6

Water availability, rivers and aquifers

Water is one of Mexico's most vital natural resources. Mexico's water resources include its east and west coastlines as well as its interior freshwater rivers, lakes and aquifers. Mexico's long seacoast strongly affects its climate and is basic to its shipping, fishing and tourism industries. Freshwater resources are essential to agriculture, industry and electricity generation as well as household and commercial activities. Furthermore, coastal and interior water resources are essential to Mexico's ecology and natural environment.

Coastal resources

Mexico's 9330-km coastline is the longest in Latin America. About two-thirds of the coastline is on the Pacific Ocean and the remaining third is on Gulf of Mexico and the Caribbean Sea.

A long coastline facilitates shipping if adequate harbors are available. Unfortunately, there are relatively few good natural harbors in Mexico. Along the Gulf coast, only the Laguna de Tamiahua, south of Tampico, and some small islands at Veracruz provide adequate natural harborage. On the west coast where the mountains plunge into the Pacific Ocean, there are better natural harbors such as those at Acapulco, Manzanillo, Topolobampo and Ensenada. Some potentially good west coast natural harbors, such as Magdalena Bay and La Paz in Baja California Sur, are quite isolated and therefore inconvenient for large scale shipping. Because of its lack of good natural harbors, Mexico has had to construct and dredge numerous harbors such as those at Lázaro Cardenas and Mazatlán. The five largest ports—Tampico and Veracruz on the Gulf as well as Guaymas, Mazatlán and Manzanillo on the Pacific—handle about 80% of Mexico's ocean freight.

Mexico's long coastline supports an enormous and rapidly growing tourism industry (see chapter 19). The biggest coastal tourist destination is the Maya Riviera extending south from Cancún almost all the way to the border with Belize. Pacific resorts include Acapulco, which has been popular for many decades, as well as rapidly growing newer resorts such as the southern tip of the Baja California peninsula around Cabo San Lucas, Mazatlán, Puerto Vallarta, Zihuatanejo-Ixtapa and Huatulco.

Mexico's coasts are also valuable for fishing (see chapter 15). The cold California Current carries plankton and other nutrients southwards along the western side of the Baja California Peninsula. These nutrients provide abundant food for marine life. In addition, the warmer water of the Gulf of California is rich with nutrients and marine life. Mexico's four northwest coastal states produce almost 60% of Mexico's total fish catch with Sonora alone contributing about 25%. The most important commercial fish in these states are shrimp, tuna and sardines. States along the Gulf of Mexico fish primarily for shrimp, carp and oysters. The seasonal migration of whales along the Pacific coast is a valuable resource for tourism.

Freshwater availability in Mexico

Mexico's freshwater resources are a function of rainfall, sun intensity and topography as well as vegetation and soil conditions. Though parts of northern Mexico are arid, the country as a whole receives an average of 760 mm of precipitation a year (slightly over 30 in).[1] This is a considerable amount, more than that received by either Canada or the USA (Table 6.1).

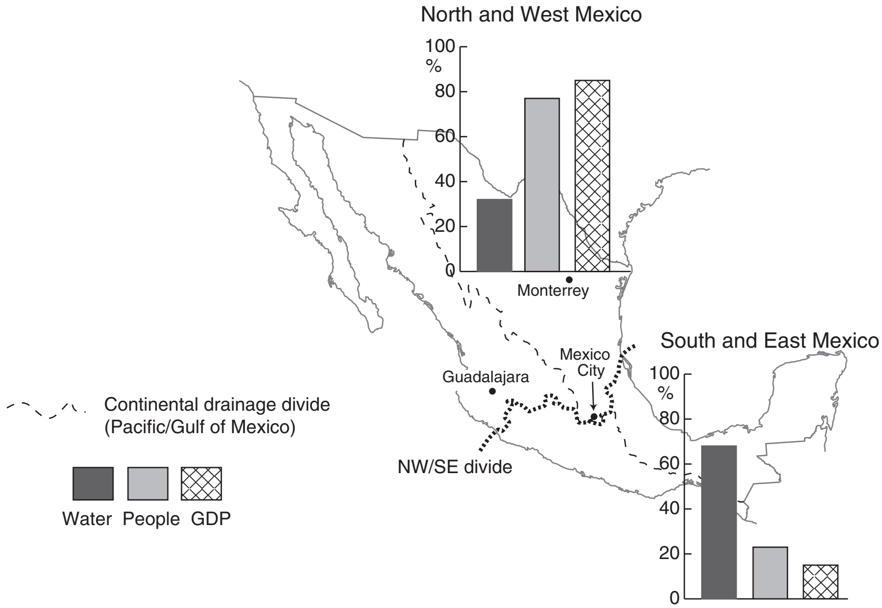

Figure 6.1 Mexico's north–south divide: water, people and GDP

It is customary to distinguish between economic water scarcity and physical water scarcity. Economic water scarcity exists when people do not have the necessary economic means to access an adequate supply of water. This is the case for much of sub-Saharan Africa, but economic water scarcity is rarely found in Mexico. Physical water scarcity exists where physical access to water is limited and when demand outstrips the natural supply. Northern Mexico suffers from physical water scarcity. Physical scarcity can result directly from human activity. For example, overuse of water in the Colorado River basin in the USA means that very little water now reaches the increasingly saline delta area in Mexico.

While Mexico as a whole gets enough rainfall, the main problem is geographical distribution. Relatively sparsely populated southern Mexico gets by far the most rain and therefore has the greatest water availability. The north, particularly the northwest, is very dry. Temporal distribution and variability exacerbate the problem; 77% of total rainfall occurs between June and October. Rainfall in heavily populated central Mexico is about the national average (772 mm); however, this region is quite dry between November and May. Regions with lower rainfall totals tend to experience higher year-on-year variability.

It is worth noting that 73% of Mexico's rainfall either evaporates directly or evapotranspirates through plants. About 25% runs off into rivers and lakes. Only roughly 2% seeps down to recharge subterranean aquifers.[2]

The spatial distribution of population and economic activity exacerbates problems of rainfall distribution. In short, too many people live in areas where there is too little water. South and southeastern Mexico (Figure 6.1) receive 68% of the rainfall but have only 23% of the population and produce only 15% of the gross domestic product. On other hand, the rest of Mexico receives only 32% of the rainfall but has 77% of the population and 85% of economic production. The problem is getting worse because the most rapid population and economic growth is in the north, the driest part of the country.

For the country as a whole, on average there are roughly 4300 m^3 of runoff per person. (Table 6.1) In terms of per person water availability, the Lerma basin between Mexico City and Guadalajara (Figure 6.3) has only about one-third of the national average while the very heavily populated Valley of Mexico, containing the Mexico City Metropolitan Area, has only one-thirtieth of the national average.[4] On the other hand, the basins in the southeast receive many times the national average.

Availability of water per person is a function of population size and the total amount of water available. Though Mexico gets more rain than the USA

Table 6.1 Water in Mexico compared to other countries[3]

	Canada	Brazil	USA	Mexico
Average precipitation (mm/yr)	537	1 782	715	760
Available water (m³/person/yr)	84 500	37 300	7 100	4 300
Water consumed (m³/person/yr)	1 472	336	1 647	759
Agricultural land total (millions of hectares)	67.6	66.6	175.5	27.3
Irrigated land	0.8	2.9	21.4	6.5
% irrigated	1.2	4.4	12.2	23.8
Water footprint (m³/person/yr)	2 049	1 381	2 483	1 441

or Canada, the availability of water per person in Mexico is only one-twentieth that of Canada and slightly more than half that of the USA because Mexico's population density is far higher. In other words, though each square kilometer in Mexico receives more rain on average, that rain must be divided among more people. Of 177 countries analyzed by the FAO, Mexico ranked 90th in terms of water availability per person.[6] However, if Mexico is divided into two zones, the south would rank 51st and the north would rank 131st.

Mexico's per person consumption of water is about half that of Canada (Figure 6.2) but with proportionately more allocated to agriculture. Nationally, about 75% of water consumption is used in agriculture while settlements and industry use about 17% and 8% respectively.

Rivers

Mexico does not have a large, important navigable river such as the St. Lawrence, Mississippi or Rhine. Rivers had only a minor influence on the pattern of Mexico's historical development. In contrast, the pattern of development of the USA was strongly influenced by such large navigable rivers as the Hudson, Ohio, Mississippi and Missouri.

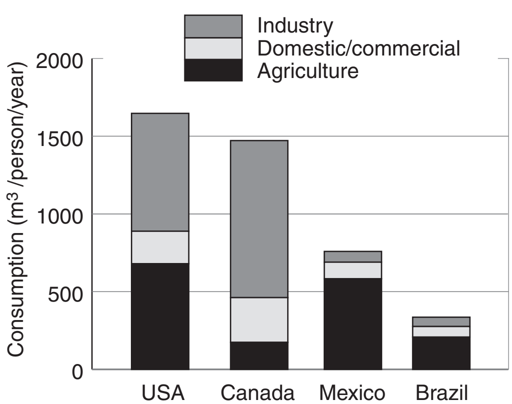

Figure 6.2 Consumption of water[5]

In looking at the size and importance of rivers there are three interrelated dimensions of particular interest: the river's length, the size of its basin or drainage area, and the amount of water that it carries (discharge) which can vary enormously from season to season as well as from year to year. Most atlases and almanacs list river sizes only by length. The Nile is the world's longest river, but the amount of water entering the sea from the Amazon River is about 10,000 times greater than that from the Nile.

Table 6.2 and Figure 6.3 show the locations and basic characteristics of Mexico's major rivers. The total amount of water that annually flows in Mexican rivers is roughly 410 km³, about 25% more than the St. Lawrence River. It is about 25% less than the flow in the Mississippi River which has a drainage basin 65% larger than all of Mexico. Consistent with rainfall patterns, the largest river flows are in the sparsely populated south.

Since Mexican rivers are used very little for transport, river length is not particularly relevant except in so far as it relates to levels of pollution or reliability of flow. The two rivers in Mexico that are the longest and have the largest drainage basins start in the US state of Colorado.

The first is the Río Bravo, known as the Río Grande north of the border, which is the longest at about 3000 km (1900 mi). It forms the border between Mexico and the USA for about 2000 km (1250 mi). It is considered Mexico's longest river. Though it drains about a quarter of Mexico's total area, its drainage basin is arid and its total flow is less than 2% of Mexico's total. The other is the Colorado River (Río Colorado), which flows almost entirely in

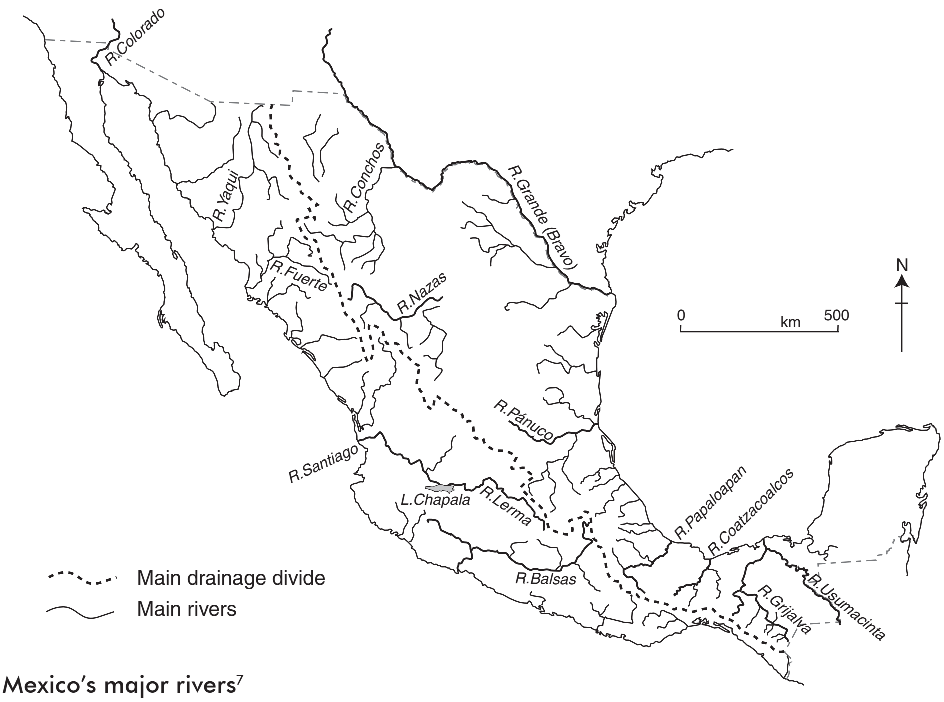

Figure 6.3 Mexico's major rivers[7]

the USA. These two very long rivers contribute very little to Mexico's water resource.

The Río Colorado formed a vast delta in the otherwise arid Sonoran desert in northern Mexico where it enters the Sea of Cortés (Figure 6.4). The delta wetlands created ideal conditions for a rich variety of wildlife. The river enters Mexico at the Southerly International Boundary where a gauging station records the river's discharge (Figure 6.5). This river is one of the most altered river systems in the world. The amount of water reaching Mexico has declined dramatically as a result of the Hoover and Glen Canyon dams and other diversions of Colorado River water in the USA. The few years of higher flows in the 1980s coincide with flood releases from US dams when they had been filled by heavy rains.

The river's drastically reduced annual discharge violates a 1944 treaty under which the USA guaranteed that at least 1750 million cubic meters would enter Mexico each year via the Morelos diversionary dam in the Mexicali Valley. The Río Colorado wetlands have been reduced to about 5% of their original extent, and the potential water supply for the rapidly-growing urban centers of Mexicali, Tijuana, Tecate and Rosarito has been compromised.

Mexico's six largest rivers account for over 60% of Mexico's total river discharge. Interestingly, the Mexican river with the greatest flow, the Grijalva–-Usumacinta, does not start in Mexico either. The river has a double name because it is actually a double river, with two branches of similar length that both start, about 120 km (75 mi) apart, in Guatemala. Each branch flows about 750 km (465 mi) through Chiapas before they unite in Tabasco about 25 km from the Gulf of Mexico. The Usumacinta forms the border between Mexico and Guatemala as well as the border between the states of Campeche and Tabasco. Each of the two branches has a flow of about 14% of Mexico's total. The flow of the combined Grijalva–Usumacinta River is about twice that of the Missouri River in the USA. They drain areas in Guatemala and the states of Chiapas, Tabasco and western Campeche which annually receive over 2500 mm (100 in) of rain.

There are several other important Mexican rivers. The Lerma River starts in the State of Mexico and flows westward into Lake Chapala and continues to the Pacific Ocean with the name Santiago. The Lerma–Santiago River system is about 930 km (855 mi) long and thus is the second longest after the Río Grande. It is the longest river entirely in Mexico. It drains about 6% of Mexico. The Lerma–Santiago, which flows through several states, is one of the economically most important rivers in Mexico because it feeds some of the country's prime agricultural areas as well as the two largest metropolitan areas:

Table 6.2 Mexico's major rivers[8]

River	Source	Outflow	Basin area	Length	Discharge	
			km² x 10³	km	m³ x 10⁹	% of total
Colorado						
(a) pre Hoover Dam (1934)	Colorado, USA	G. of California	615	2730	20	4.9
(b) post 1934			615	2730	2	0.5
Río Bravo (Río Grande)	Colorado, USA	Gulf of Mexico	840	3000	7	1.7
Lerma–Santiago	State of Mexico	Pacific Ocean	124	927	8	2.0
Balsas	Tlaxcala	Pacific Ocean	117	770	24	5.9
Grijalva–Usumacinta	Guatemala	Gulf of Mexico	84	766	116	28.3
Papaloapan	Oaxaca	Gulf of Mexico	47	540	45	11.0
Pánuco–Tamesi–Moctezuma	Puebla, Hidalgo, San Luis Potosí	Gulf of Mexico	85	680	19	4.6
Coatzacoalcos	Oaxaca	Gulf of Mexico	17	332	34	8.3
Fuerte	Chihuahua	Pacific Ocean	34	540	5	1.2
Yaqui	Sonora	G. of California	73	740	4	1.0

Mexico City and Guadalajara. However, its flow is quite small, only about 2% of the national total.

The Balsas River, which enters the Pacific well to the south of the mouth of the Lerma–Santiago, is the third longest at 840 km (520 mi) and has the third largest basin. Though its flow is about three times that of the Lerma–Santiago and offers white-water rafting opportunities, it is not as important economically.

Three major rivers flow into the Gulf of Mexico through the state of Veracruz. The Rivers Papaloapan and Coatzacoalcos start in Oaxaca and flow through southern Veracruz. Their combined flow is nearly 20% of the national total. The Pánuco–Tamesi–Moctezuma River system starts in the State of Mexico and carries nearly 5% to the Gulf of Mexico at Tampico.

There are numerous rather long rivers that flow west to the Pacific from the Western Sierra Madre, but these have relatively little water. There are also several rather long rivers such as the Nazas that flow into landlocked basins and either die or feed small drying lakes. The marked contrast in most of Mexico between a winter dry season and summer rainy season means than many streams do not flow year round but are intermittent. Their steep-sided wadi-like valleys, dry most of the year, may only carry a significant quantity of water occasionally, following heavy and prolonged rain perhaps many kilometers away. These

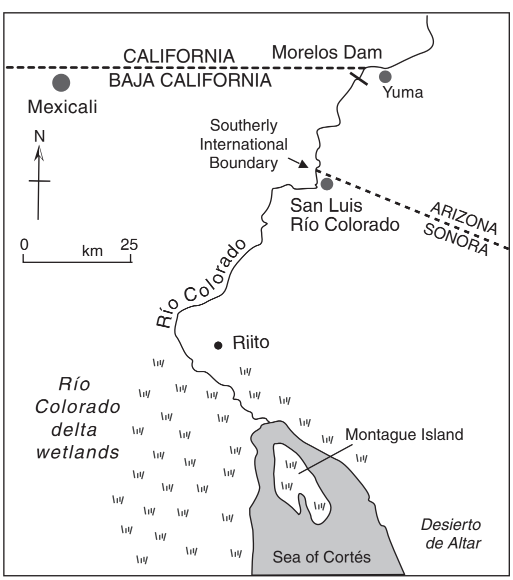

Figure 6.4 Map of the Río Colorado delta

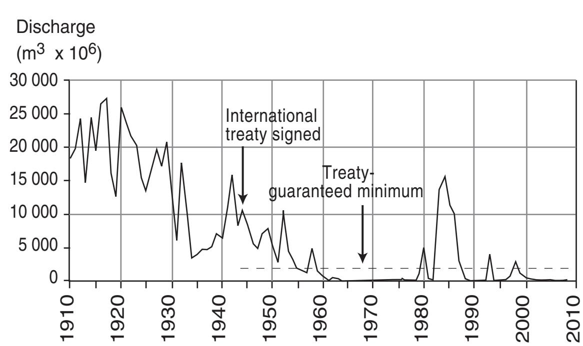

Figure 6.5 Río Colorado discharge entering Mexico[9]

channels may fill within hours during low frequency but high magnitude flash flooding events.

Drainage patterns influence how rapidly water is transferred through a river basin and therefore affect the degree of variability of a river's discharge. With a dendritic (tree-like) pattern, typical of drainage basins that are roughly circular in shape, peak water discharges tend to be much higher than with drainage patterns comprised mainly of parallel rivers in elongated basins.

Mexico has examples of almost every conceivable kind of drainage pattern. The numerous branching tributaries of many larger rivers form classic dendritic patterns. Parallel drainage patterns are found on many parts of the steep western side of the Western Sierra Madre. Radial drainage is common on volcanic cones. Endoreic drainage exists in the closed basins of semi-arid northern Mexico. A confusing network of distributaries and braided channels characterizes the Grijalva basin in Tabasco. Karstic patterns with sinkholes and subterranean channels can be found in the Yucatán Peninsula.

Almost half of the water in Mexican rivers is used for productive purposes, primarily for hydroelectric power. Mexico's dams have an installed capacity of about 11 gigawatts of electricity, roughly one fifth of the country's total generating capacity; they don't operate at full capacity, so they only generate about one eighth of the nation's electricity. While only about a fifth of the total river water is consumed for other productive purposes, this proportion is far higher for rivers in the drier northern part of Mexico.

Lakes and reservoirs

Mexico's natural lakes are small in total volume and relatively few in number as a result of its mountainous terrain and very diverse rainfall pattern. The great internal basin between the Western and Eastern Sierra Madres would form a gigantic lake if rainfall was more abundant. However, with scarce rainfall and a dry climate, the little rain that does fall tends to evaporate quickly. Consequentially, there are virtually no natural lakes in the great Mapimí basin of northern Mexico.

Where rainfall is very abundant, in the south, the terrain is quite steeply sloped. The rainfall rushes down these slopes to the sea. Mexico's natural lakes are small in comparison to man-made reservoirs that have formed behind dams. Of Mexico's fifty largest internal bodies of water, in terms of volume, only three are natural lakes. The volume of water in Mexico's natural and man-made lakes varies enormously

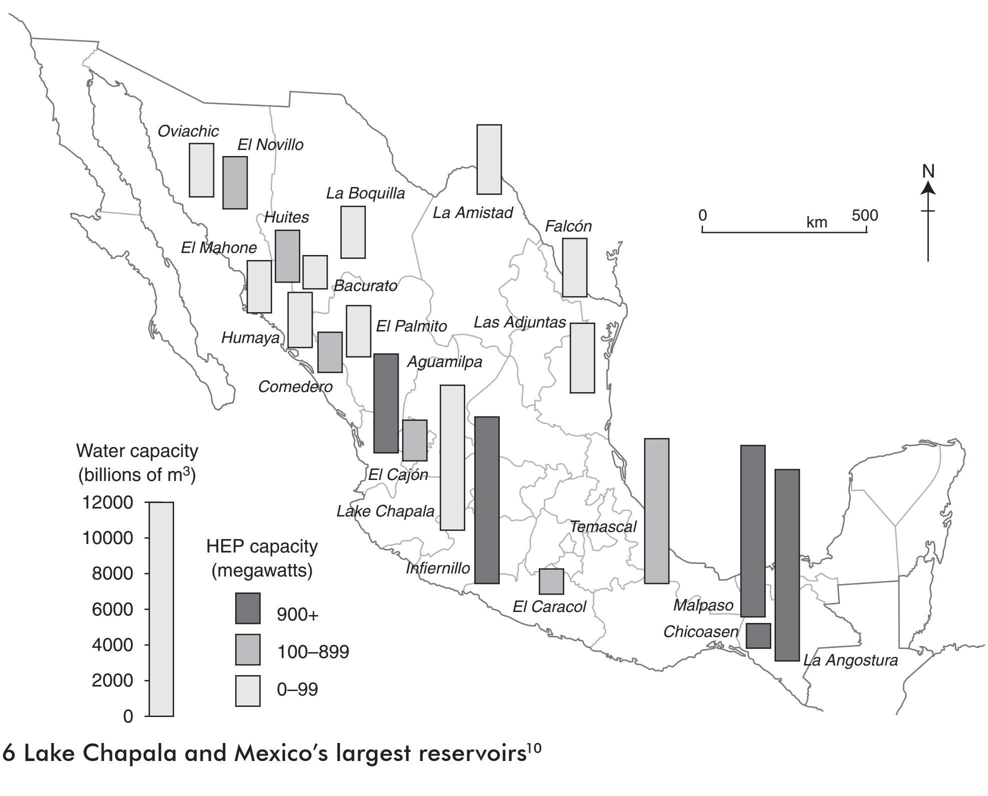

Figure 6.6 Lake Chapala and Mexico's largest reservoirs[10]

The Enchanted Lake[11]

The beautiful crater lake of La Laguna Encantada (The Enchanted Lake) in Veracruz rises every dry season but falls again during the rainy season. This lake is near Catemaco (better known for its witches) in the Tuxtlas region of the state of Veracruz. Did one of the witches cast a spell on the lake, making its level change out of synchronization with all the other lakes in the country?

The lake has a circumference of about 1500 m (slightly under one mile) and nestles on the southern flank of the 1400-m-high San Martín Volcano.

The basaltic lavas and layers of ash forming the volcano are highly permeable and porous. As a result, despite the heavy rainfall, there are no permanent streams flowing down its upper slopes.

Some distance away from the volcano, though, there are several good-sized lakes including Catemaco and Laguna Encantada. Catemaco is large enough to capture plenty of rainfall to maintain its level. Laguna Encantada's much smaller basin, however, does not receive enough rain to keep its level high.

Instead, most of La Laguna Encantada's water supply comes from underground. Water that falls on the slopes of the San Martín volcano during the rainy season soaks into the ground and then percolates so slowly towards the lake that it takes six months (or perhaps 18 months?) to reach it.

The result? The lake is unable to sustain its level during the rainy season, but the underground water reaching it every dry season is more than sufficient to replenish its level. Maybe the witches of Catemaco have something to do with it, but hydrology also plays a part!

from season to season and even more from year to year. The capacities shown in Table 6.3 are maximum values; in virtually all cases the amount of water actually present at any given time is far less.

Lake Chapala, straddling the boundary between the states of Jalisco and Michoacán, is the largest natural lake. It is surpassed in volume of water by four or five man-made lakes (Figure 6.6). In 2008, Lake Chapala appeared virtually full but still contained only about half of its "official" capacity (see chapter 7 and Figure 7.1). The amount of water in the second largest natural lake, Cuitzeo, in Michoacán, is surpassed by more than twenty-five man-made reservoirs. The third largest natural lake, Pátzcuaro, also in Michoacán, is surpassed by over thirty reservoirs.

Mexico's dams and reservoirs serve many valuable functions. The amount of power that can be generated is a function of the amount of water streaming through the generators and its pressure, which is related to the height of the dam. Just over half of hydroelectric power is generated by dams on rivers which start in southern mountain ranges and flow into the southern portion of the Gulf of Mexico (Figures 6.6 and 16.2). Most of the rest comes from dams on rivers along the Pacific coast from the Balsas basin all the way north to Sonora.

Virtually all Mexican dams, except those in the rainiest southern areas, provide water for irrigated agriculture. This is particularly true in arid northern Mexico. Mexico ranks sixth in the world with about 63,000 km^3 of irrigated agriculture. It is well behind India (558,000), China (546,000), the USA (224,000), Pakistan (182,000) and Iran (76,500). About 23% of Mexico's cultivated area is irrigated, compared to 99.9% in Egypt, 82% in Pakistan, 47% in China and only 12% in the USA.

Dams also protect against floods, especially in the drier northern areas which are very susceptible to floods from rare but torrential downpours. In addition, dams provide a source of water for urban populations, especially in the largest metropolitan areas. Finally, the reservoirs behind dams throughout Mexico are an important recreational resource.

On the other hand, the construction of dams can also have negative effects, including habitat loss, the need to relocate existing residents away from the reservoir site, adverse changes in river flows downstream of the dam and sediment accumulation behind the dam which reduces the reservoir capacity.

Mexico's freshwater aquifers

Mexico's groundwater aquifers are a very important resource. About 64% of public water supplies come from wells sunk into aquifers. Mexico City, Monterrey and several other metropolitan areas rely heavily on aquifers. Aquifers also provide about a third of all the water for agriculture and livestock.

The largest aquifer resource in terms of renewable water availability is in the Yucatán Peninsula, with about a third of the national total. A large portion of the rainfall in the Yucatán seeps into its aquifers; there are virtually no rivers to carry rainwater to the ocean. The states of Chiapas and Tabasco, where rainfall is the heaviest, account for about a quarter of Mexico's aquifer resource. The next largest sources are the Balsas and Lerma–Santiago basins but each holds under a tenth of the national total.

According to the National Water Commission, 104 of the country's 653 identified aquifers are over-exploited in that more water is withdrawn each year than is naturally replaced.[12] The velocity of water movements underground can be astonishingly slow; it may take rainwater water tens or even hundreds of years to reach the aquifer it is replenishing. (For a curious case of replenishment rates, see The Enchanted Lake box). The number of overused aquifers has increased rapidly in recent decades from 32 in 1972, to 80 in 1985, and 104 in 2004. When coastal aquifers are over-exploited, seawater seeps in to replenish the aquifer, and eventually the aquifer can become too salty to be used for irrigation. Salt-water intrusion is a significant problem for 17 aquifers located in Baja California, Baja California Sur, Colima, Sonora and Veracruz (Figure 6.7).

Nearly 60% of the total groundwater extracted is withdrawn from overexploited aquifers. As expected, the over-exploited aquifers (Figure 6.7) are in the heaviest populated and the most arid areas. Total water extraction exceeds recharge in Mexico City, Monterrey and other large northern metropolitan areas as well as irrigated areas of Sonora, the central northern plateau, the Lerma basin and Baja California.

Mexico City, which 500 hundred years ago was a city of marvelous canals, currently has a serious water problem. More than 60% of its water comes from the exploitation of deep wells sunk into its subterranean aquifers. Rainfall is only able to recharge about 1/3rd of the water extracted each year. Thus, the aquifers are losing water rapidly and receding farther and farther from ground level. This "mining of water" from the aquifer has resulted in severe subsidence problems in Mexico City. The wells must be sunk deeper every year and more energy must be used to pump the needed water to the surface. Mexico City's water issues are analysed more thoroughly in chapter 23.

There are also significant water problems in many other areas of the country. For example, Monterrey is in a closed basin without an adequate flow of river water. To get the water it needs for its residents and industries, Monterrey is also unsustainably "mining" its aquifer.

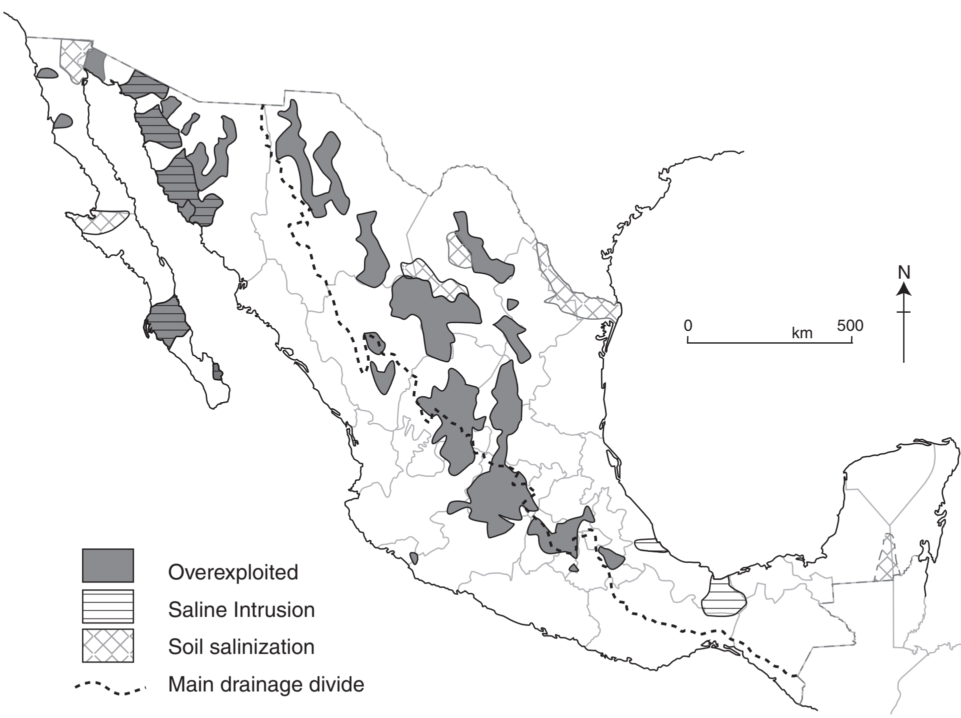

Figure 6.7 Overexploited aquifers and areas of salinization[13]