a primary interest in increasing profits. 5% of the history of humankind is related to capitalism, and it has been enough to generate the most significant environmental damage since the emergence of human, the modern technology has modified the relationship with nature, rising the exploitation rate, and diminishing the recovery one (Sartelli 2013).

Impacts attributed to this period include 40% of the world’s forest mass loss, 50% of wetlands, 35% of mangroves, and 30% of coral reefs (UNEP 2005); it is also recognized that 30% of animal species are in danger of extinction precisely due to human overexploitation (WWF 2016). In terms of the water resource, it is estimated that 248,000 km^3 have been extracted since 1900, twice the volume of planet’s lakes and 198 times the river’s water (FAO 2016; USGS 1984); welfare and development society depends on this resource, so its reduction or loss represents one of the most severe risks for ecosystems and humanity.

The planet consists of two-thirds of water. However, 97.5% available is salty, reducing that to 1% for human needs only. Availability and distribution are decisive in its use; meanwhile, Asia has 36% of fresh water, Europe has 8%. Exploitation patterns reflect that worldwide domestic consumption reaches 10%, while industry and agriculture require 15 and 75%, respectively (CONAGUA 2015a, b). However, 40% of water used in agriculture returns to the environment as evaporation, going back to the biogeochemical water cycle (UNWATER 2017). Economist criteria prevail in water use, including those of particular relevance for people, like food production, which has exceeded physiological needs reaching an exponential consumption, that is out of proportion and differentiated. For example, 1 kg of corn production requires 900 L of water, whereas to produce 1 kg of wheat requires 1,300 L of water and 1 kg of rice requires 3,400 L of water (CONAGUA 2015a, b).

The industry is a particularly demanding water sector. Paper production requires on average 473,125 L for pulp production of 1 ton of paper or rayon, on the other hand. Bleaching 1 ton of cotton requires between 181,680 and 272,520 L of water. Green beans and peaches packing consume 64,345 and 18,168 L of water, respectively (Shiva 2003), and 250 ml of beer or a bovine leather shoes need 75 and 8000 thousand liters of water (CONAGUA 2016).

According to South Network Justice and Campaign for Responsible Technology (cited by Shiva 2003), water requirement for microprocessors manufacturing averages 8,611 L of demineralized water for a single wafer or 15-centimeter silicon disk. Intel plant located in Rio Rancho, New Mexico, produces 5,000 wafers per week, which means 43,055 m^3 of water consumption per week or 2,066,640 m^3 per year.

Considering all these examples, the volume extracted to cover economic requirements responds to production and consumption patterns, under the fundamental principle of increasing the profit rate and leaving, aside living beings basic needs. This rationality was responsible for water scarcity experienced in 28 countries in 1998, and it is expected to increase to 56, by 2025. In this sense, water shortage will increase from 131 million of people in 1990 to 817 million in 2025 (Shiva 2003); considering the regional shortage, it is estimated that 1,200 million people will be affected. Meanwhile, 780 million people will not have it in a quality manner (UNWATER 2015). Also, by 2050, global resource demand will rise 55%, among other things, caused by urbanization rate (CONAGUA 2015a, b).

Economic requirements condition water consumption and local availability; as a consequence of its natural free access, profiting it as an economic factor is possible for the private sector, regardless of its social impacts. However, this kind of resources turns into discarded ones, transforming its indispensable function to an unusable waste; as it is the wastewater, which can be described as a combination of effluents with different origins, including domestic ones that are separated in sewage (excrement, urine, and fecal sludge) and gray (basin and shower water); industrial waters of commercial establishments including hospitals; effluents derived from agriculture and even rainwater (UNWATER 2017).

Regarding wastewater, it is estimated that 80% of global volume does not have adequate treatment before being discharged into the environment and 95% in underdeveloped countries (UNWATER 2017). There are differences in the degree of water treatment according to country income level; that is, highly developed countries treat 70% of wastewater, while upper-middle-income countries treat less than 38 and 28% in the mid-low countries. Also, only 8% of industrial and municipal wastewater from low-income countries has any treatment.

In this sense, the primary objective in economically developed countries is to treat contaminated water and to preserve its environment in order to maintain the water quality saving the scarcity conditions. However, the existing paradigm marginally respects the condition of social class or gender, since pouring treated and untreated urban liquid waste into nearby natural sources is a constant action on the planet (UNWATER 2017).

In underdeveloped countries cases, the common practice is to discharge wastewater without any treatment, due to the lack of infrastructure, technical or institutional capacity, and insufficient financing, among other things (UNWATER 2017). Besides, collecting or capturing wastewater does not necessarily mean that they are receiving adequate treatment; mostly is released to nearby natural sources. Unknown information about wastewater is also a severe threat; according to UN (op. cit.), 55 of 181 countries had reliable or even data outdated prepared for the global water report 2017.

Achieving sanitary conditions requires an investment of 53,000 million dollars, consecutive for five years, which means about 0.1% of 2010 world Gross Domestic Product (GDP). This scenario means that sector investment would bring economic benefits from 5.5 times to 1, in a global uncertainty about water and sanitation. At present, 748 million people have not quality water, and 2,500 million do not have adequate sanitation facilities (UNWATER 2015).

In underdeveloped regions, wastewater treatment capacity is conditioned by economic circumstances, commonly identified as inefficient, and for its adverse effects on health, food, population life patterns of most vulnerable social sectors. For instance, the undeveloped urban structure is located in urban peripheries with any consolidation and directly exposed to the effects of the residual pollutants directly discharged into the environment, and therefore, they become more vulnerable (UNWATER 2017).

As a consequence of current productive diversification, the composition of urban wastewater includes 99% water and 1% dissolved solids and also contains polluting substances like bacteria, viruses, parasites, and toxic chemicals. All of these components are released to the environment, commonly rivers, lakes, ravines, and seas, paradoxically mean that human will have contact with, thereby having direct health consequences (UNWATER 2017; NRDC 2004).

Urban municipal wastewater composition is diversified due to the range of pollutants generated by industrial, commercial, institutional, and domestic sectors, and that is why municipal residual effluents without treatment represent a global-scale challenge, directly associated with urban expansion. Since this process implies a growing reproduction of marginal urban patterns, it is estimated that vulnerability to wastewater emission will be aggravated. Nearly 30.17% of the urban population lives in irregular settlements and 32.7% in developing regions (UNWATER 2017; ONU 2016). Sanitation infrastructure is required in these urban sectors because there is a lack of latrines and toilets, sometimes for public use and without any connection to municipal drainage network. This situation forces people to defecate outdoors, increasing unhealthy conditions (UNWATER 2017).

In the world, 780 million people are estimated without drinking water access and 2,500 million without any sanitation. As a result, morbidity and mortality are increasing by 20–30% for gastrointestinal diseases and 17% for work-related deaths, respectively. One person dies for every 20 s, and 800–1,500 million deaths could be avoided each year if water contamination is reduced (OMS 2017a, b). Annually, 2 billion people are supplied with drinking water with pathogens due to feces, causing more than 502,000 deaths due to diarrhea (OMS 2018).

In the case of sanitation, although there has been infrastructure progress, there are 2,300 million people still without essential sanitation elements, including toilets or failing latrines; 892 million defecate in the open air, in sewers, shrubs, or in natural bodies of water. From another perspective, it is estimated that at least 10% of the world's population consumes food that has been irrigated by wastewater (OMS 2017c).

Derived from inadequate sanitation, not only are estimated around 280,000 diarrhea deaths per year, but there is also a high correlation with neglected tropical diseases, including intestinal worms, schistosomiasis, trachoma, as well as cholera, dysentery, hepatitis A, typhoid fever, and poliomyelitis. Also, sanitation conditions contribute also to malnutrition or infant underdevelopment (OMS 2017c, 2018). Diarrheal diseases, in particular, represent the second cause of death in children under five years, this amount is estimated in 525,000 deaths per year, and although these are preventable and treatable, they continuously occur where there are no healthy conditions (OMS 2017b).

Regarding morbidity, diarrheal diseases are estimated in 1,700 million children cases worldwide, which are susceptible to this condition due to malnutrition, and prevail as an underdevelopment characteristic or socioeconomic vulnerability. Such diseases are mainly linked to bacterial, viral, and parasitic organisms and even tend to be transmitted by the consumption of food, contaminated water, as a result of poor hygiene or when used for washing, cooking, and in general, in all primary activities and recreation of the human being (OMS 2017b). The agents that cause this morbidity are water contamination with fecal excreta, coming from latrines, septic tanks, and urban wastewater (OMS 2017b).

Therefore, this type of disease is directly related to the provision and water availability in quality, as well as sanitation and hygiene conditions; this implies addressing better conditions in order to mitigate their effects (OMS 2017a) and also to reduce their own social and economic costs. In this sense, World Health Organization mentions that for every dollar invested in sanitation sector improvement, there would be retribution of 5.5 dollars; that is, it would reduce costs for treating diseases and mortality, increasing effective productivity (OMS 2017c).

Given the diagnosis of the water situation and its contamination, contemporary society faces an increasing impact on natural resources, reflecting high rates of exploitation and water pollution which are discharged to natural tributaries without treatment, causing a public health risk. So, it is pertinent to identify the priority processes for mitigation strategies. Due to the absence of reliable information of wastewater treatment, this chapter analyzes the emission of urban waste effluents in the ravines of the Cuernavaca municipality which is studied based on an identification and georeferencing of discharge sites, collected samples in situ, according to the types of city land use regarding volume poured.

23.3 Water and Contamination by Residual Effluents in Cuernavaca

23.3.1 Water in Cuernavaca

The Cuernavaca municipality concentrates 20% of Morelos state population. It is the largest metropolitan area of the state and contributes to 24% of economic units, which is a chief factor in the growing water demand and its pollution (INEGI 2010a). Those water demands have caused the drift of water resources to urban, industrial, and tourist, designed initially for agriculture (Batllori 2001). Therefore, conventional urban structures and even those that are irregular or without the necessary planning affects important resource availability, since they generate an aggregate demand, as well as the corresponding pollutant volumes, which locate their residual effluent discharges in surface sources of water, see Fig. 23.1.

In this sense, Cuernavaca's essential services in private dwelling show that 95.12% have water, 98.7% drainage, and 98% toilet (INEGI 2010a). In terms of city water management, particularly the extraction, distribution, purification, and sanitation are carried out by the SAPAC, which finds a serious budget deficit that has given place to poor service; decreasing investment in hydraulic infrastructure and other work

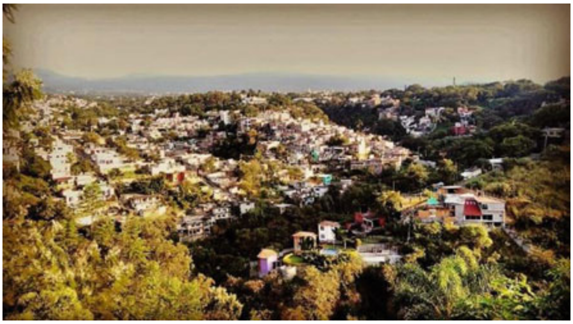

Fig. 23.1 Irregular settlements located in the ravines of Cuernavaca

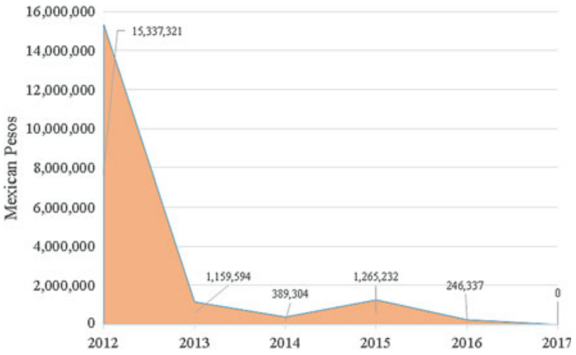

Fig. 23.2 Investment of SAPAC in hydraulic infrastructure. Elaborated with data from Morelos Rinde Cuentas (2018)

services shows a reduction of 15 million Mexican pesos in the last 5 years, see Fig. 23.2.

In general, Cuernavaca is recognized as a city with one of the worst basic services, causing a inhabitants discontent, that is why 41% shows dissatisfaction with drainage and sewer service, 30% with drinking water services; both rates municipality at 6.49 efficiency points, on a scale of 1–10 (Morelos Rinde Cuentas 2016).

The distribution water in Cuernavaca is through “tandems,” which means a distribution differentiated by zones and in different hours and days, forcing to take storage means such as water tanks, cisterns, boats, and buckets that guarantee their provisioning. Five hundred of total household intakes (0.48%) have a permanent amount, representing a below average in national terms, estimated in 75% at some places like Mérida, Mazatlán, and Colima, where it reaches 100% (Morelos Rinde Cuentas 2018).

Lack of pumping in infrastructure or payment debts in electric energy are attended in SAPAC, that operates the tandems each third day; therefore, there is a low people’s distribution average, far away of other Mexican cities, where population has a constant supply and without using water tanks or other means of storage (Morelos Rinde Cuentas 2016). It should be noted that given the economic circumstances of the Cuernavaca population, the capacity to acquire storage facilities is limited; 56% of homes have a cistern, and 87% have water tanks (Morelos Rinde Cuentas 2016).

Therefore, Cuernavaca expenditure is mostly occupied in the resource acquisition, including water service, household supply, and tanks and cisterns acquiring. These imply a different storage form without enough quality, generating population health risks due to the reproduction of vectors such as dengue mosquito, and chikungunya and zika, which represent high economic treatment costs.

In Cuernavaca city, it is estimated that a colony has not watered each third day and more than half people suffer from endowment failures (Morelos Rinde Cuentas 2016). As mentioned before, pumping equipment and electric power are factors that do not allow an efficient resource distribution; between August and December in 2017, power cuts were prevalent in 60 colonies where there was no water at all (Morelos Rinde Cuentas 2018). In this logic, infrastructure existent does not guarantee a proper

Table 23.1 Water layout in Cuernavaca

Water		
Type of consumption	Millions of m^3	%
Real consumption	21,844,000	32
Water loss	40,000,000	59
Water pipes	6,000,000	9
Total consumption	67,844,000	100

Own elaboration with data from Morelos Rinde Cuentas (2018)

distribution, as it is observed in the water network studied, which does not ensure a quantity and quality providing.

In Cuernavaca, National Water Commission (CONAGUA) authorizes to the city 133 million m^3 annually, but only 69 million m^3 are extracted. Although this volume would be enough to cover three times local demand, management and administration problems include leaks, clandestine connections, and different anomalies; for example, SAPAC invoiced 58% of total volume extracted in 2015, that is an amount equivalent to 40 million m^3 (Morelos Rinde Cuentas 2016), see Table 23.1.

From the total water volume extracted in Cuernavaca, it is estimated a 188.95 m^3/inhab/year consumption, that is, 517 L/hab./day, which is similar to the USA resident average (Morelos Rinde Cuentas 2016; INEGI 2010a), see Fig. 23.3.

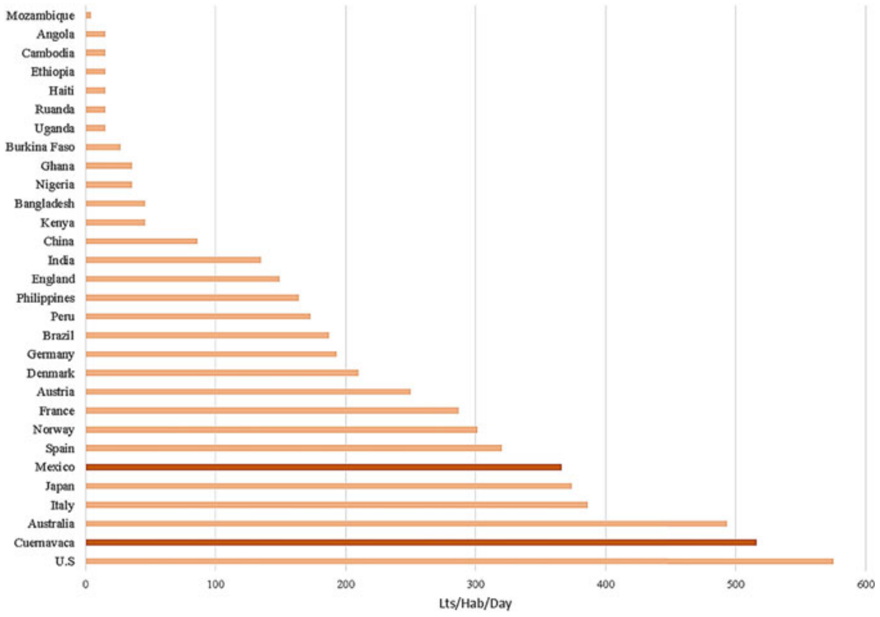

Fig. 23.3 Water consumption inhabitant per day. Elaborated with data from Morelos Rinde Cuentas (2016)

Cuernavaca's water supply and consumption are higher than the national average (41%) and compared to Australia, Japan, and Italy, but available volume per day is lower, mainly due to distribution patterns and system failures that cause loss. Spills and leaks represent 28 million m^3 per year, the 42% of extracted water. Also, it is estimated that 85% of water costs are not charged, corresponding to leaks derived from the deteriorated infrastructure. Regarding physical efficiency, this reached only 47.5% by 2015. At the same time, water wasted in leaks implies an environmental cost due to aquifers overexploitation and the cycle imbalance that deprives the respective future generations availability, and it ended in drainage or contaminates ravines (Morelos Rinde Cuentas 2016).

In 2017, SAPAC invested nearly 40 thousand pesos in repairing hydraulic infrastructure to mitigate the damage caused by leaks. The amount is equivalent to repair 20 linear pipe network of 900 km existent; as a consequence, volume wasted was estimated at 51 million liters for each kilometer of the network, 2.3 times more than the national average (Morelos Rinde Cuentas 2018).

The lost volume is equivalent to 50% of water extracted, which implies to pump the required capacity twice, demanding a considerable amount of electrical energy, and let a poor distribution service. Based on this, clandestine connections amount 15% without charging (Morelos Rinde Cuentas 2016); 30,000 of these represent an illegal consumption that does not attribute any payment. SAPAC has been unable to locate all illegal connections, even though these generate increasing economic costs (Morelos Rinde Cuentas 2018).

23.3.2 Drainage System in Cuernavaca

Cuernavaca's drainage and eviction points are nearly 100% coverage, although the infrastructure does not guarantee an adequate treatment of urban sewage since this network operates by pipe transportation or drain channels, it pours such waste in some nearby natural runoffs, mainly ravines, see Fig. 23.4. Although this represents a risk to environmental balance and population health, in 11 years, Sustainable Development Secretary has not fined anyone for spilling wastewater to ravines, either municipal, domestic, or industrial. For its part, SAPAC has not invested in drainage infrastructure in the last four years (Morelos Rinde Cuentas 2018).

The average sanitation, drainage, or place of eviction is relatively high; they are distributed in different categories: 641 private dwellings do not have drainage infrastructure; meanwhile 28,744 discharge to a septic tank and 61,646 to a drainage infrastructure which means 63.66% of total dwelling (INEGI 2010b). This amount is considered in this paper for locating and estimating ravine's wastewater volume discharged in fieldwork.

In order to identify discharges registered by the SAPAC (Potable Water System and Sewer System of Cuernavaca), was used cadaster of the municipality sewerage network each one of them was georeferenced and integrated into a gradient analysis (SAPAC 2008). As the main result, 311 discharge points were found in the nearest

Fig. 23.4 Discharge points in ravines. Photograph from the author 2018

ravine. These discharge points were categorized by land use, considering its population density or commercial and industrial activities, see Table 23.2 and Fig. 23.5.

Discharges of wastewater are considered a risk to the health of the inhabitants when they are poured in the surface water bodies. Information about the location of the points of discharges allows correlating both variables, pollution, and socioeconomic condition territory, which are social vulnerability determinants, particularly in dwelling nearby, principally are irregular settlements, without any treatment capacity and with higher morbidity, see Fig. 23.6.

Figure 23.6 shows a 311 Cuernavaca's discharge points distribution related to a marginalization degree, which is based on the index of the National Population Coun-

Table 23.2 Characteristics of land use in Cuernavaca used for the analysis of discharge points

Key	Land use	Density (hab/ha)	Lot type (m^2)	Discharge point	Territorial expansion (m^2)	% Territorial
C	Commercial	0	0	5	478,059	0.6339
CU	Urban center	0	0	11	1,565,433	2.075
H05	Residential	0 a 50	1000	34	21,398,195	28.377
H1	Residential	51 a 100	500	32	11,087,138	14.7031
H2	Residential	101 a 200	250	221	39,012,571	51.7363
H4	Residential	201 a 416	120	6	861,467	1.1424
H6	Residential	417 a 600	Multifamily	2	1,003,615	1.3309
Total				311	75,406,478	100

Elaborated with data from an urban map of Cuernavaca and SAPAC (2008)

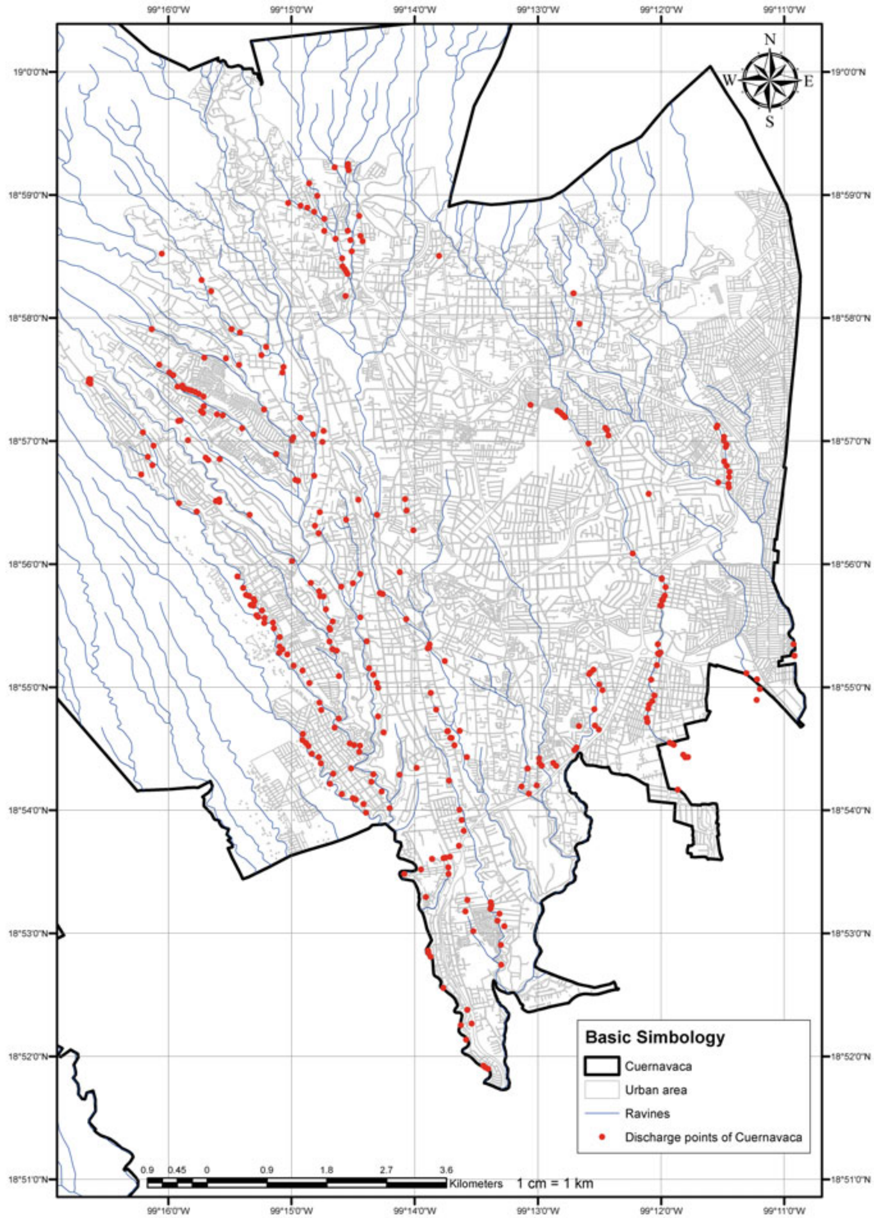

Fig. 23.5 Discharge points of residual water from the public network. Own Elaborating and analysis with data from SAPAC (2008)

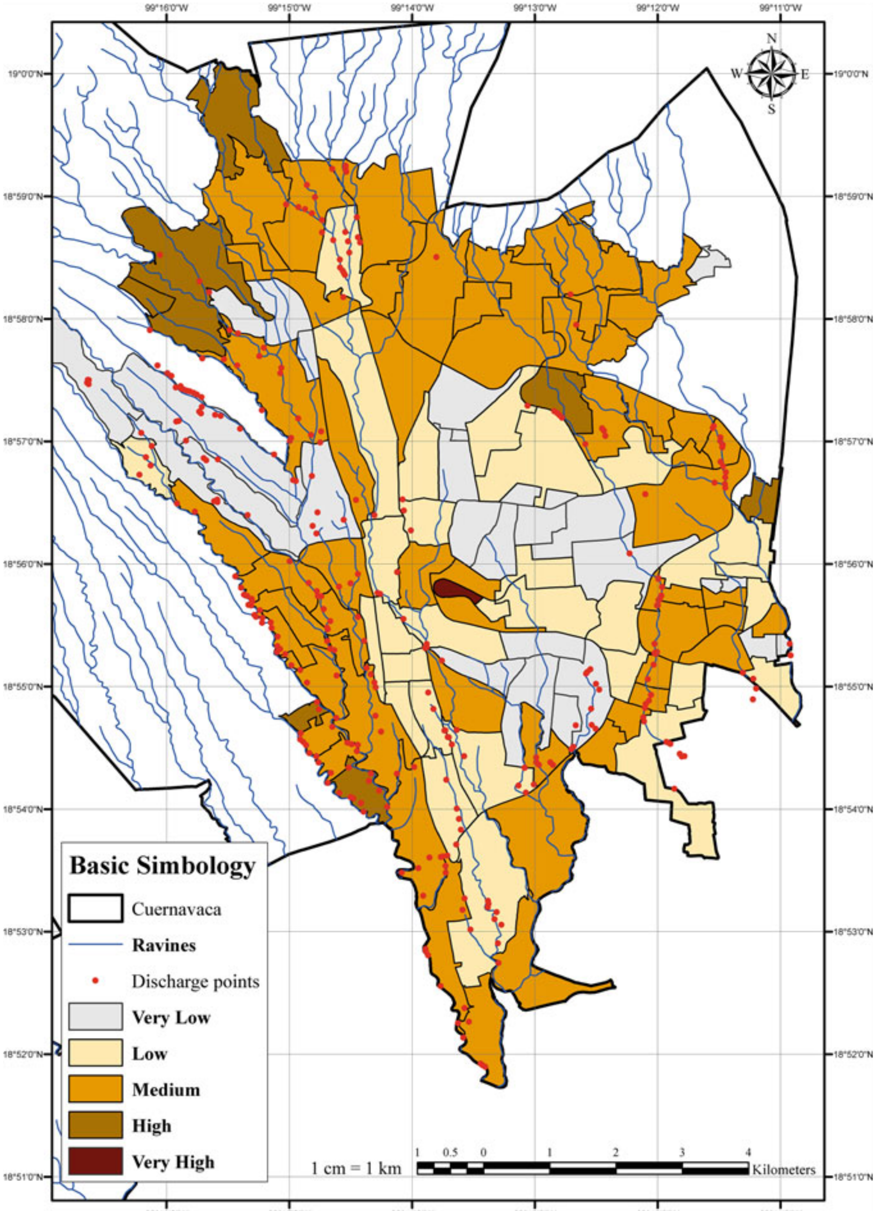

Fig. 23.6 Marginalization degree by AGEB and wastewater discharge points. Elaboration based on CONAPO (2010) and SAPAC (2008)

Table 23.3 Discharge points and dwellings by the degree of marginalization. Elaborated with data from CONAPO (2010) and Gobierno del Estado de Morelos and Gobierno municipal de Cuernavaca (2018)

Marginalization degree	Dwellings	% equivalent (%)	Discharge points	% equivalent (%)
Very high	0	0	0	0
High	12,002	3.48	20	6.43
Medium	160,956	46.80	167	53.69
Low	93,615	27.22	59	18.97
Very low	58,204	16.92	65	20

cil (CONAPO 2010), varying from ranges between "Very low" and "Very High," considering ten indicators. This territorial analysis demonstrates an AGEB (Basic Geostatistical Area) dwelling condition related to the degree of marginalization and low population quality of life, even more, if they are directly or indirectly in contact with discharge points or contaminated ravines. The worst conditions include perceiving bad smell, visual condition, and proximity to discharge points, making them susceptible to possible diseases, see Table 23.3.

Outstanding data reveal that 40% of the discharge points are distributed in places under conditions of low and very low marginalization. The AGEBs (Basic Geostatistical Area) with "very high" marginalization does not refer to any local discharge points; that is, there are none of these georeferenced sites. In the middle marginalization category, there are 167 discharge points equivalent to 53.69% of the total.

In summary, 60% of discharge points are in marginalization ranges from "medium" to "high," which are characterized as limited access to education, health, adequate housing habitat, basic services, and availability of essential goods, among the most important. Also, the remaining 40% is located between the "very low" and "low" range, where people are less vulnerable in socioeconomic terms. In general, the wastewater discharges are located in almost all the marginalization ranges, without any treatment systems. However, circumstances cause differentiated effects depending on its particularly harmful in "high," and "medium" marginalization degree, where people do not have the same ability to resilience as those with less degree of marginalization.

23.4 Residual Effluents Measured from the Discharge Points

Cuernavaca's ravines and rivers have become the primary vector and natural forms of sewage effluents storage, which undoubtedly represent a severe problem for the use of the resource and consequently an impact on the people's quality of life. Multidimensional background of water impacts is due to increasing services and domestic consumption that represents a higher effluent volume, and a minor degradation and recovery capacity of the rivers and ravines (Batllori 2001).

Urban effluent information refers particularly to that concentrated in the municipal treatment plants or to that coming from regularized urban land, leaving aside the partial sources discharges. A representative statistical sample of the discharge points is proposed, regardless of their regularization status, and to estimate the total volume generated in the municipality. The statistical representation of the sample is calculated by Eq. 23.1:

$$n = S^2 / \left(\frac{\varepsilon^2}{Z^2} + \frac{S}{N} \right) \tag{23.1}$$

where N is the size of the population (311 points); n is the necessary size of the sample; Z level of confidence (1.96); Ɛ sample error (0.1); S standard deviation (0.50), (Cantoni and Nélida 2009).

It should be noted that this representative statistical sample has a confidence factor of 1.96, which is mainly used for social studies; at the same time, error level is 0.1, depending on the land uses that discharge the polluting effluent into the ravines (Cantoni and Nélida 2009).

Seventy-four discharge points are estimated, considering the representative statistical sample of its distribution, according to seven land uses identified in the "Population Center Urban Development Program (PDUCP)" (Gobierno Municipal de Cuernavaca 2016–2018). Points were selected randomly of 311 at a raffle, in order to choose the sample to calculate the generated flow, see Fig. 23.7.

It should be noted that a minimum precaution system was implemented in order to avoid any wastewater contact and reducing disease risks; in methodological terms, a team of mouth covers was taken, as also along latex gloves, antibacterial gel, knee boots, and a liquid sterilizer. At the same time, identification measures were implemented such as badges with corresponding logos and team member's names, as well as work vests to achieve distance identification, generating trust among the residents.

The effluent calculation was made in situ, using a volumetric method, also called gravimetrically, that is a volume account or mass per unit of time, see Eq. 23.2:

$$Q = V/t \tag{23.2}$$

where Q is the flow or expense; V volume (liters); t is time (seconds) (Aguilar 2017).

This field method is considered efficient and is even based on ISO-8316: 1987 and ISO/TR 11330: 1997 (Aguilar 2017). There is a range of methods that allows calculation of the flowing including area, speed, regime change, section slope, vortex, diffusion, hydrodynamic thrust, jets, or gates. Because of its efficiency, the volumetric method was chosen; its lower cost is essential also, but above all, it was adjusted to the project's needs. For this research, 20 L graduated vessel was fitted with a 1.5 m extension of wood and a stopwatch, in order to make the relation between volume and time (L/s).

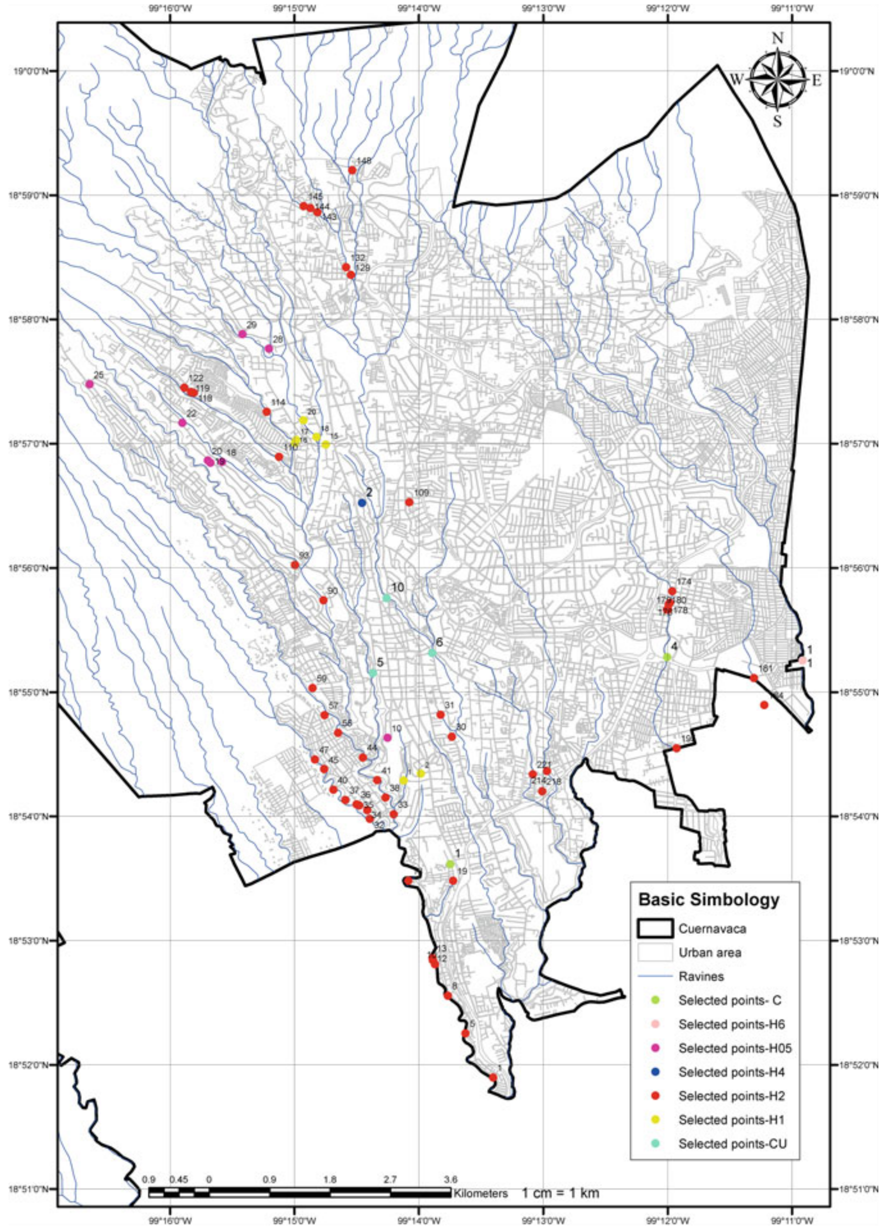

Fig. 23.7 Randomly selected points for estimating the volume generated in L/s. Elaborated with author data, 2018

Also, each calculation was made in two parts of the day (morning and afternoon) and three times for each point and after that an average was calculated. It is worth mentioning that every sample randomly selected was between January and February of 2018 made, trying to evade the rainy season, since wastewater system is also connected to the stormwater network and would skew the sample of flow, see Fig. 23.8.

Obtained sample data reflect that land uses with a significant contribution of residual water are H2 with 84.64 L/s; CU 11.69 L/s, H1 8.134 L/s, and H6 6.88 L/s. Land uses that generate a less volume are C (commercial), H05 and H4, with 3.11, 2.426 and 1.458 L/s, respectively, see Fig. 23.9.

Sampled points accumulate 118.34 L/s, which is distributed in 7 land uses mainly, corresponding to a quarter of total points recorded; as a result, 490.52 L/s are gen-

Fig. 23.8 Searching and measuring residual effluents. Photograph by the author 2018

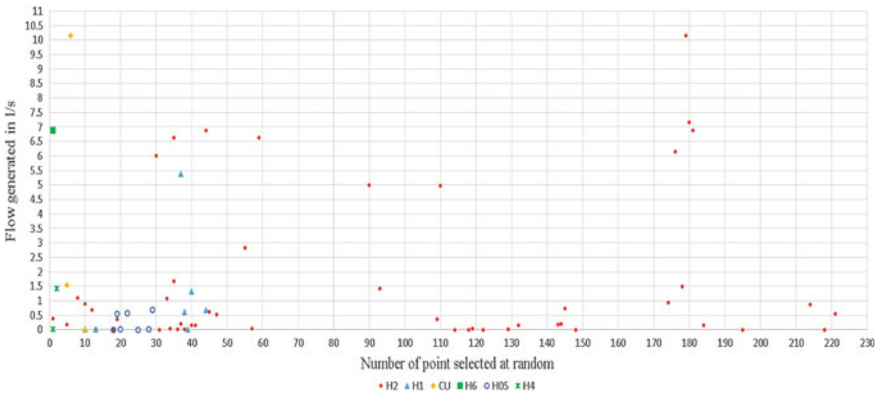

Fig. 23.9 Flow generated by land use and randomly selected point. Elaborated with author data, 2018

erated in Cuernavaca municipality, which means 15, 469,038.72 m^3 of wastewater per year. On the other hand, 70.82% of wastewater estimated is equivalent to volume extracted used in the city, see Table 23.4.

In this logic, we can mention that equivalence between actual water consumption and wastewater generated is about 71% of 21 million 844 thousand m^3 in the municipality; in other words, 7 of 10 L used became wasted. Insisting that these data belong only to the effluent of the municipal sewerage network, which is awarded only 64% of the total generated; that means 36% remains unanalyzed, which is lost in septic tanks or dwelling discharges to ravines.

The absence of wastewater treatment means in Cuernavaca that 1 of 4 treatment plants (National Institute of Statistics and Geography) doesn't work; service amount of three plants remaining represents about 20% of total volume generated, confirming that 80% of wastewater does not receive any treatment. On the other hand, SAPAC registers seven treatment plants of which five do work, and CEAGUA (State Water Commission) ensures that only one is in operation. As an annex, the three treatment plants in function, according to INEGI, discharge treated flowing to Apatlaco River, which is considered the most polluted in the Morelos State and it is also of the most polluted in Mexico.

Table 23.4 Equivalence between extracted water and wastewater generated

Type of consumption	Water		Sewage	Water
	millions of m^3	%	m^3	equivalent %
Real consumption	21,844,000	32		**70.82**
Water loss	40,000,000	59		38.67
Water pipes	6,000,000	9	15,469,038	257.82
Total consumption	67,844,000	100		22.80

Elaborated with data from Morelos Rinde Cuentas 2018 and author data, 2018

Fieldwork and visits reveal that in fact, there are seven treatment plants in Cuernavaca with different functions. In this regard, we have included our information to compare it with SAPAC's data and thereby provide the real picture of wastewater treatment locally, see Table 23.5.

Similarities between own information and those of SAPAC's are in Acapantzingo treatment plant, which is the only one within an urban area in operation. Also, treated and untreated waste are discharged in the same way to the ravines; in fact, the treatment plant located in Lomas de Ahuatlan only collects wastewater and serves as a storage medium, pouring it without any treatment. In synthesis, 80% of flow generated in Cuernavaca municipality does not receive adequate treatment, and it is indistinctly discharged at the nearest natural source, in ravines particularly. However,

Table 23.5 Treatment plants in Cuernavaca

	Wastewater treatment plant	Treated discharge (L/s)	Works?	Operated by	Final destination
SAPAC	Lomas de Ahuatlán	30	Yes	SAPAC	Ravine of "Ahuatlán"
	Lázaro Cárdenas	24	No	SAPAC	Apatlaco river
	Arboledas Chipitlán	7.5	Yes	SAPAC	Ravine of "Leyva"
	Lomas de Cortés	2.5	No	SAPAC	Municipal collector
	Buena Vista del Monte	1	Yes	SAPAC	Ravine of "Innominada"
	Zacatierra	4	No	SAPAC	Ravine of "El Salto"
	Loma Dorada	7	Yes	SAPAC	Ravine of "Amanalco"
	Acapantzingo	300	Yes	CEAGUA	Apatlaco river
Own	Lomas de Ahuatlán	0	No	SAPAC	Ravine of "Ahuatlán"
	Lázaro Cárdenas	0	No	SAPAC	Apatlaco river
	Arboledas Chipitlán	7	Yes	SAPAC	Ravine of "Leyva"
	Lomas de Cortés	0	No	SAPAC	Municipal collector
	Buena Vista del Monte	1	Yes	SAPAC	Ravine of "Innominada"
	Zacatierra	0	No	SAPAC	Ravine of "El Salto"
	Loma Dorada	0	Yes	SAPAC	Ravine of "Amanalco"
	Acapantzingo	300	Yes	CEAGUA	Apatlaco river

Elaborated with author data, 2018 and data from Morelos Rinde Cuentas 2018

20% remaining is treated and poured into ravines, contributing to water pollution cycle (Programa Estatal Hídrico 2014–2018).

23.5 Proposal for the wastewater Treatment System in Cuernavaca

Facing such lower wastewater treatment status has been directly a strategy of infrastructure expansion, however, and considering the own diagnosis over discharge points, there are some technical elements to add. General criteria include (a) the real possibility of total wastewater treatment; (b) the analysis of an available technology treatment strategy; and (c) the identification of qualitative conditions for installing particular treatment types and their corresponding distribution patterns. First, the effluents volume generated is about 15 million/m^3/year. Based on the sampled points, four generation ranges were classified, which go from 0 to 11 L/s; see Table 23.6.

In the first range, 50 discharge points are equivalent to 67% of the representative sample, but they poured only 10% of the total volume. On the contrary, rank number 3 with only 5 points generates 20.45% of this volume. The fourth rank compiles 57% of the total flow in only 9 points of discharge; in other words, with a few discharge points, ranks 3 and 4 accumulate about 80% of wastewater. In order to reduce the urban effluents contamination into city ravines, the wastewater treatment is necessary to consider. In this sense, a kind of treatment technology is suggested for attending the categorization above. Septic tanks are an efficient and relevant alternative because any discharge points do not generate a volume higher than 11 L/s.

Wells, tanks, and pits, also called septic tanks, are a primary treatment of wastewater technical elements; in general, they satisfy a capacity demand of 350 people maximum and are used in rural areas, but not for that discarded in urban areas. The primary objective of septic tanks is to create an environment of hydraulic stability, allowing treatment through primary processes, such as uptake and sedimentation. Commonly, the densest matter (mud) is converted into sedimented material and compacted in the bottom due to the volumetric weight of the water. The tanks could

Table 23.6 Flow distribution by ranges

Rank	Flow (L/s)	Points	Summa (L/s)	% total flow (%)
1	0 a 1	50	12.45	10
2	1.1 a 2	10	14.19	11.99
3	2.1 a 6	5	24.2	20.45
4	6.1 a 11	9	67.5	57.03
Total		74	118.34	100

Elaborated with collected data by the authors, 2018 be designed with one, two, or more chambers according to the effluent demand. It is estimated that this method has an efficiency of 80% for the elimination of solids and particles, depending on the size of the chambers, the resting time and its maintenance, which is low compared with large capacity treaters (Organización Panamericana de la Salud 2005).

Therefore, four prototypes of septic tanks are proposed according to the ranges and the needed capacities, which were calculated based on the guide for the design of septic tanks, Imhoff tanks, and stabilization ponds of the Pan American Health Organization. That ensures that the tanks are large enough for the accumulation of sludge and foams, preventing obstructions and ensuring adequate gas ventilation (Pan American Health Organization 2005). Prototypes for two different volumes can be seen in Figs. 23.10 and 23.11.

To specify the needs of technology, discharge points were georeferenced and matched to each prototype, considering its range of effluent generation. See Fig. 23.12.

For estimating economic feasibility for the treatment prototypes, a construction cost estimation was made, considering the effluent generation range, labor, weeding and clearing of the land, stroke and leveling, excavation, foundations, firms, walls, flat, carriers, slab, and sanitary installation. Labor costs were set based on the Mexico City unit price tab. However, it is necessary to adhere to an expansion factor, since all the points present challenges and have differentiated conditions. Economic treatment prototypes valuation by the suggested method is reflected in Table 23.7.

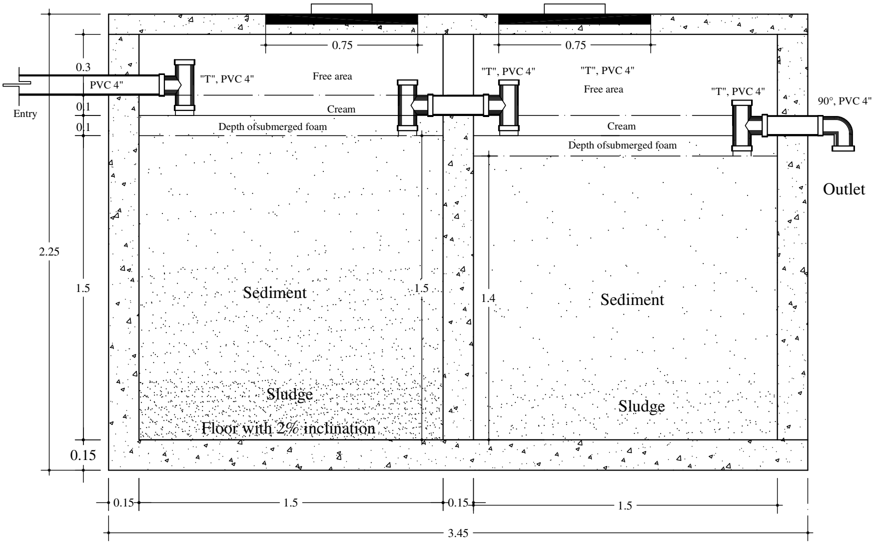

Fig. 23.10 Prototype of a septic tank for the discharge points of the first rank. Elaborated with data from the Organización Panamericana de la Salud (2005)

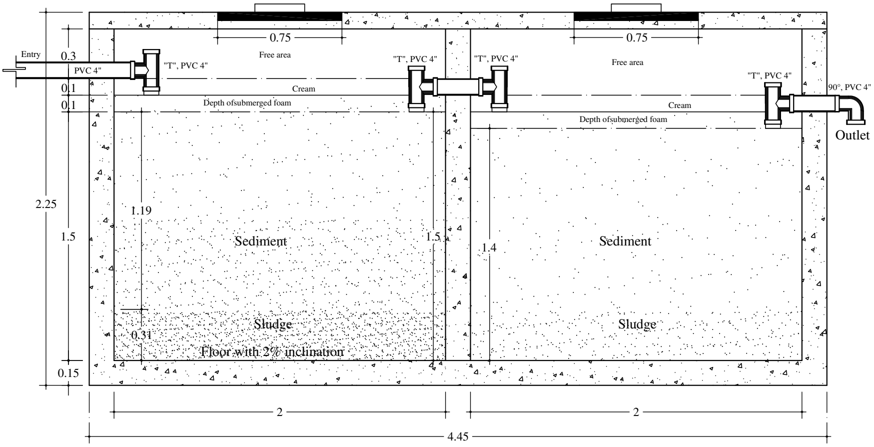

Fig. 23.11 Prototype of Septic Tank for the discharge points of the second rank. Elaborated with data from the Organización Panamericana de la Salud (2005)

In general, a prototype site in each of the 74 discharge points is estimated in 2 million pesos, equivalent to 20% of the Lázaro Cárdenas treatment plant cost (more than 10 million pesos), which is not in operation (CEAMA and Gobierno del Estado de Morelos 2006–2012). The total amount for 311 prototypes construction is about 10 million Mexican pesos. Therefore, the choice of a prototype would have a higher capacity volume and a lower cost, which represents precisely a viable proposal.

23.6 Preliminary Conclusions

The recent environmental crisis is related to water availability, as well as untreated and contaminated wastewater pouring. Its multidimensional effects are recognized in the southern hemisphere. The water availability and contamination affect people’s nutrition or health. On the other hand, recovery and water treatment conditions are inadequate and insufficient for municipal purposes in underdevelopment countries, which is about three times lower than those of its developed ones, with social and environmental impacts.

Notably, this evidence is not considered for effluent treatment. On the contrary, this is channeled through an infrastructure that directs it to natural sources only. At the same time, mitigation strategies for these impacts do not allow enough resources to address them. Morbidity increase implies a serious effect also, frequently identified in the highest rate of marginalization. In this sense, equipment and infrastructure to canalize, treat, reuse, or even recycle in poor conditions, as a consequence of the territorial expansion dynamics in underdeveloped cities, which cause unadvanced urban conditions with health or food crisis or even diseases treatment, implying costs

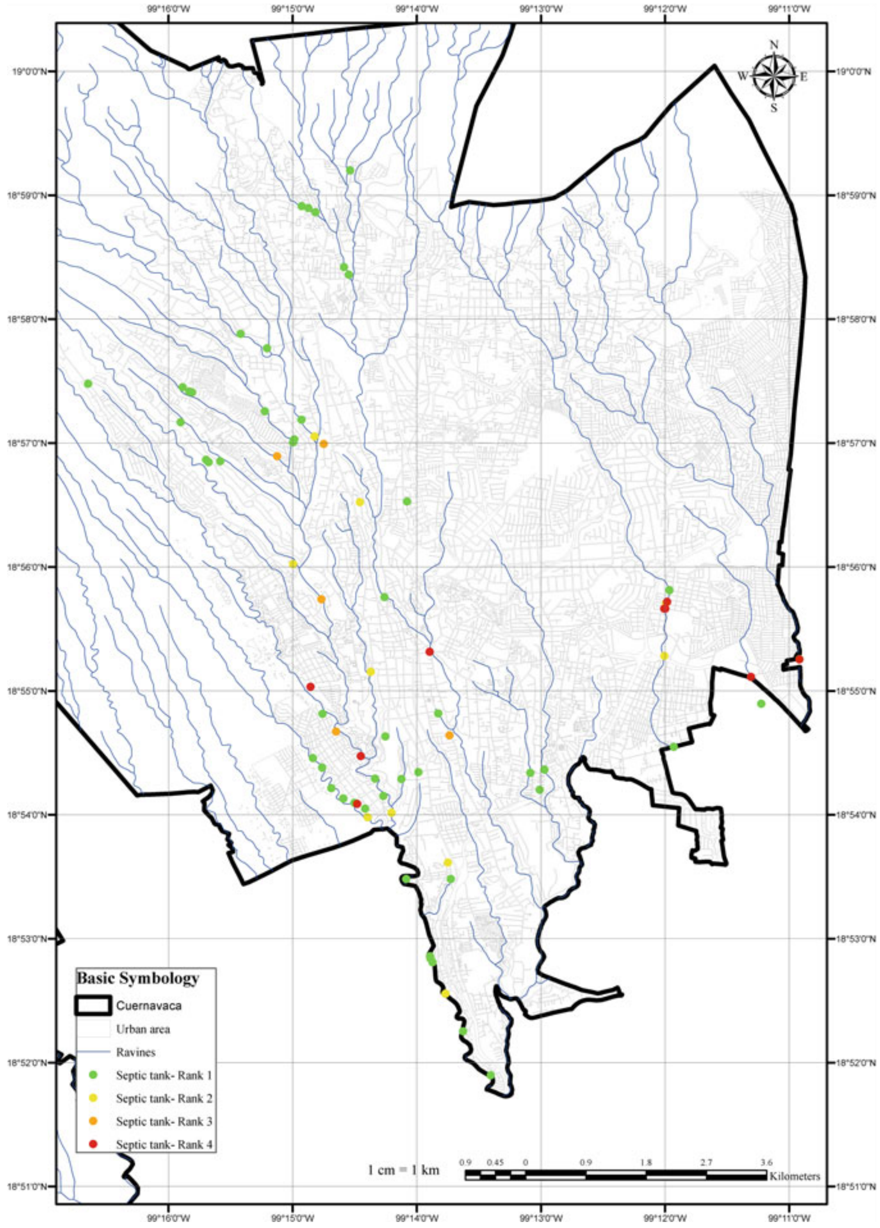

Fig. 23.12 Location for septic tank prototypes by rank. Own elaboration and calculation, 2018

Table 23.7 Estimated economic costs for wastewater treatment proposal

Rank	Necessary septic tanks	% Intervened flow (%)	Mexican pesos
1	50	10	901,963.42
2	10	11.99	270,405.30
3	5	20.45	277,049.74
4	9	57.03	889,313.57
Total	74	100	2,338,732.03

Elaborated with data of the Secretaria de Obras y Servicos de la CDMX, 2018

in private medical attention. Therefore, the review of sewage management capacity is central to face such imbalances.

In contrast with global wastewater treatment, a pollution diagnosis of surface water sources in Cuernavaca was made, and there is still an insufficient coverage for urban wastewater respect to the generated volume; such situation is similar in national terms. In this sense, the volume poured into the ravines is estimated over 15 million m^3/year, equivalent to 70% of the water extracted-consumed, locally. Those facts could be mitigated.

Although there is a public collection net for wastewater, it does not have treatment to avoid contamination when are poured into the natural effluents. Despite the lack of treatment recognition, it is possible to observe that institutions have not played a responsible role in the management and care of the resource. On the contrary, public policy refers only to the good in aspects of water distribution, as extraction and utilization stages, and not its wastewater disposal, that means recycling, reuse, or recovery which are not considered.

Although there is drainage infrastructure, it works only as a transporting mean that channels wastewater directly to some natural source, in Cuernavaca's circumstances, affecting its ravines as a common practice and the increased cost of treatment is not considered. Therefore, there is all kind of effects in environmental and human health terms, exacerbating vulnerable sectors.

As a result of this inquiry, proper treatment of residual effluents must be addressed before discharging it in natural resources, so increasing coverage of treatment plants seems like a fair possibility. The Cuernavaca's rugged topography hinders the construction of a single network that directs urban waste to treatment plants. Hence, the importance of this work, since pollution in Cuernavaca ravines is likely to be addressed as a result of the analysis of the 74 points selected in the representative sample, but there are 311 of the cities.

Based on public or independent treatment measures or technologies for generated flow are proposed, since they show a local and achievable strategy, considering its precise location and socioeconomic circumstances and volume effluent generated. An educational policy or specific urban regulations in urban programs are both central to completing a multidimensional strategy, in which an environmental prevention scheme is addressed from the very preparation of urban infrastructure, that is, with projects that result of scientific methodologies, that can interpret effects in the social and economic terms, and thereby reduce urban agglomeration conflicts.

Finally, it is possible to observe that strategies can be differentiated, particularly for treatment plants which are assumed recognizes economic conditions of local society, with inherent structural disparities including the absence of effluents treatment and their consequent health impacts. The review of technical solutions to mitigate pollution implies, in the light of the evidence, integrating economic perspectives that account for its polarization circumstance; determining its implementation requires a balance between these elements and its correspondent social participation. Otherwise, the 80% paradigm without treatment brings negative impacts on the population in underdeveloped regions.

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Correction to: Water Availability and Management in Mexico

Elena María Otazo-Sánchez, Amado Enrique Navarro-Frómeta and Vijay P. Singh

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In the original publication of this book, the volume number was incorrect. It should read “88” instead of “999”. This has now been corrected.

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