THIRSTY CITIES

Urban Environments and Water Supply in Latin America

Danilo J. Anton

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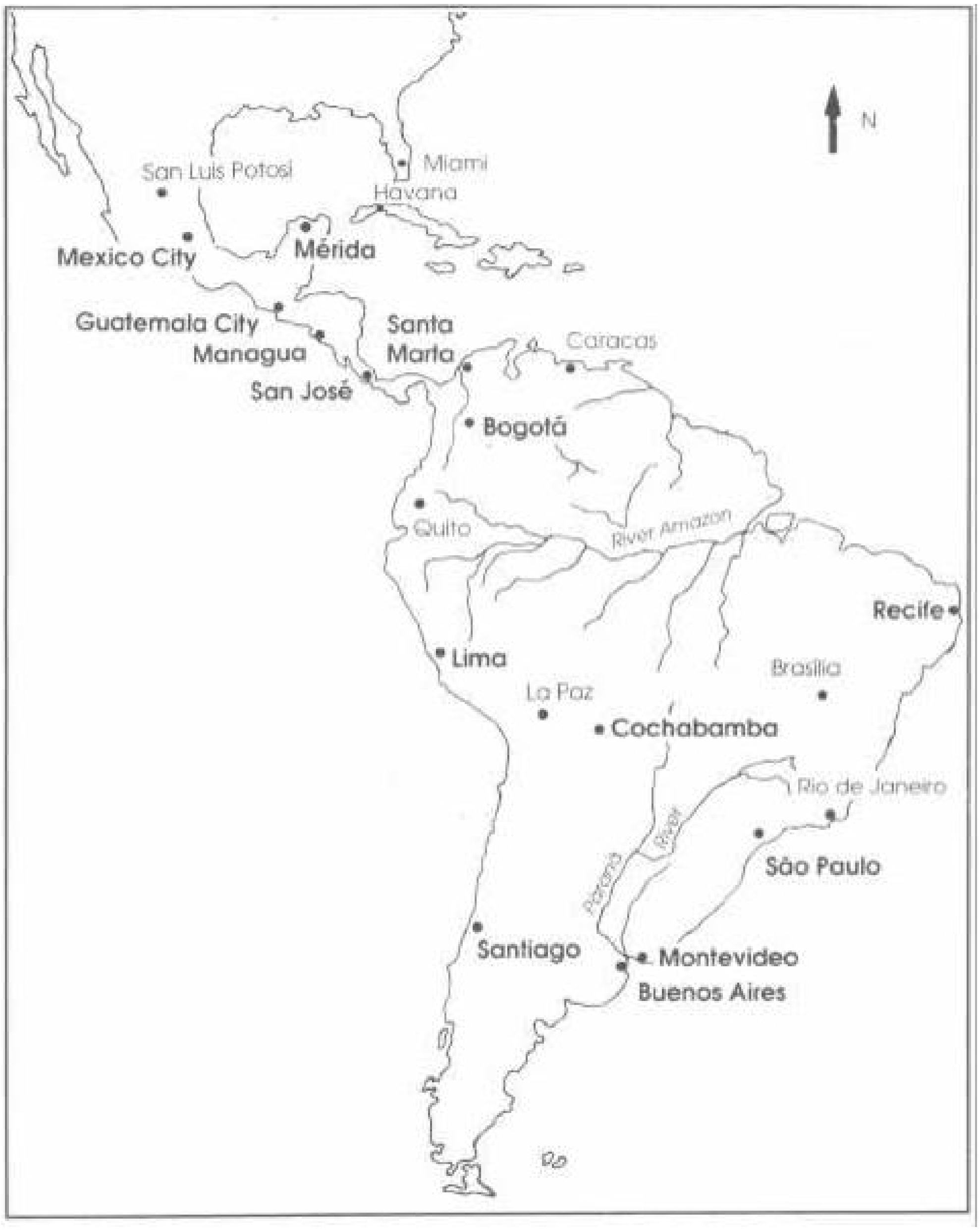

Some major cities of Latin America and the Caribbean. Cities discussed in detail are shown in bold type.

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Introduction

One of the main features of the recent historic and geographic evolution of Latin America and the Caribbean (LAC) has been a concentration of the population in urban areas. The urban population of the region is estimated to be increasing at the rate of 3.6% per year (Bartone 1990).

At the end of the 1980s, there were over 280 cities of more than 100 000 inhabitants; the 210 million people in these cities represented about 46% of the region s population. About 25% of these cities have populations above 0.5 million people, constituting 35% of the total population. Extremely high concentrations occur in the 13 largest urban centres, whose populations exceed 3 million (Table 1). The total population of these metropolises is 105 million or 23% of the total for Latin America and the Caribbean.

It is difficult to provide accurate or comparable figures for the populations of metropolitan areas. Large cities often encroach beyond their municipal or provincial boundaries. Other cities, formerly separated, may merge into the main urban area. Equally, the rate of annual urban growth for any growing city is hard to define, because the census units may become noncomparable during the intercensal period (i.e., because satellite cities are incorporated). I have tried to surmount these difficulties using different sources for some cities that appeared clearly uncomparable[1] in some data sources. Population growth projections are only indicative. In all cases, an average population growth for the period was estimated based on the growth of the last intercensal period and this figure was cumulatively applied for the projected period. I could not apply the same criteria for all cities but, in some obvious cases, corrections were made.

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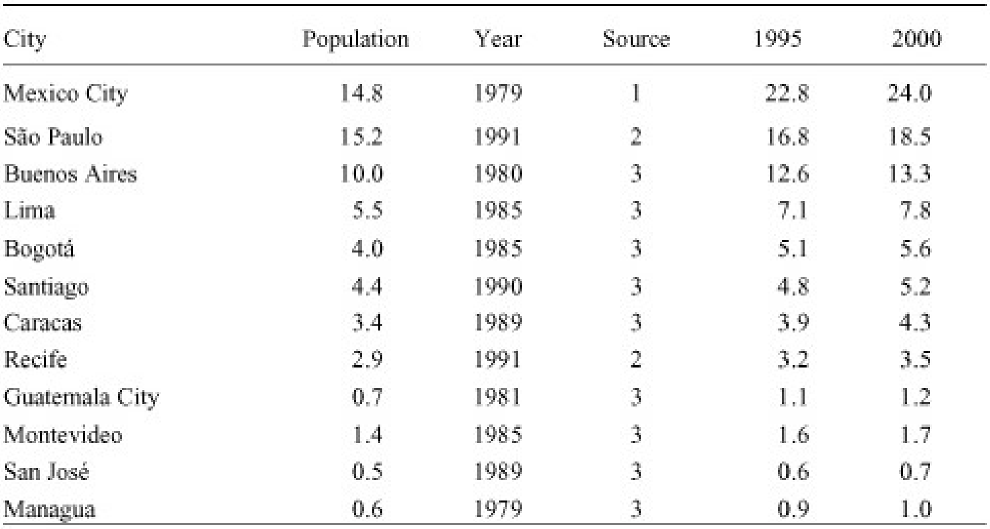
[1] In some cities, the problems are almost insurmountable. It is difficult to decide if Campinas, São Jose dos Campos, or Santos belong to the metropolitan area of São Paulo. This Brazilian city is growing through the Paraiba Valley along the Via Dutra Highway toward Rio de Janeiro: some people are already forecasting a megacity to be called São-Rio. A similar problem occurs in Mexico City because of the merging of some large, formerly independent, urban areas (i.e., Toluca, Cuemavaca, Puebla, Querétaro, and Cuautla). In the last censal survey, growth of Mexico City appeared somewhat curtailed if only the Valley of Mexico is considered, but if the other cities listed are included, the growth is even further accelerated. In the table, I have tried to conciliate statistical data (often not reflecting reality) with the actual ground truth.

Table 1. Current and projected populations (millions) for some major cities of the LAC region.



City	Population	Year	Source	1995	2000
Mexico City	14.8	1979	1	22.8	24.0
São Paulo	15.2	1991	2	16.8	18.5
Buenos Aires	10.0	1980	3	12.6	13.3
Lima	5.5	1985	3	7.1	7.8
Bogotá	4.0	1985	3	5.1	5.6
Santiago	4.4	1990	3	4.8	5.2
Caracas	3.4	1989	3	3.9	4.3
Recife	2.9	1991	2	3.2	3.5
Guatemala City	0.7	1981	3	1.1	1.2
Montevideo	1.4	1985	3	1.6	1.7
San José	0.5	1989	3	0.6	0.7
Managua	0.6	1979	3	0.9	1.0

Note: na = not available.

Sources: 1 Wilkie et al. (1988); 2 Abril (1993); 3 Europa (1991).

The largest cities have experienced the greatest increases, and demographic statistics leave little hope of any dramatic reversal of present trends. If the rate of growth is not significantly reduced, by the year 2020, more than 500 million inhabitants of Latin America (or two-thirds of its population) will be living in cities of over 100 000 people.

Overconcentration has reached alarming levels in three megacities: Ciudad de México (19.5 million), São Paulo (16.5 million), and Buenos Aires (12.2 million). Forecasters predict that the populations of Mexico City and São Paulo will soar to 25 and 22 million, respectively, well before the year 2010. By that time, several other cities will exceed 10 million, including Rio de Janeiro (12 million) and Lima (10 million) and many more will exceed or approach 5 million (Belo Horizonte, Bogotá, Caracas, Guadalajara, Monterrey, Pôrto Alegre, Recife, Salvador, and Santiago).

This degree of urban concentration is much higher than that expected in cities of developed countries, whose growth is slower. These populations are also higher than expected for the largest megacities of the most densely populated countries in the Third World. The People s Republic of China, with a population of over 1.1 billion, does not contain any city with more than 15 million people: Shanghai, the largest city in China has only 12 million. São Paulo and Mexico City are larger, in spite of the much smaller populations of their countries (14 and 9 times smaller, respectively). In India, with a population of 800 million, the two largest cities Calcutta (15 million) and Bombay (14 million) also have populations considerably smaller than the two largest LAC megalopolises.

This uncontrolled growth of LAC urban areas has occurred at the same time as one of the worst financial crises of the region s history. In almost all LAC countries, foreign debt has increased at an even faster pace than the growth of their urban populations. This problem became particularly acute at the end of the I980s in Brazil (foreign debt at that time of US$116.9 billion), Mexico (US$105.6 billion), and Argentina (US$S6.2 billion), but is also found in many smaller countries. In some cases, lack of resources prevented even the payment of interest on these debts over a relatively long period (e.g., Peru and Argentina in 1988 1989). In other countries, net transfers of resources as a result of profit repatriation and debt servicing or payment have also depleted available funds in public coffers and have jeopardized the acquisition of new credit. Little (if any) new money has been available for investment in infrastructure of any magnitude at a time when such investment is most needed to provide the necessary services for the booming urban population.

One of the public services most affected is urban water supply. Historically, Latin American cities have relied on their closest sources of water, which in most cases were freshwater streams, lakes, or springs. Soon, these resources were exhausted or degraded, and the cities were forced to invest considerable funds in the construction of dams and pipelines to bring water from more remote sources. Continually expanding cities have outgrown most water-supply systems, and new sources must be tapped to satisfy the needs of their populations.

However, funds are not available. Few new reservoirs are being built and few pipelines are being installed. In fact, expansion of the systems has been almost completely halted. Less water is available per person and this situation is gradually becoming worse.

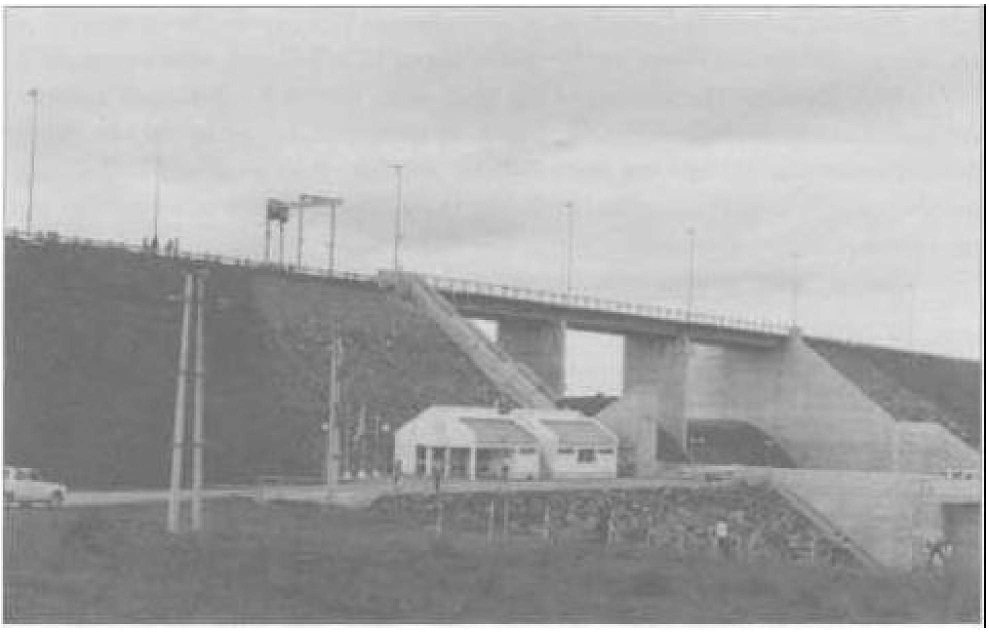
In addition, distribution systems (originally designed for much smaller populations and for limited use) are becoming not only inadequate, but also obsolete they increasingly require repairs at a time when less money is available to carry them out. As a result, the amount of leakage is increasing, augmenting water consumption from the systems. Breakages (and subsequent water losses) are common, with frequent drops in pressure increasing the risk of contamination of waterlines.

Old reservoirs are also decaying. Their storage capacity is decreasing due to silting, watershed basins are being invaded by urban and rural dwellers, and uncontrolled industrial activity is producing changes both in hydrological regime and water quality. Many reservoirs serving urban areas have become useless because of inappropriate use of their basins.

New reservoirs will be much more expensive than old ones. New dams must be built in basins unaffected by urban growth, which are often far from the people who will use the water. In some cases, water must be pumped from lower lying valleys (as in Mexico City); in other cases, interbasin water transfer may be needed (Lima). In almost all cases, increased distances and water conduction costs are unavoidable.

At the same time, consumption practices are frequently wasteful. Water policies (i.e., cost of water and available water-appliance technology) do not encourage conservation. In many cases, water costs are higher in the poorly served, low-consumption, low-income urban areas and lower in affluent neighbourhoods that have a more wasteful consumption pattern.

Sewage systems are not much better. Only 41% of the urban population is linked to sewerage systems, and over 90% of wastewater is discharged into the environment with no treatment. By the year 2000, an additional 141 million people will require these services. It is not very likely, given the financial crisis, that LAC countries will be able to obtain even a significant portion of the resources required to finance this badly needed infrastructure.



New surface-water supplies require expensive dams and pipelines.

Treatment of wastewater is rare in most cities. Wastes are discharged untreated into the environment with obvious health hazards for the population living nearby or downstream of the effluent outlets.

The consequences of this situation can be catastrophic. Millions of people are being excluded from water-distribution systems, forcing many urban communities to use various (often imaginative) ways to obtain water what little water can be acquired is usually of poor quality. Many more millions are becoming increasingly exposed to health hazards that are affecting mortality rates in these populations, e.g., the cholera outbreak in Peru that spread throughout most of the continent in the early 1990s.

In spite of this apparently hopeless situation, in many cases means are available to obtain better quality water at a much lower cost, by using groundwater reservoirs lying close to urban areas. Groundwater volumes are normally much higher than surface water, it is less vulnerable to contamination, and initial investment is only a fraction of what is needed to develop analogous surface-water resources.

Large volumes of groundwater are available close to many of the larger LAC cities; in most cases, they are only marginally used. Mexico City, the largest LAC city, draws about 55 m^3/second (80% of its consumption) from groundwater sources located beneath the urban area and in a neighbouring basin. The city also obtains surface water from the Cutzamala River basin at a much higher cost and by depriving populations downstream.

São Paulo, Brazil, the second largest city of the region, gets most of its water from surface resources (43 m^3/second from six reservoirs located in the upper Tietê River basin). However, about one-third of the suburban and urban population and industrial establishments draw their water from underlying aquifers. The suburban areas of the city are expected to become increasingly dependent on the groundwater supply. The available volume of groundwater in São Paulo and neighbouring basins is relatively large, and its use would require a smaller investment than needed to expand the surface-water system.

Buenos Aires, capital and largest city of Argentina, is next to the huge Río de la Plata estuary and draws the bulk of its water supply (about 80 m^3/second) from this surface source. However, because of the rapid expansion of the city, many suburban communities have developed groundwater-based systems tapping a relatively shallow alluvial aquifer that underlies the urban area. La Plata (600 000 inhabitants), the capital of the province of Buenos Aires and now practically a suburb of Buenos Aires, depends on groundwater for about 40% of its requirements. This resource is of higher quality than the local river water because of the high level of contamination of the Río de la Plata near the shore.

The city of Buenos Aires discharges its untreated effluent into the Río de la Plata estuary. Use of groundwater is expected to increase in the Buenos Aires-La Plata region as this contamination of surface water near the river bank increases, thus raising the cost of treatment and conduction. However, inadequate sewage systems are affecting groundwater quality in many suburban areas of greater Buenos Aires and, ultimately, jeopardizing the present and potential use of this alternative water source.

Lima, Peru, is also heavily dependent on groundwater. The city obtains its water from the Rímac and Chillón rivers, at the rate of about 12 m^3/second, after treatment at the La Atarjea plant. The balance of the city s water (about 9 m^3/second) is drawn from an underlying shallow aquifer, which, in turn, is recharged by the two rivers. Surface-water use has become more difficult because of an increased load of suspended sediments and pollutants (including those from upstream mining areas) that raises treatment costs considerably.

During the last few decades, the aquifer has been overpumped resulting in widespread saline intrusion along the coastal zones. In addition, the volume of water recharging the groundwater reservoir has diminished because the irrigation areas have been reduced and impermeability of river beds in the urban area has increased. A gradually growing water crisis will require careful management of the existing water resources. Adequate regulation of these resources should include artificial recharging of the aquifer with large volumes of surface water and intelligent extraction of water over a dispersed area of the groundwater reservoir.

In addition to the examples cited, many other urban areas in the continent obtain part or most of their water supply from groundwater sources. This is particularly true in the Caribbean region where surface water is scarce, but excellent aquifers (mainly karstic) are often suited for urban supply. In Havana, almost 100% of the water supply is drawn from groundwater; other cities using groundwater extensively include Kingston and Montego Bay in Jamaica; San Juan, Puerto Rico; Miami; Florida (which can be considered in many senses a Latin American city); Mérida and Torreón-Gómez Palacios in Mexico; Port-au-Prince, Haiti; Nassau in the Bahamas; Bridgetown, Barbados; and several others.

Many cities in volcanic areas are also well situated to draw their water supply from groundwater sources (Table 2). This is particularly true of cities located close to thick pyroclastic and associated formations and to lava rocks. Guatemala City, Managua, Mexico City, Quito, and San José, for example, have important volcanic aquifers that are tapped for their water supply. In fact, Guatemala, Managua, Mexico, and San José get most of their water from groundwater reservoirs or related springs. Quito draws about 40% of its water from groundwater sources.

A large number of other cities depend partially or totally on alluvial valley aquifers, particularly those in the Andean region. Some examples are Cochabamba, Bolivia; Valencia and Maracay in Venezuela; and Querétaro and San Luis Potosí in Mexico.

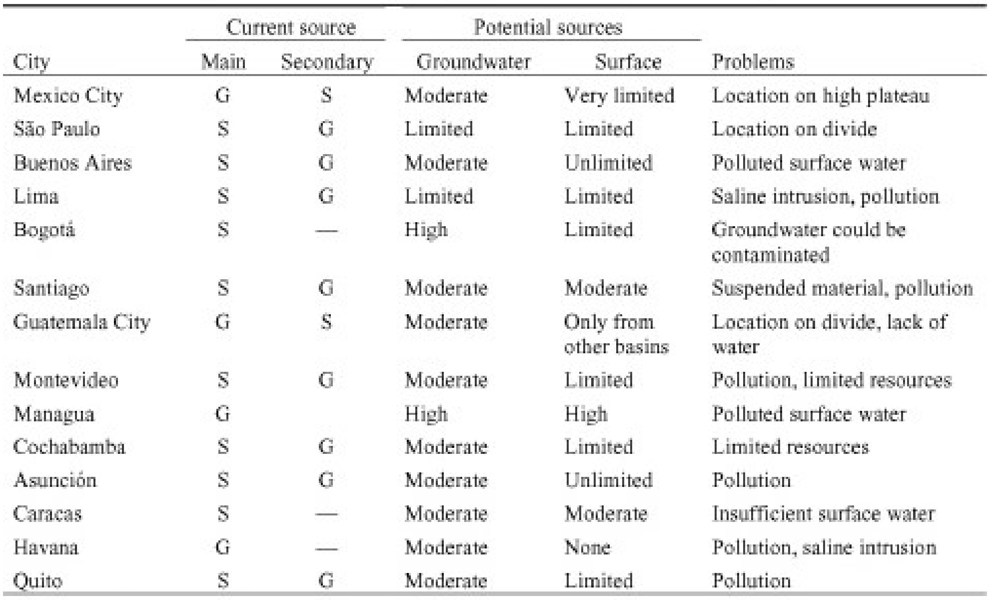
In some cases, the current water supply is obtained from surface sources that are being gradually exhausted. Groundwater may become the main source for expansion of urban supply systems in Montevideo in Uruguay, Recife and Salvador in Brazil, and others.

Often, groundwater is the only safe alternative. The quality of surface water is deteriorating in all LAC urban environments. Where stream flows are large (e.g., Asunción on the Paraguay River and Manaus on the Amazon), the effects of the various waste discharges may be small, even negligible. In other cases, when rivers are smaller or waste discharges large, surface water may be steadily deteriorating and additional treatment may be required. Below a certain quality level, water treatment becomes very costly (and sometimes technically unfeasible) and other options must be considered.

Alternative surface sources are usually farther away than the outdated ones, requiring hundreds of millions of dollars in infrastructure to tap and transport water to the cities (e.g., Lima and Mexico City). However, there is frequently a nearby groundwater source that could be exploited at a much lower cost. In some areas, quantity is also a problem. Surface sources do not provide the required volumes and underground sources are the best available alternative.

Often, even when the main sources of water supply for the urban core are bodies of surface water, the use of groundwater can be the most economical and feasible option for some sections of the city. This is the case in Bogotá, where although surface water is the best source for the northern and central neighbourhoods, it is expensive and unpractical for some of the fast-growing southern suburbs, where it could be more economical and convenient to use the underlying aquifer. Although this solution has not been implemented, it is repeatedly advocated by Colombian hydrogeologists.

Table 2. Current and potential sources of water supply for major cities of the LAC region.



	Current source		Potential sources		
City	Main	Secondary	Groundwater	Surface	Problems
Mexico City	G	S	Moderate	Very limited	Location on high plateau
São Paulo	S	G	Limited	Limited	Location on divide
Buenos Aires	S	G	Moderate	Unlimited	Polluted surface water
Lima	S	G	Limited	Limited	Saline intrusion, pollution
Bogotá	S	—	High	Limited	Groundwater could be contaminated
Santiago	S	G	Moderate	Moderate	Suspended material, pollution
Guatemala City	G	S	Moderate	Only from other basins	Location on divide, lack of water
Montevideo	S	G	Moderate	Limited	Pollution, limited resources
Managua	G		High	High	Polluted surface water
Cochabamba	S	G	Moderate	Limited	Limited resources
Asunción	S	G	Moderate	Unlimited	Pollution
Caracas	S	—	Moderate	Moderate	Insufficient surface water
Havana	G	—	Moderate	None	Pollution, saline intrusion
Quito	S	G	Moderate	Limited	Pollution

Note: 5 = surface water; G = groundwater

Where water is not supplied directly to the home, it must be carried from the nearest source.

In Buenos Aires and São Paulo, many of the new neighbourhoods and industries get their water from wells, because their distance from the municipal system and their low population density do not justify the expense of extending municipal waterlines or because the financial resources of the water companies are insufficient to install the connections. When potable groundwater is easily available, fringe communities use this resource, even in cities where surface water is abundant, cheap, and of good quality. For example, in Asunción, Paraguay, many industrial factories depend on wells in spite of the good quality and reliability of the river water in the core of the urban area.

The number of people experiencing these limitations is gradually increasing, not only because of growth of the urban population, but also as a consequence of financial difficulties of water companies to obtain funds for expansion of municipal systems. Whatever the reason, the trend is clear: Latin American urban water supply will depend more and more on groundwater reservoirs. In 1990, about 30% of the water consumed in LAC cities came from nearby aquifers. At the present and projected rate of increase in groundwater extraction, by the year 2020, up to 40% of urban water will come from aquifers.

At that time, about 850 m^3/second will be pumped from the ground to satisfy the requirements of the urban populations of the big cities. This is 3.5 times the present extraction rate (about 260 m^3/second) for the whole urban groundwater supply, including only cities with more than 100 000 people. If smaller towns and agricultural areas are included (present rate of use, 2500 m^3/second), it is easy to project the importance of groundwater use in the 21st century.

However, Latin America is not prepared to deal with this issue. In fact, lack of awareness of this resource is appalling. Few trained hydrogeologists or groundwater engineers can be found in the LAC area. There are fewer than 200 formally trained hydrogeologists in the 30 countries of the LAC (almost half are in Brazil): one for every 3 million people or one for every 3 000 wells. There are not many more groundwater engineers.

Partly as a consequence of the lack of expertise in the region, groundwater resources are poorly understood and, therefore, frequently underused. Sometimes, large amounts of money are spent on surface water-supply schemes, when readily available groundwater of good quality is within the financial and technical means of city authorities. In other cases, aquifers are overexploited and degraded because of improper management, lack of protection of recharge areas, and overpumping. As a result, some groundwater reservoirs become irreversibly contaminated, or subsidence or saline intrusion take place.

As previously stated, groundwater is much less vulnerable to degradation than surface water. However, this may become a double-edged sword. In many cases, this apparent invulnerability may give a sense of false security and no protective measures may be taken when they are required. Although groundwater is relatively safe from contamination, with time it may become contaminated in such a way as to render it completely unusable. The lack of understanding of groundwater dynamics may ultimately result in destruction of the resource. In the long term, underground water can be damaged more than surface water, because reversing the environmental messes is more difficult, expensive, and often impossible.

How is the LAC region going to cope with the need to understand the nature, dynamics, and vulnerability of groundwater systems? How is it going to deal with the contradiction arising from growing needs, increasing environmental degradation, and lack of expertise and financial resources? This book is intended to try to answer these questions using the limited available information and some common sense. I hope it will shed light on the not easily predictable future of Latin American cities in the next century.

2

The Latin American environment

Physical environment

The large cities of Latin America are located in a wide array of environmental settings: arid mountainous regions, in the middle of extensive jungles, surrounded by flat grasslands or shrubby landscapes, in the bottom of deep valleys, covered in thick forest, in sandy deserts, or next to cold steppes or icy glaciers. The variety of landscapes is staggering (Fig. 1).

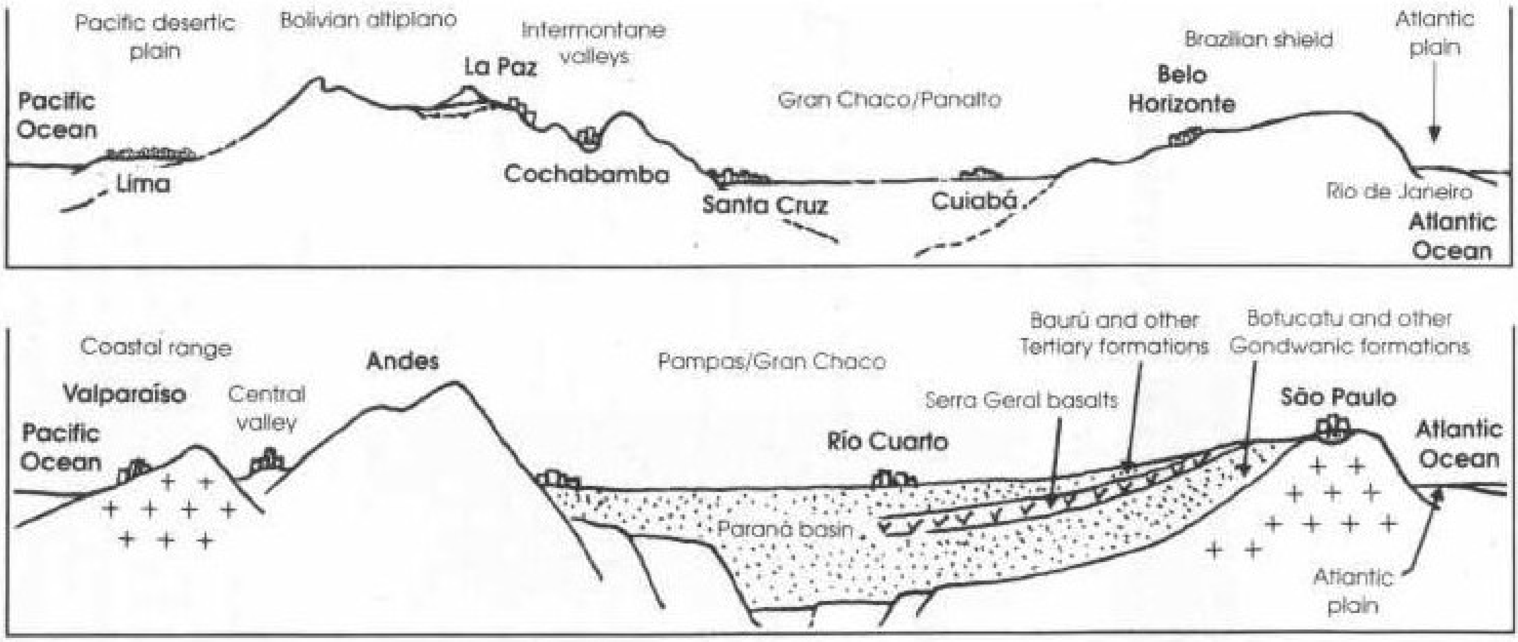
The climate of the region is also highly varied. Precipitation ranges from almost nothing along the coastal Pacific desert to hyperpluvial zones on the eastern slopes of the Andes facing the Amazon region. Extreme and average. temperatures are also very different in the various areas, depending on elevation, latitude, orography, and location in relation to atmospheric and oceanic circulation systems.

Glaciated areas occur in the high mountains near the equator and almost at sea level in the southern Andes. At the other extreme, there are regions of permanently high temperature in the Amazon basin. Relatively strong seasonal thermal variations occur in the midlatitude semideserts of the Argentinean pampas, Patagonia, and the northern Mexican mesas. Cities near the seashore experience a maritime climate (high humidity and rainfall and weak seasonal variation of temperature); those far inland have well-defined semicontinental or continental climates (dry with strong diurnal and seasonal thermal contrasts).

Geologic features are also varied. They include ancient crystalline shields (the Brazilian and Guyana shields), old sedimentary platforms and basins (the Patagonia platform and the Paraná sedimentary basin), volcanic zones (the Mexican transverse volcanic belt), huge sedimentary plains (Amazon, Gran Chaco, the pampas, and the llanos), and deeply folded and fractured landscapes (the Andes and the Mexican sierras).

There are humid regions (most of the Amazon basin, some sectors of the Colombian-Venezuelan llanos, and the humid pampas) and other areas in which water is a permanent limiting factor in the establishment of communities (the Peruvian-Chilean coastal desert, the dry pampas, Patagonia, the arid Chaco, the Brazilian *nordeste,* and northern Mexico). There are also many temperate areas where neither large deficits nor important surpluses of water occur, but where adequate management of the available water resources is required to avoid their becoming a barrier to future development.

Fig. 1. Transverse sections of South America, showing the variety of topographic and geologic features.



The soils of the continent range widely from thin, poorly developed, rocky, sandy, and salty extremes to well-developed deep ferrallitic or fersiallitic soils, with a large variety of intermediate possibilities, including many kinds of horizon differentiation, permeability, chemical composition, organic matter content, and fertility.

Vegetation is as varied as climate and soils. There are tropical humid forests with several strata, large prairies, extensive forested and nonforested savannas, steppes of varied density, bush-type vegetation, coniferous forests, cyperaceous swamps, highmountain grasslands, periglacial tundras, and various coastal communities.

In this natural diversity, Latin American cities have developed. Urban solutions to the many challenges presented by local landscapes are almost as diverse as the landscapes themselves. The degree of adaptation to the environment in the different methods of urban planning has also varied. Some cities seem to be well adapted to their environment, sometimes using technology inherited from preceding indigenous societies. In other cases, environmental adaptations are more arguable, especially in view of the profound demographic and social changes that have occurred during the last few decades.

By the same token, water resources available in the different urban settings vary from place to place and their suitability has significantly changed with the growth of many cities during the 20th century. Local streams that provided enough good water for many small cities are now insufficient and contaminated, and new sources were or must be found. Local springs and wells that formerly fulfilled all needs are now often exhausted or irremediably degraded. The problems of adaptation of the new megalopolises to their often fragile environments are enormous, and these problems will not disappear easily.

Geology and geomorphology of urban sites

The geology and geomorphology of Latin America and the Caribbean (LAC) are complex (Fig. 2). The region is composed of:

- A long mountain range (Andes, Central American ranges, and Mexican sierras), with intercalated or associated plateaus (Bolivian altiplano, Peruvian highlands, Cundi-Boyacense plateau in Colombia, and Mexican mesas), and active volcanic zones (transverse volcanic belt in Mexico, Central American volcanic belt, and Andean volcanic belt);
- A large flat area through the centre of the continent (Colombian-Venezuelan llanos, Amazonian plains, Chaco plains, and pampas);
- An extensive shield region in the east (Brazilian and Guyana shields) with associated paleovolcanic and sedimentary basins;
- A complex island arch and related continental relief in the northeast (Caribbean islands, Caribbean coast of South America, and associated North and Central American terrain); and
- A sedimentary platform in the southern tip of South America (Patagonia).

Fig. 2. Geographic and geomorphic features of Latin America and the Caribbean.

The western ranges

The western ranges have planetary dimensions, extending from 32˚N latitude in northern Mexico (although they continue further north along the west coast of the United States and Canada to Alaska) to 56˚S latitude in southern Argentina and Chile. The LAC mountain ranges are well over 11 000 km long. This band of mountains is wide in northern Mexico and Bolivia, where internal basins and plateaus have developed, but much narrower in other areas. Close to the United States border, the rugged Mexican highlands are about 800 km wide. Further south, they narrow to a few dozen kilometres in the Tehuantepec isthmus, in eastern Nicaragua, and in Panama. (This feature influenced the selection of the site for the Panama Canal.)

In Colombia, the ranges divide into three roughly parallel mountainous chains the eastern, central (strongly volcanic), and western ranges   with deep hydrographic valleys between them (the Magdalena and the Cauca river valleys). Moving south, in Pasto, Colombia, these ranges merge and in Ecuador they narrow to less than 200 km wide.

In the Peruvian section of the Andes, the ranges widen again, and near the Bolivian border two divergent chains enclose the plateaus of the Bolivian altiplano (between 17 and 20°S), a large, semi-arid plateau containing several fresh and saltwater lakes (Lake Titicaca, Lake Poopó, Salar de Uyuni, Salar de Coipasa, etc.).

At 30 40°S, the Andes narrow and rise to maximum elevations of 6 500 7 000 m above sea level. In this area, the highest mountains on the continent are found, including the highest point of the Americas, the Aconcagua peak, at about 6 959 m above sea level.

Southwards, the mountain peaks are lower and in the extreme south of the continent, they do not exceed 5 000 m. The southernmost mountainous areas are heavily eroded by the action of glaciers and by gelifraction.

The peaks of the Latin American ranges seldom exceed 6 500 m and are usually much lower: 2 000 3 000 m in Mexico and 5 000 6 000 m along the South American sections of the ranges. In the south, these highlands range from 3 000 to 4 000 m above sea level. Throughout the ranges, volcanic cones exceed the average height of the surrounding nonvolcanic highlands, frequently reaching 5000m in elevation: Popocatépetl, Iztacíhuatl, and Orizaba volcanos in Mexico; several volcanic cones in Guatemala, El Salvador, Nicaragua, and Costa Rica; Nevado del Ruiz in Colombia; Chimborazo and Cotopaxi in Ecuador; EI Misti in Peru; Tronador and Osorno in Chile; Nevada Illimani in Bolivia; and many others.

The plateaus of Mexico range from about 1 500 m elevation in the north to more than 2 000 m in the valleys of Mexico, Toluca, and Puebla. The narrow plateaus in Colombia are 2 500 to 2 800 m above sea level. The large Peruvian-Bolivian plateau reaches elevations of 4000 m and over.

There are also a large number of valleys throughout the mountainous regions of Latin America. In some cases, they are wide, of tectonic origin, and raised to high altitudes through epeirogenic phenomena. In many other cases, valleys have resulted from fluvial erosion; deeply dissected landscapes have developed with steep slopes and unstable soil.

Geologically, the western ranges of Latin America are composed of relatively young formations; the orogenesis and associated folding, fracturing, and metamorphism did not occur before the beginning of the Cretaceous period of the Mesozoic era. Most often, they arose during the Tertiary period and, in some cases, active epeirogenic phenomena are still taking place.

The rocks composing these heterogeneous mountainous areas are varied. Frequently, a core of crystalline rock (often older granitic and metamorphic) is surrounded or partially covered by a dipping mantle of folded and fractured sedimentary rocks. Normally, the stratigraphic column is based on marine limestone (e.g., the Morelos formation in Mexico, the EI Molino formation in the Bolivian sierras, and the Rio las Vacas limestones in Guatemala), covered with detritic marine, coastal, and continental fine-grained sedimentary rocks (flysch type). This is the case in the Mescala formation in southern Mexico and the Santa Lucia formation in Bolivia, which are covered by coarse-grained sedimentary rocks (molasse-type conglomerates and conglomeratic sandstones, as in the Balsas group in southern Mexico and the Morochata formation in Bolivia). This sequence is usually associated with processes of continentalization of the sedimentary environment during orogenesis.

These molasses, flysches, limestones, and underlying granitic and sedimentary rocks have been heavily eroded, and they may be found at different elevations in different parts of the ranges. In many cases, volcanic rocks have been ejected or have flowed out, and several types of volcanic deposit can be found (see Chapter 3, Main environmental issues affecting the LAC region).

Frequently, there are thick accumulations of pyroclastic materials as in the Mexico and Guatemala valleys, in the Managua region, and in Quito, Ecuador. In these areas, lava flows and volcanic cones are also found. Volcanic rocks range from very acidic rhyolites and trachytes to more basic andesites and basalts.

The volcanic formations frequently have relatively high surface permeability and poor hydrographic development (because of obstruction of developing thalwegs by lava or accumulation of ashes and mantles of miscellaneous pyroclastic material). Stream run-off may be limited and infiltration high, causing large underground reservoirs to develop. Because of the availability of groundwater and the fertility of the rapidly weathering glass-mineral soils (with their high rate of release of valuable nutrients), volcanic regions of Latin America have been favoured sites for human occupation and urban development. Many of the large cities of the continent are located in volcanic zones in spite of the ever-present volcanic and seismic risk.

In the eroded valleys of the mountain ranges, recent alluvial deposits have accumulated. In some cases, these accumulations are narrow and relatively unimportant, but in others they have formed sedimentary basins of large dimensions. These valleys are normally filled with coarse-grained sediments of high permeability on which surface streams flow with varied regularity, depending on the environment and the size of the basin. They are also relatively flat and contain friable soils suitable for agriculture and urban construction, making them attractive for settlement. Cochabamba in Bolivia, Cali and Medellín in Colombia, and Caracas and Mérida in Venezuela are all located in intramontane valleys of the Latin American western mountain ranges.

The shield region

Toward the eastern side of the continent is a large zone of crystalline shield. In the intertropical zone south of the equator, a large shield mass the Brazilian Shield covers an area larger than 3 million km^2. In its southern tip is a small crystalline shield, the Uruguayan-Río Grandense crystalline island, and some still smaller crystalline islands in the Sierras Pampeanas, Córdoba, and Tandil in Argentina.

The Brazilian Shield is an undulating, hilly plateau with elevations ranging from 200 300m to slightly more than 1000m above sea level. It is mainly composed of Precambrian rock, with associated younger sedimentary basins. The largest of these are the peripheric Paraná basin in the southwest, which is over 5 000 m deep in some places, the Maranhao sedimentary basin in the north, and the Bahia sedimentary basin toward the

Escarpment of the basaltic shield area of Brazil.

northeastern part of the shield region. Several smaller sedimentary basins have considerable economic importance because of their high population densities (i.e., the São Paulo basin, the Taubate basin, and the Alagoas-Sergipe basin).

These basins date from the late Palaeozoic era to the Miocene-Pliocene epochs of the Tertiary period. The topographic configuration of the shield is asymmetric, with a steep east-facing escarpment overlooking a large number of discontinuous, narrow strips of coastal plain, with the highest watersheds located close and roughly parallel to the coastline. As a consequence, a large number of alluvial valleys flow westward (to the interior), toward the Paraná and Amazon hydrographic basins, in which late Tertiary and Quaternary deposits have accumulated. Eastward-flowing streams, on the other hand, are short and torrential, and their deposits are foothills-type, interdigitated with the littoral and marine sediments of the coastal areas.

The main limits for urban development in the Shield are generated by the rainforest ecosystem, with its soils of limited fertility, which are inappropriate for intensive agricultural activity.

Because Brazil was colonized along the coast, its cities are on the narrow coastal plains between the sea and the eastern escarpment. Most of them obtained their water originally from escarpment streams and springs. Their growth forced some of them (Rio de Janeiro, Maceió, Recife, and Santos) to begin tapping the coastal aquifers or building reservoirs in the neighbouring highlands.

Some cities, such as São Paulo and Curitiba, became established in the immediate interior, a few dozen kilometres from the coast on top of the escarpment. These were in a relatively inappropriate position in terms of water supply, because of their proximity to the headwaters of the rivers and the small size of the upper basins. São Paulo, today, has trouble meeting the water needs of its population because of its location. Instead of being able to solve the problem with one or two large reservoirs, the city was forced to build a

Matanza River at Buenos Aires: major rivers that are routes for transport are often contaminated.

complicated system of dams and pipelines to take advantage of all the small basins upstream of the city site (Kawamura et al. 1989). São Paulo has the option of using the small hydrogeological Tertiary basin on which the city is located, and, in fact, some of the water used in the metropolitan area comes from this aquifer (see Chapter 6).

In the interior, cities have developed near rivers to assure a good water supply or to facilitate transport. This is the case for most of the cities in the Amazon basin (e.g., Manaus, Santarem, and Belem). In other areas, cities grew up near mineral resources and local water is often scarce (e.g., Belo Horizonte in Minas Gerais).

In the northeast part of the South American continent lies another large shield region: the Guyana Shield. This sparsely populated region is undulating to hilly and is covered with dense rain forest. Only a few cities are found on the shield, most near its periphery. Along the coastal plains, few settlements have developed (e.g., Georgetown, Paramaribo, and Cayenne). They use the nearby rivers mainly for transport and only secondarily as a source of water because they are brackish near the coast (Sattaur 1990). These cities also use the alluvial aquifers of the foothills, which are usually interdigitated with various coastal sedimentary formations. In the neighbouring alluvial plains of the Orinoco in the northwest, a few other cities have recently developed, i.e., Ciudad Bolívar and Ciudad Guayana in Venezuela. These cities are on the boundary between the Guyanese region and the large llanos plains and use the mighty Orinoco River for water and transport, although the local alluvial aquifers are also exploited.

The central plains

Through the centre of the South American continent, from the Venezuelan Andes to Patagonia, stretches a vast flat region (pampas, Chaco, the Amazon, and llanos), composed mainly of Quaternary and Tertiary sediments. These plains are the geomorphologic result of subsidence and contain huge sedimentary basins, which are almost continuous, except where less-subsident or nonsubsident blocks can be seen (e.g., the hills of Serranía de la Macarena in Colombia and the Sierras Pampeanas in Argentina). This graben is actually composed of several subbasins, which include the northern llanos basins, the large Amazon basin, and the Paraná basin (which is partly plain and partly in the planalto plateau).

The subbasins contain a wide array of sedimentary formations, ranging in age from Devonian, normally in the bottom of the graben, but with local outcrops, to Quaternary. The. shallow formations of the plains usually date from the Quaternary and Tertiary periods and are composed of relatively thin veneers of fine alluvial, eolian, or lacustrine sediments (or a combination) covering coarser alluvial units that cross the plains forming wide, shallow belt-shaped basins. This succession is clearly visible in the Argentine pampas and the southern Gran Chaco near the Paraná River, where a well-defined extensive alluvial basin (Arenas Puelches) underlies eolian and lacustrine deposits (pampeano and postpampeano formations). Similar local sequences are observed in the llanos and Amazon regions.

These sedimentary units are usually good aquifers that are characterized by their accessibility (they are only a few dozen metres deep), volume (although relatively shallow, they extend over a large area), and renewability (related to the size of the recharge area in spite of overlying aquitards throughout most of the plains region).

The plains are crossed by many long rivers. The llanos are drained by the Orinoco and its many large tributaries. The Amazon region is largely fluvial; high levels of precipitation, the huge area covered, and its location downstream of the eastern slopes of the Andes combine to produce a number of large waterways the Amazon, the Maranhon, the Negro, the Madeira, the Tapajos, and many others, which together form the largest (volume) hydrographic system in the world. The Chaco and the pampas are traversed by the mighty Paraná River and its tributaries (Paraguay, Pilcomayo, Bermejo, and Salado rivers among others) and the Uruguay River, which together form the Río de la Plata estuary.

Ease of transport and, to a lesser degree, water supply have prompted the establishment of many cities along the shores of these rivers: Ciudad Guayana and Ciudad Bolívar next to the Orinoco; Belem, Santarem, Manaus, and Iquitos on the Amazon; Rosario, Santa Fe, Paraná, Resistencia, Corrientes, Posadas, Foz do Iguaçu on the banks of the Paraná River; Asunción on the Paraguay River; and Buenos Aires-La Plata at the confluence of the Paraná River and the Río de la Plata. Most of these cities get their water from the rivers, although the easily accessible aquifers are used in suburban areas and for industrial purposes (Menendez and Araujo 1972; Brinkmann 1983; Fili 1983). In some cases, large urban municipalities depend to a considerable extent on their groundwater resources, e.g., La Plata and Quilmes municipalities with a combined population in excess of 1 million.

In cities of the plains region that are located far from a main river, local streams cannot provide the necessary volume of water, because their flow .may be irregular, they contain too much suspended material, or they are contaminated (Herrero 1983). In many of these cases, local water companies are using or are planning to use groundwater sources instead. This is the situation in a number of cities in Argentina (Río Cuarto, San Nicolás, and Junin), Paraguay (Mariscal Estigarribia), and Brazil (Corumba).

Near the Andean foothills, altitude increases as the terrain gradually slopes up toward the descending mountain valleys. This foothills region forms a 100- to 200-km wide belt along the eastern edge of the mountain ranges, in which an interdigitation of alluvial formations of varied grain size (but predominantly coarse) is found. On a geological map, these alluvial formations resemble fans diverging from the valley outlet toward the lower flatlands. In many cases, the fans are buried by younger formations (frequently due to local subsidence relative to the neighbouring mountains) and present interesting potential groundwater reservoirs with a large storage capacity and high hydraulic conductivity.

A chain of good aquifers runs along the eastern foothills of the Andes from Venezuela to southern Argentina, and several cities have taken advantage of this. Many more cities have recently begun, or are planning to begin, using this groundwater resource to satisfy the growing need for water and compensate for the deteriorating quality of nearby surface water. Cities currently using these alluvial aquifers include Villavicencio in Colombia, Santa Cruz in Bolivia, and San Juan and Mendoza in Argentina.

The eastern foothills of the Andes also provide good sources of surface water because of the many rivers descending from the neighbouring mountainous areas, which are frequently humid because of their exposure to the Easterlies (intertropical trade winds) and often possess large volumes of water stored as snow, especially in the midlatitude regions.

Several factors have promoted the development of groundwater supplies in some of the urban areas mentioned above. The surface sources, which generally have a seasonal or irregular flow, have become more unreliable because of deforestation and degradation of the landscape in the upper basins. Also, various human activities in the Andean highlands have had deleterious effects on the quality of water in the streams flowing toward the plains. Mining has not only devastated landscapes and, therefore, increased erosion and the amount of transported soil material in the streams, but is also a source of a number of toxic substances (e.g., mercury and cyanide in the widespread gold-mining areas) that may seriously affect the potability of the surface water. The growth of the cities themselves also may make the continued or expanded use of traditional water resources difficult or uneconomical.

The islands of the Caribbean and Central America

The Caribbean-Gulf of Mexico region is completely different from the previously described zones. It is composed of several hundred islands of varied size and geological characteristics and an extensive flat, low-lying coastal zone on the mainland. The islands may have a crystalline core (e.g., Cuba and Hispaniola) or they may be mainly volcanic (e.g., Martinique) or sedimentary, frequently calcareous (e.g., the Bahamas, Barbados, and Grand Cayman). Some have a complex landscape with various geological formations, as is the case in all the largest islands (Cuba, Hispaniola, Jamaica, Puerto Rico, and Trinidad). By and large, water on the islands is obtained from two sources: reservoirs in the highlands (Kingston, Jamaica; Port-of-Spain, Trinidad and Tobago; and San Juan, Puerto Rico) and aquifers, usually karstic, in the coastal plains (Havana, Cuba; Bridgetown, Barbados; Nassau and New Providence in the Bahamas; Kingston, Jamaica; and along the northern coast of Puerto Rico) (Quinones and Alicea-Ortiz 1985; Gomez-Gomez 1986; Gonfiantini and Simonot 1989; Gonzalez Piedra 1989a).

The mainland area of the Caribbean-Gulf of Mexico is a relatively narrow belt extending for several thousand kilometres along the coast through northern South America, Central

America (from Panama to Honduras), the Yucatán peninsula, the coastal plains of the Gulf of Mexico, and along the coast of Texas, Mississippi, and Louisiana to Florida in the continental United States. In general, this is a typical coastal region, with foothills alluvial deposits intercalated with sedimentary basins, including locally elevated sedimentary blocks and various marine and palustrian formations.

Surface water is usually confined to the relatively short rivers descending from neighbouring highlands. In some cases, the volume of water is considerable (e.g., the Usumacinta River in Mexico and the San Juan River in Nicaragua), but in others it is insufficient to meet the requirements of existing cities. This is typical in karstic areas where run-off is extremely limited because of high infiltration rates, e.g., in the Yucatán peninsula, Cuba, the Nuevo León-Monterrey region, and Florida. These four areas depend almost exclusively on groundwater for their municipal water supplies, which they extract from highly productive limestone aquifers. Karstic aquifers provide almost all the water consumed in the cities of Mérida (Yucatán), Miami (Florida), and Havana (Cuba).

The Patagonia platform

In the southern tip of South America, the relatively large sedimentary platform (Patagonia) does not have significant water requirements, because of its low population density. The region is arid (annual precipitation less than 400 mm), but it receives a portion of the fluvial outflow from the adjacent humid Pacific Andean region. A considerable proportion of the water used by the few cities of the Patagonia comes from this surface source. Although there are aquifers containing significant volumes of water, they have not yet been heavily used.

Socioeconomic environment

Latin American society is a result of a process of colonization and conquest of a large number of indigenous peoples inhabiting a relatively isolated continent by expanding European political powers. Indigenous American societies were poorly developed technologically, particularly with respect to their military potential. The wheel, iron, gunpowder, the horse, and many other tools commonly used in Europe were unknown in America. Most indigenous American populations were organized in small political units of a few tens of thousands or, at most, a few hundred thousand people. This was the case in the Caribbean islands that suffered the first onslaught of the Spanish invasion.

The arrival of the Spanish was traumatic. In Haiti, almost all of the indigenous population, nearly I million people, was exterminated in less than 50 years. The people of Cuba suffered a similar fate; after 40 years of Spanish domination, the population was reduced from more than I million to only a few hundred people. According to Fray Bartolome de las Casas (1552), the indigenous populations of Jamaica and Puerto Rico were reduced from several hundred thousand to a mere few hundred in slightly more than 40 years. In Mexico, Peru, Guatemala, and other areas of Spanish America, the conquest was equally genocidal. The chronicles of the 16th century describe innumerable cases of destruction of communities for no reason, burned cities, enslaved men and women, and destitute children throughout the continent.

Probably, with only a difference in degree, other colonial powers behaved in a similar fashion. When they found a local population to enslave, they did so. The Portuguese in Brazil, in particular, based their colonization on Indian slave labour and only at a later date imported African slaves. When the French, British, Dutch, and other European powers arrived in the Caribbean, most of its indigenous population had already disappeared.

In some areas of the continent, the indigenous population survived. In Mexico and Peru (which included present-day Ecuador and Bolivia), the large aboriginal population of several million (probably 10 million in the Inca region and about the same in the present Mexican territory) was inconvenient and even impossible to eliminate. In these countries, as well as in Guatemala, Nueva Granada (Colombia), and a few other areas of the New World, the Indian population remained a significant demographic force.

In countries without precious metals or. stones, the arrival of the Spanish and Portuguese was delayed, but in almost all cases a similar genocide was carried out. Hundreds of communities, ethnic groups, and cultures were drastically reduced. Only a small fraction of the original ethnic groups survived to the 20th century.

In spite of this widespread elimination of native societies, Latin America remains, in large measure, a mixed-race continent because of strong interbreeding between the original Indian population, the European immigrants, and descendants of the African forced migrants.

By the 1810s, the Spanish empire had disintegrated and gradually most of the Spanish provinces of America became independent countries under the rule of *criollo* elites of Spanish or Métis descent. Only Cuba and Puerto Rico remained under Spanish control until the Spanish-American war in 1901. Although the Portuguese empire survived until late in the 20th century, its main American colony, Brazil, became independent by 1823.

This history produced a heterogeneous demography. In Bolivia, Ecuador, El Salvador, Guatemala, Mexico, and Peru, the population is almost exclusively Métis and Indian; in Brazil, Cuba, the Dominican Republic, Guyana, Haiti, Jamaica, and other Caribbean islands, the African element is important. Argentina, Uruguay, and Venezuela have a high proportion of people of European descent.

Economically, LAC countries became dependant on the main economic powers of the world. Their economies were based on the production of raw material for the more developed countries of Europe and America. During the late 19th century and the beginning of the 20th century, the dominant influence was the United Kingdom and, to a lesser degree, France and Germany. Early in the 20th century, the growing importance of the United States was strongly felt in the nearby Caribbean region, particularly after the construction of the Panama Canal. Over time, the influence of the United States increased and, after the World War II, became the predominant force throughout the continent.

Meanwhile, the industrial development of Latin America was limited to central regions of the largest countries. Probably the fastest developing urban centre was Buenos Aires in Argentina, fostered by the influx of money from export of food to war-torn European countries. Other centres that developed strong economies were São Paulo in Brazil (based on the export of coffee); the Valley of Mexico; Santiago de Chile in the central valley of Chile; Havana, Cuba (based on the export of sugar and tobacco); and Montevideo, Uruguay (based on the export of beef and wool). After the 1950s, several other areas followed this pattern: the Caracas Valley in Venezuela; Lima in Peru; Bogotá and Medellín in Colombia; Pôrto Alegre, Curitiba, Salvador, Recife, Belo Horizonte, and Brasília in Brazil; Guayaquil in Ecuador; Guatemala City in Guatemala; Santo Domingo in Dominican Republic; and San José in Costa Rica.

Currently, the continent is unevenly developed, with large, highly industrialized megacities (of which the largest are Mexico City, São Paulo, and Buenos Aires), a large number of medium-sized urban centres, of 0.1 to 2 million inhabitants, acting as both industrial and commercial cities, and a huge agricultural hinterland of rural areas and small towns with variable population density.

The Andes and the mountainous areas of Mexico and Central America are populated by a large number of peasant communities, based to a large extent, both culturally and biologically, on the main pre-European agricultural civilizations. Although these communities have lost most of their ancient lore, they have preserved many useful (appropriate) technologies that are now being threatened by the so-called modern technologies.

The plains of the Amazon jungle are sparsely populated, mainly by itinerant farmers, hunters, and gatherers composed of a myriad of micronations. They are gradually being marginalized in the more remote comers of the forest. A few large urban centres (Belem, Iquitos, Manaus, and Santarem) are developing quickly along the Amazon River and its tributaries, and large tracts of forest are being burned or cut every year to clear land for short-term farming activities (usually rain-fed rice) and extensive animal production.

In the savannas and prairies, production is concentrated on cereal crops (Buenos Aires, Santa Fe), oil seeds mainly soybean (Mato Grosso, Brazil), or cattle (the Colombian-Venezuelan llanos, the Argentinean pampas, Uruguay, and Rio Grande do SuI in Brazil).

The Caribbean islands are even more heterogeneous than the continent. Because of their colonization by several European powers and the strong African influence, many languages and cultural styles have developed in isolation from neighbouring islands. In Cuba and the Dominican Republic, Spanish is spoken; Puerto Rico is a bilingual Spanish-English country; Antigua, Barbados, Grenada, Jamaica, Saint Lucia, and Trinidad and Tobago are English-speaking nations; Creole and French are spoken in Guadaloupe, Haiti, and Martinique; and there are even some Dutch islands, such as Aruba, Bonaire, and Curaçao. These countries, which originally concentrated on growing sugar and other tropical produce, are now becoming dependent on tourism, particularly North American, but also European and, to a lesser degree, Venezuelan and Mexican.

As a result of recent trends toward economic globalization, the Latin American continent is experiencing important changes that will probably deeply affect its socioeconomic structures. Mexico is entering the North American Free Trade Agreement (NAFTA), which was preceded by a continuous influx of *maquiladora* industries that have completely changed the face of northern Mexico, allowing the development of several large industrial cities in previous small towns. With NAFTA, this process will accelerate, increasing the stress on local resources and the environment.

In South America, a new trading bloc is developing; Argentina, Brazil, Paraguay, and Uruguay have joined to form the Southern Cone Common Market (MERCOSUR). Increasing access to markets will have important consequences for some of the partners of this new agreement. The Andean countries are moving gradually to formalize the Andean Pact with similar characteristics, and the Central American countries already have an analogous agreement.

The trend seems to be toward increased industrialization and concentration of population. Rural migration, which has been a significant tendency in the 20th century, is probably going to continue for many more years. The traditional farming villages are becoming more and more company towns producing typical commercial crops (e.g., barley, sugar, bananas, pineapple, cucumber, broccoli, and citrus fruits).

All these processes are putting more and more pressure on the limited water resources of the continent. Originally, this pressure was felt only where streams and bodies of water were small. However, even larger rivers are becoming highly contaminated to the point where only a few remain safe. Groundwater reservoirs are suffering similar threats, reducing options for meeting the growing needs of industry and the population.

3

Environmental degradation and inadequate policies

Latin America and the Caribbean (LAC) were originally populated by traditional societies that were in equilibrium with their environment. The agricultural communities of the Andes and other mountainous or highland areas had developed cultivation systems based on indigenous crops, such as corn and potatoes, and indigenous animals, such as llamas and turkeys. Soil protection systems, such as crop rotation and planting in terraces, were developed. Thus, by the time the Europeans arrived, although the population density was relatively high, the farming systems were well adapted to the geography of the occupied sites (i.e., mainly Andean valleys, foothills, slopes, and plateaus).

The extractive communities of the tropical rain forest had also developed a sophisticated culture, exploiting the myriad of plants and animals found in the jungle environment. Associated with these extractive activities, the people of the rain forest practiced an itinerant agriculture, growing a few edible species, such as cassava. Other regions of the continent were also inhabited by various types of extractive communities (hunters, fishermen, gatherers, and itinerant farmers). The population density of these cultures was low and, therefore, their effect on the environment was limited.

Although these pre-Columbian societies did not have institutionalized environmental policies, they had developed environmentally friendly traditional beliefs, behaviours, and knowledge (Le., hunting taboos, totems, and an in-depth empirical knowledge of the surrounding natural world). With the arrival of the Europeans, America was integrated into the global system and became, primarily, an exporter of minerals and various agricultural products of interest to the colonial powers. The ancient, environmentally friendly, agricultural and extractive systems were disrupted, and widespread degradation took place in many areas. Overplanting, overgrazing, and relentless mineral extraction became the rule, and the effects were soon felt in the most fragile ecosystems, e.g., the arid areas and steep slopes. Gradually, the new exploitative practices spread through most of the continent. However, in spite of this invasion, the traditional systems survived in isolated areas of the continent and, even in the 20th century, many pockets of traditional farming or extractive communities still exist in equilibrium with their environment.

Colonial and *criollo* societies did not define environmental policies, but rather adopted a permissive attitude based on a semi feudal system of private property and the search for immediate returns. With increased demographic growth, industrialization, and urbanization, the effects of this attitude began to be felt throughout the natural environment. There was widespread degradation of vegetative cover, soil erosion, increased flooding and drought, water and air pollution, and an increase in the number of previously unknown diseases. Now, the LAC is confronted with a serious environmental crisis at the regional level with potential planetary effects.

The issues resulting from or causing this crisis are many, some at the global level and some at the regional, national, and local levels. There is a clear and urgent need to address them. The following sections provide a brief description of the main environmental problems requiring immediate attention.

Main environmental issues affecting the LAC region

Global issues

The LAC region is very large: over 20 million km^2, i.e., 15% of the world's land area. The region contains more than 50% of the planet's remaining rain forests and 20% of the world's rivers by volume. The population has exceeded 400 million and is expected to double in less than 30 years.

Environmental issues that have an effect at the global level or are a regional expression of global issues are:

- Climatic changes;
- The greenhouse effect, the ionospheric hole in the ozone layer, and other modifications of the radiation balance;
- Degradation of oceanic waters;
- Losses in biodiversity;
- Losses of traditional knowledge;
- Human rights of traditional societies; and
- Irreversible losses of planetary natural resources.

The size and population of the LAC determine that major events taking place there will produce significant effects at the world level. Probably the most important of these is the progressive and rapid elimination of the tropical rain forests, which are considered an important source of planetary oxygen and allow the fixation of atmospheric carbon dioxide, a factor in the "greenhouse effect." The rain forests also contain a considerable proportion of the world's gene pool. Many of the plants and animals surviving in the LACs tropical forests may provide benefits through various and not always predictable uses.

Over many generations, the traditional communities of the forest region have accumulated considerable empirical knowledge about useful properties of a large number of plants and animals, which is now being lost at an accelerated rate. In recent times, scientists have become increasingly aware of the advantages of many forest management practices used by these societies compared with modern approaches. Clearly, there is a great deal to learn from these not-so-primitive cultures. More important, because of its ethical connotations, is the progressive physical and cultural elimination of these traditional populations and the lack of recognition of their basic right to life, to practice their beliefs, to control their territories, and to continue their way of life without unwanted interference.

Regional issues

Some LAC environmental developments have regional or multinational implications, particularly those affecting resources or ecosystems. Shared water resources, for drinking water and for fisheries, provide an acute example. The headwaters of many hydrographic basins are in one country, whereas the middle and lower courses are in a different national territory. Coordination of some or many activities carried out in the basin may be required. Similar problems are encountered with respect to coastal seas and the release of material into the atmosphere.

Environmental issues with regional implications include:

- Degradation or overuse of water resources in internationally shared hydrographic basins;
- Degradation of atmospheric resources with effects beyond national borders, e.g., acid rain;
- Degradation of internationally shared coastal waters; and
- Losses of aquatic biological resources in internationally shared waters.

In the LAC region, critical problems of national scope are:

- Losses of terrestrial biological resources (flora and fauna);
- Losses of aquatic biological resources (oceanic and lacustrine);
- Soil erosion;
- Water contamination;
- Increased frequency of natural disasters because of human action;
- Increased negative effects of natural disasters because of increased population and inadequately located settlements;
- Damaging effects of inadequate waste disposal or recycling systems;
- Damaging effects of inadequate basin management; and
- Degradation of coastal waters.

National and local issues

At the national and local levels, the environmental issues are varied and depend on the particular country or national region under consideration. However, they can be categorized according to the type of resource being degraded: water, air, soil, geological resources, biological resources, or human (artificial) environments.

Future trends

The consequences of the continuation of these damaging phenomena are difficult to predict with accuracy. However, in a very general way, at the national and regional level there will be a decrease in the quality and quantity of most natural resources. This will affect production of goods and quality of life will also be gradually eroded, especially among the less fortunate social sectors.

At the global level, if unabated, the environmental trends in the region will add to the planet s load of hazardous anthropogenic modifications. The implications of these changes are not fully understood, but sooner or later they will endanger not only the region, but also the whole of humanity.

Halting current trends and managing the environment

It will not be easy to stop or even slow down the present damaging trends. During the first half of the 20th century and until the early 1980s, strategies of a purely developmental nature were given overwhelming priority over environmental concerns. Hundreds of dams, highways, pipelines, power lines, factories, and cities were built, forests were logged or burned for agricultural production, and huge quantities of fish were removed annually from the seas without allowing for replenishment of the stock. Environmental considerations took a back seat to gigantic engineering plans, which, in large measure, were financed by the generously available petrodollars in the late 1970s, producing as an unwanted bonus the similarly gigantic foreign debt that has affected almost all countries of the region.

The effects of these expenditures and works were at best mixed. Standard of living increased substantially for many millions of LAC inhabitants. Access to electricity and water increased, land and air communications have expanded, and telecommunications can reach even the most remote corners of the countries. Health has improved, level of literacy has increased, and access to luxury items such as appliances, radios, and television has been enhanced. In this sense, the balance has been positive. On the other hand, many millions of people were left out of this development, because demographic growth and urban migration outpaced expansion of services and job opportunities. Today, there are many more urban slum dwellers than 40 years ago (not only in absolute numbers). At the same time, it is becoming increasingly clear that the rural poor are not much better off. The trends have favoured increased disparity over social equalization.

Unfortunately, this developmental period had an effect on the environment. Complete ecosystems were wiped out or deeply disturbed. Huge forests have become artificial grasslands, e.g., the Araucaria forests of southern Brazil and the tropical forests of the Mato Grosso; the former were almost completely eliminated during the 1960s and 1970s, the later are still in the process. Plentiful species, such as the anchoveta on the Peruvian coast, have become scarce.

During these years, LAC communities increased their relentless exploitation of the environment through overlogging, overhunting, overgrazing, overfarming, overwatering, overpumping, and overfishing, bringing about a significant reduction in resources and in some cases their disappearance. For some native people, development meant genocide: the roads brought settlers and miners, native lands became valuable assets, and little by little these ethnic groups and their environmentally friendly land-management practices have been replaced or are restricted to the most marginal lands.

It has become clear that there is a need for less permissive and more rational environmental policies than the often unspoken ones practiced over the last three or four centuries. Some countries have begun to take measures or approve legislation to reverse the trend. At least seven countries have approved comprehensive environmental laws (Colombia, *Código Nacional de Recursos Naturales Renovables y de Protección al Medio Ambiente,* 18 December 1974; Venezuela, *Ley Orgánica del Ambiente,* 16 June 1976; Ecuador, *Ley para la Prevención y Control de la Contaminación Ambiental,* 21 June 1976; Costa Rica, *Decreto sobre Formación del Sistema Nacional de Protección y Mejoramiento del Ambiente,* 22 January 1981; Cuba, *Ley de Protección del Medio Ambiente y del Uso Racional de los Recursos Naturales,* 12 February 1981; Brazil, *Lei sobre a Política Nacional do Meio Ambiente, seus fins e mecanismos de formulacao e aplicacao e outras providencias*, 2 September 1981) and Brazil, Mexico, Uruguay, and Venezuela have created environmental ministries.

There has been a continued trend toward international and regional cooperation in environmental policy, particularly in the last two decades. Some of these agreements include:

- Treaty for Cooperation in the Amazon Basin: Brasília 1976;
- Treaty for Conservation and Management of the Vicuna: Lima 1979;
- Treaty for the Conservation of Marine Resources: Canberra 1980;
- Treaty for the Protection of the Marine Environment and the Coastal Zone of the
- Southeast Pacific; Lima 1981;
- Agreement of Regional Cooperation for Hydrocarbon and other Toxic Substances Contamination in the Southeast Pacific: Lima 1981;
- Convention on Marine Law: United Nations 1982;
- Agreement for the Protection and Development of the Marine Environment in the Greater Caribbean region: Cartagena de Indias 1983;
- Vienna Convention for the Protection of the Ozone Layer: Vienna 1985; and
- World Agreement on the Control of Trans-Border Movement of Hazardous Substances: Basel 1989.

Environmental policies for the region

Current environmental policies

Although in many countries it is difficult to identify a logically consistent set of policies, their actual results can be observed and measured. In most cases, the policies are expressed through various mechanisms that affect the behaviour of the population and enterprises, e.g., rules of land allocation, tax structure, criteria for credit assignment, and types of fines for environmental transgressions and their effective enforcement. A typical example of a well-defined policy is the Brazilian one that encourages deforestation in the Amazon (Binswanger 1991). Its principal elements are:

- Agriculture is almost exempt from income taxation and has become a tax shelter.

- The rules of land allocation tend to favour clearing of land, recognizing the *direito de posse:* if the *posseiro* (squatter) has effectively used the land for a period of 1 year and 1 day and issuing the title to the land after 5 years. In the Grande Carájas area, INCRA (Instituto Nacional de Colonização e Reforma Agraria) uses the rules: a claimant living on the land can obtain preference over other potential claimants to obtain a title for up to three times the land area that he or she has cleared in the forest. In this way, the practice of clearing the land, even beyond farming needs is actively encouraged.
- Although the *Estatuto da Tara* provides for a progressive land tax, the tax actually paid can be reduced by up to 90% if the forest is cleared. The reason for this is that forest land is considered unused and, therefore, pays the maximum rate. Converting forest to farming lands or pasture will decrease the land tax. Again, deforestation in clearly encouraged.

The consequences of these policies have been environmentally catastrophic.

In many other cases, taxation and land-allocation policies are used (consciously or unconsciously) with similar effects. Obviously, these mechanisms can be used in a completely different manner. Taxes and land-allocation criteria can promote rather than discourage environmentally friendly attitudes, as can criteria for obtaining credit or pricing water, electricity, and other services. The tools for a rational approach to environmental management are many and can be very effective. Research has a role to play in this area.

Basic frameworks

Environmental policies are the courses and methods of action selected, in light of given conditions, to guide and determine present and future decisions about the environment.

Defining detailed environmental policies requires a thorough knowledge of the environment, which in many cases is not available. In these cases, baseline studies or research on specific environmental topics may be necessary. In the LAC, knowledge about the environment is clearly insufficient and, when information exists, it is often not readily available.

A second key element for an appropriate policy formulation process is the existence of an adequate institutional framework that allows for the jurisdictions of the various decision-makers to be defined. In other words, it defines who must decide what and where, at both the policy-formulation and the implementation levels. This framework usually evolves simultaneously with the need to reformulate policies, and it is very difficult to change it in advance. However, the more progress achieved in the institutional area, the easier it becomes to produce an environmentally friendly set of policies.

The interrelations between the institutional aspects and the various approved and implemented policies provide a rich field for useful research. In the LAC region, the institutional framework in the area of environment has progressed slowly. Only four countries have environment ministries; in the rest, decisions about the environment are made in various government departments of different ministries and public commissions or boards.

A third element, closely linked with institutional framework, is the legal framework the set of laws, decrees, municipal bylaws, etc., that are applicable to environmental issues. In many LAC countries, these rules are dispersed throughout the system and are not always easy to identify. At least seven countries, however, have comprehensive environmental laws (Brazil, Colombia, Costa Rica, Cuba, Ecuador, Mexico, and Venezuela). The field of environmental law is complex and rapidly evolving. Research on this topic may be very important to allow optimization of efforts.

Another basic element required for the formulation of environmental policies is the socioeconomic framework in which the courses of action will be decided. Environmental decisions affect various social sectors and economic groups, whose input may be not only desirable but also, in many cases, unavoidable. There is growing evidence that, in the LAC region, special- and public-interest groups are becoming increasingly interested and active in environmental matters. There are tens of thousands of community, sector, and public-interest organizations, of which several hundred are nongovernmental organizations (NGOs), partly or wholly dedicated to environmental matters. Their number is growing quickly, not only in neighbourhoods of the large cities, but also in smaller urban centres, as a natural response to the perceived environmental catastrophe that seems to be developing.

Policy formulation and implementation

Once the basic framework is in place, a process of policy formulation can develop. However, even if all the elements are in place, there is no guarantee that the policies will be appropriate. It is important to ensure that all those interested, especially those defending the public interest, are able to play their roles. As a general rule, the more open the process of policy formulation, the more likely it will be that the policies will respond to the public interest and that their implementation will be successful. Policies defined in an arbitrary and authoritarian manner against the will of the population are destined for failure, even when they seem to be correct from a technical point of view.

In the LAC region, processes of defining environmental policies have often been initiated or decided in a bureaucratic way without, or with inadequate, public or community participation. New ways must be explored to produce appropriate policies with the participation of those affected by the courses of action to be decided.

The policy-formulation process may include an implementation strategy, although it may be modified in light of actual conditions. However, if the implementation of environmental policies is separate from the formulation process, it may be more difficult and even ineffective.

Changing existing damaging policies

Changing existing policies when their effect on the environment has proved to be negative is not always an easy task. In many cases, these policies comprise a collection of attitudes, traditions, behavioural patterns, and particular interpretations of existing rules. Even when it is obvious that the policies should be changed, many of the following obstacles must be overcome.

Lack of public awareness Lack of public awareness of the need for more rational environmental policies is a result of inadequate environmental education, in the media and in educational institutions, and inertia. However, the situation is changing as a consequence of deterioration of the quality of life and, to a lesser degree, increasingly effective education, not only in schools, but also through the action of NGOs and other community organizations.

Lack of awareness by decision-makers Decision-makers are key members of the environmental political equation, because they define the policies to be applied. However, the response of decision-makers to problems is often delayed. Governmental solutions to environmental problems (particularly when they imply a cost) tend to take place after public pressure is felt. These responses could be at the normative level (new rules), at the executive level (preventive or corrective actions, defining criteria for credit, tax exemptions, or reductions, etc.), or at the administrative level (monitoring, fining, and effectively applying existing rules).

Lack of adequate legal support Legal systems are slow to change. The new environmental situation requires a complete revamping of the legal systems of most LAC countries. Some changes have taken place. Several countries have approved environmental laws (PNUMA/ORPALC 1984); national parks have been created throughout the region; water laws have been approved or are under study in most countries; and environmental requirements have been introduced for hydraulic works and other types of structures. However, on the whole, the legal systems remain unresponsive to the actual needs of the rapidly developing industrial and agroindustrial LAC societies. This is particularly true in the most densely populated and highly urbanized areas of the continent, where concentration of the population and industrial activities has produced serious deterioration of most environmental elements. In addition, in many cases, the most effective laws for environmental protection (or nonprotection) are not in environmental codes, but rather in incentives for action (e.g., tax laws or civil or criminal codes).

Lack of an adequate institutional framework In some countries, attempts have been made to create an institutional base with environmental jurisdiction. In four countries, specific environment ministries were created and in other cases supraministerial, interministerial, or autonomous councils were formed. However, in most LAC countries, institutional support for environmental-policy formulation and implementation is still limited.

Poor knowledge of the nature, characteristics, and effects of existing environmental problems In-depth information on environmental problems, including policies being applied, is scarce and difficult to obtain. Efforts must be made to fill the existing gaps at the level of data acquisition, filing, and retrieval for specific purposes.

Few and **insufficiently trained environmental scientists** LAC educational systems train few environmental scientists or policymakers. Such experts must be drawn from other professions, e.g., social sciences, engineering, biology, geology, and architecture, and require retraining, which is not always available.

Approaches to policy formulation

The formulation of environmental policies goes beyond a simple statement of good intentions. It is the expression (spoken or unspoken) of a social and governmental will to carry out a specific course of action in the management of the environment. Because the environment affects, to a greater or lesser extent, all human activities, formulation of environmental policies traverses the whole spectrum of social and government actions. There is an environmental aspect to every method of action selected.

Even if it appears that no method of action has been selected, the functioning of the social system produces effects and these effects constitute a way of selecting. The approaches to environmental policy formulation can be:

- Developmental (or exploitationist), where priority is given to production. A typical developmental view was expressed by Gilberto Mestrinho, the governor of the State of Amazonas, Brazil, who stated, Only after we have improved the lives of humans can we begin thinking of the fauna and flora (*Time*, 16 September 1991).
- Conservationist, where the aim is to harmonize production and conservation of the natural environment through careful management.
- Preservationist, where priority is given to the full preservation of nature.

Issues in policy formulation and implementation

Principal actors

International	International agencies, for financial and technical support in national issues; on global issues, they may have decision-making power
Governments	Executive: Decrees, enforcement of laws, political decisions in various areas, definition of tax policies, credit assignment, land allocation, control, fining, etc. Presidency, Environment ministries, Other ministries (mainly health, agriculture, water resources, but also finance and public works), and Interministerial councils
	Parliament: Laws
	Judicial: Application of various rules
	Government corporations, e.g., water and electricity companies
	Provincial governments
	Municipalities
Social actors	NGOs
	Community and neighbourhood organizations
	Workers unions
	Professional associations
	Private sector

Problems in formulation of environmental policies

- Lack of public awareness of the need for more rational environmental policies;
- Lack of awareness by decision-makers of the best methods to define and apply appropriate policies;
- Lack of adequate legal support;
- Lack of an adequate institutional framework;
- Poor knowledge of the nature, characteristics, and effects of existing environmental problems; and
- Few and insufficiently trained environmental scientists, including policymakers, to assist or participate in the formulation process.

Issues in policy formulation and implementation

Problems and bottlenecks in implementation

- Unrealistic policies (too ambitious, unrelated to actual conditions);
- Difficulty in changing the whole set of rules affecting environmental actions (e.g., tax laws, environmental-responsibility laws, land-allocation laws, etc.).
- Partial changes may be ineffective; total changes may imply agreement among many parties, which is difficult to obtain;
- Lack or inadequacy of implementation tools: not enough personnel, not enough infrastructural support (laboratories, transport, etc.), not enough financial support
- Bureaucracy and corruption at the implementation level;
- Lack of public support or opposition by some affected groups; and
- Lack of government commitment at some levels or in some ministries.

Potential research areas

- Key environmental topics;
- Effects of specific existing environmental policies;
- Methods of policy formulation using the whole battery of potentially effective mechanisms;
- Institutional aspects of policy formulation and implementation;
- Legal aspects of policy formulation and implementation;
- Impact of social initiatives in the environmental field and on the role of these organizations in policy formulation and implementation; and
- Bottlenecks in implementation.

4

Hydrological basins

A hydrological basin is composed of the various terrestrial environments through which water moves toward an outlet, i.e., the territory drained by a water body or stream. Basins may include both surface and underground waters, which are closely interrelated and must be considered together. The three main components of a typical basin are:

- Slopes and watersheds,
- Hydrographic networks, and
- Groundwater systems.

These three elements are interconnected. Slopes and watersheds receive precipitation, which infiltrates the groundwater systems or flows toward the valleys forming streams. Part of the groundwater can be returned to the streams and water from the stream beds often recharges underlying aquifers. Some of the water evaporates into the atmosphere and falls again in the watersheds, closing the cycle. However, the cycle is open, because most basins exit into the sea or other major water bodies. The outlet of the basin is also an outlet for sediments, dissolved salts, and contaminants.

Surface water[2]

Surface water comprises the complex systems of streams, lakes, swamps, and other flowing or lentic water bodies. Streams are fed from two main sources: rain and springs (groundwater discharge). In arid climates, streams are mainly fed by run-off. Rain falls on unprotected soil and water does not penetrate the soil, but flows down slopes toward the thalweg. In humid areas, the opposite occurs; rainwater is intercepted by the vegetation, some evaporates, some infiltrates the soil, and only a small fraction flows away as runoff. Here, streams are fed mainly through groundwater discharge.

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[2] Updated information on administration of water resources and their uses can be found in ECLAC (1990).

Lakes and swamps are sustained in a similar way. In some cases, mainly in arid climates, the supply depends on runoff; in humid areas, most of their water comes from springs. Lakes in arid regions tend to have high levels of dissolved solids; in humid environments, the concentration of dissolved material is low.

Rivers and lakes often act as water sources for the large urban centres of South America. Rivers are usually dammed to create large reservoirs to store water and regulate its flow. Lakes are natural storage reservoirs and are often used directly for municipal supply.

Vulnerability to contamination depends upon volume of flow: large rivers are less vulnerable, small rivers are very vulnerable. The same rationale applies to lakes, although their susceptibility is usually higher than that of rivers because their water is renewed less frequently.

In spite of their exposure to pollution, which makes them hazardous in densely populated, industrial, and mining areas, surface water sources are relatively easy to clean up. This is particularly true of rivers and lakes with a high rate of renewal.

Anthropogenic impact on hydrographic basins

Hydrological basins evolve at a pace that depends on climatic, geological, and biological factors. Since the beginning of history, communities have introduced changes into this natural evolution. Agriculture, cattle-raising, logging and forest fires, quarries, and artificial structures have had an effect on the hydrological dynamics of slopes and plains.

With the growth in world population, particularly after the industrial revolution, effects of human settlement have gradually increased in intensity. Rural overpopulation and development of cities have modified the land-surface dynamics and increased use of water resources. The effects of human action on hydrological basins have been especially intense during the urban revolution of the 20th century. Large cities with populations numbering in the millions have developed throughout the world, and water use has become increasingly concentrated.

In the Latin American and Caribbean CLAC) region, these trends have been especially strong since the 1950s, as the population has become concentrated in the main industrial areas of the continent. As a result, demand for water has increased for domestic, industrial, agricultural, and other purposes. Dams were built, wells were drilled, and water is being removed from natural bodies at a high rate. Water taken from the environment is being returned to it with a much lower quality, thus degrading groundwater reservoirs and streams.

Hydrographic basins as management units

In the management of natural resources in hydrographic basins, one must consider the criteria employed to define the management unit. Hydrographic basins are frequently chosen as management units, rather than ecological, geomorphologic, or geological regions or political units. The reason for this choice may be that ecology, soils, rocks, or political jurisdictions are not as important as water, from the point of view of regional management.

Management of water must include the whole hydrographic basin from the mountain snows to the valley streams and lakes as well as underground water.

Although hydrographic basins should not be considered necessarily as the most adequate management units, they have, in fact, served the purpose many times throughout the world. They may be the best choice when water is a central focus in planning, i.e., when it is scarce or when it becomes a key factor, not only for drinking and irrigation, but as a source of energy and a pathway or barrier to transport. The more important that water resources are in communities, the better suited are the hydrographic criteria for appropriate management.

The Amazon basin

The largest basin in the world, the Amazon, covers an area of 6.157 million km^2, of which almost two-thirds is in Brazil; the rest is in Peru (almost 1 million km^2), Bolivia (0.825 million km^2), Colombia, and Ecuador. Water flow near its outlet averages 150000 m^3/second, by far the largest flow volume on earth. Geographically, the basin is divided into a mountainous upper basin in the Andes and Bolivian plateau, the hilly, undulating area of the Brazilian and Guyana shields and the wide, low-lying plains on both sides of the central valley.

The Amazon basin is sparsely populated by about 25 million people, of whom a significant number inhabit the highlands and slopes of the Andes. The flatlands of the Amazon rainforest have a much lower population density, with settlements mainly along the rivers. The major cities of the basin are Manaus and Belem, with about 1.5 and 2 million people, respectively. Other large cities of the basin include Iquitos in Peru and Santarem in Brazil. Travel between communities of the basin is by air or water. Land routes are few and almost nonexistent in the heart of the forest.

Because of the importance of the hydrographic network and its relatively homogeneous character, the Amazon basin should be managed as a unit, particularly from the point of view of transport and communications. (The Amazon basin is not completely homogeneous; there are hilly, mountainous, and flat areas and various ecosystems. However, the many large homogeneous units are much larger than similar units in other basins.) In addition, the many dams that have been built and are planned are expected to have a damaging effect on the fluvial ecosystems throughout the basin. Viewing the basin as a unit will facilitate sound and sustainable management strategies for the Amazon region.

The Río de la Plata basin

This multinational basin, covering 3.8 million km^2, comprises the Río de la Plata and its main tributaries, the Paraná and the Uruguay rivers. The average flow in the lower reaches of the Paraná River is about 20 000 m^3/second (14 457 m^3/second at Rosario; 15 862 m^3/second at Corrientes). In the smaller Uruguay, the volume is about 5 000 m^3/second (4 708 m^3/second at Concordia and Salto). The main tributaries of the Paraná are the Paraguay (flow, 2940 m^3/second at Asunción), the Iguazú (almost 1000 m^3/second above the junction with the Chopim River), the Tietê River (600 m^3/second at Pereira Barreto), and the Paranapanema (915 m^3/second north of Londrina). The Uruguay s main tributary is the Negro River (about 700 m^3/second 100 km above its junction with the Uruguay).

This hydrographic network serves a population of about 70 million people, of whom about 47 million are in Brazil, 15 million in Argentina, and the rest in Paraguay (4 million), Uruguay (2.5 million), and Bolivia (1.5 million). The Río de la Plata basin provides:

- The water supply for many cities (Buenos Aires, São Paulo, Asunción, Rosario, Santa Fe, Paraná, Posadas, Corrientes, Cuiabá, and many others) and hundreds of thousands of farms;
- Irrigation water for crops (sugarcane, rice, fruit trees, etc.) in five countries;
- Energy, through large hydroelectric dams (Itaipú, Salto Grande, and the almost completed Yacireta, among others), for four countries;
- Transport, particularly the Paraná-Paraguay system, which provides the main route for produce from Paraguay and the South American Mesopotamia;
- Water for industrial and mining activities; and
- A disposal site for most liquid and soluble effluent from cities, industries, farms, and mines.

It is impossible to plan satisfactorily for these uses if the whole hydrographic basin is not taken into account. Water evaporating in the Pantanal will not reach Asunción, water pumped from the Uruguay River into the rice fields of Uruguaiana will not feed the Salto Grande reservoir, water polluted in the upper Tietê will be unusable or of poor quality in the lower Tietê, and, in the upper Paraná, a dam may become an obstacle to navigation, but improve land transport. For comprehensive planning of communications, farming, urban development, and energy production, the basin must be treated as a unit.

The Magdalena basin in Colombia

The Magdalena River basin is entirely in Colombia, descending 1 550 km from the highlands of the main Andean ranges toward the Caribbean with a flow in excess of 2 000 m^3/second in its lower reaches. Like the Río de la Plata basin, the Magdalena basin serves many purposes and is used extensively. Bogotá, Cali, Barranquilla, and Cartagena all take water from the system. Generation of hydroelectric power is important. Fluvial navigation and fisheries are less important now than they were in the past, but the potential for these activities remains with adequate planning and implementation.

On the other hand, the Magdalena River and its tributaries are the main drains for the sewage systems of most Colombian cities. The worst problem is caused by the Bogotá River, which receives all the effluent from the Bogotá metropolitan area (over 4 million people) and joins the Magdalena near the city of Girardot. Downstream from Girardot, the quality of the river water becomes so poor that it is hazardous to human health.

The Magdalena basin should be managed as a hydrographic unit, because water is the common denominator of most activities with economic or social significance in the region.

The Rio de las Balsas basin in Mexico

The Balsas is the outlet for a complex hydrographic basin that includes important parts of the Mexican volcanic plateau and limestone (karstic) areas with sinks and underground courses (the complex cave systems in the Morelos formation, including the well-known Cacahuamilpa and La Estrella caves) forming the Amacuzac River, one of the main tributaries of the Balsas. The southern watersheds are composed of humid and subhumid forested mountain areas of the Sierra Madre del Sur. The lower areas of the middle course are hot, semi-arid regions, and further downstream are coastal plains near the Pacific Ocean.

The Río de las Balsas is not a communications route nor an important barrier. It is not used for urban water supply (except by some small towns), it is not a major source of electric energy, and its tributaries are not extensively used for irrigation. In this case, therefore, the hydrographic basin may not be the most practical planning unit. Geomorphologic, geological, or political areas, or a combination, may be more suitable for management (Carabias et al. 1992).

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5
Groundwater sources

Groundwater constitutes one of the main sources of water for human consumption. Underground reservoirs contain much more water than is available as fresh surface water, and it usually does not require treatment before it can be used. Groundwater is also often close to where it is needed, making long pipelines and storage structures unnecessary. Capital investment can be incremental and, therefore, groundwater is better suited to developing countries.

In many urban areas, groundwater can provide the most appropriate solution to the population s water needs, because it can be used inexpensively to supply a large volume of good quality water. However, the suitability of groundwater for urban use depends not only on need, but also on the hydrogeological characteristics of the aquifer under consideration. In Latin America, these characteristics can vary widely.

Suitability of groundwater reservoirs

The hydrogeological systems of Latin America and the Caribbean (LAC) are as varied as its geography. Aquifers have a wide range of hydrogeological properties: highly permeable or relatively impermeable; porous or fractured; containing only a few thousand litres of water or many billions; their waters can be fresh or briny; and they may be pristine or highly contaminated. However, when groundwater is considered as a potential source of water for urban or suburban communities with high consumption requirements, the spectrum of possibilities is considerably reduced.

Generally, the main limitations in tapping groundwater sources for urban use are economic, because of the cost of exploration, extraction, conduction, treatment, storage, and distribution. In deciding on the type of supply to be used, groundwater costs should be compared to the cost of other available water resources. Only when groundwater is the only source of water that is readily available, is cost not an important factor.

Some of the geological and geographic conditions that favour the use of groundwater for urban water supply are:

- Proximity to the consumption area;
- Large-volume reservoir;

- Shallow depth and low pressure; High water yield;
- High rate of renewal; Acceptable water quality; and
- Low risk of unwanted effects due to intense pumping.

Proximity to the consumption area

One of the highest costs of supplying water to cities is associated with its conduction from production to consumption sites, especially when this route is uphill or through some geographic obstacle, such as mountains or canyons. Consequently, the closer an aquifer is to a city, the more attractive it is as a water source.

The ideal situation occurs where an aquifer underlies the consumption area, particularly when it is artesian because no pumping or extensive conduction would be required and risk of contamination would be low. These conditions are (or were) relatively common in many cities of the world. However, urban use of artesian aquifers often lowers the water level below that of the well head; natural pressure is lost and pumping may be required. Even with this added cost, the economic convenience of having a groundwater reservoir under a city often easily outweighs other considerations.

Cities in which aquifers lie under the consumption areas include Mexico City, Buenos Aires-La Plata, Bangkok, and Lima. Other cities using aquifers must transport water over a considerable distance, e.g., Guadalajara and Monterrey in Mexico, Havana in Cuba, and Jakarta in Indonesia. Distance from the wells, springs, or galleries to the consumption area is always a major factor in the cost of water and a consideration in selection and development of well fields.

Large-volume reservoir

A suitable aquifer must also contain a sufficient volume of water for use over a relatively long period, i.e., 10 years or more. For example, consider the requirements of a city with 100 000 inhabitants, consuming water at the rate of 500 L/day per person. This city would use over 18 million m^3 of water per year. Assuming an annual average recharge rate of 10% of the stored volume, at least ten times as much stored water (180 million m^3) is needed to satisfy requirements without undermining existing reserves. To contain that volume of water, a geological formation must have a total volume several-fold bigger, e.g., 10 times as much for an effective porosity of 10% or about 1.8 billion m^3. That volume would be contained, for instance, in a formation that is an average of 10 m thick and extends over 180 km^2.

If we look at the requirements of a large metropolis, such as Mexico City, with a daily consumption rate of about 7 million m^3 (2 500 million m^3 annually), the usable volume (not considering the normal variation in hydraulic parameters) must be about 150 times larger than the hypothetical city above to accommodate Mexico s medium- and long-term needs, i.e., a 2 700-km^2 formation with an average productive thickness of 100 m. As discussed in Chapter 8, the aquifer in the valley of Mexico meets these requirements, with some limitations.

These figures are arbitrary, and the actual calculation of available water volumes is not, unfortunately, so simple, but the examples give a general idea of the size of aquifer that may be required to satisfy the water requirements of a large city.

Shallow depth and low pressure

Water for urban consumption must be easily or economically (or both) available. Depth is especially important, as drilling costs increase considerably if aquifers are more than a few hundred metres below the surface. Drilling costs are also high if piezometric levels (static levels) and pumping levels (dynamic levels) are far from the ground surface. In this latter case, operational costs can be radically increased by pumping costs.

With increasing depth, there is a tendency toward compaction and consolidation of sediments and an associated decrease in storage capability and hydraulic conductivity, with greater mineralization of the water. For this reason, and due to increased costs, most deep aquifers are unsuitable for water supply. However, deep aquifers occasionally contain good drinking water and may yield larger volumes. An excellent aquifer, meeting these conditions, is located in the Botucatu sandstone of Argentina, Brazil, Paraguay, and Uruguay; it is well over 0.8 million km^2 in area and several hundred metres thick (Montano and Pessi 1988; Kimmelman et al. 1989).

The Botucatu sandstone contains one of the largest aquifers in the world with high permeability and low mineralization of the water. In spite of its depth, which frequently exceeds 1 000 m, and the presence of overlying, hard basaltic rock, which is expensive to drill, its high piezometric levels (frequently giving rise to artesian conditions) keep extraction costs low. However, this aquifer has been used only in a limited way in areas where access is difficult and expensive. Only recently have a significant number of wells been drilled into it.

High water yield

A key element in the use of aquifers for urban supply is sustainable well yield. Yield limits the number of wells that can be drilled. For example, to supply our hypothetical city of 100 000 (yearly consumption, 18 million m^3; daily consumption, about 50 000 m^3), 200 wells producing 1 750 L/minute or 1 000 wells producing 350 L/minute would be needed. Mexico City draws 55 000 L/second from 5 000 wells located throughout the city: 10–12 L/second or 600–720 L/minute per well.

The principal intrinsic property that determines the yield of wells is the hydraulic conductivity or permeability of the aquifer. Highly permeable formations provide the conditions for construction of high-yielding wells.

High rate of renewal

One of the most important features of an aquifer allowing its intense, long-term exploitation is its renewability. Renewability can be defined as the capacity of an aquifer to sustain its volume against a given level of extraction. It is related to the balance between the water recharged from and discharged to the surface and the inflow and outflow from and to contiguous water-bearing hydrogeological units.

In most cases, the key element for renewability of an aquifer used for urban water supply is the recharge volume from the surface (i.e., streams, lakes, rainfall, and melting snow), which, in turn, depends on precipitation in the recharge area or at the basin's headwaters. Recharge rate is also a function of the permeability and state of the ground surface, slope, development of the hydrographic network, vegetation, artificial structures, and depth of the water table.

Some aquifers have a high rate of renewability, e.g., due to high rainfall, large recharge area, or poorly developed outflowing drainage, and they can be used heavily with little harm. Others have a limited rate and are, therefore, sensitive to overpumping. Assessing the renewability of an aquifer is essential in appraising its potential for urban use.

Acceptable water quality

Aquifer water must be of appropriate quality for human consumption. It must have a low level of dissolved solids, meet required standards for microbiological content, and be free of other impurities (miscellaneous organic or inorganic gases, liquids, or suspended solids), excessive radioactivity, or other health hazards. Poor quality water can often be treated to bring it up to standards. However, the high costs associated with treatment of heavily contaminated waters may make their use prohibitive.

The location of the recharge area of an aquifer, underlying a densely populated area, often makes the aquifer vulnerable to contamination from anthropogenic causes. This problem must be addressed when an aquifer is, or will be, used for drinking water.

In some cases, degradation of water quality may be related to hydraulic connection with aquifers of lesser quality or with surface-water bodies, e.g., seawater and salty lakes. Heavy pumping might promote the invasion of the unsuitable water from below or next to the aquifer. This phenomenon (called saline intrusion) is the main cause of aquifer degradation in coastal areas.

Low risk of unwanted effects due to intense pumping

Intense pumping, as is usually required to supply cities, may produce unwanted effects, such as subsidence or intrusion of unsuitable recharge waters or contiguous underground waters of poor quality or other fluids. Although assessment of these and other potential problems is not always carried out in advance, in many instances, overpumping has caused degradation, not only of the aquifer, but also of the overlying land on which the city is located.

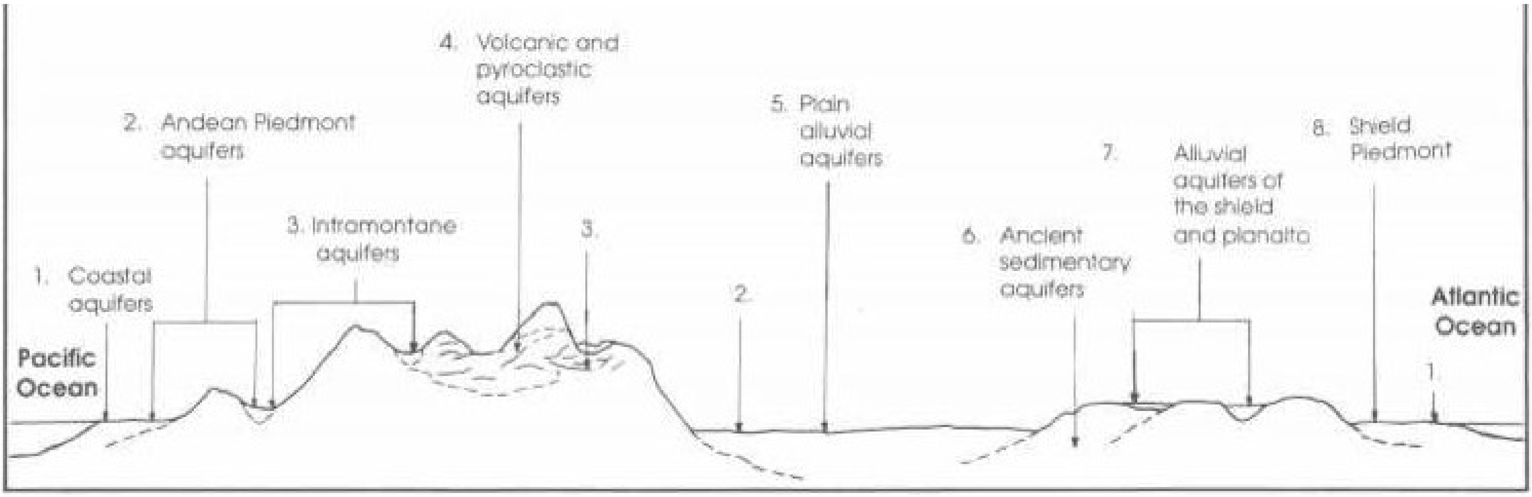
The difficulties caused by pumping are related to dewatering or decreasing water pressure in the aquifer. The serious problem of subsidence in Bangkok, Mexico City, Shanghai, and Venice is a result of consolidation of dewatered sediments after intense pumping that exceeded the renewability of their aquifers. This phenomenon has illustrated the extent of the damage possible when hydrogeological conditions are not appropriate to the pumping rates and volumes being extracted.

Aquifers suitable for groundwater use

Only a few hydrogeological environments provide the volumes, well yields, renewability, accessibility, and water quality necessary to meet the requirements for urban water supply. For this reason, the list of water-bearing formations of interest to city hydrogeologists is much shorter than is shown in general hydrogeological surveys. The main high-production aquifers whose water is suitable for urban use are (Fig. 3):

- Volcanic aquifers,
- Alluvial aquifers,

Fig. 3. Cross-section of South America showing the location of various types of aquifers. 1. Lima, Iquique, Mar del Plata, Natal, Salvador, Maceió, Fortaleza; 2. Lima, Villavicencio, San Juan, Mendoza, Maracaibo, Santa Cruz; 3. Cochabamba, Valencia, Maracay, Querétaro, San Luis Potosí, Santiago; 4. Mexico City, Guatemala City, Managua, Quito; 5. Buenos Aires, San Nicolás; 6. Ribeirao Preto; 7. São Paulo, Santa Lucia (Montevideo) 8. Georgetown, Mar del Plata, several cities on the Brazilian coast.



- Carbonate aquifers,
- Pre-Tertiary sandstones and conglomerates, and
- Coastal aquifers.

Volcanic aquifers

Volcanic regions contain some of the most productive aquifers. Several large LAC cities obtain a significant portion of their water from volcanic aquifers (Fig. 3).

Mexico City's main sources of water (about 80%) are the aquifers contained in the complex pyroclastic formations filling the valley of Mexico basin. Guatemala City depends to a large degree (about 70%) on the groundwater reservoirs found in the Tertiary and Quaternary pyroclastic and lava formations of the Guatemala valley in the country's volcanic highlands. Managua, the capital of Nicaragua, extracts all of its water for urban consumption from the pyroclastic Las Sierras formation, both directly from wells and indirectly from the crater lake, Asososca. Quito, Ecuador, obtains nearly 40% of its water from the colluvial and alluvial deposits of pyroclastic origin and tuffs of the Callejon interandino valley. Other cities using volcanic or related aquifers to some degree include Guadalajara, Puebla, and Toluca in Mexico; Quetzaltenango in Guatemala; Riobamba in Ecuador; La Paz in Bolivia; and San José in Costa Rica.

The volcanic complexes of Latin America are of three main types: the Mesozoic basaltic regions of Serra Geral; the island arch volcanoes of the Caribbean region; and the volcanic formations in the mountain ranges.

The basaltic areas of southern Brazil, northern Uruguay, and northeastern Argentina are composed of relatively compact rock, several hundred metres thick, which contains only minor volumes of water in fractures, in intercalated sandstones, in interflow porous zones, and in the weathered material of the surface. These waterbearing zones are not only difficult to find (particularly the first three types), but they usually do not provide sufficient water to sustain long-term high extraction (Da Cunha Rebouças and Fraga 1988).

The volcanic areas of the Caribbean islands occupy a relatively reduced region above sea level in several of the smaller Caribbean islands (Dominica, Martinique, Montserrat, and Saint Lucia). As a result of their limited size and the presence of better aquifers in most volcanic islands, these formations are used for water supply only by small towns and farms.

The volcanic zones of the mountain ranges, on the other hand, are extremely important water sources, because of both high population densities nearby and the frequent presence of excellent and abundant aquifers. These zones extend along the whole eastern Pacific "arch of fire" near the coast, from southern Chile through Bolivia, Peru, Ecuador, Colombia, Central America, and Mexico (and continuing further north through the western United States, western Canada, and Alaska) (Bedinger et al. 1989). They consist of a wide array of rocks of varied composition, petrography, and structure, including acid, neutral, and basic magmatic compositions, unlike the trap basalts of Serra Geral, which are systematically basaltic. Rock types found in the mountainous volcanic districts include rhyolites, trachytes, dacites, andesites, basaltic lavas, widespread pyroclastic formations, and associated alluvial and lacustrine deposits. From a geological perspective, these volcanic regions can be extremely heterogeneous, mainly because of the complexity of the petrogenesis associated with volcanic processes.

Depending mainly on its silica content, an ascending magma may solidify before reaching ground level (this is normally the case with rhyolitic and trachytic magmas) or it can reach the surface and flow downhill until it cools and hardens. The effusion of lava is normally accompanied by degasification, with ejection of various magmatic products into the atmosphere. In acid magmas, gas pressure builds up behind the solidified rocks and explosions may occur, causing widespread ejection of solid fragments and fluid material, which may fall as large fragments (bombs or scoria), medium-sized fragments (lapilli), or ashes. These materials can also flow downhill embedded in hot fluids, i.e., various hot gases (of which steam is by far the most common), water (often from phreatic eruptions or sometimes from melted snow), and liquefied soils (usually composed of volcanic materials from previous eruptions).

Volcanic formations are frequently altered by water erosion and transported downstream where alluvial and lacustrine deposits may accumulate. On less-exposed or gentle slopes, weathering processes may develop rapidly, and the volcanic glasses and proto crystals may be transformed into clay with the liberation of various chemicals, among which may be important plant nutrients. Soil formation in loose volcanic deposits can take place quickly (a few years). Where volcanic rocks are more compact, soil formation proceeds much more slowly (tens or hundreds of years).

Soil formation is important from a hydrological point of view because of the increased impermeability caused by the argillization of glasses. One of the main obstacles to the recharge of aquifers in volcanic areas (and to vertical flow in general) is related to the presence of a succession of buried palaeosoils, produced by the weathering of pyroclasts.

The main volcanic rock formations found in the mountainous volcanic areas of Latin America are:

- Agglomerates and breccias;
- Ash-flow tuffs;
- Ash-fall tuffs;
- Mud-flow and laharic tuffs;
- Alluvial pyroclasts and reworked tuffs;
- Lacustrine reworked tuffs; and
- Lavas.

Agglomerates and breccias

Agglomerates and breccias form near the foothills of volcanoes as a result of local landslides, rolling of large and medium-sized rock fragments (blocks and lapilli), and the fall of various types of pyroclasts near the volcano (including bombs, miscellaneous scoria, pumice, blocks, lapilli, and ashes of various types and grain size). Hydrologically, they can be very productive, but their limited area reduces their use as water sources.

Ash-flow tuffs

Ash-flow tuffs result from the flow of pyroclasts, liquefied by water or volcanic gases, which often gives rise to thick accumulations in valleys and depressions. Pyroclastic materials formed in this way can be composed of solidified live lava, fragments of dead lava from previous eruptions, pyroclasts from previous eruptions, or fragments of rocks tom from the walls of the substratum as the volcanic fluids rise to the surface.

These tuffs can be welded or nonwelded depending on their degree of consolidation. Nonwelded tuffs frequently contain water in usable volumes, because of their thickness, area, and effective porosity, which may average 35% (Bedinger et al. 1989), but their yields are somewhat smaller than those of welded tuffs, where porosity is secondary (related to fracturing) and much lower (about 3%).

Mean hydraulic conductivity (K) for welded and fractured tuffs is about 1 m/day; for nonwelded and friable tuffs, K is 4×10^{5} m/day (Bedinger et al. 1989). However, the average values do not always reveal the high hydrologic potential of tuff deposits that are suitable for urban water supply. Bedinger and colleagues (1989) found K values of about 5 to 5×10^{3} m/day for the 83.5 percentile, with effective porosity ranging from 4% for welded tuffs (few fractures) to 33% for nonwelded tuffs (friable).

Tuffs have good hydrogeological potential (particularly when fractured), with high yield. When their available volume is sufficient, they can be used as a source for urban water supply.

Ash-fall tuffs

Wind-driven tuffs can extend over large areas, accumulating as a: thin blanket over existing topography. Usually, they are composed of fine pyroclastic particles, with grain size decreasing with distance from the volcanic source. In spite of their areal extension, their potential as a water source is limited because they are seldom more that 10 m thick.

Mud-flow and laharic tuffs

Mud flows and lahars are catastrophic phenomena that may occur regularly at some locations, giving rise to important accumulations of poorly sorted sediments below volcanic slopes. These formations can extend many dozen kilometres down valleys to flatter land below.

When weathered, mud-flow and lahar sediments produce highly fertile soils. They may also contain abundant groundwater suitable both for urban supply and irrigation, when their area and thickness are sufficient. Because of these characteristics, mud-flow and lahar zones are often densely populated, although they may present a permanent threat to local populations. In 1985, Armero in central Colombia was buried by a lahar caused by sudden snowmelt on the slopes of the Nevado del Ruiz volcano during an eruption; 20 000 people were killed. Several other cities are located in similar high-risk areas, e.g., Ibague, not far from Armero, with a population of 400 000 people.

Alluvial pyroclasts and reworked tuffs

Because the surface of recently deposited tuffs is devoid of vegetation, they are exposed to erosion, and their particles may be transported by local streams toward lower-lying areas, where they accumulate to varying thicknesses. Alluvial pyroclasts of this nature are frequently found intercalated and interdigitated with other volcanic formations. They can have high values of hydraulic conductivity and contain suitable aquifers. When their volumes and rates of renewal are sufficient, they may also provide sufficient water to serve urban areas.

Lacustrine reworked tuffs

lakes are common features in volcanic areas because existing waterways are frequently obstructed by volcanic accumulations of various types. In most volcanic areas, lakes of various sizes and stages of evolution can be found. The last stage of evolution is their transformation into a lacustrine plain. lacustrine sediments are normally finer than alluvial ones. For this reason, lacustrine formations tend to act as aquitards (or quasi-aquicludes) rather than aquifers, and their yield of groundwater is usually small to nil.

Lavas

lavas are primary volcanic rocks. They form by solidification of magmas, under atmospheric or quasi-atmospheric conditions. lava rock formation can take place inside the volcano, in the case of silica-rich, high-viscosity magmas, or outside, when the magma has lower viscosity and is silica-poor; the latter consolidate as lava-flow rocks. Magmas of intermediate composition may produce rocks of either type. Rhyolitic, trachytic, and dacitic magmas frequently produce explosive eruptions, whereas basaltic and andesitic magmas give rise to more peaceful volcanic episodes.

lava-flow rock formations are heterogeneous; a vitreous crust of solid rock forms on their rapidly cooling external surfaces and a more crystalline core of materials cooling at a slower rate forms toward the centre and base of the mass. Gas bubbles are often trapped beneath the solid crust, producing highly porous material containing vacuoles and vesicles. In some cases, these spaces may be interconnected, giving rise to high effective porosity in which water circulation is facilitated (i.e., high hydraulic conductivity). In other cases, the vacuoles and vesicles remain isolated and water circulation is more difficult. The base of the flow normally includes fragments of rock that create many anfractuosities and empty spaces, producing a highly permeable solidified material.

Because of these processes, lavas can develop a network of open fractures, usually interconnected, allowing the flow of significant volumes of water. In brief, lavas can form hydrological units of high productivity if they possess large volumes of gas, experience intense contraction phenomena, or flow over loose rocky surfaces. On the other hand, when gas content is low (as in most basaltic flows), contraction fissures are few and small, or foreign rock fragments are not picked up from the substrate, the hydrological potential of the solidified rock can be limited (e.g., the plateau lavas of Serra Geral in southeastern South America).

Lava flows in various volcanic areas of North America have effective porosities averaging 15% for cavernous and fractured lavas and 1% for moderately dense to dense ones (Bedinger et al. 1989). Hydraulic conductivity values average 0.5 m/day and 4×10^{4} m/day, respectively.

Groundwater renewability

An important element that facilitates groundwater exploitation in volcanic areas is the normally high rate of renewability, due to the continued youth of the hydrographic systems in these areas. Fluvial valleys do not have time to form, because of continuing obstruction of their courses, as a result of the various volcanic accumulations (e.g., lava flows, landslides, mud flows, lahars, and ash flows).

The various lakes and depressions formed in volcanic regions frequently become recharge areas, i.e., surface sinks, for existing aquifers. In many volcanic aquifers, infiltration can amount to more than half of the precipitation. From this point of view, volcanic regions share characteristics with karstic areas: poorly developed hydrographic drainage, presence of recharge lakes or depressions, and fracture flow through open fractures (as in lavas and welded tuffs). The main difference from karstic areas is the less-important role of dissolution along the fractures.

Alluvial aquifers

Alluvial aquifers are those contained in sediments of alluvial origin. In this section, . only the less-consolidated Cenozoic alluvial formations will be considered: older alluvial formations are included in the section on pre-Tertiary sandstones and conglomerates later.

Alluvial formations are found throughout Latin America, from Punta Arenas in southern Chile to Tijuana in northwestern Mexico and from Trujillo in Peru to Fortaleza in Brazil. They are the most abundant type of aquifer, both in number and area. Alluvial aquifers can be found at high altitudes, sometimes over 4 000 m above sea level (as in the Peruvian-Bolivian altiplano) or several hundred metres below sea level (as in a number of regions in the continental margins).

These aquifers have a wide range of characteristics: they can vary in area from a few square kilometres, with low productive volume, to tens of thousands of square kilometres, with huge production capacity. Yields can also vary. In some cases, well productivity may be as low as a few litres per minute; in others, it can reach hundreds or even thousands of litres per minute. Not all alluvial aquifers can provide the sustainable output of good quality water required for widespread urban use. In fact, most cannot.

However, there are still a large number of alluvial formations that do contain enough renewable groundwater to meet water demand in many cities of the continent. Some cities obtaining a significant amount of their water from alluvial aquifers include Buenos Aires-La Plata, Junin, Río Cuarto, and San Nicolás in Argentina; Cochabamba and Santa Cruz in Bolivia; lea, Lima, Piura, and Trujillo in Peru; Santa Marta, Sincelejo, and Villavicencio in Colombia; Maracay and Valencia in Venezuela; Aguascalientes, La Paz, Mexicali, Querétaro, and San Luis Potosí in Mexico; and Olinda, Natal, and Pelotas in Brazil. A large number of other cities that obtain most of their water from surface sources, draw a portion from alluvial aquifers, often for industrial use (e.g., Santiago, Chile; Asunción, Paraguay; and Montevideo, Uruguay).

In addition, many aquifers not classified here as alluvial were deposited as a result of alluvial action. They are included elsewhere, because of other characteristics that are more significant in defining their properties and dynamics, e.g., many alluvial carbonate sediments, alluvial deposits of pyroclastic origin, some coastal alluvial sediments interfingered with marine littoral deposits, and pre-Tertiary consolidated conglomerates and sandstones of alluvial origin.

Alluvial formations are composed mainly of detritic sediments of varying grain size and composition. Their granulometric fractions can include gravel, sand, silt, clay, or any intermediate or composite grain size. In general, the larger the predominant grain size, the higher the porosity of the material. Also, well-sorted alluvial sediments have a higher porosity than poorly sorted sediments of comparable mean grain size.

Only the coarser sediments (fine sand to gravel) may contain enough water and have a high enough permeability to give rise to aquifers suitable for urban use. Effective porosity and hydraulic conductivity values of coarse sediments in alluvial aquifers range from 12 to 25% and 1 to 0.7 m/day, respectively (Bedinger et al. 1989). Silty and clayey formations are not usually good aquifers, but behave as aquitards or aquicludes, i.e., they have low hydraulic conductivity.

These characteristics apply not only to alluvial sediments, but also to any sediment with similar granulometric properties. However, the vast majority of detritic sediments containing aquifers in Latin America are of alluvial origin.

Classification of alluvial aquifers

Detritic sediments undergo considerable changes with age. The older a sediment, the more likely it is to have experienced consolidation and diagenetic processes. These processes are often, but not necessarily, associated with the depth to which the sediment has been buried at some time in its geological history. The older a sediment, the greater its chances of being affected by secondary processes that modify its properties.

Consolidation processes include general compaction, hydrolysis of ferromagnesium minerals and feldspars, formation of clays and other secondary minerals, and cementing with silica, iron hydroxides or oxides, or carbonates. Deeper in the earth, where temperature and lithostatic pressure increase beyond a certain degree, other petrogenetic phenomena of a more diagenetic nature occur: neoformation of clays and micas, anhydritization of calcium sulfates, formation of some sulfides (as pyrites), crystallization of graphites and magnetites, and hematitization and goethitization of limonites.

All these processes tend to decrease porosity, hydraulic conductivity, and storage capacity. Because of slower flow and longer contact with mineral surfaces, groundwater becomes increasingly mineralized, i.e., total dissolved solids increase. Higher temperatures at greater depths promote this mineralization. Therefore, as a rule, relatively recent detritic formations contain better aquifers than older formations of . the same type.

With consolidation, however, porosity and flow may increase. Consolidated sedimentary rocks have a greatly diminished intergranular porosity (and flow), but fracturing can reverse this trend causing them to behave like a fractured aquifer, e.g., in crystalline rocks.

In this book, I have arbitrarily divided detritic alluvial formations into three categories according to their age:

- Young alluvia, still associated with present fluvial valleys or basins;
- Older alluvia that have suffered some consolidation, usually of Tertiary origin and only infrequently related to the largest present orographic and hydrographic features; and
- Older sedimentary rocks of alluvial origin, generally pre-Tertiary, without any direct association with existing reliefs and having often experienced a relatively high degree of consolidation and some diagenesis.

Another key criterion for classifying alluvial sediments is general geomorphology. Alluvial sediments from the foothills of the Andes are completely different from the sediments of the large central plains; alluvial deposits from the undulating shield plateaus are different from the sediments of the intra montane Andean or sierra basins. I have subdivided modem sediments (late Pliocene to Present), in which present relief is still a determinant factor in the geological and hydrogeological characteristics of the formation, according to their geomorphic location. Alluvial basins of Tertiary origin are included here as a separate subtype of alluvial aquifer. Pre-Tertiary sedimentary rocks are dealt with in a separate section along with other rocks of similar age, but different origin.

Alluvial formations containing aquifers that are suitable sources of urban water supply include:

- Tertiary alluvial and molassic basins;
- Intramontane alluvial basins;
- Foothills alluvia;
- Plains alluvia;
- Shield and platform alluvia; and
- Coastal alluvia.

Tertiary alluvial and molassic basins

Throughout the Latin American continent, there are a large number of older alluvial deposits, more or less consolidated, that contain usable aquifers. Aguascalientes in Mexico and São Paulo in Brazil draw their water from this type of aquifer. These formations are often thick, frequently exceeding 200 or 300 m, and contain water with a relatively high degree of mineralization, particularly in their deeper zones. Because of their age, they are frequently cemented with various types of matrix (clay, silica, carbonates, iron oxides and hydroxides; sulfates, etc.), which considerably reduces their actual and effective porosity and, therefore, their permeability.

However, because of the great volume of these deposits, even a small proportion of the formation can provide sufficient water for urban use or irrigation.

Intramontane alluvial basins

Intramontane alluvial basins are alluvial valleys located throughout the mountainous regions. They can be relatively narrow with steep longitudinal profiles, steep slopes, and narrow alluvial plains on their floors or wide valleys with more gently sloping thalwegs and moderately inclined lateral slopes. Narrow, deep valleys are usually the result of strong river-bed erosion, as opposed to slope erosion which tends to produce wider valleys and more abundant accumulations on the valley floor.

The largest alluvial deposits are built in fluvial valleys downstream from semi-arid or arid (or periglacial) upper basins, where slopes are devoid of vegetation and are, therefore, subject to severe erosion. In humid areas, valleys are narrow and deep and alluvial deposits are less important. However, even in areas that are now humid, large alluvial deposits, which have been inherited from more arid geological periods, may be found.

When large, broad accumulations of alluvia are found in humid or subhumid regions, they are frequently of tectonic origin. Important alluvial aquifers of this type are found in the Lake Valencia graben in north-central Venezuela (Peeters 1968), the Cauca graben in Colombia, and the longitudinal valley graben south of Santiago, Chile.

Valleys of an intermediate type are the Cochabamba valley in Bolivia (Von Bomes 1988) and the upper Magdalena valley near Neiva, Colombia, which are relatively narrow and steep (although they appear to be also tectonically generated). The valleys of Querétaro and San Luis Potosí in Mexico, on the other hand, are wide, with relatively gentle longitudinal and lateral slopes.

Intramontane valley aquifers usually provide good quality groundwater, but the volumes are not always large enough to supply cities or irrigate farms. Cochabamba and Cali withdraw large amounts of water for urban use and irrigation in Cochabamba; mainly for irrigation of sugarcane crops in Cali. Often, the presence of a significant volume of surface water has limited the development of groundwater resources, as in Cali and Neiva in Colombia where most water comes from the Cauca and Magdalena rivers, respectively. However, irregularity of river flow (Cochabamba) and degradation of the surface water (Lake Valencia near Valencia and Maracay, Venezuela) have caused these cities to use groundwater almost exclusively for human use and sometimes for irrigation as well.

Foothills alluvia

Aquifers in foothills alluvia occur on both sides of the Andean and Sierra ranges. Similar aquifers can be found in the foothills of the mountainous areas of the shields (Brazilian and Guyanan), of the coastal escarpments in these regions, and of the basaltic plateaus of southeastern South America (i.e., the foothills of the Serra do Mar escarpment in the states of São Paulo, Paraná, Santa Catarina, and Rio Grande do SuI in Brazil).

The characteristics of the alluvial formations containing these aquifers are similar throughout the region. They usually consist of coarse deposits (agglomerates or conglomerates, gravelly sands or gravelly sandstones, and various other types of sandy deposits with varying degrees of consolidation and silt and clay content). These formations arise from the merging of a number of alluvial fans at the outlet of mountain valleys, as they spread out over the level plain.

Locally, the presence of less subsident (in relation to the plain) or less elevated (in relation to the mountains) blocks of rock next to the foothills, frequently covered with older sedimentary formations, may prevent the accumulation of foothills formations to any appreciable thicknesses. In other cases, active faulting and strong subsidence processes may allow the accumulation of very thick layers of foothills alluvial deposits.

The thickness of these sedimentary units is variable, but it normally increases gradually from lowlands toward the mountains. Maximum thickness of the coarse alluvial formations (which usually contain the water) is found a few kilometres or a dozen kilo metres from the foot of the escarpment, where they may be several hundred metres thick. Further away, although the actual thickness of the whole sedimentary sequence increases, the alluvial formations become shallower and finer, with lower hydraulic conductivity and poorer well yield.

Among the many cities that obtain their water from foothills alluvial aquifers, Villavicencio in Colombia and Santa Cruz in Bolivia are perhaps the most representative examples.

Plains alluvia

A significant area of the South American continent (as much as one-third) is occupied by the vast flatlands extending from the llanos in the Orinoco delta to the lower pampas south of Buenos Aires. In large measure, the upper parts of these basins were filled during the last geological epochs (Pliocene to Holocene) by alluvial (but also lacustrine and eolian) deposits, transported from neighbouring highlands: the Andes in the west and north, Brazilian and Guyana shields and basaltic planalto in the east.

Toward the south, these deposits are affected by the irregular flow of streams from the semi-arid foothills of the Andes through the dry pampas and, therefore, contain intercalated layers of coarser and finer fluvial deposits, often including sediments of fine grain size and salts (halite, gypsum, and anhydrite) or lenses of lacustrine or eolian sediments. In the north, the climate is more humid and, therefore, the intercalated deposits include more sandy and finer lenses and fewer very coarse layers, except where they are close to mountains or related to channel deposits in the larger rivers. This type of sedimentation varies with successive local environments and climatic changes, sometimes providing a record of fluvial activity during the Quaternary period.

Similar plain accumulations are found in the rivers draining plan alto and shield basins (e.g., the Paraná River and its tributaries), where alluvial deposits are also a succession of sandy formations with frequent lenses of finer elements and carbonate-cemented or silicified lenses or layers.

Many Argentinean cities draw part or all of their municipal water from these aquifers, e.g., Junín, San Nicolás, and several municipalities of the greater Buenos Aires-La Plata area (La Plata and Quilmes). Cities obtaining part of their water from the Paraná sands or correlative formations (called the Arenas Puelches in the southern Paraná region) are Asunción in Paraguay and Rosario, Santa Fe, and other smaller urban centres in Argentina (Fili 1983; Herrero 1983; Auge et al. 1988).

Similar alluvial deposits, although devoid of silica and carbonates, occur near the Orinoco flood plains, where sandy (mainly quartzic) accumulations have resulted from both sediment transport by the main river and lateral supply provided by the tributaries descending from the Guyana shield and the mountain regions of the north and west. Two of the largest cities of the llanos (Ciudad Bolívar and Ciudad Guayanain Venezuela) use alluvial aquifers of this type to complement the water drawn directly from the river (Menendez and Araujo 1972).

Shield and platform alluvia

Quaternary alluvial formations are found throughout the shield regions, both in the valleys within the shields and at their periphery at the outlets of alluvial streams, existing and ancient, where they encounter the lower-lying inland flatlands or the narrow coastal plains. These deposits vary in thickness, but are somewhat thinner than analogous deposits in the intramontane valleys of the mountain-sierra region and its foothills. They are particularly well developed in the semi-arid Brazilian northeast, along the Brazilian coastal plains (where they frequently occur as foothills deposits of the Serra do Mar escarpment and its northern extension), and in the fluvial valleys of the Uruguayan-Río Grandense crystalline island.

These formations, which are frequently formed of quartzic or arkosic sandy or gravelly material, may contain significant volumes of groundwater and can deliver relatively high yields because of their porosity and hydraulic conductivity. Several cities of northeast Brazil and the Atlantic southern coastal plains use groundwater from this type of aquifer. In the northeast, groundwater is widely used because of the lack of surface water. Along the southern coast, there are few large rivers because the divides are not far enough from the ocean to allow development of extensive fluvial systems (Geyh et al. 1983). Coastal rivers in Brazil tend to be short, with small basins, and average flows are rather limited in spite of high local levels of precipitation. This has promoted the use of groundwater in these areas, sometimes resulting in the intrusion or upwelling of saline water in aquifers.

Some of the larger alluvial valleys in the states of São Paulo and Minas Gerais also draw water from alluvial aquifers, but to a lesser degree because of their access to permanently flowing streams, which are a consequence of higher precipitation volumes.

Aquifers in the alluvial deposits of the Guaíba, Maranhão, San Francisco, and Tietê rivers in Brazil and of the Demerara and Essequibo rivers in Guyana are tapped for urban use. In Uruguay and Rio Grande do SuI state (Brazil), alluvial deposits are relatively thin. However, several cities use them. In Uruguay, several small cities surrounding the metropolitan area of Montevideo draw water from the Pliocene Pleistocenic (sandy-gravelly) Raigón aquifer and there is potential for additional use by the city of Montevideo itself. In southern Brazil, Pelotas gets water from the Graxahim formation underlying the São Gonzalo waterway and Uruguaiana uses an aquifer on the margins of the Uruguay River.

Coastal alluvia

Coastal alluvia formations occur in all coastal areas of the LAC: from northwestern Mexico (La Paz, Mexicali, and Tijuana) to the Pacific coastal plains of South America (Lima, Trujillo, and Valparaíso) and the southern pampas (Mar del Plata, next to the crystalline islands of Tandil and La Ventana), and from northeastern Brazil and Guyana (Fortaleza, Georgetown, Maceió, and São Luis island) to the coastal regions of the Caribbean and the Gulf-of Mexico (Santa Marta in Colombia, Maracaibo in Venezuela, and Veracruz in Mexico among others).

These alluvial deposits are frequently interdigitated with sediments of littoral origin that can also act as good aquifers if they consist of coarse material (beaches, bars, and eolian ridges) often without a break in hydraulic continuity. These complex groundwater reservoirs are usually easily accessible; water is abundant and not far below the surface.

However, coastal aquifers are susceptible to saline intrusion (or upwelling) when water is extracted too rapidly. Some cities experiencing salinization of wells include Lima in Peru, Santa Marta in Colombia, Coro in Venezuela, Rio Grande and Natal in Brazil, and Mar del Plata in Argentina. Buenos Aires-La Plata also has a salinization problem, but, in this case, the salinity is coming from salts contained in a coastal formation.

Conclusion

Alluvial aquifers are the most common aquifers in the LAC region. Their dimensions, grain size, and petrographic composition vary widely, as does porosity and hydraulic conductivity. However, on average, these units are hydrologically highly productive, with frequent potential for urban water supply. Problems are mainly associated with their shallowness, which, although it is an advantage economically, may lead to contamination from surface sources. The use of alluvial aquifers requires special care, but their potential as a water source for urban use can be high.

Carbonate aquifers

Carbonate rocks are abundant throughout the world. Some occur on sea bottoms and near shores at various depths (oceanic organic muds, reefs, tidal plains, and calcareous beaches), some in lacustrine, palustrine, or even alluvial environments. They can be of igneous origin (carbonatites) or they may have undergone metamorphic transformation (marble).

Carbonate aquifers can contain material with high primary porosity and relatively less-important fracture porosity (e.g., reef and lumachelle formations, calcarenites, carbonate tuffs, and miscellaneous detritic sedimentary materials). However, porosity may be secondary, having developed through fracture and chemical dissolution (e.g., most aquifers occurring in compact limestones and dolomites).

Carbonate rocks are often hydrogeologically dynamic. With time, diagenetic processes tend to reduce primary porosity, through local dissolution and recrystallization of the carbonate minerals contained in the formations. On the other hand, circulation of water through fractures tends to dissolve minerals of the walls, eroding them and forming underground waterways that grow gradually. Because these processes often take place simultaneously, some carbonate aquifers have relatively high primary porosity (still not completely affected by diagenetic processes) and developing secondary porosity (in fractures).

These rocks can contain considerable volumes of water in intergranular spaces and in fractures. Water action can enlarge the fractures and therefore, facilitate water circulation. These mechanisms are called karstic processes and the aquifers contained in these formations are often called karstic aquifers. When wells (or springs) connect with the main karstic waterways, these aquifers can be extremely productive and highly suitable as water sources for large cities and agricultural irrigation.

However, there are a number of limitations to use of this type of groundwater resource. First, because carbonate aquifers frequently are highly discontinuous, not all boreholes are productive; many can be dry if they do not contact the main fracture system. Second, although yields can be impressive, they may not sustain extraction of large quantities of water. In many cases, the reservoirs contain less (sometimes much less) water than other types of formations with smaller yields. An additional element of concern, relates to the fast flow of the groundwater through the open fractures. The rapid movement does not allow for degradation of contaminants that may be carried from the surface into the groundwater system. However, in spite of these problems, karstic aquifers remain among the best and most reliable for urban water supply.

Karstic aquifers of Latin America

Although carbonate formations are widespread in Latin America, highly productive carbonate aquifers are most frequently found in the north, in the Caribbean and Gulf of Mexico. Important carbonate aquifers are located in Barbados, Cuba, Jamaica, Puerto Rico, and several islands of the Bahamas archipelago, in the neighbouring Yucatán and Florida peninsulas, in the Mexican hinterland (Nuevo León, Tamaulipas, and Coahuila states), and in the coastal areas of northern South America.

Bridgetown (Barbados), Havana (Cuba), Montego Bay Oamaica), Mérida (Mexico), and Miami (USA) depend exclusively on groundwater obtained from carbonate aquifers. Other cities that depend to a large extent on this type of aquifer include Nassau (Bahamas), which also uses desalinized seawater, Kingston Oamaica), and several of the largest cities of Puerto Rico (San Juan, Ponce, and Arecibo).

Carbonate formations in Latin America are heterogeneous in composition and genesis, with varied porosity and degree of fracture and consolidation. Their hydrogeological properties are similarly diverse. Some are very compact, nonfractured limestones or dolomites with low porosity and almost no useful water content. On the other hand, a number of high porosity, densely fractured carbonate formations provide huge volumes of water and have excellent potential for urban water supply. Highly porous carbonate aquifers can be found in the molassic basins of the Sierra Madre del Sur, Mexico (e.g., in the Huacapa River basin near Chilpancingo), in the foothills of the Jamaican highlands toward the northern side of the island, in southern Puerto Rico, and along the coast of Venezuela. Typical karstic aquifers (with fracture flow) are found in Havana South (Cuba), Montego Bay Oamaica), the Yucatán peninsula in southeastern Mexico, Nuevo León in northeastern Mexico, and the Morelos formation of south central Mexico.

Karstic aquifers are especially vulnerable to contamination. They are located near cities (even beneath urban areas in some cases) and, therefore, domestic and industrial wastes can easily find their way into the groundwater reservoirs. Second, agriculture is more intensive in areas surrounding the cities; hence fertilizers and pesticides are abundant. Third, rapid water circulation within the karstic aquifer system does not allow for adequate filtration and purification of the recharged water.

These problems are encountered in all karstic regions of the continent. Industrial and domestic wastes contaminate the urban aquifer in Kingston Oamaica) and Mérida (Mexico). In Havana, it is suspected that the intensive agricultural activity in the recharge area of Havana South is polluting the karstic aquifer that is the main source of water for the city of Havana and surrounding areas. Carbonate aquifers are very sensitive to anthropogenic interference and careful management is necessary for their continued use.

Pre-Tertiary sandstones and conglomerates

Although other formations, e.g., carbonate rocks and lavas, are found in the large pre-Cenozoic sedimentary basins of South America, the main groundwater reservoirs are contained in the sandstones and conglomerates of these regions and are of alluvial, coastal-marine, or eolian origin. The characteristics of the older sandstones and conglomerates that make their aquifers suitable for urban use are:

- Sufficient thickness, at least several hundred metres;
- Sufficient lateral extension, several thousand to tens of thousands of square kilometres;
- Not overly affected by macro faulting and folding, which may disrupt hydraulic continuity;
- Primary porosity at least in the medium range, in general over 5%; in some cases, fracture flow may compensate for reduced primary porosity;
- Hydraulic conductivity at least 0.1 1 m/day;
- High well yields of at least 100 L/minute (depending on investment);
- Depth not more than 1 000 2 000 m;
- Relatively shallow static and dynamic water levels (sufficient pressure to give rise to artesian wells is desirable, but is often lost with heavy extraction);
- Sustainable rate of renewal, normally related to recharge volume from the ground surface; and

- Low level of mineralization of the water, i.e., concentration of total dissolved solids less than 0.05%.

The main sedimentary basins of the continent, whose hydraulic continuity has been relatively unaffected by tectonic events, are located around the cratonic or tectonic regions of South America and in the central plains. An example is the huge Amazon sedimentary basin, which is composed of pre-Cenozoic sedimentary fill covered by a large Cenozoic sequence. It is virtually untapped, because of its depth, the low population density in the region, and the abundant surface water available.

Another large sedimentary basin, the Paraná basin, underlies the Paraná River and its tributaries. It is very deep (6000 7000 m along its central axis under the Paraná River in Argentina) and is composed of an impressive sequence of Paleozoic to Cenozoic sedimentary rocks. It contains a large number of conglomerates and sandstones that contain regionally or locally usable volumes of water. The Devonian deposits consist of older formations of arkoses and coarse sandstones and a younger unit of sandstones. Because they are normally found at great depths, their use is impractical.

The Permo-Triassic layers also possess coarse detritic formations at their base. They are the conglomerates (tillites) of glacial origin (Itararé-San Gregorio) and the sandstones formed in a fluvial-glacial environment (Rio Bonito-Tres Islas). These units contain water, but their use is limited due to their depth over large areas and poor water quality. The upper part of the neo-Gondwanan sequence is also composed of sandstones (Estrada Nova) that are locally used as aquifers in southern Brazil and Uruguay.

The upper filling of the Paraná basin is neo-Gondwanan and is composed mainly of eolian sandstones (paleodesert of Botucatu-Tacuarembó) and a thick accumulation of basaltic flows. Botucatu is a medium- to high-porosity sandstone, poorly consolidated, and contains one of the largest aquifers of the continent, extending from Mato Grosso to Uruguay, with an estimated storage capacity of 10 000 20 000 km^3. The Botucatu aquifer contains good-quality potable waters, produces high yields (often 500 L/minute), and is artesian over a large portion of its area. Despite these advantages, the aquifer is used only near its outcropping, because the formation is covered, over most of its area, by a basaltic mantle several hundred metres thick (locally over 1 000 m) that is not only largely unproductive hydrogeologically, but is also difficult and expensive to drill through (Da Cunha Rebouças and Fraga 1988; Montaño and Pessi 1988; Kimmelman et al. 1989).

The upper part of the Paraná basin sequence comprises relatively thin deposits of late Cretaceous and Cenozoic origin. Some of these contain usable groundwater, e.g., the Bauru formation in Brazil and the Mercedes-Asencio formations in Uruguay, but the most commonly used aquifers are in the Pliocene-Pleistocene alluvial sediments described earlier.

Coastal aquifers

These aquifers are defined simply by their location near the coast. There are many possible types depending on the historical geology of a specific area. Many are the result of the geological interactions of continental and littoral or marine formations. In some cases, they are composed exclusively of coarse marine or coastal detritic deposits, e.g., beach or dune sands, or miscellaneous shallow-water sandy deposits. Others are made up of marine or littoral carbonate rocks. A considerable number of coastal aquifers are alluvial, with or without intercalation of coastal or marine formations, and a smaller number can be volcanic, composed of older coarse detritic sedimentary rocks or crystalline rocks.

In spite of the variati9ns in genesis and sedimentological characteristics, their location next to the sea puts these aquifers into close contact with the highly saline groundwater usually contained in suboceanic geological environments. They are, therefore, especially sensitive to overpumping. These hydrogeological units are low-lying, frequently below sea level or only slightly above, and occur at the mouths of current and ancient fluvial basins, in close association with existing waterways, at their point of maximum flow near the ocean.

The main problems involved in using these aquifers relate to salinization of their waters. Because of its lower density, fresh water floats on more saline water. However, the difference in density is only 2.5%, and the relatively thin layer of fresh water that frequently overlies saltier groundwater can be many metres below sea level. However, when careless pumping removes the fresh water too quickly, salty water will tend to replace it from below. This upwelling of the salty water may not occur for several years; thus, the effects of overpumping may not be felt until it is too late to remedy the problem.

A large number of Latin American cities are located along the Atlantic, Caribbean, and Pacific coasts, and 30 40 of them rely on groundwater drawn from various types of coastal aquifers, Among them are Mar del Plata, Argentina (taking water from an alluvial aquifer on the shores of the Atlantic); Natal and Recife, Brazil; Santa Marta, Colombia; Havana, Cuba (which gets all its water from a karstic aquifer on the southern coastal plain); and Lima, Peru (which obtains about 40% of its water supply from a coastal alluvial aquifer).

6
Cities depending on surface water

Most Latin American cities draw their water supply primarily from surface bodies, most commonly rivers. Water from streams is obtained directly, through various intake structures (Asunción, Buenos Aires, and Montevideo), or via reservoirs (Bogotá, Rio de Janeiro, Recife, and São Paulo).

Lakes are seldom used, even by cities located next to them, because they are brackish, like lakes Maracaibo and Managua, or contaminated, like Lake Amatitlan near Guatemala City. Managua actually uses water from Lake Asososca, but because this is a small crater lake without a basin, it acts more like a wide natural well. One case where lake water is used in conjunction with groundwater (Cochabamba) is discussed in Chapter 7.

São Paulo metropolitan region[3]

In spite of its relatively small area by Brazilian standards (248 000 km^2 or just over 3% of the national territory), the state of São Paulo contains 33 million people or 23% of the total population of the country at a density among the highest in the Latin American region (almost 140 inhabitants/km^2). More than 65% of the industrial output of the country is concentrated in this state, and it is the largest agricultural producer. Its sugarcane, coffee, and citrus-tree plantations are the largest in Brazil and among the largest of the world. Cattle stock in the region number nearly 12 million, and it is the primary producer of milk and dairy products.

The state population is mainly urban (over 80%); 29 of its cities have over 100 000 people. The largest of these, the state capital, is the city of São Paulo with a population estimated at 16.5 million in early 1990. The 38 municipalities forming the greater São Paulo metropolitan area are home to 55% of population of the state and 15% of the total population of Brazil. The São Paulo urban area alone produces more industrial goods than the rest of the country. More jobs, by far, are created in São Paulo than in any other major city of Brazil. The city continues to attract people from other parts of the country

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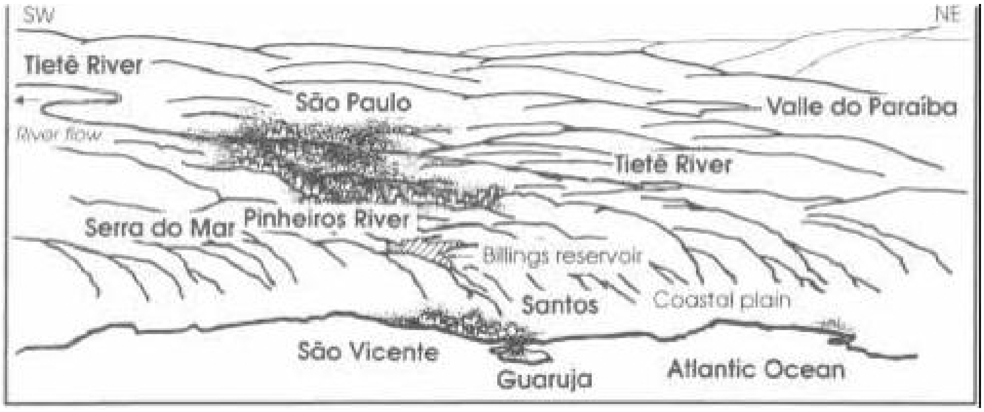
[3] Material in this section is drawn from Gardner (1977), Hermann (1979), DAEE (1988), and Mariani Neto et al. (1988).

Fig. 4. Aerial view of São Paulo, Brazil, and the surrounding region.



and, if present trends continue, the greater São Paulo region, including Campinas, Santos, and the valley of Paraiba will contain over 25 million people by the year 2000 (18.5 million in the metropolitan area alone) and nearly 30 million by 2010. By then, the city s outer limits may have merged with Rio de Janiero s farther suburbs forming a single megalopolis of nearly 40 million people.

Historical background

Portuguese settlement in the São Paulo region started in 1532, when Martin Alfonso de Souza founded the city of Sao Vicente on the Atlantic coast about 400 km south of the bay of Rio de Janeiro. In that part of the country, the coastal area is a narrow plain at the foot of the Serra do Mar escarpment, with little room for agricultural expansion. In 1554, the Jesuits, who already had established missions in the upper Tietê basin, founded a city in the interior beyond the coastal range; São Paulo de Piratininga or São Paulo dos Campos (which was to become simply São Paulo) was situated on a hill between the Anhangabau and Tamanduatei rivers, tributaries of the Tietê River (Fig. 4).

During the 17th and 18th centuries, the growth of São Paulo was tied to its role as a centre for the slave traffic for the sugarcane plantations of the northeast and the mineral exploration areas in the hinterland (particularly in what was going to become the state of Minas Gerais). Later, in the 19th century, the city played a role in the establishment of coffee plantations, which were to produce the main export item of the region and the country for many decades.

During the 20th century, especially in the last few decades, the city has become a strong industrial centre, producing goods for both national consumption and for export. Some of the most important industrial activities include metallurgy, automobile manufacture, and chemical, mechanical, textile, and food industries.

Geology and hydrogeology

The city is located in the heart of the Planalto Paulistano, a 5 000 km^2 area of undulating relief, with elevations ranging from 715 to 900 m above sea level. Underlying the region is crystalline shield, which includes phyllites, mica schists, gneisses, various types of migmatite, and isolated granitic intrusions.

At São Paulo itself, there is a sedimentary basin of tectonic origin, developed during the Pliocene and Pleistocene epochs of the Cenozoic era. The sediments of this basin extend over about 1 000 km^2, with a maximum thickness of 300 m. They are composed of clays, silts, clayey sandstones, and some sandy and gravelly lenses. The crystalline areas of the Planalto Paulistano are deeply weathered, with weathering mantles 70 80 m thick in some areas (Fig. 5).

The main aquifers of the São Paulo region are the coarse sandy lenses of the São Paulo formation and the thick mantle of weathered material in the crystalline areas. The wells in the São Paulo aquifer are usually screened at depths from 100 to 200 m and deliver 50-1 700 L of water per minute.

The environment

The area has a subtropical, humid climate; its average annual temperature is 20˚C, varying from a low average of 14˚C in winter (July) to a high of 26˚C in summer (January). The São Paulo region is among the most humid in Brazil. Average annual rainfall ranges from 1 500 to 2 000 mm, and can reach more than 3 000 mm/year in neighbouring hilly areas.

The city is located close to the divide between the large Paraná basin to the west and the small steep coastal basins of the Serra do Mar escarpment to the east. The city itself, has grown to occupy the Tietê River valley and that of its largest local tributary, the Pinheiros River. The Tietê River is the hydrographic backbone of the state of São Paulo, draining an area of 150 000 km2 and flowing west from its source in the Serra do Mar highlands to the upper Paraná, about 250 km north of its confluence with the Paranápanema River.

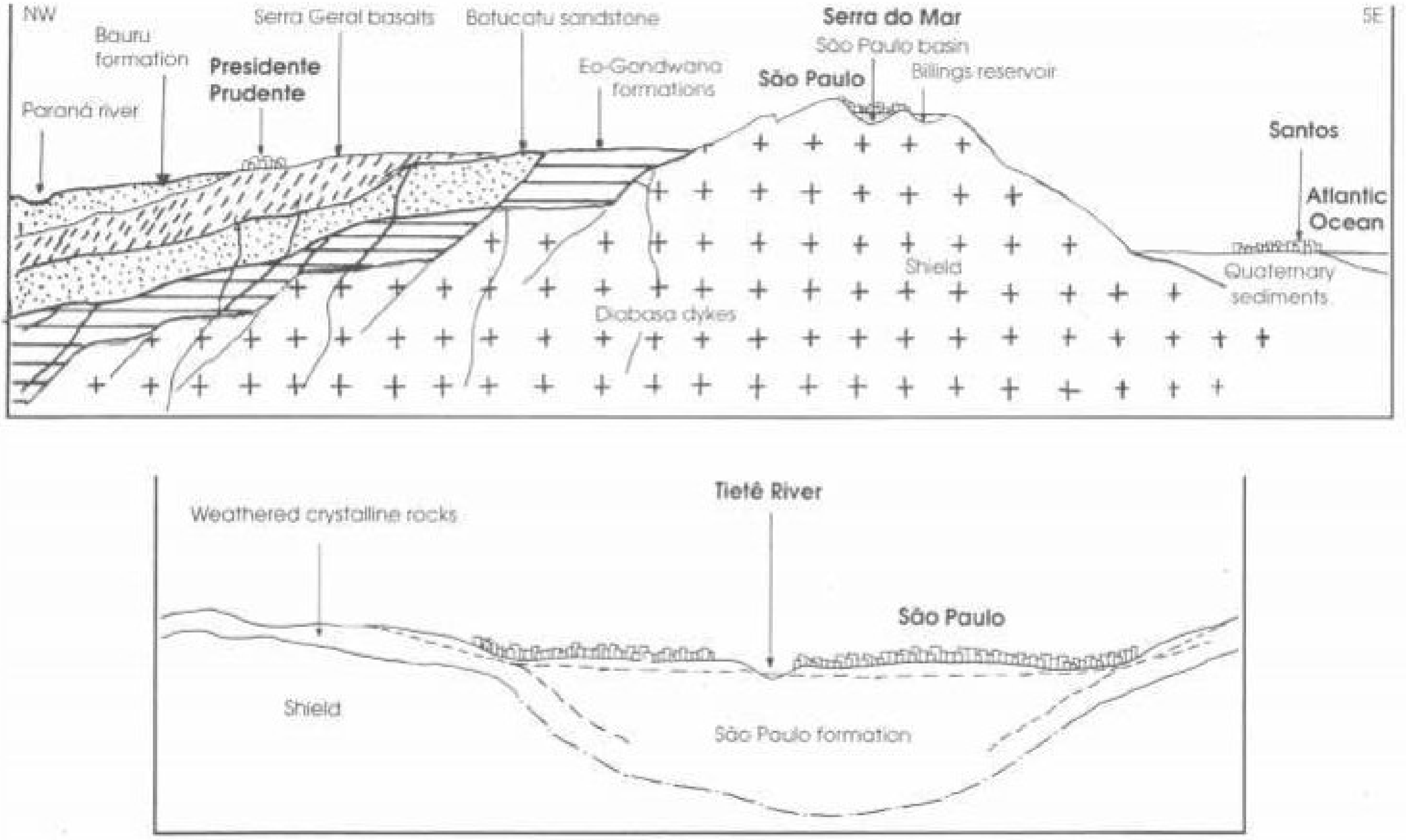
Water supply and management problems

When the city was founded, its water supply came from several surface sources and springs and was delivered in carts under doubtful sanitary conditions. In 1877, when the city had grown to 50 000 people, the private Companhia Cantareira de Esgotos was created to take care of its water and sanitation needs. A few years later, the small da Consolacao reservoir was built. Ten years later, due to general dissatisfaction with the company, the government took over its functions under the direction of the Reparticao de Agua e Esgotos (RAE).

In 1897, water from the Tietê River was being used at Belenzinho. However, the river was already showing signs of contamination. In 1914, a severe typhoid fever epidemic developed in the poor neighbourhoods of the city.

Originally, all the water used in São Paulo was drawn from streams draining toward the Paraná basin. However, in 1920, the Billings reservoir was built in the upper Pinheiros basin to take advantage of the Serra do Mar drop toward the Atlantic to produce hydroelectric power. The generating system included a pumping station to take water from the lower river into the reservoir. At that time, the Pinheiros River was not contaminated because the city had not yet expanded to its banks. Now, however, the river has become an open sewer; it contains highly contaminated urban wastewaters and storm waters, and this mixture is being pumped into the Billings reservoir.

Fig. 5. Cross-sections of the geological formations surrounding São Paulo, Brazil.



Instead of discontinuing use of the reservoir for water supply, it has been divided into two parts: one portion receives water from the Pinheiros; another smaller section provides water to the large suburb of Santo Andre (with over 1 million inhabitants) and other urban and suburban neighbourhoods. The two sections of the reservoir are separated by a relatively permeable earth dam that allows flow in both directions. However, the safe section is kept at a higher level than the contaminated water to prevent water from entering it. The Billings reservoir probably also receives polluted water from urban areas in its basin. Close monitoring of quality is required to prevent the hazards associated with using a water body in these circumstances.

The upper course of the Tietê River, near and downstream from São Paulo, has also become highly contaminated another virtual open sewer. Its waters irrigate vegetable farms (for produce consumed in the city of São Paulo), then continue downstream through the Paulista hinterland, where they are used as a water supply by several communities of the São Paulo interior. Several attempts to improve this situation have failed. Now huge investments in the order of billions of dollars would be required to clean up the river (a recently developed plan will cost an estimated US$2.5 billion at least).

The water supply for the city of São Paulo and neighbouring municipalities is obtained mainly from a complex network of reservoirs in many small tributaries in the upper basin of the Tietê, including the Billings reservoir in the upper Pinheiro basin. Total municipal water consumption of the greater São Paulo area is 50 55 m^3/second. By the year 2000, it is expected to reach 65 70 m^3/second, and 80 85 m^3/second by 2010. These estimates are for surface water sources and do not include water from private wells. Although some groundwater for municipal use is drawn from the aquifers contained in the São Paulo formation and the weathered mantle described above, the main use of groundwater is by the industrial sector with a consumption volume of 20 25 m^3/second (slightly more than one-third of the total) .

The 60 industries in the 38 municipalities of the metropolitan area produce over 20 million t of waste per year. Of this, 388 000 t can be classified as hazardous wastes, but only 184 000 t receive any treatment. The rest is disposed of unsafely or temporarily stored in the state s interior. Other regions of the state produce their own hazardous wastes, contributing 530000 t/year to the growing environmental problem. These untreated wastes are among the main causes of environmental degradation, especially water contamination as they are carried into aquifers or join surface run-off into streams.

Summary

Although the city of São Paulo is located in a high-rainfall region, available water is limited by the proximity of the Serra do Mar divide. Rivers and catchment basins are small, and many dams have been built to store the water required by the huge population. A complex system of pipelines, tunnels, storage tanks, and other conduction and storage structures have been constructed (and more are required) to bring water to São Paulo from the surrounding small basins and reservoirs.

Unfortunately, groundwater resources are not abundant either. São Paulo is located on the crystalline Brazilian shield, which contains few hydrogeologically productive areas. The São Paulo tectonic basin permits some storage under the city and water is also available in the mantle created by weathering of crystalline rocks. However, these volumes are also limited. In addition, the city has failed to control waste discharge for too many years. Its rivers are heavily contaminated, some catchment basins are threatened by urban expansion and, therefore, pollution, and groundwater reservoirs are not protected.

São Paulo is facing a difficult environmental future unless careful management of its water resources and appropriate environmental policies are implemented. Only then, will it be possible for the city and its population to survive in this hydrological environment, which was able to satisfy the needs of a small or medium-size city, but is unable to sustain a population of nearly 20 million people.

Montevideo and southern Uruguay

Environment and history

Uruguay, with an area of about 180 000 km^2 and 3 million inhabitants, is one of the smallest countries of South America in size and population. Most of the country s economic activities and people are concentrated in an area of no more than 15 000 km^2, forming a strip along the southern part of the country (Fig. 6).

In that area is the national capital, Montevideo, which contains more than 1.5 million people, almost half the population of the country and probably accounting for over three-quarters of the industrial and commercial activity of Uruguay. Also in this zone are about 20 smaller cities with populations around 5 000 people (including most tourist resorts and beaches) and about half the total agricultural production of the country (mainly dairy farming and fruit and cereal growing, but also some poultry, pigs, beef cattle, and sheep).

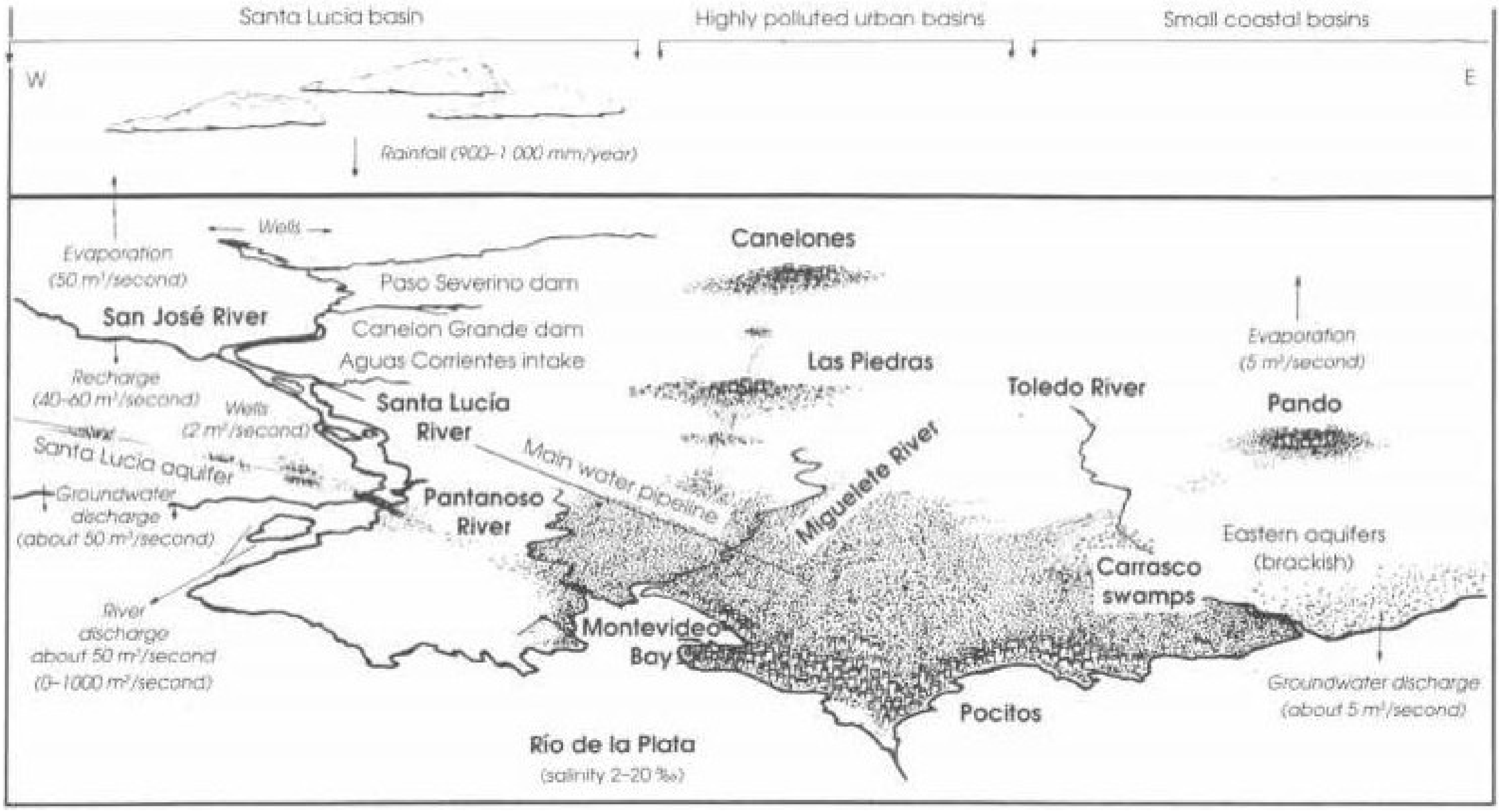
This concentration, which is particularly acute in the city of Montevideo itself, is among the most pronounced in Latin America and is the result of a singular combination of historic and geographic circumstances. Montevideo is located in a strategic site. The Bay of Montevideo is the best natural port in the Río de la Plata estuary. It is a natural gateway to one of the largest water systems of the continent, including three of the largest navigable rivers of South America: the Paraná, the Paraguay, and the Uruguay.

The port of Montevideo is an almost closed circular bay, well protected from the sea winds and surrounded by undulating, low crystalline hills. This terrain is covered by a discontinuous mantle of predominantly silty deposits of mainly eolian origin, covered with deep, fertile soils. The bay was originally deep enough for most commercial vessels and its entrance is partially blocked by a peninsula providing an excellent configuration for defensive purposes against 18th and 19th century military technology.

In spite of its excellent location, the city of Montevideo was established only in 1726, mainly as a base to defend the eastern province of Virreinato del Río de la Plata from Portuguese incursions. A few years after its foundation, Montevideo became the main city of the region north of the Río de la Plata and east of the Uruguay River, competing with Buenos Aires for dominance in maritime commerce.

In addition to its strategic location, the city had the advantage of being surrounded by a sedimentary basin (Santa Lucía basin), in which soils were even deeper and more fertile than in Montevideo itself, and by abundant fresh water (small streams and springs near the city and the larger Santa Lucía River about 20 km from the urban core).

Fig. 6. Aerial view of Montevideo, Uruguay, and the surrounding region.



The surrounding countryside consisted of grassland, except near rivers and isolated hilly areas where forests and shrubby areas were found. Herbivorous animals, e.g., nandus, deer, armadillos, capibaras, and South American otters, were numerous. The indigenous population (Charrua and Minuano nations) were hunters and gatherers related to the Pampidos people of Buenos Aires. Because of their nomadic way of life, population density was perhaps as low as one person for every 20 km^2.

When the Spanish arrived, they introduced cattle, which gradually replaced the native herbivorous animals, and settled the land, pushing the Charruas and other native groups toward the north to the farthest reaches of the province and into the areas colonized by Jesuit missionaries.

Originally, the city obtained water from the springs of La Aguada and various small streams near by (Miguelete, Pantanoso, Malvin, Pocitos, and Seco). Over time, these sources were exhausted or became insufficient and, by the end of the 19th century, the city was forced to bring water all the way from the Santa Lucía River. Because the water of the lower Santa Lucía was often brackish, the intake system and treatment plant were built some 25 km upstream from the mouth of the river, about 40 km from the city itself.

During the second half of the 19th century, Montevideo grew very quickly from 30 000 inhabitants in 1850 to 300 000 by the end of the century. This growth was the result of migration from Europe, which has determined the present ethnic make-up of the country. Growth continued, largely unabated, during the first half of the 20th century, and the population reached 1 million in the early 1950s. At that time, Montevideo was the fifth largest city of Latin America. Since then, the rate of growth has slowed considerably; the population of the metropolitan area is now slightly over 1.5 million.

During the two and a half centuries of urban development, the environment in and around Montevideo has been seriously disturbed. The streams within the bay basin have become filled with wastes from tanning and wool processing, slaughterhouses, and textile industries, e.g., Pantanoso and Miguelete rivers, or have been incorporated into the storm-water system.

East of the city, the Carrasco basin was also disturbed. Originally, the stream extended over a wide swampy area (the Bañados da Carrasco) with dense natural vegetation, in which the industrial and domestic wastewaters of the upper basin were naturally purified. During the late 1970s, these swamps were reclaimed in an environmentally damaging decision, and the wastewaters now flow directly onto the beaches and resorts of Carrasco, which have become highly polluted.

During the 20th century, Montevideo stretched rapidly toward the sandy littoral plains of the east. These sandy coastal deposits of the Chuy formation contained a shallow fresh-water aquifer, which was overexploited and, as a result, suffered saline encroachment from the brackish Río de la Plata. This process was further exacerbated by the excavation of numerous sand pits, in which phreatic lakes formed, increasing evaporation from their surfaces and the concentration of salt in the aquifer. Today, the whole eastern sector of the Montevideo metropolitan region obtains its water from the Santa Lucía River, which lies to the west of the city, 30 60 km from the consumption areas.

As a result of this evolution, greater Montevideo depends heavily on the Santa Lucía River. A few hundred private wells are still used by industries, residences, and soft-drink and mineral-water companies, but they provide not more than 5 10% of total consumption.

The Santa Lucía basin

The Santa Lucía is a medium-sized river with an average flow of about 10 m^3/second, i.e., sufficient to satisfy the present needs of the region, if properly managed. However, because the flow is irregular (ranging from almost nothing to several thousand cubic metres per second), water must be stored for use during dry periods. In times of prolonged drought, saline water from the Río de la Plata moves upstream as far as the intake system. Additional problems are created by sediments, which clog intake pipes during floods.

To help regulate the flow of the river, two dams were built (in the Canelon Grande and the Santa Lucía Chico tributaries); they prevent floods, but do not allow for comprehensive management of the basin. During droughts, when consumption is highest, the city s water demands still exceed the volume of available river water. During the summer, there is no flow downstream of the Aguas Corrientes, although there may still be a small amount of water downstream of the confluence with the San José River, about 15 km from the Río de la Plata and a few kilometres downstream from the intakes. One solution to this problem of irregular water supply is use of groundwater from the aquifers of the Santa Lucía basin to satisfy demand during summer peaks and to accommodate future growth in consumption.

The aquifers of Santa Lucía

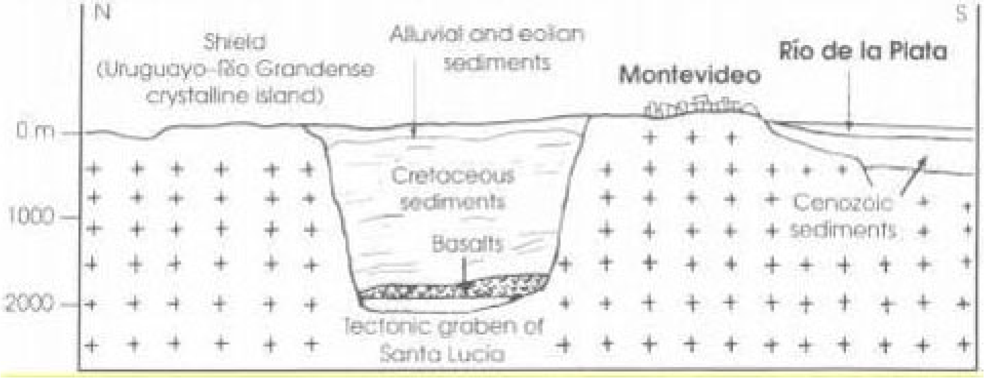
The Santa Lucía sedimentary basin coincides approximately with the Santa Lucía hydrographic basin, although it is smaller (Fig. 7). It lies in a deep graben (2000 m deep) almost completely filled with sediments dating from the early Cretaceous to Quaternary period. The early Cretaceous sequences (Migues formation) are up to 1 800 m thick in the deepest part of the basin and are composed of consolidated detritic deposits, mainly sandstone, but also siltstone and claystone. The Migues formation is covered by sandstones of the Asencio formation (late Cretaceous), over which lie the moderately consolidated and poorly sorted siltstones and sandstones of the Fray Bentos formation (Miocene). These formations have a combined thickness of up to 150 m.

Above these geological units, there is the poorly consolidated gravelly and sandy alluvial Raigón formation, covered discontinuously by the poorly sorted silts of the Libertad formation; the latter is probably of eolian origin and is stratigraphically related to the Pampeano of Buenos Aires.

Not much is known about the hydrogeological characteristics of the Migues, Fray Bentos, and Asencio formations. They contain water, but their aquifers have not been investigated or exploited. The Raigón aquifer, on the other hand, has been relatively well studied and extensively tapped by several hundred municipal and farm wells over its 1 000 km^2. The average thickness of this aquifer is 30 50 m, its effective porosity is about 15%, and its wells yield up to 15 000 L of water per hour.

Most of the water recharging the Raig6n aquifer infiltrates through the Libertad sediments, which seem to act as an aquitard. Discharge from the Raigón aquifer flows down the river valleys. It is not known, however, whether the river valleys are always discharge zones or whether they can also serve as recharge sources, locally or when water levels are high.

Fig. 7. Cross-section of the geological formations near Montevideo and the Santa Lucía basin, Uruguay.



Total potential yield from this aquifer is estimated to be 10 15 m^3/second; 35 m^3/second is already being used to supply the cities of Villa Rodriguez and Libertad and other smaller communities and farms. At the current renewal rate, there is considerable potential for additional urban use (for Montevideo). Some 2 3 m^3/second or more could be drawn over long periods to satisfy increased consumption or up to 5 m^3/second could be used over short periods to offset peak summer requirements. These volumes of water could be obtained from several hundred wells adequately distributed throughout the basin.

Montevideo uses almost 500 000 m^3 of water per day (about 5 m^3/second). If aquifers were tapped during the summer over the next decade and more continuously over the following decade, the problem of water supply for Montevideo would be solved for some time to come. However, if the city s growth and water consumption accelerate, other alternatives may need to be considered as well, including use of water from the Rio Negro or the Río de la Plata at Colonia, with the limitations imposed by the increasing contamination of the latter.

Water supply and environment in the sabana of Bogotá

Site and history

Looking at a map of Colombia, it is difficult to understand why the capital is located in the centre of the country. Bogotá, with nearly one-fifth of the country s population, is difficult to reach by land from any direction. The closest seaports, Santa Marta and Buenaventura, are 1 000 and 900 km away, respectively, through mountainous terrain; the closest river port is Honda on the Magdalena River, about 150 km from Bogotá down a steep escarpment. (The Magdalena, in its middle to upper courses, is a fast flowing and rocky river, which makes upstream navigation difficult and slow.) In addition, Bogotá is about 2 700 m above sea level, in one of the coolest environments of the country; its average temperature is 13°C and the weather is usually cloudy and wet, with few warm periods.

However, in spite of these apparent inconveniences, Bogotá was preferred to other warmer and more easily accessible sites, such as the ports on the Caribbean coast or Cali in its pleasant, warm, and productive valley not far from the Pacific coast. The reasons why the early founders and subsequent leaders of the country chose Bogotá as the capital may be:

- The Cundi-Boyacense plateau, where the city is situated, was the centre of the most technologically developed culture in pre-Hispanic Colombia: the Chibcha culture. When the Spanish arrived, the Chibcha nation had an estimated population of nearly 1 million people, engaged in various farming, mining, and metal-crafting activities. The Chibchas were organized politically into several ministates, and it was easy for the colonizers to enlist the local population by taking advantage of the existing socioeconomic structures.
- The Cundi-Boyacense highlands were also the main source of gold and precious stones (emeralds) in the newly colonized American territories. The famous legend of El Dorado probably arose from the Chibcha practice of throwing gold, as a religious offering, into the Guatavita meteor crater near Bogotá.
- The sabana de Bogotá contained rich agricultural lands, suitable for both indigenous crops and European-style farming (e.g., wheat, barley, cattle, and other farm animals).
- The climate of the sabana was similar to that of the cool Castillan-Leónese plateau in Spain.
- The environment of the sabana was healthier than other parts of the region. Tropical illnesses that were common (or became common) in neighbouring lowlands were rare in Bogotá; yellow fever, cholera, and malaria are still uncommon there. Before antibiotics were discovered, when plagues could kill tens of thousands of people in a short time, the cool climate of the highlands helped to slow the spread of diseases and reduce their effects.

Whatever the reason, the first group of Spaniards, who arrived in the area in 1538 under the leadership of Gonzalo Jimenez de Quesada, found a prosperous society in which several states governed by kings shared the green highlands of the present-day Colombian departments of Cundinamarca and Boyaca. One of the most powerful Chibcha kings was the Zipa of Bacatá, who was based at the village of Bacata not far from what is now downtown Bogotá. The Spaniards settled next to the Chibcha village, establishing the city of Santa Fe de Bacata, or Bogotá as it was called later. They gradually took control of the region, exploiting the mineral and agricultural resources using Indian labour, but for a long time Bogotá remained only a remote city of the colonial territory of Spain in northwestern South America.

At that time, the port cities of the Caribbean, such as Cartagena and Santa Marta, were more important both in size and commercial activity, although they were also more vulnerable to attack from pirates and foreign powers. This may also be why Bogotá was selected as the capital of the Vice-Royalty of Nueva Granada, when this Spanish administrative and political entity was created in 1716.

In 1819, during the Bolivarian period, Cucuta was made the capital of the Gran Colombia, but it was from Bogotá that Simon Bolivar made the first and last attempt to build a Latin American federation. After Bolivar s death in Santa Marta (in 1830) and the failure of the grandiose Gran Colombia plan, the present Republica de la Nueva Granada was formed, with its capital in Santa Fe de Bogotá. The name Republica de Colombia, was finally adopted in 1884.

During the colonial era and well into the 20th century, Bogotá remained a relatively small and neatly planned city, thriving in a fertile, highly productive area of the eastern range plateau. At the end of the 19th century, the population did not exceed 100 000 people, and it was not until 1955 that it surpassed the 1 million mark. The city is approaching 5 million inhabitants in 1993 and its population is expected to grow to nearly 6 million by the end of the century and 7.5 million by 2010.

The environment

Bogotá is on a high, flat-bottomed valley, surrounded by mountains, which together form the Cundi-Boyacense plateau (Fig. 8). This plateau is a 300-km-long, narrow, flat to hilly region situated along the highlands of the eastern range of the Colombian Andes, 2 500 3 700 m above sea level. Near Bogotá, the flat valley floor widens considerably to about 25 km, and this area is called the sabana.

Forest probably covered the area originally, but hundreds of years of cultivation, both before and after the Spanish conquest, replaced it with crops and grasslands. In the last few decades, the expanding city has spread over nearly half of the total area of the sabana.

Geology and hydrogeology

Geologically, the sabana is a Tertiary-filled graben that includes a lower unit of clays and shales (Villeta formation), a middle unit of sandstone that is about 300m thick (Guadalupe group), and an overlying clayey formation (Guaduas formation) (Saldarriaga Sanin and García Durán 1979; Rodriguez 1988a, b). Over these deposits, there is a Quaternary lacustrine and alluvial sedimentary sequence comprising clays and intercalated sandy lenses (La Sabana formation), on top of which thin younger alluvial lenses can also be found.

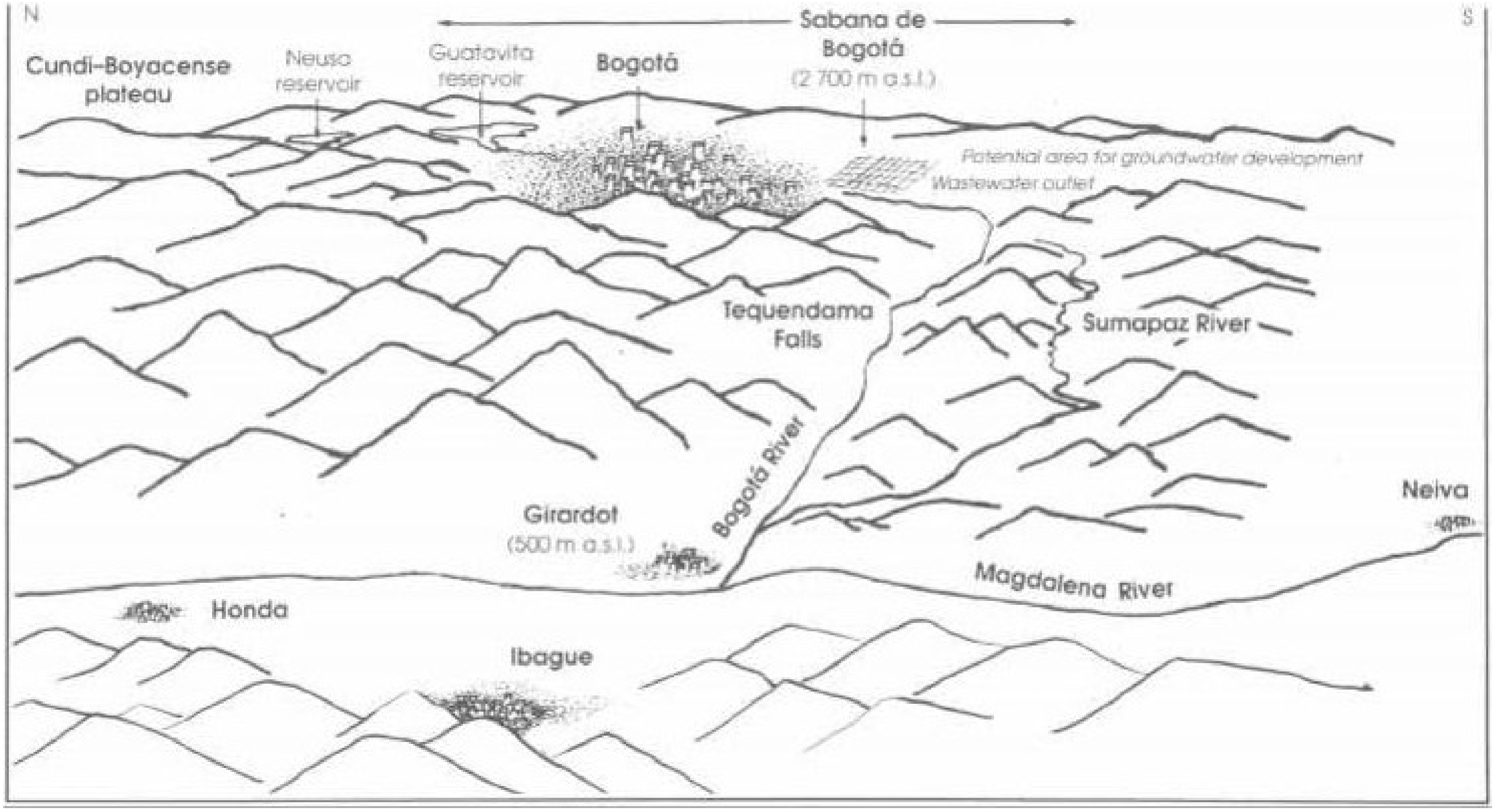
The main water-bearing rocks of these sequences are the upper units of the Guadalupe group (particularly the Areniscas de Labor and the Areniscas Tiernas), with a total thickness of about 160 m, and the sandy lenses of the La Sabana formation. Currently, groundwater is obtained from the shallow sandy lenses; little, if any, is extracted from the deeper sandstones.

The Bogotá River

The Bogotá River is one of the most important tributaries of the Magdalena. It drains a basin of about 6000 km^2 that provides most of the water for the city of Bogotá and neighbouring municipalities and serves as a drainage channel for city s wastes. The upper basin, about 1 800 km^2 with a population of slightly less than 100000, is the main source of water, which is collected in reservoirs constructed there. Its elevation varies from 2 590 to 3 700 m above sea level, and the average precipitation is about 850 mm/year.

The middle basin has an area of 2470 km^2 and a population of over 5 million people. Mean annual precipitation in this mainly flat area, situated at about 2 500 m above sea level, is 900 mm. Most water consumption takes place here.

Fig. 8. Aerial view of the region around Bogotá, Colombia.



The lower basin extends over about 1 800 km^2 and has steeply sloping terrain. The river falls about 2 000 m in this 35-km section. At the Salto del Tequendama, the Bogotá River falls about 180 m. The average rainfall in the lower basin is 1 200 mm annually.

In addition, water is brought into the basin through a tunnel from the eastern slopes of the neighbouring mountain range (Macizo de Chingaza and Embalse de Chuza).

Water use

Water supply The population of Bogotá consumes about 200 L/day per person and this figure is expected to increase to 300 L/day by the end of the century. Current total consumption is about 17 m^3/second, of which 85% (or 14.5 m^3/second) is returned to the Bogotá River downstream. The other municipalities in the basin use about 1 m^3/second, for a total of 18 m^3/second for the whole basin. This amount will increase to 23 25 m^3/second by the year 2000 and to 27 32 m^3/second by 2010. Currently, about 700 000 people in the metropolitan area and 75 000 in other municipalities are without water services.

Wastewaters Liquid wastes from the city are flushed untreated into the Bogotá River at the lower edge of the sabana, a few kilometres upstream of the Tequendama Falls. At this point, the river contains mainly wastewaters and storm water from the city and is heavily polluted. Downstream from Bogotá, the river is filled with sewage; the Tequendama Falls has the dubious honour of being the largest wastewater falls in the world.

Irrigation Because of the relatively high levels of precipitation, little water is needed for irrigation by farms in the Bogotá region. About 6 7 m^3/second is used for irrigation; the watering of flowers in many Bogotá greenhouses is probably the most important such activity (Colombia is one of the largest exporters of flowers of the world).

Electrical power Because of large differences in elevation and steep slopes, energy generation has dominated water strategies in the Bogotá region. A complex system has been built, taking advantage of natural water falls or channeling and piping water to steep slopes to produce hydroelectric power. About 670 MW are now generated in the Bogotá region alone. An additional 600 MW are expected to be produced by the Chingaza project.

Summary

In an urban region as complex as the Bogotá valley, a careful strategy for water management is required. Until now, plans have been oriented toward using available surface water and disposing of the used water in the rivers, on the assumption that the large fluvial volumes would somehow disperse and purify the contaminated water.

It now appears that the resources of the Bogotá basin are barely sufficient to satisfy the requirements of the city. Moreover, the cost of providing water to some neighbourhoods, located south and east of the metropolitan area, has become too high, using the distant northern sources.

In the opinion of some Colombian hydrogeologists, the solution is to tap the groundwater supply. According to Rodriguez (l988a, b), 26000 million m^3 is contained in the Guadalupe aquifer, i.e., 30 times the amount of water stored in all the reservoirs of the city. Groundwater lies unused. No recharge takes place, because the aquifer is saturated and there seems to be no outflow to the lower terrain surrounding the Bogotá plateau.

Water drawn from the aquifer could be replaced with overflow from the Bogotá River during periods of high water, controlling flooding at the same time.

However, the problem of contamination of the Bogotá River must also be solved. The Magdalena River is becoming affected by the polluted Bogotá waters. Although the volume of flow in the Magdalena is much larger than in the Bogotá (25 50 times more), during some periods the Bogotá may contribute up to 10% of the Magdalena s water at their confluence. The level of pollution in the Bogotá River is so high that even this 10% is affecting the quality of the water in the larger river. Because so many cities and people depend on the Magdalena River, for their water supply and for fishing, the health risk must be eliminated.

The once pristine sabana de Bogotá has become a surrealistic nightmare. While many tens of thousands of people continue to move to the city from all over Colombia, the environment is deteriorating and it may soon be too late to prevent the total destruction of the hydrological systems of the Magdalena basin and the sabana.

To solve these problems, investments will be needed and decisions must be made to provide for treating wastewater, for constructing wells, and for building a comprehensive water-distribution system. The cost of *not* undertaking this work may be much higher.

Santiago de Chile

Site and history

In 1541, Santiago del Nuevo Extremo (Santiago of the New Frontier), as it was known, was founded in the territory of the Picunche Indians, in the foothills of the Andes, by the Spanish explorer Don Pedro de Valdivia. The humid and semi-arid lands of Chile are isolated from the Peruvian silver-producing colonies by 2 000 km of desert and from the cities of Río de la Plata by the colossal Andes. Santiago s access to the rest of the world was restricted to the oceanic routes ending at its Pacific port, Valparaíso, founded 5 years earlier, in 1536, by the conquistador Juan de Saavedra.

The climate is often compared with the European Mediterranean: warm, dry summers and cool, relatively wet winters. The average summer temperature does not exceed 20°C (the average temperature of the hottest month, January) and annual rainfall is only 400 500 mm. The native vegetation consisted of shrubs, grasses, and locally limited forests. (Typical trees were the *peumus* and the *litre* still found northeast of Manquehue and east of Penalolen.)

The city is situated at an altitude of 520 m in the valley of the Mapocho River, a tributary of the Maipo River. The Maipo basin is relatively large (nearly 5 000 km^2) and lies upstream of the central valley, south of the Aconcagua River basin and north of the Cachapoal basin. The Maipo enters the Pacific Ocean near the city of San Antonio, south of Valparaíso. Like other rivers in the area, the Maipo s tributaries are short and flow down steep slopes. Their volumes depend mainly on the amount of snow melting in the upper Andes. As a result, the rivers are larger in summer and much smaller in winter. The total flow reaches 2 600 million m^3/year (about 83 m^3/second). Annual flow in the Mapocho River (catchment area: 1 000 km^2) is about 250 million m^3/year (almost 8 m^3/second).

The city grew slowly to 10 000 people, with an area of about 100 ha by 1700. By 1800, it covered 6 km^2 and the population had reached 25000 inhabitants.

Water supply

Originally, the city depended on the local rivers for water, especially the Mapocho and the Zanjón de la Aguada, and to a lesser degree on a number of wells that provided water to areas farther from the river channels.

More important than the urban water supply was the need for irrigation. The central valley of Chile is a semi-arid area with a Mediterranean climate. Although the area produces grapes, oranges, lemons, mandarines, and vegetables, rainfall alone is insufficient for agriculture. From the time of the early settlements, the largest water consumer in the area was the farming sector. Over time, the Maipo River has become less and less able to meet the valley's water requirements.

The problem of inadequate water quality has aggravated the situation. Some of the water in the Maipo basin contains an excess of dissolved solids (e.g., chlorides and sulfates) and suspended solids; its high alkalinity (pH 7–8) makes it unsuitable for drinking. In addition, the Mapocho is polluted with copper and arsenic discharges from upstream mining operations; in the middle Mapocho, unacceptable levels of copper, chromium, phenols, and detergents have been detected. Local aquifers show high nitrate concentrations arising from domestic wastes. Additional problems have been identified in the farming areas near the city, where sewage water is used to irrigate vegetable crops, thus creating a health hazard.

The quality of groundwater in the region, which is contained in alluvial Quaternary and Tertiary formations, is generally acceptable; it has a low degree of hardness and of bacterial contamination. However, in newer districts, adequate sewage facilities are lacking and overflow from septic tanks can jeopardize groundwater quality. In other areas of the city, potential for leakage from the old sewer systems is high.

The city's rate of growth has increased the problems. During the 20th century, Santiago's population grew from 250 000 in 1900 (occupying an area of25 km^2) to over 5 million people spread over 500 km^2 in 1992. Santiago has become an important industrial centre, with more than 20 000 industries producing over 50% of the country's output.

The Santiago metropolitan region is star-shaped, following the morphology of the valley lowlands and the axes of the major highways, particularly along the north-south central valley. However, recently, the city has also extended westward, to the point where it is expected to merge with Valparaíso and Viña del Mar in the next few years, creating a huge megalopolis, housing nearly 8 million people (half the population of the country) in an area of more than 2 000 km^2. Although some of the water requirements of this megacity will be satisfied by the Aconcagua River (the main source for Viña del Mar and Valparaíso), a significant increase in urban demand, . coupled with the ever-growing need for agricultural irrigation, will certainly put a strain on local water resources, prompting the development of a new management scheme for the basin, which is expected to become operational soon.

Average per capita water consumption is 350–400 L/day, which represents more than 1.5 million m^3/day for the whole city (20 m^3/second). Forecasts for the year 2025 project a need for more than 42 m^3/second.

Irrigation

Agricultural areas are irrigated by flooding, with low efficiency of water use because of losses through infiltration and evaporation. Estimates of irrigation efficiency range from 20 to 60% depending on local conditions. Water consumption per hectare is as high as 20 000 m^3/year and, for the total irrigated area of nearly 100 000 ha, may be over 1.5 billion m^3. The trend will clearly be toward decreasing the area under irrigation, because of competition from the city for the limited water resources and land (which is more scarce than the water). This already occurred between 1956 and 1970, when 123 km^2 of agricultural land was absorbed by the city. However, in spite of this reduction, irrigated farming still represents an important land use in the vicinity of Santiago.

Summary

The large metropolitan area of Santiago is located in a fragile environment and is reaching its limits in many senses. As is the case with many other Latin American megacities, the hydrographic basins are becoming insufficient to meet the demands of irrigated farming and urban activities. As usual, for political and other reasons, urban use is given priority over farming and agricultural activities are being gradually suppressed because of the scarcity of water. In addition, increasing land prices near the city make crop production uneconomical.

However, cities not only consume water, but also have a negative effect on its quality. Santiago is no exception and degradation of both surface and underground waters has clearly occurred. Some of the problems can be solved through adequate and intelligent investment. Others can only be resolved by stopping the city's growth.

From many points of view, the environment in Santiago's central valley is under siege. The air of the city is unbreathable because of the enclosed nature of the city site, the meteorological patterns, and the output from almost 1 million vehicles. Water resources are insufficient and the threat of earthquakes is ever-present. Several million people are concentrated in this increasingly hostile environment and many thousands of immigrants from the rest of the country are moving to the city.

As in many other parts of the continent, Chile must begin to move toward demographic and economic decentralization. Environmental problems in the Santiago area are becoming unmanagable. As in other Third World countries, the Chilean model of development is not sustainable and, sooner or later, the politicians must face the fact that megacities are not viable, at least in terms of the interests of the human: beings living in them.

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Cities depending on both surface and underground water

Many Latin American cities draw on both surface and underground sources for their water supply. In some cases, for example Buenos Aires, surface water is used predominantly in areas near rivers, whereas groundwater is used in more distant neighbourhoods where bringing water from the river would be expensive or impractical. In other cases, such as San José in Costa Rica, the city originally depended on groundwater, but with the construction of a reservoir a significant area of the city began to use surface water. Cities such as Santa Marta, Lima, and, to a lesser degree, Recife are near small rivers with insufficient volumes to supply their populations and activities; groundwater is tapped to make up the deficit.

Greater Buenos Aires and La Plata

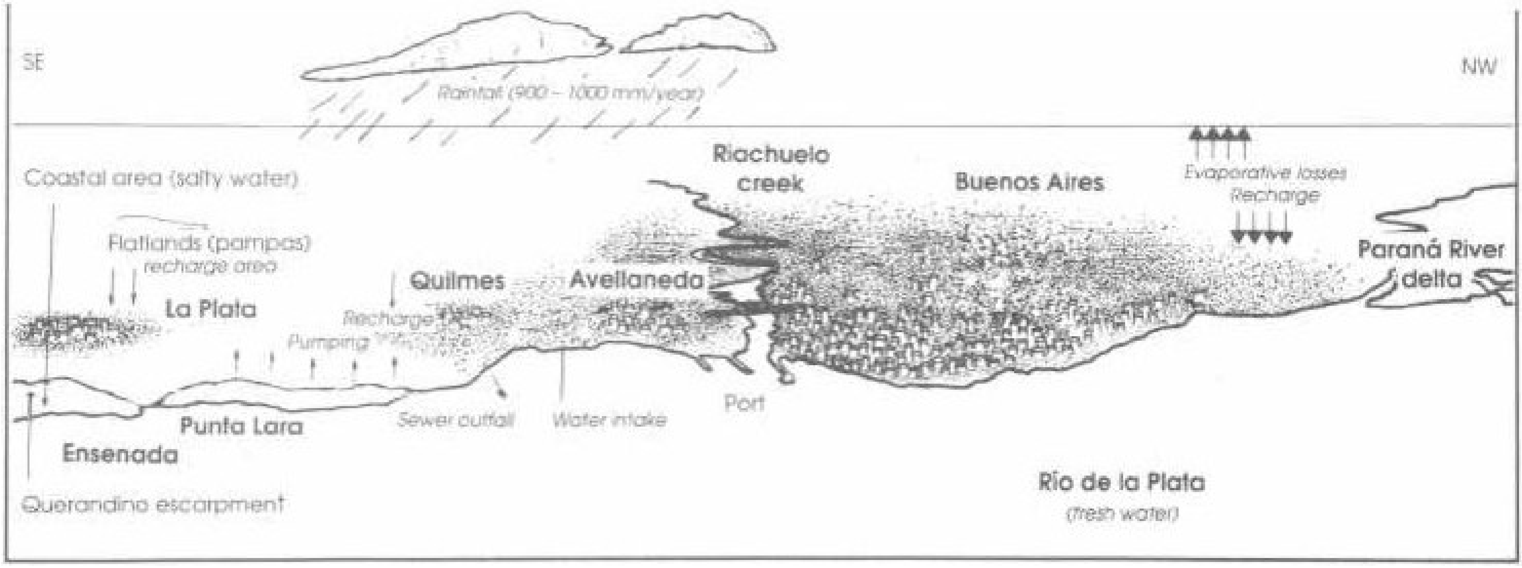
Environment and history

The city of Buenos Aires was founded in 1536 by the Spanish explorer, Pedro de Mendoza, near the confluence of the Paraná and Uruguay rivers on the southwest shore of the Río de la Plata estuary. The city is located on one of the largest grassland plains in the world: the pampas. These plains cover a vast, almost flat area of about I million km^2. The inclination of slopes in the region is less than one per thousand, drainage is poor, and lands are easily flooded.

Before the Spanish arrived, the pampas were the domain of a large number of herbivorous mammals (e.g., deer, capibaras, armadillos of several species, and nandus) and birds that sustained a sparse nomadic population of hunters and gatherers. The most important ethnic group among these early people was the Pampa nation. The new colony was destroyed by the indigenous population within a few years of its establishment; in 1580, it was rebuilt by Juan de Garay.

From a purely environmental point of view, the original site of Buenos Aires could not have been better chosen (Fig. 9). It enjoyed a moderate subhumid climate, excellent agricultural lands, easy maritime access, good land communications, and practically unlimited volumes of water. The city was also located at the mouth of one of the largest navigable waterways of the continent.

Fig. 9. Aerial view of the region surrounding Buenos Aires-La Plata.



As a result, the city developed quickly from a small village in the 16th century, to a medium-sized town in the 1800s, and to one of the largest metropolises of the world in the 20th century. In 1990, the population of greater Buenos Aires exceeded 12 million and, although its rate of growth has slowed somewhat, it is expected to reach almost 14 million by the year 2000 and 16 million in 2010.

The city is the capital of the Republic of Argentina and home to almost 40% of the country's population (Pirez 1991). The area around Buenos Aires has also become densely populated, with intensive agricultural and industrial activities; it has become one of the most important grain- and cattle-producing areas of the world. Industrialization is related to agriculture (e.g., slaughterhouses, tanning and textile factories, mills, and food processing) and metallurgy (e.g., foundries and automotive industries). The province of Buenos Aires, which contains the almost 300 000 km^2 surrounding the federal capital, is the site for most of this activity.

In 1888, a new city was designed and built on a site not far from the city of Buenos Aires to house the provincial government. The population of the provincial capital, La Plata, rapidly grew to 600 000. Because of the rapid expansion of suburban neighbourhoods, La Plata has almost merged with the outer suburbs of Buenos Aires to form a single macrourban region.

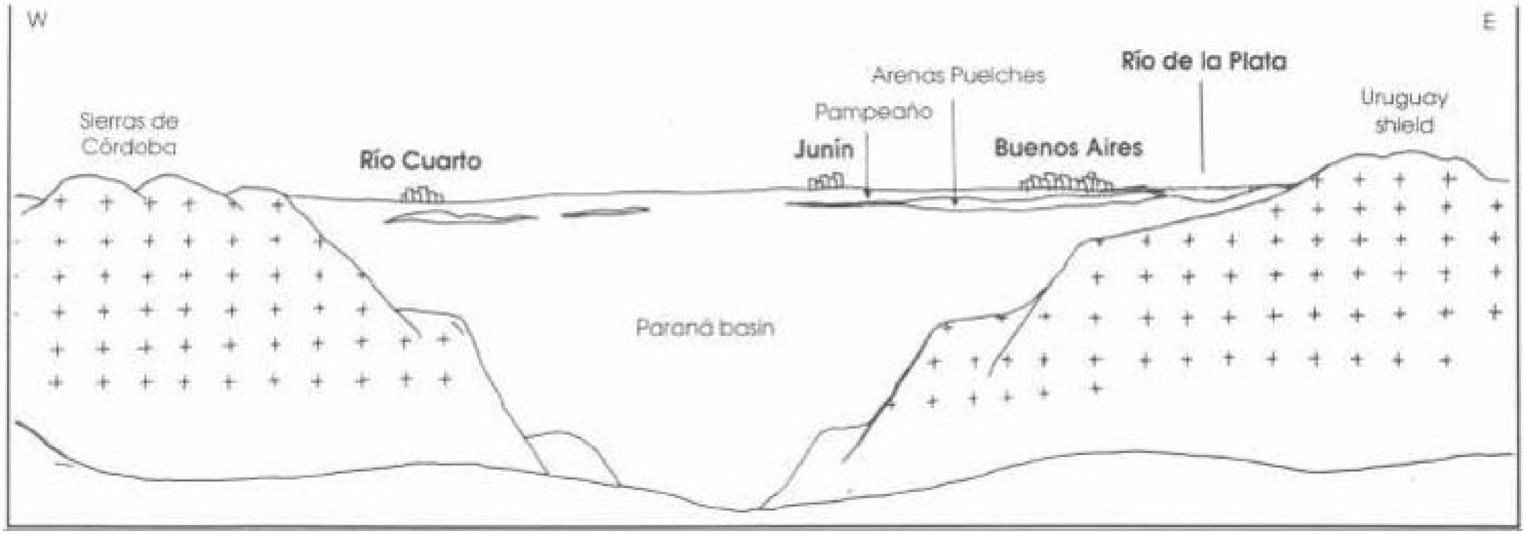
Water supply

The phenomenal growth of Buenos Aires has begun to have overwhelming, deleterious effects on the environment. Originally, the city's water came from small streams, such as El Riachuelo (also called the Matanzas River), and a number of shallow wells. With time, these water sources became insufficient and contaminated (El Riachuelo contains sewage and all the older wells have been abandoned) and a municipal water system was developed to use water from the Río de la Plata. In many cases, the outlying suburbs, such as the large municipality of Quilmes east of the federal capital and La Plata, preferred to use groundwater obtained from underlying alluvial aquifers.

Most of the groundwater used in Buenos Aires and surrounding areas is drawn from the Arenas Puelches (Puelches sands), a permeable, alluvial aquifer, 30–50 m thick, filling a paleovalley (the ancient wide, flat Paraná alluvial plain) and covered by a semipermeable, silty eolian formation (Pampeano) that is about 40 m thick (Fig. 10). Unfortunately, a narrow strip of Quaternary material (Querandinense-Platense) along the edge of the Río de la Plata, which is a remnant of the late Pleistocene and Holocene marine encroachments, contains highly saline groundwater and is hydraulically connected with the Puelches sands. In fact, along the coastal fringe, the whole Quaternary sequence (including the Arenas Puelches) contains salty water. The level of total dissolved solids in the Puelches sands is usually higher than in the Querandino or the Pampeano. Whether the original Querandino salty water contaminated the Puelches aquifer is not known (although it is likely). On the other hand, the Río de la Plata at Buenos Aires contains fresh water.

As a result of overpumping, saline groundwater has entered a large number of coastal wells and they have had to be closed. The unusual feature of this problem is that the saline intrusion is not related to the nearby estuary, but in all likelihood to a narrow saline remnant of a marine transgression (or ingression).

Fig. 10. Cross-sections of the alluvial plain in the Buenos Aires-La Plata region.



All of the water for the federal capital, and a considerable volume of the suburban water supply, is obtained through intakes located in the Río de la Plata. The intake system was originally situated a few kilometres upstream of the Buenos Aires port, not far from the coast, but a new one was built in the 1950s near Bernal, downstream from the federal capital.

Changes in quality of the water in Río de la Plata

Water quality and treatment problems are associated with the use of the Río de la Plata waters for urban supply. The Río de la Plata receives water from the Paraná and Uruguay rivers, which in turn drain a vast basin of nearly 2 million km^2. The composition of the water in the estuary is affected by the activities taking place throughout its large hydrographic basin. Most of the water comes from the humid highlands of the Brazilian shield, the planalto, and the subhumid Chaco-Mato Grosso regions.

The Río de la Plata originally contained almost sediment-free water; its volume was fairly constant throughout the year, except for short periods of flooding in the irregular tributaries of the western portion of the basin. A considerable volume of water flows into the Paraná during the rainy seasons in the semi-arid Chaco and the arid cordilleran foothills. One of the main rivers draining this western area of the basin is the Bermejo, which is heavily loaded with reddish suspended solids during wet periods. Smaller quantities of sediment enter the Paraná-Paraguay main valley from the right margin, e.g., in the Pilcomayo and Salado rivers. In spite of the relatively small volume of water contributed by the western tributaries, it is concentrated over a short time and, during these periods, the Río de la Plata receives a considerable volume of suspended sediments.

In the days when dense forest covered their catchment areas, the Paraná and Uruguay rivers, flowing from the north and northeast, had constant volume and clean water. Most of the planalto and shield highlands consisted of single-species *Araucaria* forests (Brazil pine) and other less-extensive forest systems; the Mato Grosso was covered by tropical rainforest and the Chaco by dense xerophytic forest vegetation.

During the last 20 50 years most of these forests have been destroyed. The *Araucaria* forest of the planalto has almost completely disappeared, astonishingly in less than 20 years. The trees were cut for lumber and land was cleared mainly to provide not only for grazing land for cattle, but for other agricultural activities as well. The forest survives only in isolated pockets and on the steepest slopes. The Mato Grosso forest is rapidly giving way to short-lived rice fields, which are finally used for raising cattle. A large tract in the Chaco hinterland has also been heavily damaged. As a result of these changes, fluvial regimes have been substantially modified and the percentage of suspended materials in the Río de la Plata has dramatically increased.

A second problem is the increase in the outflow from city sewers and storm-water systems, which is approaching 100 m^3/second. This wastewater is heavily contaminated and is flushed, untreated, into the Río de la Plata.

Third, because the city has a large port, intensive shipping activity takes place in the waters surrounding the port the same water that is used to supply the city. Ships are known to be sources of heavy pollution and their presence affects the quality of the city s water at the intake point.

Because of these problems, treatment of the municipal water supply for Buenos Aires is costly and probably insufficient. The risk of contamination is increasing, to a point where wastewater treatment must be implemented or alternative sources of uncontaminated water must be found.

The groundwater alternative

Groundwater is one alternative source. It is used at present to a considerable extent in some municipalities of greater Buenos Aires. Metropolitan Buenos Aires consumes 85 m^3 of water per second: 65 m^3/second is for domestic use and 20 m^3/second for industry. Of the 65 m^3/second used for domestic consumption, 24 m^3/second (37%) is obtained from groundwater sources; the rest (63%) comes from the Río de la Plata. A considerable volume of the industrial water supply is also obtained from groundwater (probably as much as 40% or 8 m^3/second). Therefore, over 30 m^3/second of groundwater is already consumed in the Buenos Aires area; this appears to exceed the current recharge volume, at least locally.

The presence of a protecting aquitard over the Puelches aquifer does not seem to prevent some contaminants from entering the groundwater reservoir. Many wells are located close to industrial areas in which various hazardous wastes are disposed of without adequate control.

In addition, many zones supplied by groundwater have no sewers. Contamination from domestic septic tanks is affecting or might affect the water supply of as many as 3 million people in greater Buenos Aires, particularly at present when a cholera epidemic has extended throughout the Latin American region.

These factors may make the use of groundwater in Buenos Aires and surrounding areas an unsustainable proposition unless sound environmental controls and water management practices are introduced. Buenos Aires has placed itself in a difficult position because of irrational use of its abundant water resources. The solution to its water-supply problems will have to consider the growing degradation of the environment.

The Cochabamba valley

Environment and history

Cochabamba is one of the largest cities in Bolivia. With nearly 0.5 million inhabitants, it has become the capital of the sierra region, located in the dissected mountains of the intermediate zone between the altiplano to the west and the llanos de Santa Cruz to the east. The department of Cochabamba is one of the most densely populated of the country, including not only the city of Cochabamba, but also other cities and villages in the valley and on the neighbouring highlands.

The geographic character of Cochabamba is partly a result of its altitude (2 550 m above sea level), which is intermediate between La Paz (3 700 m above sea level in the downtown area) and Santa Cruz (415 m above sea level). The climate is also intermediate between the 100˚C annual average temperature of La Paz and the 27˚C of Santa Cruz. Average rainfall in the city itself is about 450 mm/year, concentrated mainly during the summer months of January and February. The valley can be classified as semi-arid, with a considerable water deficit during the winter and spring. Because of this climate, crops are subtropical and temperate; fruit is grown there as well as several kinds of grains and vegetables and dairy farming is common.

The Spanish city of Oropeza (later renamed Cochabamba) was founded in 1574 by Sebastian Barba de Padilla. During the few centuries before the arrival of the Europeans, the region around Cochabamba was part. of the mighty Tahuantisuyu, the Incan empire that extended from Ecuador to Argentina. The capital of the Tahuantisuyu was Cuzco (in Peru) and the whole altiplano and sierras of Bolivia were part of the Incan domain.

The dominant ethnic group of the Incan empire was the Quechuas, who gradually extended their cultural control over most of the empire. Some areas of Bolivia retained their ancient culture and language (e.g., the Aymaras of the altiplano and the La Paz region). However, by and large, Cochabamba was Quechuanized and now represents one the most important Quechua-speaking regions south of Cuzco.

During the centuries of Spanish and *criollo* domination, Spanish became the dominant language in the city. Quechua, however, has remained the main language used in rural areas, in urban shanty towns, and in folklore. As a result, Cochabamba is considered to be the Quechua capital of Bolivia.

Because of its climate, agricultural productivity, and commercial importance, Cochabamba has recently attracted a number of people displaced from the mining communities of Oruro and Potosi in the altiplano during the tin crisis. The newly arrived migrants are mainly Aymaras, adding a new element to the cultural diversity of the city.

In spite of its demographic growth, the valley of Cochabamba remains a predominantly agricultural region and is one of the most productive areas of Bolivia. Because precipitation is low, a significant number of crops must be irrigated, which adds to the water requirements of the valley. The high volumes of water needed for irrigation and for the dense local populations make management of water resources one of the key elements in the sustainable development of the valley and the urban region.

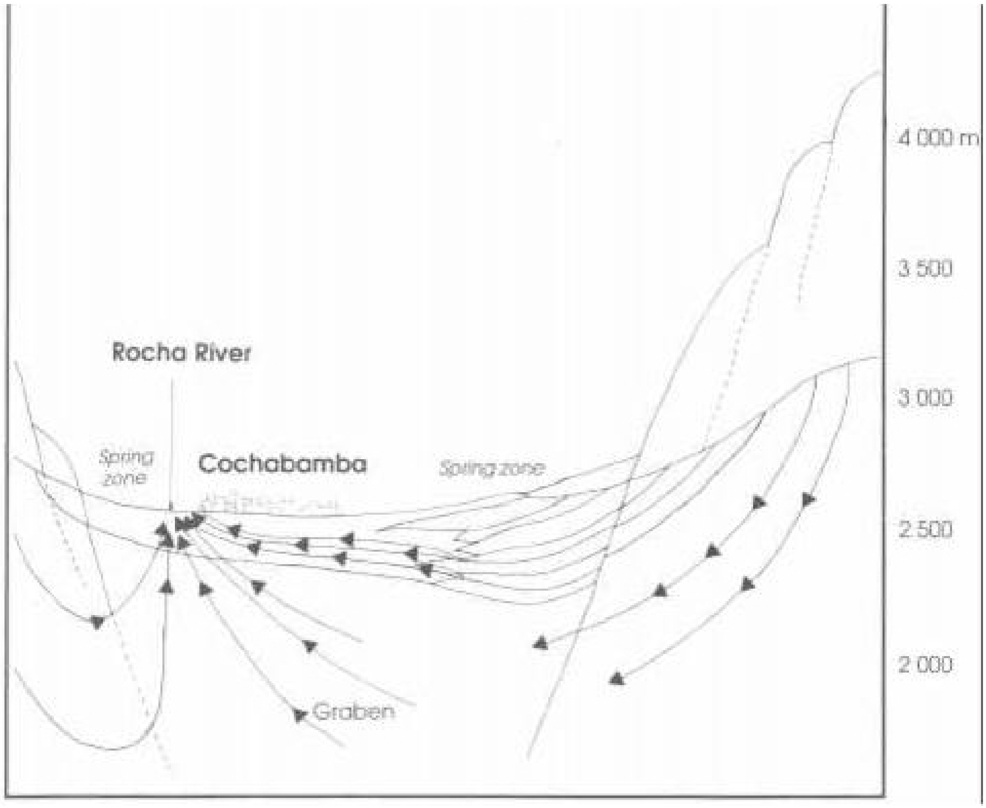
Another factor that cannot be overlooked is the transformation of Cochabamba into one of the main regional centres for the processing and sale of cocaine. Coca leaves are produced in the hot, humid areas of El Chaparé, Chungas, and other isolated sites on the lower slopes of the sierras. Traditionally, coca leaves have been used by the Andean peoples as a stimulant and a medicine; their legal use is still widespread. The processing of coca leaves to extract cocaine is a relatively new activity.

Cocaine is believed to be produced in the Cochabamba valley using the recently arrived migrants as a source of cheap labour. Because processing requires kerosene, sulfuric acid, and other environmentally harmful substances, there is some concern not only about the social impact of drug production, but also about its environmental effects, particularly on water resources.

Geology and geomorphology

The Cochabamba valley is narrow (5 10 km wide), apparently at least partly of tectonic origin, and overlies a Paleozoic and Mesozoic basement (Ordovician, Silurian, and Cretaceous periods) (Fig. 11). The Ordovician formation is composed of a lower sequence of siltstones, claystones, and sandstones (Cuchu-Punata formation) and an upper sequence of quartzitic sandstones (San Benito formation). The Silurian section contains a lower formation of quartzites and clay grits (Cancaniri formation) covered by claystones (Uncia formation).

Fig. 11. Cross-section of the Cochabamba aquifer. Note: arrows show groundwater flow.



Mesozoic sedimentary rocks of the Cretaceous period are also found overlying the Paleozoic rocks. They are mainly limestones and marls at the bottom (El Molino formation), underlying a flysch-type sequence of calcareous sandstones, marls, and clays (Santa Lucía formation). During the Paleocene epoch of the Tertiary period, the molassic deposits of the Morochata formation were laid down; they consist of conglomerates covering a limited area.

The bottom of the valley is filled with a thick sequence of Quaternary deposits beginning with Pleistocene lacustrine deposits (clays, sandy and silty clays, etc.) in the lower areas that develop into fluvio-lacustrine and fluvial sediments toward the top. In the foothills on the lateral slopes, coarse deposits have accumulated (agglomerates, gravels, and coarse sands) related to the alluvial fans of a number of torrential streams descending from the neighbouring highlands.

Only the fluvio-lacustrine, fluvial, and fan deposits have demonstrated potential for groundwater extraction. Yields in the lower fluvio-lacustrine deposits vary from about 1800 L/minute at the edges of the basin to less than 100 L/minute in the centre. Fluvial and fan sediments have a much higher permeability with yields of fluvial deposits reaching 3 600 4 800 L/minute and those of fan sediments even higher. The quality of water in the fluvial and fan aquifers is good (Von Borries 1988).

Hydrology

The Cochabamba basin covers about 1150 km^2. The main river is the Rocha, which has a low flow volume during dry spells, but can cause destructive floods during intense rainy periods. The Rocha receives water from the Cuchu-Punata basin, via the Tamborada River, whose flow is controlled by the Mexico dam forming Lake Angostura.

A number of lakes (some natural, some artificial) are found throughout the basin. The natural lakes are presumably of glacial origin and, together with the artificial reservoirs, they constitute one of the main sources of water supply for the city.

Water supply

Water for the Cochabamba region is derived partly from surface water, brought by open aqueducts from lakes Warawara, Escalerani, and Saytokocha in the neighbouring highlands (about 4 000 m elevation). The rest is extracted from the alluvial aquifers of the valley. Under the direction of the Servicio Municipal de Agua Potable y Alcantarillado, several batteries of wells are in operation: 14 in Muyurina, 10 in Vinto, 9 in Cona Cona, and 3 in El Paso. In addition, there are many private wells.

At the edge of the valley, wells are phreatic; in the centre of the valley, they are usually artesian. Currently, intense extraction has significantly lowered water levels and, therefore, many wells are no longer free flowing and pumping is required.

Water consumption in the urban region is 0.65 0.75 m^3/second (60 00070000 m^3/day). About 60% comes from surface sources and 40% from the aquifers, perhaps as much as 25 000 m^3/day. In addition, a significant amount of groundwater is used for irrigation and other farming activities; this volume is probably as much as that drawn for the city.

Environmental problems

Both surface and groundwater in the Cochabamba valley are vulnerable to damage from overuse. Drilling of wells continues at an unabated pace with no legal constraints. As a result, overextraction may lower the level of groundwater, thus increasing pumping costs and risking complete loss of water from higher areas of the aquifers.

Recharge areas are not protected and waste disposal is relatively unrestricted. Currently, the alluvial fans constitute the main recharge area, and they have not been strongly affected by urban encroachment, but the threat is increasing as the cities grow. In the central part of the valley, the aquifers are semiconfined and the risk of contamination is lower, although, if water levels continue to drop, contaminants are more likely to make their way into groundwater reservoirs.

Surface waters are also threatened. The Rocha River is heavily polluted and, therefore, cannot be used for water supply or irrigation. The lakes are less threatened because of the relatively low population density around them, but they must be protected.

There are other environmental risks in the city, mainly relating to the irregular flow of the Rocha River and its flood-control systems. To prevent destruction during periods of high-volume flow of the river, a diversion scheme was established. An artificial lake (the Laguna Alalay) stores excess water during floods; water is diverted through a tunnel excavated through hills arising in the centre of the valley near the city s core. Settlement on the shores of this lake, however, has caused it to become a dumping ground for various types of wastes and local sewage. Lake Alalay has become a primary environmental concern in the Cochabamba urban area. In addition, Cochabamba periodically suffers acute droughts. Surface water cannot be used at these times, putting greater demand on limited groundwater sources.

In spite of its moderate size, Cochabamba has many actual and potential problems that must be solved if the city is going to continue growing in a sustainable manner. More studies, investment, and action are required to prevent further degradation of the beautiful Cochabamba valley.

The aquifer at Lima

Environment and history

Lima, the capital of Peru, is located in the foggy coastal desert of the Pacific facade of South America at a latitude of 11°S. This desert is characterized by a quasipermanent layer of stratocumulus clouds, formed when the lower layers of the atmosphere cool as they come into contact with the cold waters of the Pacific Ocean. The ocean temperature along the coast from Chile to Peru is strongly affected by the cold Humboldt current and the upwelling of deeper, cooler waters from the bottom.

As a result of these phenomena, Lima s climate is cooler than cities of the same latitude and altitude in other parts of the world. Its precipitation is also one of the lowest on the continent (about 10 mm annually). However, the city s air is relatively humid, because of frequent fogs and heavy dew.

The city has developed near the foothills of the Andes, on the ancient alluvial fans of the short, torrential Rímac River descending from the neighbouring mountains (Fig. 12). Recently, the northern suburbs have extended onto the alluvial fans of another river with similar characteristics, the Chillón.

The city was founded by the Spanish as a port, mainly for export of precious metals from upper Peru, e.g., Cuzco and Potosi. The actual port city was Callao; the colonial city of Lima was founded at a prudent distance of 10 km from the coast. When Peru declared its independence in the early 19th century, Lima became the country s capital.

The city grew slowly until the 1940s, when the population reached 300000. Since then, its growth has accelerated and, today, the population of metropolitan Lima is close to 7 million people. According to Olivera (1991), the city of Lima now contains 28% of the national population of Peru, 45% of the urban population, 69% of the industrial internal product, 70% of industrial enterprises, 87% of the fiscal income, 83% of the bank deposits, and 98% of the private investments.

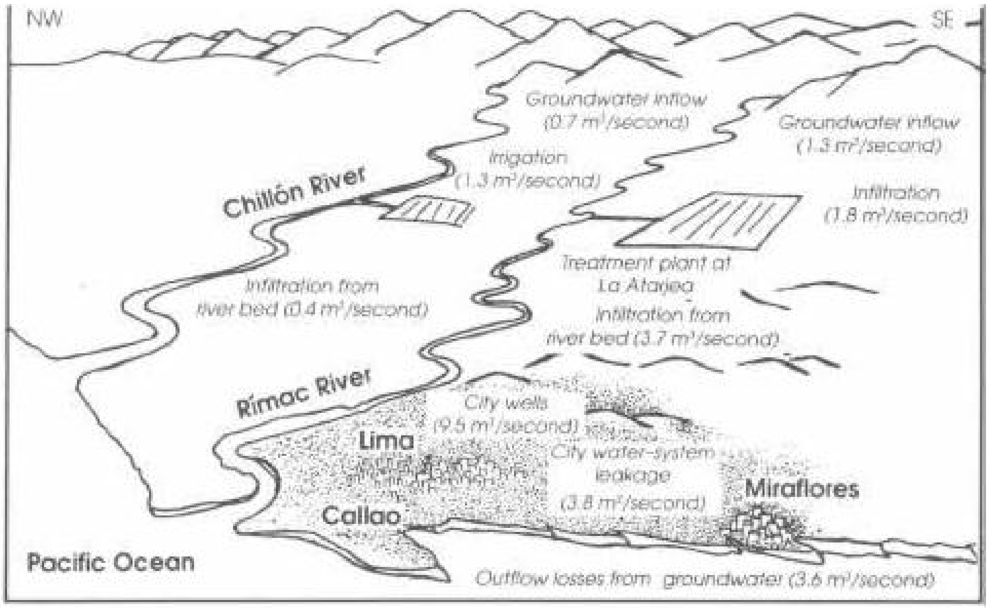
Water supply

Almost all of the water for Lima and its suburbs comes from two sources (Binnie and Partners 1987):

- The Rímac River, via a treatment plant at La Atarjea and its distribution system, and
- Wells drilled in Lima s coastal alluvial aquifer.

Total water consumption in the Lima metropolitan area in 1986 was estimated at about 21 m^3/second: 11.35 m^3/second from the Rímac River and 9.45 m^3/second from groundwater

Fig. 12. Aerial view of the Lima-Callao region, showing inputs to the underlying aquifer from various sources.



sources. In 1990, demand had increased to about 25 m^3/second and will continue growing at a rate of about 4% per year to reach 33 m^3/second in the year 2000 and 45 m^3/second in 2010.

The La Atarjea distribution network serves about 60% of the population with water from the river and 106 (42%) of the 253 producing wells. In 1985, it was estimated that about 70% of the population was legally connected to the main municipal water system. An additional 16% obtained their water illegally from the system, and the remaining 14% had to get water from public faucets or water tanks. With the recent growth, it is likely that the actual number of people not connected or illegally connected with the main network may be closer to 40%, i.e., 2.8 million people.

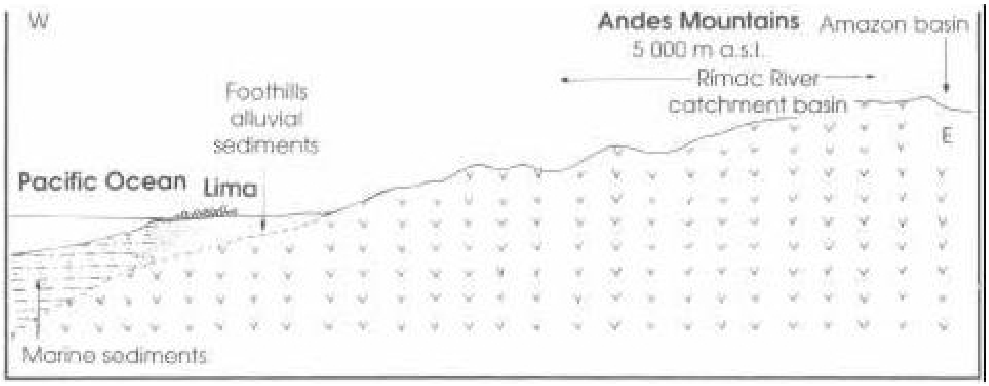
The remaining 147 wells are connected to local distribution networks. Industries, commercial businesses, and irrigated farms receive most of their water from these.

The aquifer

The area of the Lima aquifer is 390 km^2, including the lower Rímac and Chillón alluvial basins and associated coastal deposits. Water is contained in a coarse-grained formation of sands and agglomerates with thickness ranging from zero in places to probably about 500 m, although accurate figures are not available (Fig. 13).

The upper 100 m consists of highly permeable, relatively clean sands and gravels with few finer elements. From about 100 to 200 m to the bottom of the aquifer, the general permeability of the formation decreases, although little information is available about the structure below 200 m.

Fig. 13. Longitudinal section of the Rímac River basin.



Overpumping has caused water levels in most wells to drop by 1 2 m/year. A number of wells near the coast had to be closed due to high salinity; others further inland stopped producing. To compensate for the decrease in available water, new wells had to be constructed and pumping rates were increased in a number of existing wells.

Between 1969 and 1985, groundwater levels in the coastal zone dropped at least 10 m and up to 30 or 40 m in the higher plain near the foothills (Fig. 14).

Operational problems encountered in using water from the Lima aquifer (Binnie and Partners 1987) include:

- Pumping costs have increased because of lower well yields;
- Wells have become and are becoming dry, even when they are drilled into the bedrock;
- Salinization of groundwater has occurred near the coast because of lowering water levels;
- Pumps are (or have become) too large for the current yields, i.e., cost of running them is higher than necessary; and
- Dynamic water levels have fallen below the upper limit of well screens, producing encrustations on the screens and reducing well yields.

The rate of renewal of the aquifer is considerably lower than the rate at which water is being extracted. Recharge of the groundwater from the surface, which is the main route for water renewal, comes from several sources:

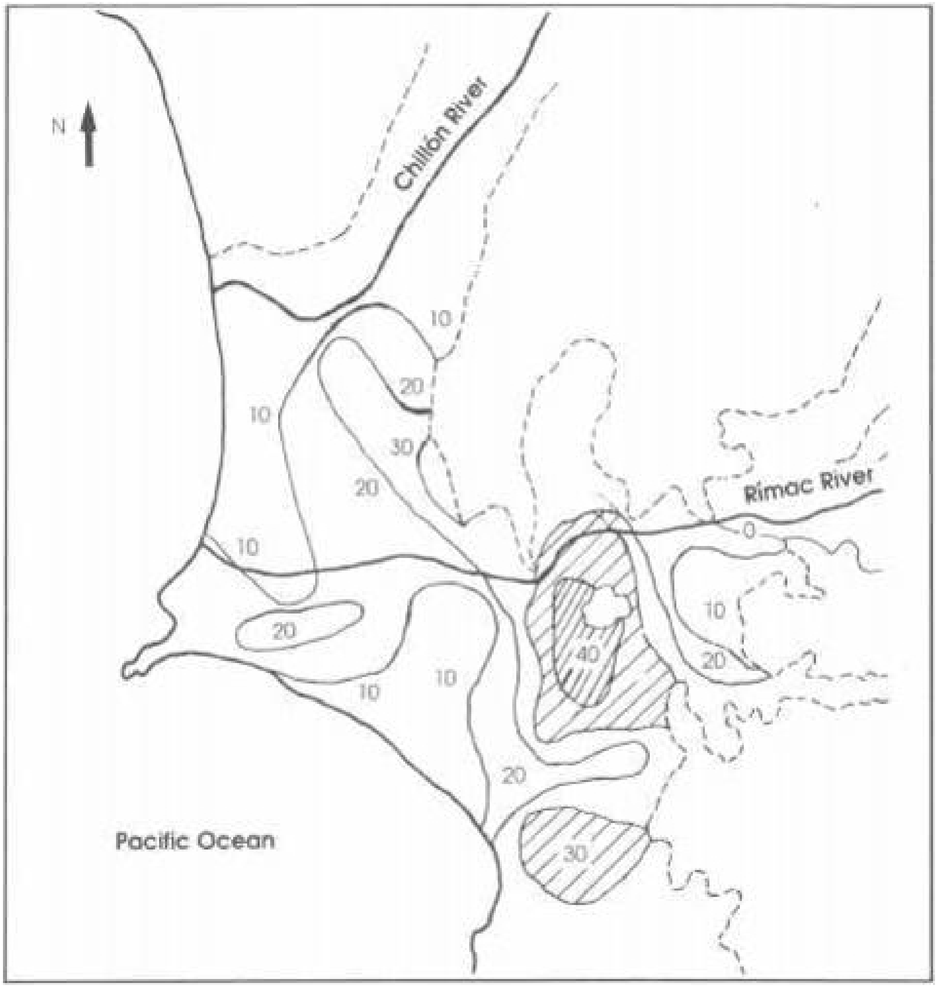
- River beds, mainly the Rímac River, but some also comes from the Chillón ; Swamps and other naturally vegetated areas north of the city;
- Agricultural irrigation in the nonurban areas of the coastal plain;
- Garden irrigation in urban areas;
- Losses from the water-distribution system; and
- Losses from the sewage system and disposal of untreated domestic wastewater.

Almost no direct recharge takes place, through rainfall or local run-off, because of the low level of precipitation in the Lima area (10 mm/year) and the type of precipitation (drizzle and dew). Run-off on the slopes surrounding the city and infiltration in the foothills and local fans are extremely rare.

Of the sources of recharge water listed above, the most important are the first four. Current rate of recharge from these sources is about 11 m^3/second: about 4 m^3/second from river beds; 3 m^3/second from farms, parks, and gardens; and 4 m^3/second from losses from the water-distribution system (Fig. 12). If underground water flow from upstream alluvial areas is included, the total input to the aquifer is about 13 m^3/second.

Several of these sources of recharge are being threatened by urban growth. Many irrigated farms and parks surrounding the city have been displaced. If the current trend continues, recharge from these sources could be reduced by half in the next 20 years. The city is also encroaching on the river channels where a significant amount of infiltration takes place. For example, a new highway is being built along the Rímac River, which will make several dozen hectares of the valley surface impermeable.

Fig. 14. Decrease in groundwater levels (m) in the area around Lima between 1969 and 1985. Source: Binnie and Partners (1987).



The current hydrological balance of the aquifer is negative; at least 1 m^3/second more is extracted or lost to the sea through underground flow than is recharged from the various sources. Rate of extraction has not been reduced in spite of the decrease in recharge volume. As water levels become lower and saline intrusion continues, pumping costs are going to increase and many old wells will become dry or saline. On the positive side, a project is under way to artificially inject water into the aquifer to restore the balance.

Surface water sources

Surface water provides 55% of the urban supply in the Lima area. The present average rate of flow of the Rímac River is 32.3 m^3/second in Chosica, upstream from Lima; that of the Chillón River is 7.5 m^3/second in Larancocha close to the exit to the coastal plain. About 10 m^3/second is lost to the sea during flooding of the Rímac River; during these high-flow periods, too much water, loaded with sediments, finds its way into the sea. In the Chillón, such losses amount to about 2 m^3/second. About 12 m^3 of water per second from the Rímac River is used by the city and 4 m^3/second is used for irrigation. About 5 m^3/second infiltrates the aquifer. The Chillón is used almost exclusively for agricultural irrigation (4.4 m^3/second).

Lima is using most of the water available in the two rivers; only a relatively small volume (12 m^3/second) is lost during the most intense floods. Although this flood water is difficult to use because of the large amount of material in suspension and its rapid flow, it could contribute an additional volume to the urban supply.

An increasing problem is the risk of contamination of both surface and groundwater. Activity in the middle and upper Rímac basin is affecting the quality of water in this river. All wastewaters from the communities and cities located upstream of Lima enter the stream. Second, mining and industrial wastes are also disposed of in the river. In Lima itself, the river is further polluted by uncontrolled garbage disposal. As a result, the concentration of heavy metals and other toxic substances already constitutes a potential hazard to the city s water supply. The Lima aquifer is also at risk. The alluvia are permeable throughout their depth, and hazardous wastes may find their way into the groundwater.

Conclusions

The continuing growth of the city of Lima and the lack of financial resources to implement environmental control measures are contributing to degradation of water quality. The city is growing at an accelerated rate, and water resources are fragile and limited. If the present growth continues, Lima will have a population of more than 10 million people by the year 2000 and close to 15 million by 2010. By then, the Rímac and Chillón rivers and the aquifer will be unable to satisfy the domestic, industrial, and environmental requirements of the urban region.

Alternative sources of water are difficult to find. The best options are probably in the mountain region, especially beyond the continental divide, in the headwaters of the Amazon s tributaries. However, any project attempting to bring water from such distant and inaccessible sites will be extremely expensive almost certainly in the order of several hundred million dollars.

Peru s national debt is large and its credit rating in the international financial system is low. The level of investment required to tap new sources of water is unlikely to be attainable in the foreseeable future. Therefore, for the time being, the solution to the problem must include better management and protection of the Rímac and Chillón basins and the Lima aquifer, reuse of wastewaters (at least for irrigation and industrial purposes), and better control of losses in the water-distribution system.

The final solution will be to reassess the environmental potential for growth of the city of Lima. The environment is fragile, and there is a limit to the degree of urbanization that can be sustained. This limit was certainly exceeded a long time ago. The coastal plain cannot sustain a population of 7 million people (much less one of more than 10 million as is projected for the next decade) without suffering irreparable damage.

Santa Marta on the Caribbean coast

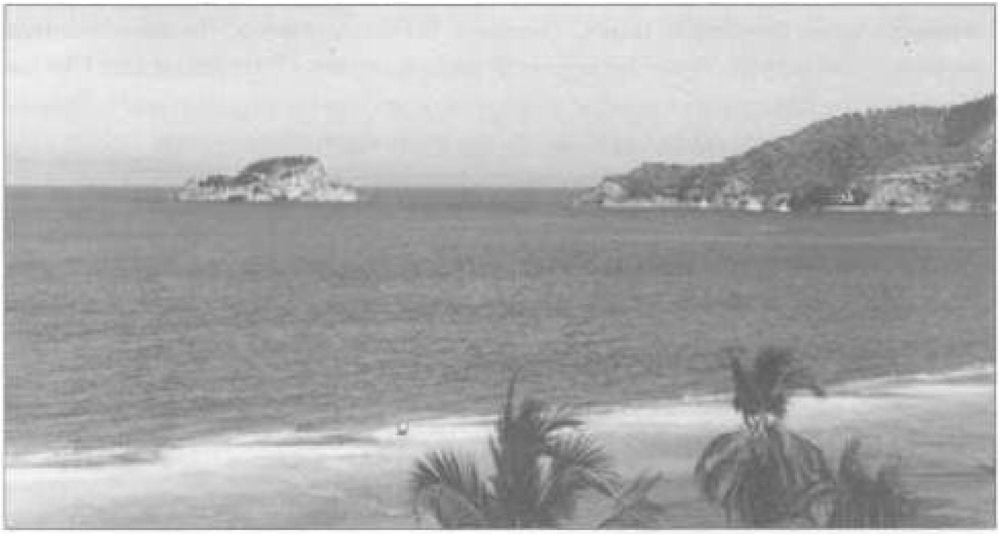
Environment and history

Santa Marta, the oldest city in Colombia, was founded in 1525 and became one of the main centres of the Caribbean in colonial times. The city is located near the Sierra Nevada de Santa Marta, a large mountain massif close to the coast. Several short rivers descend the steep slopes of the Sierra toward the sea. Santa Marta is at the outlet of one of these rivers: the Manzanares. Since the Spanish colonial era, the city has developed slowly and was outstripped by the other two coastal metropolises of the Colombian Caribbean: Cartagena and Barranquilla. Its role has been mainly as a centre for tourism, although it remains a principal market for products of the Sierra Nevada and its port is still active.

The urban area of Santa Marta has a population of over 300 000 and is growing at the rate of 2 3% per year. The area is facing serious water-supply problems because surface-water sources are insufficient and its groundwater is becoming salinized. These problems have become critical, as demand is increasing and there is less potable water to go around.

Most neighbourhoods of the city are well established and living conditions are stable. However, about 15% of the population (40 000 50 000 people) live in slums *(barrios de invasiones).* These marginal communities usually house recent migrants from the countryside. Although no major health problems have been identified, water is scarce and there is concern over the possibility of waterborne diseases.

Santa Marta s communities are organized under Juntas de Acción Comunal. These grassroots organizations provide lines of communication for community input and support for water and sanitation plans and activities. Research into the water-supply problem is being supervised by a committee that includes representatives of selected Juntas de Acción Comunal that are directly affected. The committee also includes a representative of the Corporación Nacional de Turismo; this body is concerned about safe water, because of the importance of the tourist industry in Santa Marta.



The Caribbean coast of Colombia: tourism depends on a reliable supply of clean water.

Water supply

Traditionally, the city depends on two main sources of water: surface water from the Manzanares River and groundwater from the narrow alluvial aquifers along the coast. Present water demand in Santa Marta is over 1.2 m^3/second, but less than 0.8 m^3/second is actually available. The current deficit (0.4 m^3/second) is expected to double or triple by the year 2000. Studies to formulate a master plan for the city s water-supply system (IFM 1979) have indicated that the integrated exploitation of surface and groundwater sources (Manzanares River and adjacent aquifers) is the most feasible solution to meet the increasing need for water, both technically and economically.

Surface water is treated at the Mamatoco plant, located 3 km upstream of the city; its intake area is at Paso del Mango about 3 km further upstream. The treatment plant s output ranges from 160 to 340 L/second depending on river flow. When the river is low, additional water is drawn through an intake next to the plant (at La Solución). Surface water is treated using standard techniques (flocculation, filtration, and chlorination) with daily physical, chemical, and bacteriological analysis.

About 45% of the municipal water comes from 11 wells with yields ranging from 10 to 60 L/second. The main wells are: La Carcel 1 and 2 (60 L/second each); La Federación (35L/second); Tanaca (35L/second); EI Estadio (18L/second); Universidad (17L/second); Bavaria (17L/second); Santa Catalina (14L/second); Los Trujillos (10 L/second); and Bastidas 1 and 2 (10 and 40 L/second, respectively). Total output from the wells amounts to 0.33 m^3/second. During the dry season (November-May), which is also the tourist season, demand increases considerably and groundwater contributes 60% of total consumption. Groundwater quality is good, except in some areas near the seashore, where saline intrusion. may occur.

The aquifer at Santa Marta is an alluvial coastal aquifer. Water is drawn from it through a number of municipal and private wells, 50 100 m deep. Because of the coarse-grained texture of the sediments, the aquifer s conductivity and capacity are high. However, overuse has caused several of the wells near the coast to become brackish.

The aquifer is hydraulically connected with the Manzanares River, which is its main source of recharge water. However, because of the steep longitudinal slope of the river bed and to its torrential flow, a considerable volume of water flows into the sea, especially during the rainy season. Probably less than one-quarter of the flow volume of the Manzanares River enters the aquifer through the river bed and the permeable Quaternary filling.

The aquifer is currently under considerable stress as a result of continuing extraction and the limited volume of recharge water available. Preliminary studies carried out by Cesar Rodríguez of the Universidad Nacional at Bogotá have shown that recharge water must be augmented; research is being done on this project. In addition, the city s water supply and sanitation company, Metroaguas, is planning to pipe water from the nearby Piedras River with a hydrological regime similar to the Manzanares, i.e., high rate of flow over short periods and considerable losses to the sea. Some of the excess water entering the Piedras River during flooding episodes could also be stored underground through artificial recharge of the aquifers.

Water supply and sanitation were originally under the direction of the municipal government. Two years ago, a private company was formed to take over this responsibility, but the plan was unsuccessful and the municipality has recently taken over the company. Both the municipality and Metroaguas are responsible for water quality and environmental control in the city and will decide whether artificial recharge will be attempted to augment to the water-supply system.

Deficiencies in quantity and quality

Some pollution of surface water occurs in the upper parts of the river. However, the main sources of contamination are in the city itself below the intake area for the treatment plant. Some contamination is caused by a slaughterhouse just upstream from the lower intake (La Solucion), especially during periods of low flow. According to Metroaguas, the treatment plant reduces the pollution to acceptable levels.

The slum areas get water from public faucets or water trucks. Typically, trucks deliver water once a day to strategic locations in these neighbourhoods, not more than 500 m from most homes. Another 25% of the population, although connected to the system, does not receive a regular supply and must also get water from the trucks. Wells are connected to the municipal system and in continuous operation. They are the main source of water during the dry season.

Water received through the municipal system is metered at one of six rates depending on consumption and social status. Families pay from 400 to 8000 COP/month (400 Colombian pesos (COP) = US$1), which is less than 2 3% of the average family income.

Solutions

Water shortage in Santa Marta is mainly, but not exclusively, a hydrogeological engineering problem; the situation can be significantly improved by tapping new sources. Additional water will increase pressure in the pipes and allow water to reach the poorer neighbourhoods located in higher areas of the city.

However, water resources must be properly managed. Leakage from the municipal system is high (up to 40%). Metroaguas may be able to reduce these losses marginally through better monitoring and maintenance. However, to reduce leakage significantly (20 40%), it may be necessary to make investments that are clearly beyond the scope of the water company.

Reducing demand through pricing policies could be a temporary solution. According to Metroaguas estimates, increasing prices in high-consumption areas would not improve the situation, because there is already a forced reduction over long periods because of insufficient water or pressure. (Some neighbourhoods that depend on surface water may be without water for weeks.)

Excessive consumption by industries could also be controlled. The main industries in the area (a beer factory, a soft -drink company, and a dairy) have wells of their own and are only partly dependent on the municipal water system. It would also be difficult to penalize these industries, whose products compensate for the frequent lack of water in the city.

Sewerage exists in only one sector of the city, serving about one-third of the population. Any increase in the amount of water used in the city should be complemented by an improvement in the sewage and storm-water systems. However, the current belief in Santa Marta is that it is better to have water without sewerage than no water at all. Increasing consumption may put more pressure on the municipality to provide the needed infrastructure for disposal of wastewater.

A preliminary evaluation shows that the current deficit of 0.4 m^3/second can be reduced through increased pumping if more water from the Manzanares River (and the nearby Gaires River) can be retained. The additional water might amount to as much as 1 m^3/second, meeting the needs of the city for another 15 20 years, depending on its rate of growth. At the same time, transfer of water from the Piedras River basin, part of which could be stored underground through artificial recharge of the aquifers, would provide another 1 2 m^3/second to satisfy further expansion for the next 20 30 years.

Recife and the Pernambucan lowlands

Environment and history

The city of Recife, capital of Pernambuco state in Brazil, was founded in the,16th century. It is situated on a flat coastal flood plain near the confluence of the Capibaribe and Beberibe rivers. A line of coral reefs protects this area of the coast from the strong wave action and currents.

The city was originally founded as a port for Olinda, the main city in the Portuguese colony of Pernambuco. Although it was attacked by French and English pirates in 1561 and 1595, it remained in Portuguese hands until 1630 when it was captured by the Dutch who remained in control of the city for 24 years. By 1710, the inhabitants revolted against Olinda in the War of the Mascates and established an autonomous municipality. The city grew to prominence and, in 1823, became capital of Pernambuco.

Recife is now the centre of the largest metropolitan area of the Brazilian northeast. Its population is about 2.8 million, which according to the 1991 census represented 40% of the total population of Pernambuco. The city s annual growth rate has decreased from

2.7% in 1970 1980 to 1.8% in 1980 1991. However, the city is still gaining 50 000 new inhabitants per year.

The stagnation in growth is probably related to the decrease in birth rate, which was 51.4 per thousand in the 1960s, 35.1 per thousand in the 1970s, and less than 30 per thousand in the 1980s. The fertility rate also decreased during this period, and there has been a simultaneous increase in life expectancy from 43.2 years in the 1960s to 52.2 in the 1970s.

The population of greater Recife has one of the lowest per capita incomes of all the cities in the Brazilian coastal region. In 1988, according to the Fundaçao Instituto Brasileiro de Geografia e Estadistica (FIBGE, Brazilian Institute of Geography and Statistics), 70.2% of the economically active population earned less than US$50 per month.

Water supply

Over the last 14 years, efforts have been made to reduce the number of homes without water service: in 1978, 38% of homes were in this category; in 1992, only 11% remained in this situation. The rapid growth of the slums and their concentration in inaccessible areas makes their linkage to the main water network more complicated.

Between 1975 and 1990, the *favelas* have grown by 50%; a third of them are in the hills and two-thirds on the flood plains.

The increase in service was not accompanied by an increase in the supply of available water. Thus, strict rationing has been imposed. Sanitation facilities are lacking in 72% of residences and almost all homes without a reserve tank receive water for only 12 hours/day; in low-income neighbourhoods, the level of service is even lower. The lack of sanitation in such a large portion of the urban area is One of the causes for degradation of the streams, canals, and coastal waters of the city. The polluted water provides a potential breeding ground for mosquitoes, rats, and disease and is a threat to human health.

The price of water has increased considerably because of the large proportion that is not accounted for (estimated at 45%), the elimination of subsidies, the increased cost of treatment because of contamination of surface waters, and the heavy administrative costs incurred by the Companhia Pernambucana de Saneamento (COMPESA). The high price still does not cover the capital costs of new infrastructure.

Rationing has increased the risk of contamination when the pipes are empty, forcing COMPESA to add large amounts of chlorine to the water daily when the pipes are refilled. The turning off and on of the water every day also creates unusual pressures in the system and surrounding surface waters.

The quantity of available water in the area is estimated to be 9.25 m^3/second, but demand is 14.79 m^3/second. COMPESA forecasts a reduction in this deficit by decreasing the high losses from the system. This plan does not seem to be realistic, considering the level of expenditure on maintenance and new equipment it would require. Although leakage from the Recife system is significant, other Brazilian cities show similar losses of nearly half the water pumped into their systems, e.g., Rio de Janeiro loses about 50% of the systems water, although it has spent more money than Recife on repairs.

Only 49% of connections to the system are metered. Consumption by other homes is estimated at 10 m^3/month. However, this figure is probably too low (there are 4.2 people per connection and per capita consumption is 200 L/day). The actual amount of water used is probably closer to 25 m^3/month. The number of illegal connections and bypasses is probably high.

It is increasingly clear that the solution to Recife s water problems must include, not only an increase in supply, but also better management including: reduction of leakage, bypasses, and illegal connections; installation of hydrometers; and policies to reduce wastage.

Problems in the use of surface water

A large portion of Recife s water is drawn from one large surface reservoir, the Tapacura dam, from which 2.8 m^3/s, on average, enters the Presidente Castelo treatment plant. Other smaller reservoirs are Botafogo, Monjope, Gurjau, and Duas Unhas. A new reservoir, Pirapama, is under construction. It will provide 6.8 m^3/second, but by the time it opens, in 1994, the city will have outgrown its capacity.

Because surface sources depend on rainfall, they are limited and unreliable in times of drought. Alternative surface sources are too far away to be used economically.

Some reservoirs are showing signs of contamination. The Tapacura dam is located downstream from a sugar-producing area and a city of 50 000 people (Vitoria de Santo Anilio), which flushes untreated wastewater into the river. In summer, eutrophication occurs in the Tapacura reservoir and water quality is poor.

In late 1991 and early 1992, a cholera epidemic, which began in Peru, reached the state of Pernambuco. Because of poor sanitation and lack of safe water-supply systems, the disease spread through most of the state s municipalities. In April 1992, over 600 cases of cholera were confirmed (the actual number was probably three or four times higher). A large proportion of the reported cases (about 100) occurred in the greater Recife region and other municipalities sharing its hydrographic basins. Vitória de Santo Antão, immediately upstream of the Tapacura dam, had the fifth highest number of confirmed cholera cases in the state; this city does not treat its sewage. The largest concentration of cholera cases (322) occurred in Bezerros, a small town located about 90 km from Recife. The epidemic caused a huge reduction in the number of tourists visiting Recife. In the first quarter of 1992, hotel accommodations were 30 40% below average. This affected the livelihood of several thousand people employed in the tourist industry, including a large number working in informal, tourism-dependent activities.

Additionally, there is growing feeling in the population that large infrastructural waterworks, such as dams, may entail an unacceptable natural and social impact. Construction of the Pirapama dam has forced the evacuation of 1 170 peasants; 836 received no compensation because they did not have a valid land title. According to local residents, before 1988, water from the Pirapama River was not considered acceptable for human consumption, even after treatment. Suspiciously, the water was declared potable in 1988 (data presented at a meeting organized by the Companhia Pernambucana da Poluição Ambiental e de Administração dos Recursos Hídricos, 23 March 1992). The dam will also reduce the volume of the river downstream, increasing contamination and promoting saline encroachment in the lower reaches of the river valley that will damage the fluvial and mangrove ecosystems.

Exploiting groundwater

In 1968, estimates had already shown that the cost of constructing and operating groundwater-extraction systems for urban supply was considerably lower than the cost of structures necessary for using surface water. This assessment was widely accepted and several hundred private wells were drilled. (At present, more than 1 400 private wells are used by industries, including soft-drink companies, hotels, and commercial buildings.) However, lack of government intervention has resulted in risk to the main aquifer (Beberibe) from overexploitation and saline intrusion.

The absence of an adequate legal framework for groundwater use certainly contributes to the current water problems. Only after the constitution of 1988 was enacted were underground waters considered *to* be public property. Since then, the government can, in theory, authorize their use and impose and enforce rules governing it. The actual application of this constitutional right requires a federal law (now, 1992, under study in the Congress) to transfer power to the jurisdiction of the individual states.

Surface-water pollution will not be reversed easily. Meanwhile, several aquifers, close to the city, can provide good-quality water that, if well managed, would satisfy the growing needs of the metropolitan region of Recife. Even if present trends continue, by 1995, about 0.5 million people in greater Recife will depend on groundwater. At the same time, the number of people not connected to the municipal water system could reach 0.5 million.

Groundwater has received little attention from the federal government, which has favoured reservoirs and surface-water systems. However, in Recife, as in other densely populated areas of Brazil, groundwater reservoirs contain much more water (probably as much as 100 times more) and are less vulnerable to contamination and leakage from the distribution networks (because conduction distances are shorter). Groundwater requires less treatment than surface water and a much smaller financial investment is needed to install and operate equipment to tap it.

At Recife, an important reservoir containing good-quality water lies under the city. However, this aquifer is thin just under central Recife, and larger volumes of groundwater can be obtained toward the north. In the past, the city used the thin reservoir, but because no management strategies were developed, water levels dropped and saline encroachment forced the closure of many wells. Today, only 98 wells remain in use. They are all located in the northern part of the city and are not always in operation.

The main reservoir on the coastal plain is the Beberibe aquifer, which is contained in Cretaceous sandstone. It is up to 100 m thick and overlies the crystalline rocks of the Brazilian shield along the coast. In Recife, the Beberibe sandstone is covered by Quaternary deposits (sands and clays) and by Upper Cretaceous and Paleocene limestones toward the north (Gramame and Maria Farinha formations). In addition to this productive aquifer, groundwater is found in the weathered mantle of the crystalline bedrock. Yields from these rocks are much lower, but they may be suitable for local use, particularly by *favelas* located on crystalline hills.

In many ways, Recife has outgrown its environment, partly because of inadequate and insufficient investment in its water supply and sanitation systems. Water-supply problems are especially critical for a city that depends to a large extent on tourism. One of Recife's main advantages is its location, in a warm, coastal environment with pleasant beaches and a strategic position on the northeastern edge of the continent. Protecting its urban environment may, therefore, be the difference between prosperity and poverty in the city's future.

San José in the central valley of Costa Rica

Environment and history

San José, the capital of Costa Rica, is located in a valley in the Central American volcanic range at an altitude of 1 150 m above sea level. The valley contains several other urban centres, including three major cities: Alajuela, Cartago, and Heredia. The proximity of these cities (Alajuela and Cartago, at the extremes, are only 40 km apart), coupled with the recent accelerated population growth of the country's urban areas, has resulted in a gradual merging of these four cities around the metropolitan area of San José (Lungo Uclés and Pérez 1991).

The oldest city of the central valley is Cartago, which was founded in 1563 and remained the main city and political centre of the Costa Rican territory until the 19th century. The city was destroyed by volcanic eruptions and earthquakes several times. The worst catastrophe was probably the eruption of the Irazu volcano in 1723, when the city was completely demolished. Cartago was also strongly affected by the earthquakes of 1841 and 1910.

San José was established in 1736 as a centre for tobacco trade, but did not become the main political city until 1823 when the capital was transferred there from Cartago. During the 19th century, San José was a relatively small town, depending on coffee production, only exceeding 25 000 inhabitants at the end of the century. The later growth of San José, Alajuela, Cartago, and Heredia produced a large urban conglomerate that is frequently called the Gran Area Metropolitana. The valley now contains almost 1 million people (of whom 0.6 million are in the San José metropolitan area), which represents nearly 35% of the population of the country. The population of the San José region and neighbouring cities is expected to reach 1.5 million by the end of this century.

Water supply

Surrounded by volcanoes and other geomorphological features of volcanic nature, the cities of the valley have traditionally obtained their water supply from a number of springs flowing out of the lateral slopes and from drilled or excavated wells in the Quaternary volcanic aquifers.

The groundwater sources in use are mainly fractured lavas corresponding to the Colima (upper and lower levels) and Barba formations. Some water is obtained from the El Llano dam, which was built in the 1960s to generate electricity. This dam mainly supplies Cartago and parts of San José; its water is treated in a plant located at San Ramon de Tres Ríos.

The city of Alajuela (population 50 000) is self-sufficient, depending on three main springs for its water supply (La Chayotera, Sabana Redonda, and Ojo de Agua) and its system is municipally controlled. The other three cities are served by the national system (Servicio Nacional de Acueductos y Alcantarillados) and share their main (present and future) sources of water: the well field of La Valencia, the El Llano supply system, and the proposed Orosí project.

Over 90% of the population in the metropolitan area has access to water. Groundwater constitutes about 40% of this, not including the springs, which are actually groundwater discharges. Current average consumption in the region is 6.8 m^3/second; this is expected to increase to 7.85 m^3/second for the year 2000 and 10.5 m^3/second for 2015. About 50%

of the water supply is unaccounted for. Probably as much as two-thirds of this is loss to leakage from the conduction and distribution system. Future water needs of San José, Heredia, and Cartago, will be satisfied by two new well fields, now being planning: del Norte and Potrerillos.

San José and its sister cities are located in a high-risk seismic area, raising concerns about the reliability of the aqueduct bringing water from El Llano to the valley. From that point of view, the groundwater sources are more reliable, because they are connected with their users through several distribution lines and seismic damage would normally not jeopardize the overall supply, which might be interrupted if only a single pipeline was in place (as proposed for the Orosí project).

Pollution is an ever-present problem, because more than 60% of the metropolitan area is not served by the sanitation system. These residences have septic tanks and frequent overflow from them may reach the upper aquifer. Wastewaters are discharged, untreated, through a main collector pipe into the Rio Grande de Tarcoles, which flows into the Pacific Ocean. This river has lately become almost dead. Sanitation companies that empty the septic tanks usually dispose of the used liquid into the sewerage system, substantially increasing contamination of the system.

8

Cities depending mainly on groundwater

Several cities in Latin America and the Caribbean depend heavily on groundwater, generally because surface water is scarce. These cities are in volcanic regions, where river valleys are obstructed by lava flows or other volcanic features (e.g., Guatemala City, Mexico City, and Managua) or in karstic regions (e.g., Mérida and Havana).

The valley of Mexico[4]

Environment and history

There are probably few places in the world, where the physical environment has been as completely transformed by urban development as in Mexico City. The valley of Mexico is a 9 600-km^2 closed basin in the heart of a neovolcanic belt, that has been raised by geological forces to more than 2200 m above sea level (Fig. 15).

About 700 000 years ago, obstruction of drainage by volcanic material caused several lakes to form on the floor of the valley. Their total area was about 2 000 km^2 and they were connected during periods of high water. Three of the lakes (lakes Mexico, Chalco, and Xochimilco) contained fresh water; the other three (lakes Texcoco, the largest at 800 km^2, Zumpango, and Ecatepec) were brackish (Fig. 16).

The area was (and to a certain extent still is) sub humid. Annual rainfall was probably slightly higher than the current 600 mm at the bottom of the valley to 1 200 mm in the surrounding mountains. Average temperatures were relatively cool for the subtropical latitude, ranging from 8 to 15°C depending on altitude. The deep soils were highly fertile and easy to work. The land was completely covered by thick forests, particularly on the slopes of the mountains and in highland areas. The valley plains, which were also covered by forests, were soon cleared for agriculture. A number of springs, around the lakes and on the foothills of adjacent mountains, provided considerable volumes of good-quality water.

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[4] Material in this section is drawn from Herrera et al. (1982), Castillo Benhier (1983), Granados Velazco (1988), Ortega (1988), Cortes et al. (1989), Gonzalez Moran and Rodriguez Castillo (1989), Herrera (1989), Ryan (1989), Ward (1990), and Yepes (1990).

Fig. 15. Aerial view of Mexico City and the surrounding area.

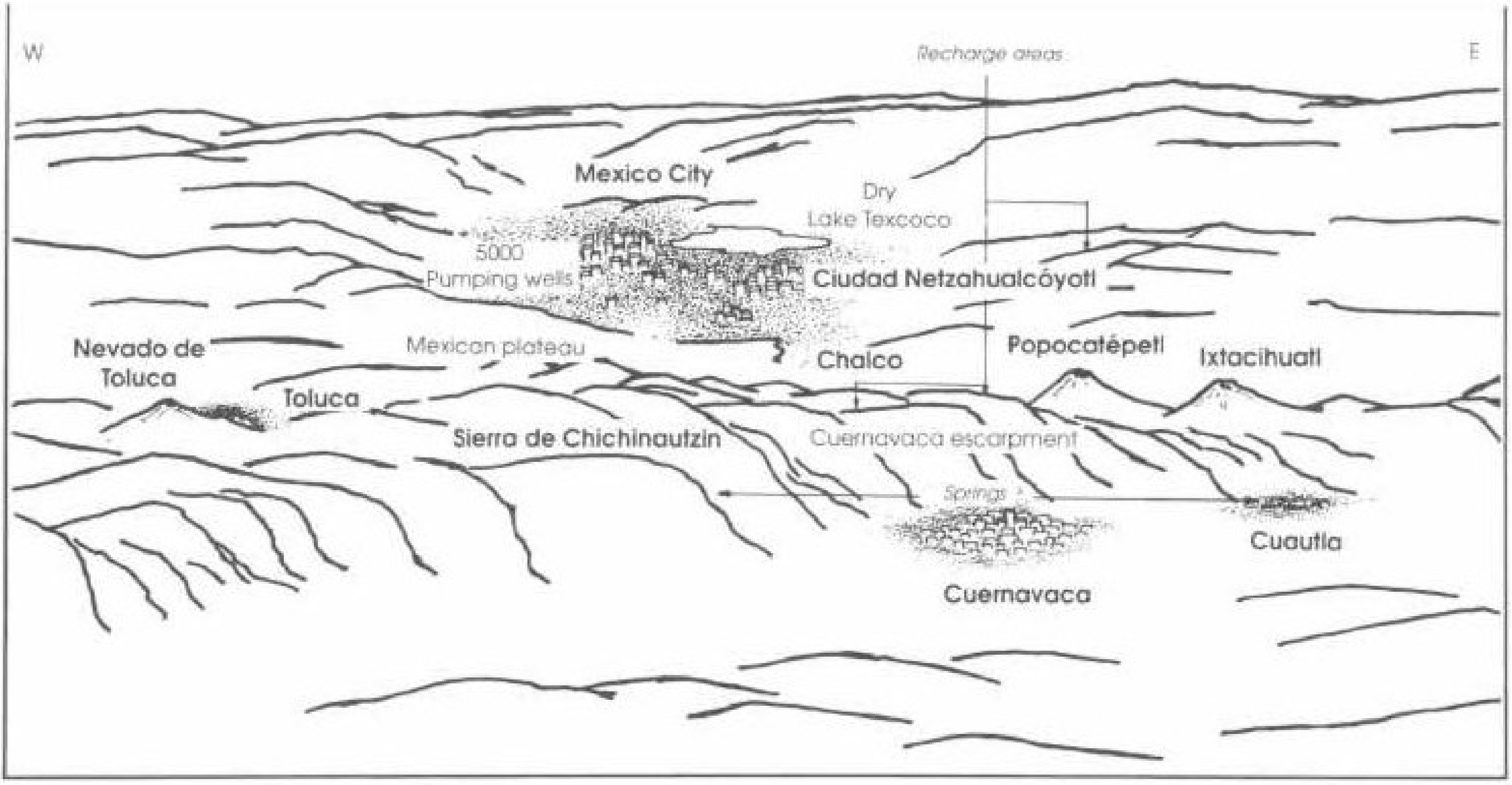
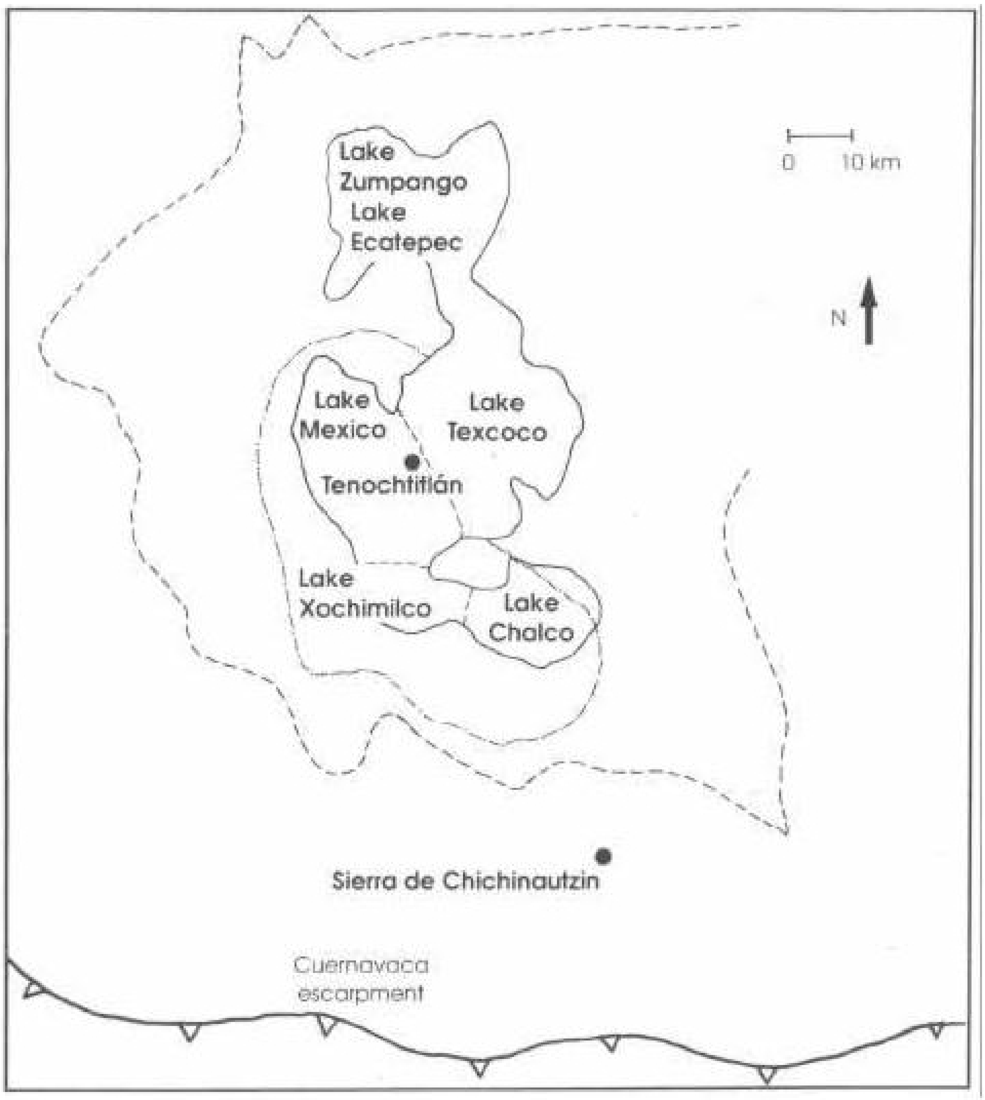


Fig. 16. Ancient lakes in the valley of Mexico.



These features made the valley attractive to early indigenous people, who, over several thousand years, developed an economy based on locally domesticated crops and farm animals (e.g., corn, tomatoes, chilies, cacao, turkeys, *escuincle* dogs, and honey bees) and fishing. Because these civilizations did not have domesticated draft animals and did not use the wheel, most commerce depended on boat traffic.

Several groups successively inhabited and controlled the lacustrine area during the last few centuries before the arrival of Europeans. The last of these was the Aztecs. This group had arrived from the legendary land of Aztlán (probably located to the north in more arid territories) during the 14th century and, because the lake shores were already occupied, they were forced to settle on swampy land in the lake and make their living by fishing and trade with neighbouring communities.

Gradually, the Aztecs built an island in the southern part of the lakes, in the middle of Lake Mexico and a town developed (Tenochtitlán), which was later to become the main city of the valley. Through alliances and wars, the Aztecs built an empire, and Tenochtitlán grew to become a thriving city of several hundred thousand people. A bridge was built to join the island with the mainland, and large boats were used to transport people and merchandise throughout the area.

The Aztecs built earth dikes to control flooding and to separate brackish lakes from those containing fresh water. In addition, aqueducts were built to bring fresh water from springs, through the lake, and along the dikes to the city.

From Tenochtitlán to Mexico City

It is difficult to comprehend the extent of the change that has taken place in the few centuries since the Spanish conquest that began in 1521. Today, proud Tenochtitlán has disappeared, and excavations reveal only scattered archaeological remnants. In its place stands the highly urbanized downtown part of Mexico City.

Lake Mexico is gone. On its site are several hundred square kilometres of urban neighbourhoods. Lakes Chalco and Xochimilco are also gone. Only a few canals and small lakes remain. The rest of the area is covered by streets and buildings.

The three northern lakes have also been drained. The bottom of the former Lake Texcoco is a vast, flat plain, on which little vegetation grows because of the high alkalinity (pH over 10). Today, an intricate maze of wells and pipes pumps the brine contained in the lacustrine sediments out of the ground for extraction of sodium carbonate and sodium chloride.

The springs that provided water to the riverine populations are also gone. Now more than 5 000 wells extract over 50 m^3 of water per second from an average depth of 100 m, gradually lowering the level of water in the aquifer by as much as 1 m/year. Overpumping and compression of the upper layers of sediment have caused widespread subsidence. Several areas have sunk more than 6 m. Because subsidence rates vary, many structures have been weakened and, in some cases, lean dangerously, e.g., the cathedral, the older Basilica de Guadalupe, and the Palacio de Bellas Anes. This phenomenon has been exacerbated by frequent seismic activity, of which the most recent destructive example was the earthquake in September 1985.

The forests that covered the adjacent hilly slopes have almost disappeared and widespread soil erosion occurs. Most agricultural land has been covered by pavement, houses, and other urban structures. Quarries have been excavated throughout the region to obtain construction materials. Some became garbage dumps, into which a portion of the annual 10 million t of garbage is thrown.

A significant portion of the garbage is disposed of on the shores of the former Lake Texcoco, especially in the southern section. Ciudad Netzahuatcóyotl, which is located in that part of the city, is a neighbourhood of 3 million people, built on the bottom of the lake. The environment in this recently created urban area has become highly degraded and developed areas alternate with garbage dumps and slums.

The valley's drainage system, which used to enter the lake, is now channeled out of the basin, together with urban wastewaters, through a system of canals and tunnels into the Gulf of Mexico. A number of pumping wells that supply the city are located next to the Chalco canal, which carries away both wastewater and excess storm water. The risk of contamination is obvious and, in fact, some wells had to be closed because of nitrates in the water.

The atmosphere of the valley has also changed with growth of the city. Emissions from 4 million vehicles and 25000 industrial establishments in a poorly oxygenated environment (because of the altitude) have created a serious health hazard. The air in the downtown core is particularly noxious.

More than 19 million people live in Mexico City, making it one of the largest urban centres in the world. Every year, the birth rate and migration from the rest of the country increase the population by nearly 0.5 million. By the year 2000, the city may have 25 million people and, by 2010, over 30 million. If corrective measures are not taken, the current problems will become worse, and the ancient valley may become one of the worst environmental nightmares of the 21st century.

The aquifer and the urban water supply

The aquifer underlying Mexico City provides the bulk of the city s water. Some water is brought from outside the basin (from the Lerma-Cutzamala basin), but this amounts to less than one-fifth of the total volume. Bringing water into the valley from elsewhere is becoming impractical and too expensive. Although the resources of the Lerma-Cutzamala basin are almost exhausted, tapping the Balsas or the Amacuzac basins would mean pumping water 1200 1500m upwards and constructing long pipelines, storage reservoirs, and other costly engineering works. Using water from outside the valley would also affect communities that are dependent on that water for irrigation and their own supply.

Geology and hydrogeology of the valley

Mexico s aquifer is contained in a number of Tertiary and Quaternary units with a thickness ranging from a few hundred metres to nearly 2 000 m. These units comprise a wide range of sedimentary materials, including various pyroclastic and alluvially reworked pyroclastic sediments, breccias, conglomerates and agglomerates, several types of sandy volcanic formations, volcanic ashes, lacustrine lenses, and intercalated lava flows (Fig. 17). These deposits are closely related to the volcanic activity that took place during the formation of the trans-Mexican neovolcanic belt and synchronous epeirogenesis.

The base of the sequence lies over the Cretaceous limestones of the Morelos formation, a 1 000-m-thick, heavily karstified unit that constitutes the floor of the volcanic sequence. The base is composed of conglomerates and sandstones of the Balsas group (Eocene-Oligocene epoch). This molassic group filled the grabens that developed during the post-Laramidic orogenetic period. It includes up to 500 m of conglomerates, covered by poorly sorted finer deposits (sandy, but also silty and clayey), that is up to 2 000 m thick.

Overlying the Balsas group is a complex volcanic sequence of early Miocene age, composed of various types of pyroclasts (tuffs, breccias, and agglomerates) and intercalated alluvial clastic sediments and lava flows. Its thickness varies from 390 to 1 750 m. Overlying the Miocene sequence is a 300- to 800-m-thick volcanic sequence that includes andesitic lavas, volcanic breccias, and tuffs, which in turn is covered by andesitic and dacitic volcanic material of early Pliocene age, including lava and associated unconsolidated pyroclastics (300 600 m thick). On top of these extrusive rocks, the pyroclastic flows of the Otomi formation are found, with ash-flow and ash-fall tuffs, breccias, and associated andesitic lavas.

The Otomi formation is covered by a complex sequence of volcanic units including Las Cruces, Zempoala, and Navaja formations and undifferentiated Pliocene pyroclastics and the Llano Grande, El Pino, Tlaloc, Popocatépetl, Chichihuanitsin, and Iztaccihuatl formations of Quaternary age. Finally, the plateau depressions are filled with a 500-m- thick sequence of alluvial and pyroclastic accumulations, called the Tarango formation in Mexico's valley, over which a few dozen metres (locally up to 400 m) of lacustrine deposits are found.

The Mexican valley, therefore, has formed as a result of continuing volcanic accumulation, in which the molassic detritic formations of the early Tertiary era were covered by a long and complex succession of volcanic extrusions that include a large amount of pyroclastic material (reworked to some extent by fluvial action) and intercalated lava flows. During volcanic eruptions, tuffs, breccias, ash, and lava were formed; between these episodes, alluvial and lacustrine action was more important.

The main water-bearing rocks are those of the Tarango formation and associated alluvia and the Cenozoic sequence of fractured pyroclastic and lava flows. These are covered by younger lacustrine sediments, confining the main aquifer. This whole sequence can be up to 2 000 m thick, but the lower 1 500 m is more consolidated; the lower effective porosity (associated with fracturing) lowers the production potential of this section. Because the upper few dozen metres of the aquifer are too close to the upper lacustrine clays, continued pumping may produce dewatering and consolidation of these clays, unleashing subsidence processes. The usable portion of the aquifer is between 100 and 500 m below ground level.

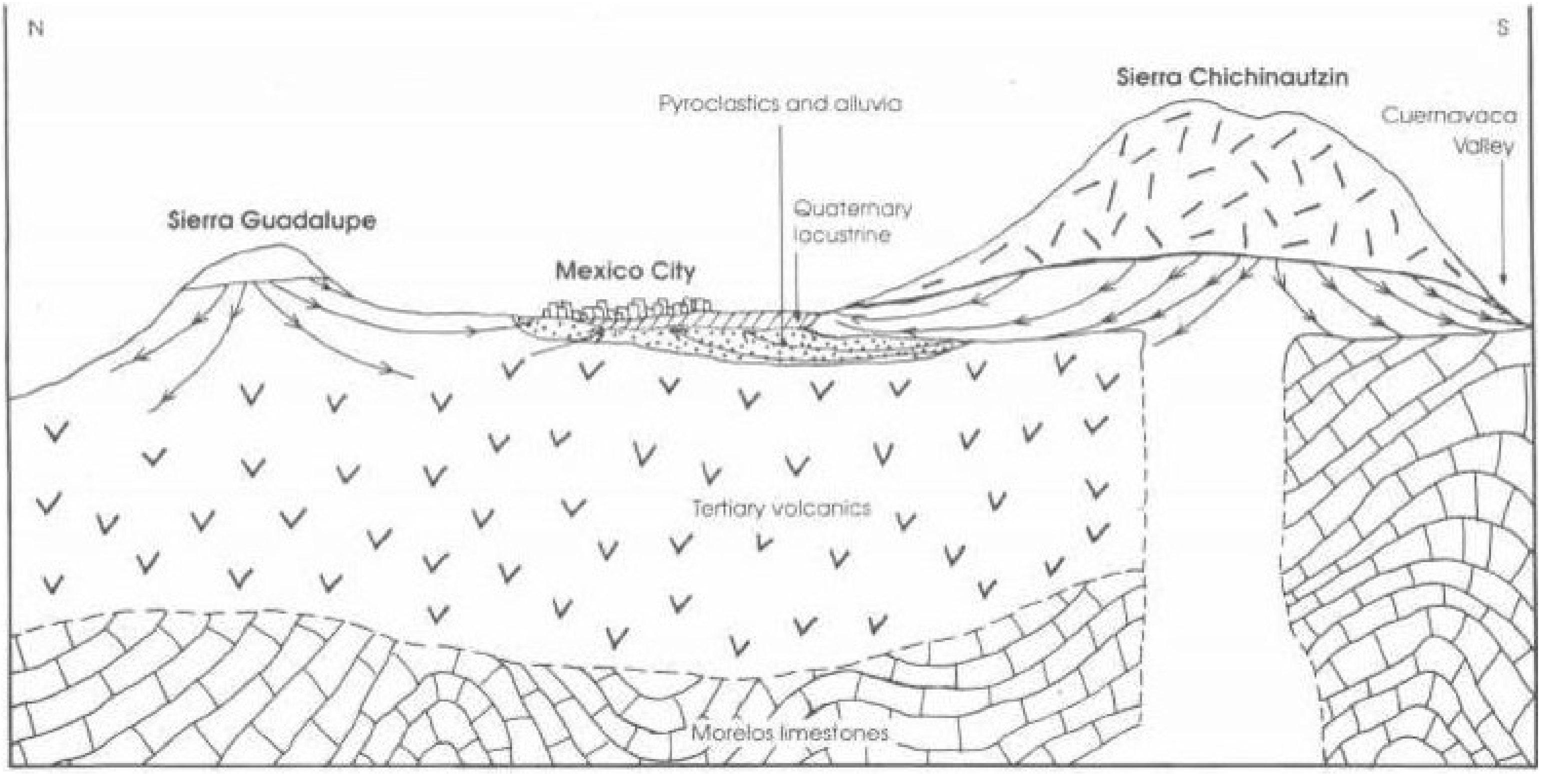
The aquifer is recharged in the mountains (Sierra Chichinautzin in the south, Sierra las Cruces in the west, and Sierra Nevada to the east). The total recharge volume is estimated to be 25–50% of the precipitation (25% in Sierra Las Cruces, 35% in Sierra Nevada, and 50% in Sierra Chichinautzin). Of this volume, about half flows toward the valley of Mexico, the rest moves outward to other basins.

Accurate figures for inflow to the valley aquifer itself are difficult to obtain. However, recharge volume is certainly below 50 m^3/second, which is the rate of extraction, because the aquifer is becoming depleted. An estimated inflow of 30–40 m^3/second is probably fairly accurate. Additional lowering of the water level in the aquifer will cause an increase in flow from the sierras, because of the increased gradient. However, it is not enough to make up the deficit, especially if the extraction rate increases.

Precise forecasting of aquifer reaction to prolonged pumping requires accurate modeling. Only recently has adequate information on the geometry and hydraulic properties of the reservoir become available. A model of the aquifer has been developed at the Instituto de Geofísica of the Universidad Nacional Autónoma de México (Herrera et al. 1982). Use of the model in conjunction with newly acquired information is expected to allow assessment of the groundwater resources of the valley.

However, Mexico's problems can only be solved if a different development approach is adopted. The valley's environment has reached its limit, and the megacity is no longer sustainable. A much less concentrated and centralized countrywide plan must be implemented to encourage a better distribution of the population. Only a drastic change of course will allow the survival of the valley.

Fig. 17. Cross-section of the aquifer underlying Mexico City and surrounding geological structures. Note: arrows show groundwater flow.



The valley of Guatemala

Environment and history

The city of Guatemala, the national capital of the Republic of Guatemala, is by far the most prominent city in the country. It is located in a high valley on the Guatemalan volcanic plateau, at an elevation of 1 800 m above sea level.

Before Europeans conquered the country, the Guatemalan highlands were already densely populated by a civilization, whose economy, like that of the Mexican indigenous peoples, was based on the cultivation of com, chili peppers, tomatoes, and other local crops. When the Spanish arrived, the highlands region was inhabited by the Cakchikel nation of the Mayan group, with their capital in Iximche. As they had done in Mexico, the Spanish conquerors established their capital (in 1523) on the same site as the existing one. Iximche was about 100 km west of and at a higher elevation (about 2 000 m) than the present Guatemala City.

In 1527, after a destructive earthquake, the city was moved to a site about 80 km to the east at a lower elevation (1 530 m). The new city, Santiago de los Caballeros, was established at what is now Antigua. This site is at the foot of a high volcano (the Volcan de Agua) whose main crater contains a lake. In 1533, the Volcan de Agua erupted. The lake caused a flood and a mudflow destroyed and buried large sections of the city. Several hundred people died and most buildings were demolished.

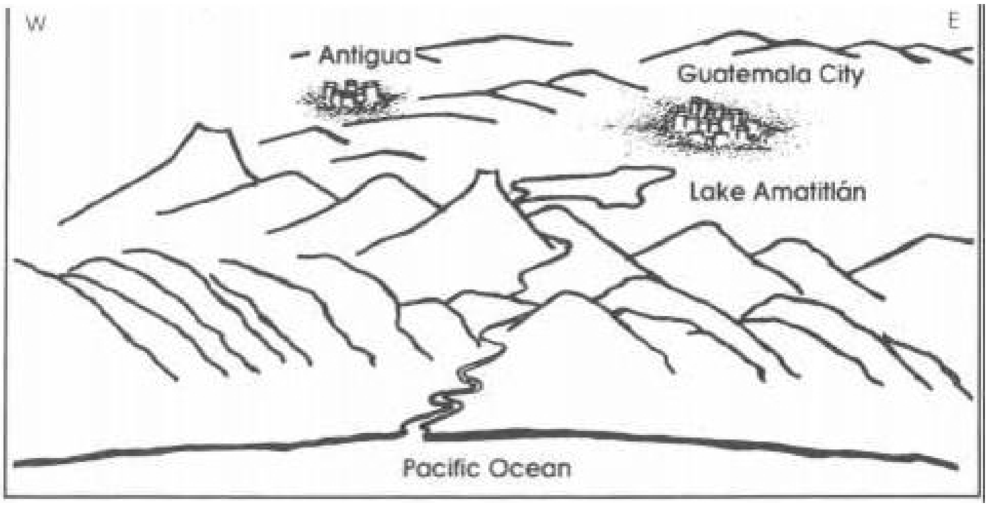
In 1543, the city was rebuilt in the same valley, but was again destroyed by an earthquake in 1773. In 1776, it was established at its present location and named Nueva Guatemala de La Asunción. The old city was gradually rebuilt and today it is a medium-sized city of about 50 000 people (Antigua).

Guatemala City, which remained the capital of the colonial Capitania General de Guatemala, became the capital of the independent Republic of Guatemala in 1837. The city has grown from tens of thousands of inhabitants at the beginning of the 20th century to the current 1.5 million people, with all the requirements and strains on the environment that accompany accelerated urban growth.

The Guatemalan highlands are in an area of volcanic and seismic activity (Fig. 18). Twenty large volcanic cones, with elevations ranging from 2 000 to 4 220 m, and several hundred smaller ones dot the southern mountainous areas of the country. Volcanic eruptions and related seismic activity are common, and recent geology and geomorphologic development are closely tied to these phenomena.

The climate of the highlands is subhumid to humid, with annual precipitation ranging from about 1 000 mm in the drier north-facing slopes to more than 2 000 mm in the south. In the city of Guatemala itself, annual rainfall averages 1300 1500 mm, concentrated in the summer (June to September). Natural vegetation is deciduous forest up to 2 200 m and coniferous forest above this altitude. This forest was partly cleared (even during pre-Hispanic times) to make room for agriculture. This process has continued and has accelerated during the last few years. Today, the forests of the highlands have been reduced to small pockets on the steeper slopes that are not suitable for farming.

Fig. 18. Aerial view of the Guatemalan highlands.



Geology and geomorphology of the valley

The geology of the Guatemala valley is relatively complex (Fig. 19). Over a base of Cretaceous limestones and plutonic rocks, intense and prolonged volcanic activity gave rise to large accumulations of various volcanic rocks and associated deposits.

The valley is an elongated depression oriented in a north-northeast to south-southwest direction. Water flows both northward and southward from a portion of the continental divide that lies more or less perpendicular to the main axis of the valley.

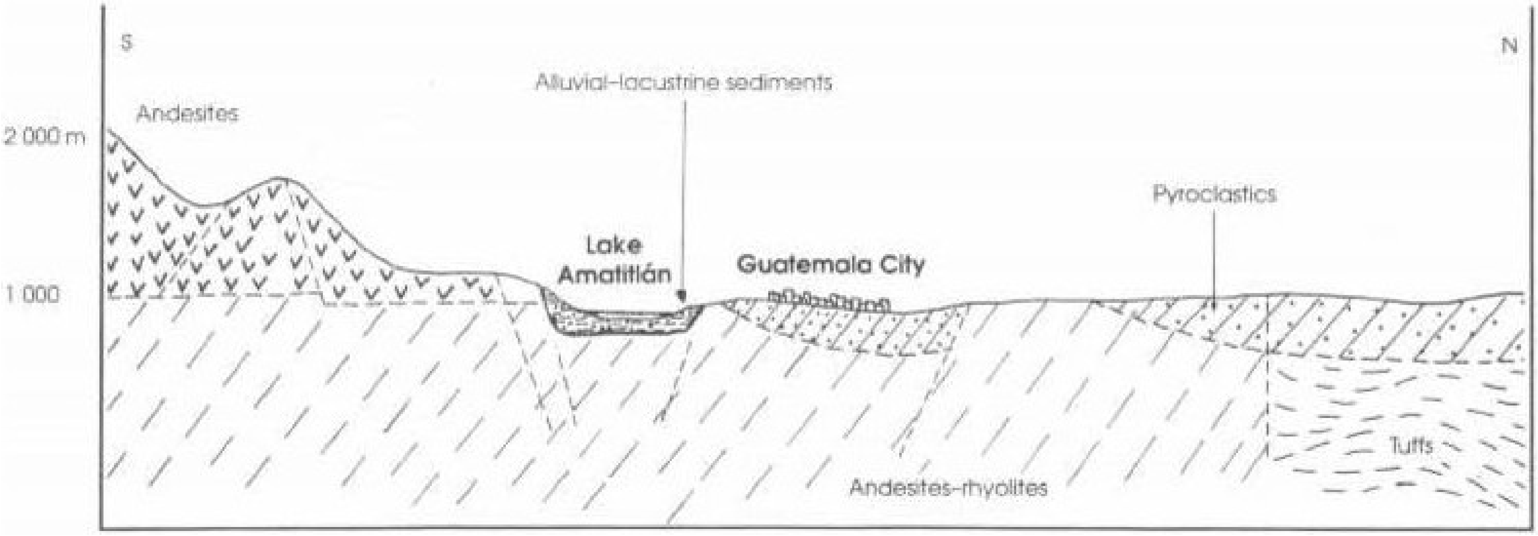
A large lake (Amatitlán) has formed in the southern part of the valley, because of volcanic obstruction of run-off. It is drained by the Michatoya River, which flows to the Pacific Ocean. The northward flowing rivers (Las Vacas and its tributaries El Zapote and Tzalja) drain the smaller northern part of the valley toward the Caribbean sea.

Volcanic cones surround the city, the largest ones being the Volcan de Agua, about 20 km southwest of the city, whose summit is over 3 000 m above sea level; and the Pataya, about the same distance to the south, with an elevation slightly above 2 000 m. The valley is a large graben with locally intercalated horsts. Both the elevated and depressed areas are composed of volcanic rocks, although older limestones are found in the Las Vacas River in the northern part of the valley.

The oldest formation identified in the Guatemala valley is a calcareous unit of fractured limestones in the Las Vacas basin, with limited outcropping. Overlying the Las Vacas limestones, a thick sequence of lava flows and associated deposits of Tertiary age are encountered. These lavas are heavily fractured, resulting in high secondary porosity. The Tertiary lavas are covered by two sequences of fluviolacustrine and volcanic deposits of Quaternary age:

- A sequence of fluvio-lacustrine deposits, composed of volcanic materials alluvially reworked and deposited in river beds and plains or in lakes. Their thickness does not exceed 100 m. The alluvial sediments have a relatively high permeability, but the lacustrine deposits can act as aquitards or aquicludes.

Fig. 19. Cross-section of the Guatemala valley, showing geological formations of the region.



- A sequence of volcanic deposits, formed by a large accumulation of pyroclastic products including ash-flow tuffs. These materials have a wide range of consolidation levels, from loose to well-compressed. The maximum thickness of this formation exceeds 200 m. It is moderately to highly porous and contains an excellent aquifer, which is heavily used.

Water supply

Guatemala City gets 80% of its water from groundwater sources; this amount probably represents the maximum obtainable from these aquifers. Of the 5 m^3/second required by the city (somewhat higher during peak periods), up to 4 m^3/second comes from 200 wells distributed throughout the valley. The remaining 1 m^3/second is obtained from surface sources outside the local valley.

A pipeline was built to bring river water into the city. Its capacity is 2.5 m^3/second, although current flow is less than half of this. There are plans to build a battery of wells in the volcanic aquifer at Antigua to augment the volume transported by the pipeline. The only other surface water available is in Lake Amatithin, which is heavily polluted.

Because recharge of the aquifers takes place mainly in urban and suburban areas, strict controls are required to avoid degradation of the groundwater. Currently, controls are virtually nonexistent. However, decision-makers will have to remedy this situation, because Guatemala cannot afford to lose this key resource through lack of adequate protection or planning.

The Managua basin

History

The city of Managua is located in the large volcanic valley of central Nicaragua. It developed as a small Indian farming and fishing village by taking advantage of fertile volcanic soils, the abundance of water, and the proximity of the large Lake Managua (or Xolotlan).

When the Europeans arrived in 1522, the population of the territory was moderately high. The indigenous people south of the lakes, the Nicaraos, were of Mexican origin. They cultivated corn, cacao, chili peppers, and tomatoes and raised turkeys and dogs. At that time, Managua was a prosperous community of 40 000 people located on the shores of Lake Managua.

When the Spanish arrived, they settled on the narrow strip of the Pacific highlands and the shores of the large lakes Managua and Nicaragua (or Cocibolca). Managua was strongly affected by the Spanish conquest. Its population decreased to,a mere few thousand people, and it took three centuries to return to the pre-Hispanic level.

With the Spanish conquest, a relatively large colonial urban centre developed northwest of Lake Managua: the city of León. This city was destroyed by an earthquake in the 17th century, and a new city was founded on the western shore of Lake Nicaragua (Granada). Colonial history, and later that of the Republic of Nicaragua, was heavily influenced by the rivalry between the old city of León and the newer Granada.

Nicaragua became independent upon disintegration of the Union of Central America in 1838. After the formation of the newly declared republic, there was a period of conflict between the liberal factions based in León and the conservative ones in Granada. In 1852, as a compromise, a new capital was chosen on the site of the small village of Managua, which grew to become the largest city in the country.

In 1973, the city suffered a major earthquake that destroyed almost the whole downtown area. The city centre was not rebuilt, in spite of assistance that poured into the country from all over the world. The new government, which took power in 1979 after a long civil war, decided to conserve the area as a “green” core in which public parks and squares have now been established.

From 1979 to 1989, the country was in an almost continuous state of war. It was also under commercial boycott by the United States until the 1989 elections, and this seriously harmed the economy of the country. As a result, the city suffered enormously: basic goods were scarce, public services were unable to function properly, and capital investments were not available. The war also meant heavy casualties and a flow of war refugees from the countryside to the city. Managua’s population is nearly 1 million, or almost one-third of the country, and the city covers an area of more than 60 km^2.

The environment of Managua

Managua is located on the southern shores of Lake Managua, on land sloping from the Cordillera del Pacifico (locally called Las Sierras de Managua). The Cordillera del Pacifico reaches elevations of 900 m above sea level, whereas the lake is at an altitude of only 40 m. The depression extends southeastward through the Tipitapa plains to Lake Nicaragua, which is some 9 m below Lake Managua (Fig. 20).

Excess water from the Managua basin flows into the Tipitapa River and as groundwater toward Lake Nicaragua. The outflow of the Nicaragua basin reaches the Caribbean via the San Juan River. These two lakes cover 9000 km^2 (Lake Nicaragua, 8 000 km^2; Lake Managua, 1 000 km^2).

Several other smaller lakes of volcanic origin complete the lacustrine panorama of the Nicaraguan valley. The largest are lakes Masaya, Apoyo, Apoyeque, and Jiloa. Near Managua, there are a number of crater lakes, including Asososca, Nejapa, and Tiscapa.

The climate of Managua is subhumid-tropical with warm temperatures all year around. The lowest monthly average is 23°C in January and the highest is 31°C in April. Mean annual precipitation is about 1 200 mm, mainly falling from May to October, at the time of the arrival of the intertropical convergence. The dry season is from November to April.

Almost no permanent streamflow occurs on the slopes in the region; sporadic flow can be observed immediately after high rainfall in the largest drainage channels (e.g., the Rio Borbollon, which flows near the Las Mercedes airport). The main reasons for this limited stream flow are the high permeability of soils and surface formations, the concentration of rainfall, and the poor development of the hydrographic network, which is a common feature in volcanic landscapes because of frequent accretions of volcanic materials.

Geologically, the area is composed of various types of volcanic rocks and deposits. A volcanic range forms the western edge of the depression, extending in a northeast-southwest direction. It includes symmetric volcanic cones, explosive craters, and calderas.

Fig. 20. Aerial view of the Managua-Nicaragua valley.

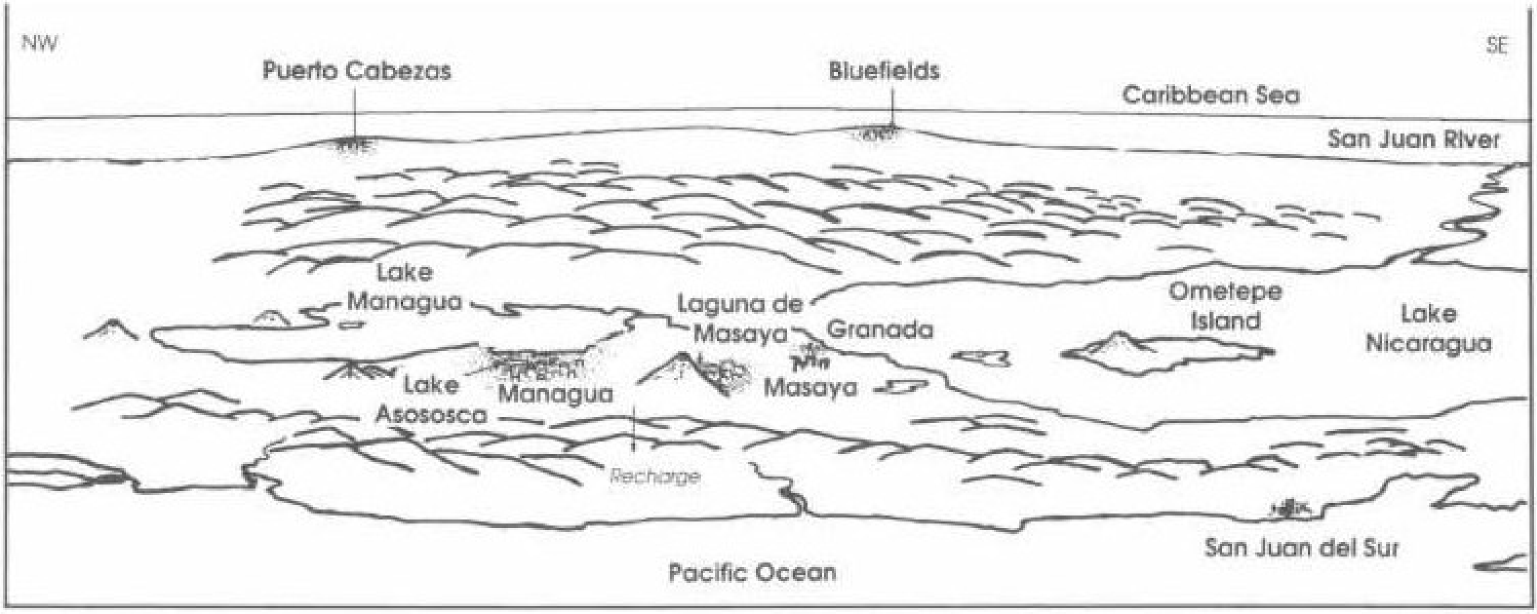
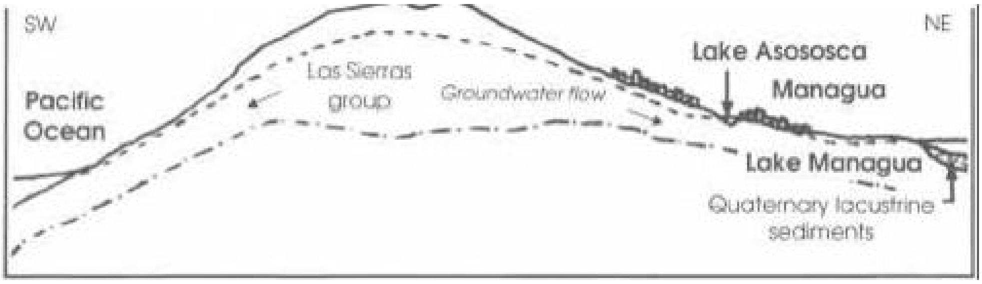


Fig. 21. Cross-section of the geological structures near Managua.



All Cenozoic geological formations in the Managua area are, directly or indirectly, of volcanic origin. The oldest stratigraphic unit is a pyroclastic sequence called the Las Sierras group (Fig. 21). This group is composed mainly of relatively uniform, massive agglomeritic tuffs and breccias that outcrop in several areas within and near the city. The thickness of this unit is about 680 m and its total volume is 450 km^3. Although the precise age of Las Sierras is not known, existing information indicates Quaternary age (or at least late Pliocene) for the group. Younger deposits have been shown to be older than 100 000 years. The relation between these deposits and the volcanoes surrounding the Masaya caldera has not been confirmed.

Overlying the Las Sierras group in the Managua region is a thin (10 20 m), layered volcanic sequence called the Managua group that includes airfall tuffs, ash, and lapilli beds. The source of these deposits seems to be related to recent volcanic activity in the Masaya caldera and the Nejapa-Miraflores area. Above the Managua group, a formation of ash, lapilli cinders, and lapillis is found (Motastepe formation). The source of this unit seems to be the volcanic structures of Cerro Motastepe, and the volcanic chimney found in the Caldera of Asososca.

The youngest deposits in the area are of lacustrine origin, related to sedimentation in the bottom of the large lakes and the smaller lagunas, and alluvially reworked volcanic material. The lacustrine layers are relatively thin, not more than a few dozen metres, although maximum thickness is not accurately known; the alluvial-volcanic sediments range from 0 to 90 m thick.

Hydrogeology[5]

Because of its permeability, thickness, and area, the Las Sierras group offers the greatest potential for groundwater extraction. It currently provides most of the water used in the Managua area. The Las Sierras aquifer is uniform in shape. In the area of the Pacific range, where the saturated zone is 200 300 m below the surface, most of the recharge takes place.

Groundwater flow seems to follow surface topography: either toward the Pacific Ocean, giving rise to several streams at the bottom of the deepest valleys, or toward Lake Managua. Some of the groundwater flowing toward the lake is discharged into small streams. near the Managua plain in several places where the water table intersects the

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[5] Material in this section is drawn from INETER (1988) and Krasny (1987).

surface. Some groundwater recharges lakes Asososca, Tiscapa, and Nejapa; the rest flows into Lake Managua.

The city of Managua has been using water from the Las Sierras aquifer, directly or indirectly, for some time. The main source of supply had been Lake Asososca, but as the city grew, its water requirements began to exceed the amount of groundwater feeding the lake. From 1914 to 1975, extraction rates increased to slightly more than 80 000 m^3/day, causing the level of water in the lake to drop from 40.57 m above sea level in 1960 to 35.38 m in 1975. Since then, pumping rates have been reduced to 50 000–75 000 m^3/day or less, and the water level has stabilized at around 36 m above sea level.

The Carlos Fonseca Amador well field is located in the area of the aquifer where conductivity is high (near Sabana Grande and the A.C. Sandino International Airport). At present, 12 wells are producing an average of 50 000–60 000 m^3/day. Recently, two more wells were drilled. The amount of water pumped from wells in the Managua area is now slightly more than the amount drawn from Lake Asososca. The total amount supplied to the city, by the Instituto Nicaragüense de Acueductos y Alcantarillados, in July 1988 was 165 000 m^3/day. This still does not meet current demand in the Managua region, which is now over 200 000 m^3/day and is growing quickly. Interruption in water service can last up to 15–20 h/day; sometimes neighbourhoods do not receive service for days at a time.

Proposed new sources of water supply

Potential sources of water for the city are: Lake Managua, Lake Nicaragua, new wells in the Las Sierras aquifer, and the lagunas.

Lake Managua

Excess water from Lake Managua, which is slightly brackish, flows to Lake Nicaragua via the Tipitapa River. Over the last few years, however, the lake has behaved as a closed basin and its salt concentration has increased due to evaporation.

Intense agricultural activity, including the use of pesticides, and continuing disposal of wastewater from Managua into the lake have affected the quality of its water to the point where it is unsafe for drinking or bathing. The dumping of toxaphene (a pesticide related to DDT (dichlorodiphenyltrichloroethane)) and other waste substances, including mercury, into the lake by the Pennwalt and Hercules chemical plants during the 1970s was especially damaging. According to one United Nations environmental study, the water contains 60 t of mercury. According to another study, 17% of all deaths in Managua are related to mercury poisoning and pollution in the lake.

Lake Nicaragua

Lake Nicaragua contains good-quality fresh water with only minor sources of contamination from Granada and other smaller towns. There is a positive balance between inflow and evaporation; average flow in the San Juan River, which flows from the lake to the Caribbean, is high.

This lake probably represents the best option for water supply, not only for Managua, but also for other towns and for irrigation. However, because of its distance from Managua (40 km) and lower elevation, water extraction from Lake Nicaragua could be beyond the economic means of the country at this time.

New wells in the las Sierras aquifer

The aquifer provides a good alternative for increasing the water supply, although the volume of water available from it can be somewhat limited. Aquifer conductivity is high, and its uniformity makes well location simple. There is, however, a need to ensure that long-term extraction does not upset the balance of the aquifer. It is important to consider the water taken from the lakes in this balance, because, hydrogeologically, these surface bodies act as open wells.

The lagunas

The small lakes (lagunas) in the area are, in effect, "groundwater outcrops." Their use, therefore, must be limited by the same constraints affecting long-term operation of well fields. They also need special protection because of their exposure to potential sources of contamination.

Of the eight largest lagunas near Managua, Asososca is the only one used as a source of water for the city. Three others are situated in or close to the Managua metropolitan area: Acahualinca, Nejapa, and Tiscapa. The first two are inadequate sources, because of insufficient volume and poor water quality. Only Lake Tiscapa, which is similar to Lake Asososca, might be appropriate. It has the added advantage of being in the centre of the city, but the consequent disadvantage of higher vulnerability to contamination.

The northern lagunas (Apoyeque and Jiloá) located in the Chiltepe peninsula near Lake Managua are not suitable (chemically) for urban water supply.

The remaining two lagunas (Apoyo and Masaya) are east of Managua, outside the city, but close enough to be accessible. Lake Apoyo's water is of poor quality, but the water in Lake Masaya is acceptable and its volume is eight times that of Lake Asososca. However, the rate of renewal of water in this lake is low and communities near it are already consuming a significant amount. It is unlikely that bringing water from this lake to Managua would be economically feasible.

Conclusions

The environment in and around Managua has been damaged, particularly as a result of poor management of its abundant water resources. Unfortunately, correcting the problems that have accumulated over years of environmental degradation and mismanagement will require considerable effort and investment that is not readily available, given the country's difficult economic and political situation. Although a first step toward the necessary social awareness and understanding of the problems is being taken, much work and international assistance will be required to turn the Managua basin into the harmonious environment of the past.

The capital of the Mayan nation: Mérida of Yucatán

With 700 000 inhabitants, the city of Mérida is the largest urban area of the Yucatán peninsula in Mexico. It is situated in a fragile environment: the flat limestone platform of northwest Yucatán. Mérida was founded by the Spanish conquistadors in 1542 on the site of the Mayan city, Tho. It became the principal city of colonial Yucatán and later the capital of the state of Yucatán.

Geology

The city is located on a limestone plateau. The oldest outcropping sedimentary rocks are Paleocene limestones, overlaid by the Eocene microcrystalline, white, carbonate rocks of the Chichen-Itza formation. The Miocene epoch is represented by the Bacalar formation of white marly limestones, over which lie the Pliocene carbonate formations Carrillo Puerto and Estero Franco. Overlying the latter are less-pure limestones. They gradually become more clayey, and yellowish and reddish, forming lateritic soils. The younger (upper) levels are hard white limestones, which are covered by Quaternary deposits (more commonly found to the north and west of the peninsula).

The Yucatán peninsula has been affected by the northeast-southwest oriented tectonic activity (which is the cause of the faults associated with the Hondo River, Lake Bacalar, Chetumal Bay, and Ascensión alignments and the northwest-southeast topographic divide of the Sierrita de Ticul).

Geomorphology

The peninsula is part of the coastal plains of the Gulf of Mexico, with average elevation less than 30 m above sea level. The Sierrita de Ticul, which is the highest point on the peninsula at 275 m, has a typical karstic geomorphology with almost no surface hydrographic network. Most rain water filters into the underground systems through sinks or *cenotes.*

Climate

The climate of Mérida is tropical-subhumid, with an average temperature of 26°C and annual precipitation of about 1 050 mm (potential evapotranspiration is 2 000 mm). In the rest of the peninsula, the level of annual precipitation varies from a minimum of 500 mm near the northwestern shore to more than 1 300 mm in the northeast.

Hydrogeology

Yucatán s limestone formations contain a huge groundwater reservoir, which in the northern half of the peninsula (62 240 km^2) receives as much as 9 350 million m^3 of water per year (Lesser Illades 1976). This is a typical karstic aquifer, with the water contained in a network of open fractures that has developed through dissolution of carbonate minerals, such as calcite, aragonite, and dolomite. The depth of the groundwater varies from 100 m in the south to less than 10 m in the north. The maximum thickness of the aquifer is not much more than 160 m; the average is much. less. The weak gradient of the water table (about 4 m from the middle of the peninsula to the sea) is certainly the result of high conductivity in the aquifer.

Environmental problems in Mérida

Mérida is completely dependent on groundwater for its supply, and karstic aquifers are sensitive to contamination. Water moves quickly through the open fractures and its quality is not improved significantly as it is in other types of aquifers. Polluted recharge areas can, therefore, quickly become public health hazards if they are upstream of the pumping wells. Overpumping, on the other hand, brings sea water into the system and wells must be closed, reducing the amount of water available and making parts of the distribution, conduction, and storage system useless. In addition, the city has also been disposing of its liquid wastes into the aquifer system for some time.

The result of these practices has been deterioration of the only available water source in the Mérida region. For Mérida to continue to develop in a sustainable manner, water management methods must change, taking into account the vulnerability of the karstic aquifers.

9

Management of water resources

Complexity of water management in urban areas

From the moment precipitation hits the ground, several factors begin to affect its future use as a source of water for human consumption. Without human intervention, rain infiltrates the ground, flows on the surface, or evaporates according to natural patterns. In forests, most of the water filters into the soil recharging the groundwater or is absorbed by plants that later return it to the atmosphere by transpiration. There is little run-off, although groundwater is discharged into nearby streams. In steppe or desert areas, where there are fewer plants to hold the water, run-off predominates. On flood plains, the amount of water entering aquifers can be large. On the other hand, evaporation may be the main water outlet in closed or semi-closed basins. In subhumid grasslands, the hydrological cycle behaves in an intermediate manner.

When humans alter the ground surface, natural hydrological dynamics are affected. When herbaceous crops are substituted for forest, the proportion of run-off is usually significantly increased. When trees are planted on a former grassland area, the opposite frequently occurs.

Agriculture has a strong effect on the water balance. To grow most types of crops, land must usually be cleared of any existing vegetation to eliminate competition for the future crop. For some time before the crop begins to grow, the land is bare, which will drastically affect the fate of water falling on it.

Once the crop has grown, the hydrological behaviour of the area changes again. Crops pass through various stages of soil cover and height during the year. In all agricultural landscapes, the hydrological balance is strongly controlled by the characteristics of the farming activities taking place.

Urbanization affects water dynamics even more strongly. First, a considerable portion of the ground is covered with relatively impermeable layers of various paving materials; infiltration and evaporation are almost nil and most precipitation runs off. Second, some of the land is excavated, removed, or buried under fill materials brought from somewhere else, producing significant hydrological changes. Third, many types of structures are inserted into or laid on top of the ground surface with important effects on the water dynamics. These structures can sometimes collect precipitation (roofs) or, in other cases, obstruct surface or groundwater flow.

In addition, urban design includes (well-planned or not) comprehensive water management schemes. Storm water falling on pavement and roofs is collected in culverts, canals, and pipes and removed from the city through a conduction network.

Cities must also import water to satisfy the needs of their populations. Water is drawn from nearby streams, lakes, or wells; treated, stored, and conducted to the residents; used for various purposes; and disposed of as wastewaters. The disposal is carried out by means of another water conduction system. In some cases, water is returned to the natural hydrological system, treated or untreated, in a much different state than when it was originally extracted.

These processes imply dramatic changes to the environment in the urban region. Rivers are channeled or piped, their flow volumes and regimes are substantially modified, and their waters are loaded with artificially produced and relocated natural substances. Groundwater levels and, therefore, groundwater flow are also changed; they are usually lowered, although in some cases they may be raised.

Changes to the natural water system may occur at the site of extraction (e.g., reduction in river volume or drawdown of water level through wells); during conduction and storage (e.g., leakage from water pipes, tanks, canals, and sewers); or at the disposal end of the system (discharge of sewage). These processes are closely interconnected. Natural and anthropogenic systems must be considered as a single unit (Fig. 22).

Forests in catchment areas control the flow of water toward downstream reservoirs from which water-treatment plants receive water for homes and industries. If a forest is destroyed, the water regime in the reservoir will change. If water is withdrawn from a river and disposed of somewhere else, the river regime downstream will change. If groundwater is pumped from an aquifer, discharge and recharge volumes to and from hydraulically connected streams will be modified and the stream regime will change. If surface water is used, related groundwater will be affected. If vegetation is eliminated, both surface and groundwater in the downstream basins will be affected.

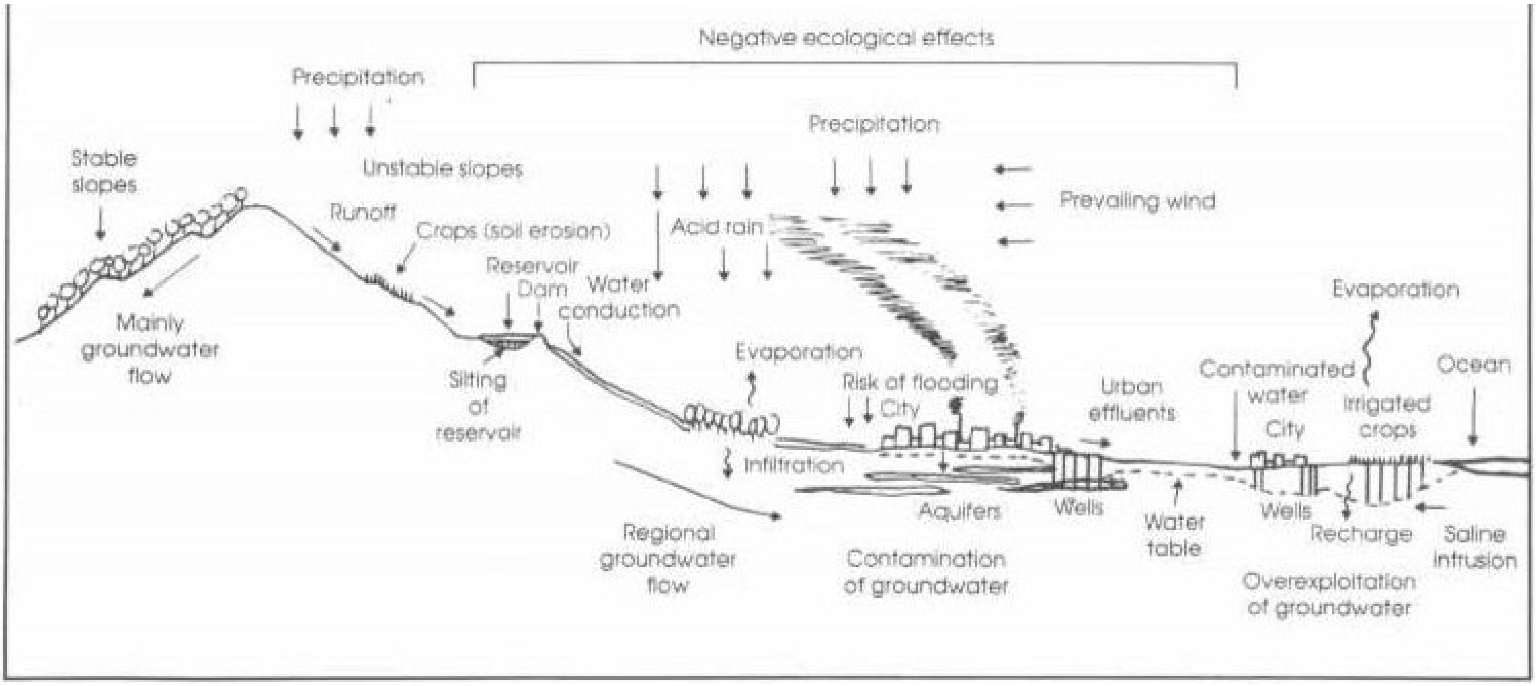
All parts of the water system are closely linked, and the effects of any action can be much more complex than is obvious at first glance. Therefore, it is important to define who has the right and authority to make modifications that will produce changes that may affect other people living in the same hydrological region.

Environmental problems and their costs

The large cities of Latin America and the Caribbean (LAC) are experiencing serious environmental problems, at the regional, municipal, and neighbourhood level. Problems are widespread and complex, affecting not only water but also the land and air. Polluted air changes solar radiation, both the quantity and the wavelength received at the ground level, and precipitation (volume, pattern, and quality).

These changes affect both the land and the water. When land is changed, through excavation, disposal of earth or debris, construction, farming, or deforestation, the water system is affected. Variations in albedo, evapotranspiration rate of the vegetation, or amount of dust generated modify the city's atmosphere.

Fig. 22. Human actions that modify the hydrologic cycle.



When water quality deteriorates, the air is also affected, through changes in amount of evaporation and radiation, and the land is changed by increased erosion and sedimentation, flooding or drying up of rivers or lakes, clogging and salinization, and rising of shallow water tables.

However, to remain within the bounds of the subject of urban water supply, we will summarize the main problems caused by city development and affecting water resources (Stoker and Seager 1980).

Effects of urban development on water resources

Changes in the flow of streams

Human actions in urban areas often result in decreased volume of water in adjacent streams and rivers. These activities include:

- Changing land use in catchment basins;
- Withdrawing water for irrigation, with subsequent evaporation, infiltration, or diversion to other basins or to a location further downstream;
- Withdrawing water for urban consumption;
- Withdrawing water to recharge groundwaters (planned or unplanned); and
- Building dams, with associated evaporation or infiltration.

Changes in the hydrological patterns of streams

The natural cycles of streams may be altered by changes in land use (e.g., deforestation and agricultural activities), but can also be affected by withdrawal of water, the building of dams, and changes in the discharge-recharge relations between groundwater and streams.

Changes in the amount of suspended sediment

Increases in the concentration of sediments carried by a stream are often the result of increased erosion in catchment areas. It may cause sedimentation downstream on flood plains and in reservoirs.

Sedimentation and silting of reservoirs

These processes are usually a consequence of normal fluvial evolution. Flood plains are natural sedimentation areas and reservoirs behave in the same way. However, anthropogenic degradation of watersheds often gives rise to an increase in the sedimentation rate and can lead to rapid silting of reservoirs and a subsequent decrease in their storage capacity. The useful period of operation of some reservoirs has been reduced by an order of magnitude due to inadequate management of their basins.

Contamination of surface waters

Pollution occurs when wastewaters and other debris are dumped into streams and lakes.

The main sources of such contamination are:

- Domestic and municipal sewage;
- Industrial wastes;
- Farming;

- Mining;
- Fertilizers and pesticides; and
- Acid rain.

The main contaminants found in water include:

- Detergents (e.g., soaps, miscellaneous washing compounds, and solvents);
- Pesticides (e.g., chlorinated hydrocarbons, chlorophenoxyl acids, organo phosphates, and carbamates);
- Petroleum and derivatives;
- Toxic metals (e.g., lead and mercury);
- Fertilizers and other plant nutrients, either from raw domestic or farm sewage or from compounds applied in agriculture;
- Oxygen-depleting compounds (e.g., wastes from canneries, meat-processing plants, slaughterhouses, wool-washing, tanning, paper and pulp processing, and wastes from domestic animals and raw municipal or farm sewage);
- Disease-causing agents, i.e., various pathogenic microorganisms responsible for infections of the intestinal tract (e.g., typhoid fever, dysentery, and cholera) and hepatitis; and
- Radioactive substances, resulting from disposal of wastes from mines extracting uranium and other radioactive substances or disposal of radioactive material from power plants, industries, hospitals, and research institutions.

Contaminated wastewaters are frequently used for irrigation. For example, since the beginning of the century, about 90 000 ha of agricultural land in the Tula valley has been irrigated with wastewater from Mexico City. In Lima, 2 000 ha of vegetable crops are irrigated with urban wastewaters. In São Paulo, the contaminated waters of the Tietê River are used to irrigate vegetable gardens downstream from the urban core. In Santiago, 62 000 ha of vegetables are grown using water from three courses located downstream from Santiago s sewage outflow.

The risks to human health and well-being are not negligible. However, there is potential for reuse of urban wastewaters if appropriate treatment procedures are implemented. Recently, the World Health Organization published guidelines for the use of wastewater in agriculture and controlled, safe use of urban sewage and storm water is expected to increase in the future.

Contamination of groundwater

Wastewaters, other liquid wastes, and water percolating through garbage can find their way into groundwater reservoirs. Sources of pollution and the main contaminants are the same as those listed for surface water. Because there is little oxygen in the underground environment, wastewaters there are not oxygenated. On the other hand, many contaminants are filtered from the water by the geological formations through which it flows. Disease-causing agents, for example, are removed rapidly. However, the filtering capacity of formations varies considerably; some are very effective (silty sandstones), but more permeable units may allow contaminants to move quickly through their underground conduits (karstic aquifers).

Groundwater may also be contaminated naturally, e.g., by contiguous aquifers or surface-water bodies with high concentrations of unwanted substances, such as chlorides or sulfates.

Excessive drawdown of groundwater levels

When the rate of extraction from an aquifer, together with its surface discharge, exceeds its rate of recharge and groundwater inflow into the aquifer, the level of water will fall. Excavations (e.g., tunnels and quarries), in some extreme cases, may also lead to dewatering of aquifers.

Flooding

Excessive run-off or a rise in the water table near or above the surface of the ground causes flooding. Elevation of groundwater levels may be related to artificial obstruction of the discharge route (underground or on the surface) or increased recharge.

Summary

All of these environmental problems can be observed in the LAC region. The water supply for many cities of the continent has decreased because of reductions in overall stream flow or changes to their hydrological patterns. In most peri-Amazonian areas, river levels are now very low during the dry season and flood during the wet period. Cuiaba, capital of Mato Grosso, Brazil, can no longer draw enough water from the Cuiaba River to fully satisfy the needs of the city during the dry period. Similar problems are occurring in many cities of the Brazilian shield and in Mexico.

Suspended sediments are creating problems at the intake level in many Latin American cities. Extreme cases are found in several cities in the Colombian mountains, e.g., Ibague, at the foot of the central range; Popayan in the south; and in other cities depending on torrential rivers for their water and hydroelectric power. These rivers are being filled with sediments at a growing rate, as is also the case in the upper Papagayo reservoir, upstream of Acapulco, Mexico.

Water contamination is widespread in the region. There is almost no stream, lake, or groundwater reservoir that has remained untouched by anthropogenic pollution. The largest cities are the ones with the biggest problems. All rivers draining urban wastewaters from the major cities are highly polluted: the Riachuelo in Buenos Aires (Argentina); the Tietê and Pinheiros in São Paulo (Brazil); the Mapocho River in Santiago (Chile); the Bogotá River in Bogotá (Colombia); the Almendares River in Havana (Cuba); the Miguelete and Pantanoso arroyos in Montevideo (Uruguay); and the Guaire River in Caracas (Venezuela). All the substances listed earlier can be found, to a greater or lesser degree, in these urban streams, with the possible exception of radioactive wastes, which are not common in Latin American cities.

Groundwater reservoirs are somewhat better protected from contamination. However, there are indications that the aquifers of Buenos Aires, São Paulo, and Mexico City, among others, are beginning to suffer the consequences of uncontrolled disposal of wastes.

Excessive lowering of water tables is taking place in many cities where pumping is intensive (e.g., some suburbs of Buenos Aires, Mexico City, and Lima). In some cases, overpumping has led to saline encroachment (Mar del Plata in Argentina, Nassau in the Bahamas, Santa Marta in Colombia, Havana in Cuba, Lima in Peru, and Coro and Maracaibo in Venezuela).

Flooding has become common in cities located downstream of deforested areas. The northern Colombian cities of Monteria and Sincelejo are affected by the increasingly threatening flooding of the Sinu River. Even Lima suffers periodically from destructive flooding of the Rímac River.

The economic and social costs of these environmental problems are huge and difficult to calculate. Although these disasters affect the population at large, by far the most vulnerable sectors of the population are the communities of urban poor. They do not have the financial resources to buy bottled water, drill their own wells, install a pump with its own generator, or set up their own treatment systems. Nor do they have the means to move to the suburbs, out of the crowded, unhealthy parts of the city.

The urban poor, however, can seldom choose not to live on flood plains, unstable slopes, or next to garbage dumps. They get water from carriers, trucks, or public faucets, or from a municipal system that is frequently more unreliable for them than for other sectors of the population. If the water is contaminated, they get sick first and they have less access to medical services or money to pay for them. Paradoxically, in spite of the inadequate service, poor people of the cities must pay more for each litre of their insufficient, poor-quality water than the price charged in more affluent neighbourhoods (ODC n.d.).

Deterioration of water supply systems

The municipal water supply systems of cities throughout the LAC continental region are becoming increasingly obsolete and inefficient. Waterlines bringing water into the city are old and are breaking or leaking. Recently, almost the whole city of Bogotá was deprived of water for 48 h twice in 6 months while an old pipeline bringing the water from the northern reservoirs was being repaired.

Distribution pipes also leak (although it is difficult to calculate how much is leakage and how much is illegal consumption). In Lima, I observed many urban trees thriving without being watered, in areas where the water table is several dozen metres below ground level, beyond the reach of the roots. I believe they are using water leaking from the water distribution system or from the sewers and storm-water conduits. In any case, losses from the distribution systems may amount to 30–40% of the total input to the system.

These losses, combined with increased consumption (partly due to poorly controlled patterns of demand and partly to demographic growth) and insufficient input, frequently cause pressure in the pipes to fall, often forcing interruption of the service. When service is interrupted, pressure in the pipes may become negative and contaminated water is drawn from the soil surrounding the lines, introducing another source of contamination into the system.

Another factor affecting the systems' efficiency is the clogging of pipes by various deposits, such as carbonates and hydroxides. In the treatment plant at Aguas Corrientes in Montevideo, large sponges have grown in the canals and pipes leading into the plant, apparently feeding on nutrients in the incoming water.

Added to the environmental problems mentioned in the first part of this chapter, these deficiencies in the water systems make life for the poor in many Latin American cities a risky proposition. They breathe polluted air, drink contaminated water, eat unsafe food, and live among the garbage. They are subjected to earthquakes, mud slides, and floods from an early age and have limited access to health and education, no money, and no work. The situation is becoming critical.

A key issue in measuring quality of life, productivity, and sustainability of societies is the availability of potable water. This availability depends on the sound management of existing resources in the natural systems and on the effectiveness of the artificial water systems making use of those resources. However, water resources are frequently poorly managed.

The use of water by societies interferes with natural water systems. The modified systems, partly natural, partly artificial, must be treated in an integrated manner to obtain the desired effects. It is necessary to develop a systemic approach to issues surrounding water use. In most cases, especially in developing countries, water is consumed without regard for the natural system. As a result, the effects of this use may be unexpected and unwelcome.

A priority in the field of water use is to define a method for managing water resources in an integrated way. The approach should cover the various stages in the water acquisition: identification of existing water resources; assessment of volume, quality, renewability, environmental impact of its use; extraction; storage; treatment; distribution; consumption; treatment and use of wastewaters; and disposal of effluent (Table 3). The development, application, and adoption of appropriate, environmentally friendly technologies for sustainable use of water resources is one of the goals. However, integrated management of water systems cannot be carried out effectively without an appropriate legal and institutional framework supporting the necessary policies, decisions, and actions.

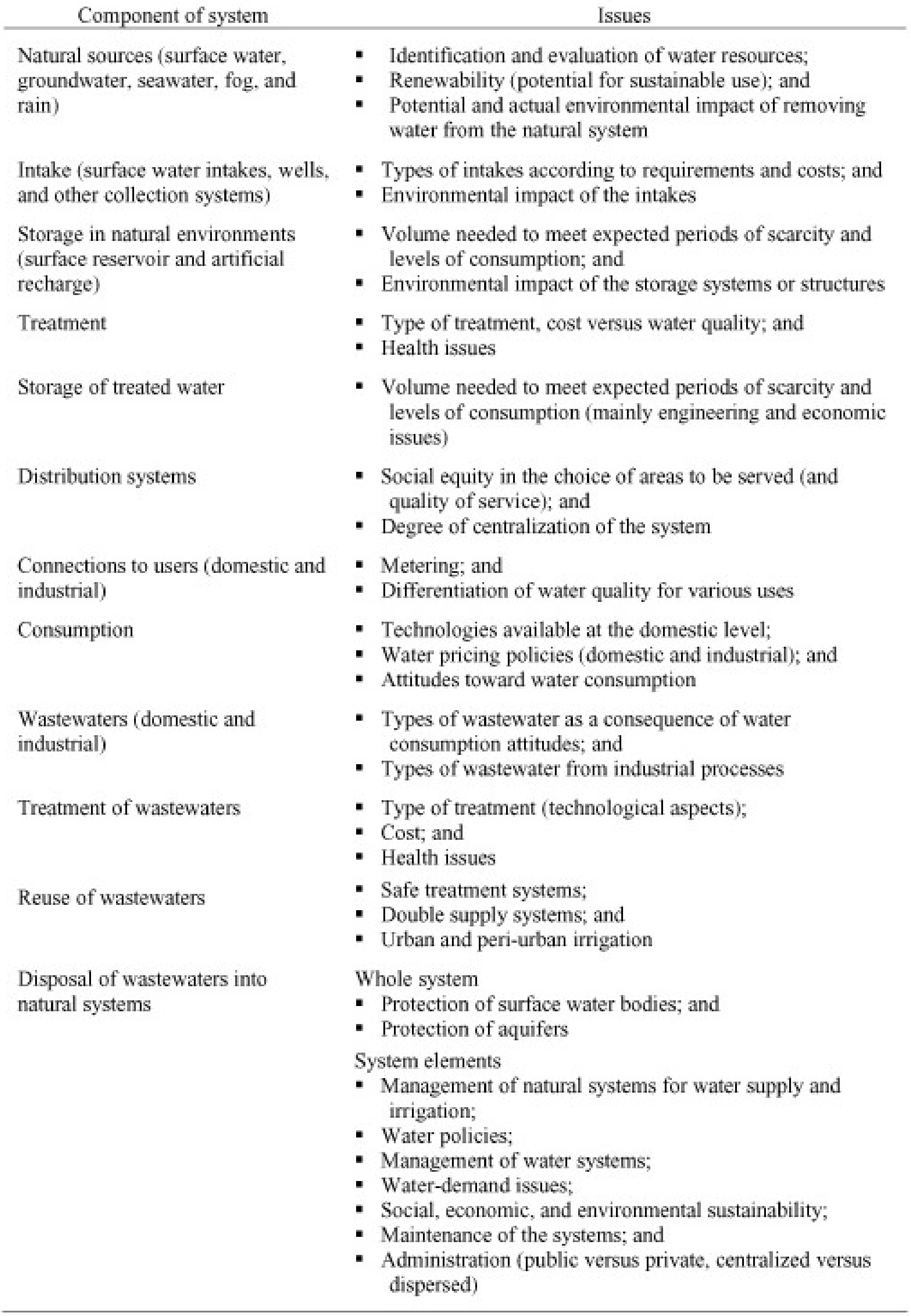
Another factor that has been problematic is inequity of access to water by the population. A large proportion of people in developing countries do not have access to safe, sufficient water. The reasons for this are many: lack of nearby sources, insufficient investment, inadequate or inequitable planning or implementation of plans, inadequate consumption attitudes, and environmentally unfriendly behaviour. Sometimes these problems can be overcome. However, the potential for success in solving these problems are highest if they are approached from the bottom up, through the participative intervention of the affected communities. No one is as interested in resolving the difficulties as the communities that are experiencing them.

Thus, another important priority is developing participative channels or tools for action at the community level. This implies moving toward decentralized systems of a modular nature. Decentralization should not mean lack of coordination; mechanisms must be put in place to compensate for the decentralization.

Another element affecting the effective functioning and sustainability of water systems is proper evaluation of the cost of water. In many developing countries, only operating costs are included in water companies budgets. However, the cost of water includes many other components that must be considered in the development and implementation of realistic plans. Some costs that are frequently overlooked are:

- Maintenance of the systems;
- Replacement of components;

Table 3. Issues related to urban water use.



Component of system	Issues
Natural sources (surface water, groundwater, seawater, fog, and rain)	▪ Identification and evaluation of water resources; ▪ Renewability (potential for sustainable use); and ▪ Potential and actual environmental impact of removing water from the natural system
Intake (surface water intakes, wells, and other collection systems)	▪ Types of intakes according to requirements and costs; and ▪ Environmental impact of the intakes
Storage in natural environments (surface reservoir and artificial recharge)	▪ Volume needed to meet expected periods of scarcity and levels of consumption; and ▪ Environmental impact of the storage systems or structures
Treatment	▪ Type of treatment, cost versus water quality; and ▪ Health issues
Storage of treated water	▪ Volume needed to meet expected periods of scarcity and levels of consumption (mainly engineering and economic issues)
Distribution systems	▪ Social equity in the choice of areas to be served (and quality of service); and ▪ Degree of centralization of the system
Connections to users (domestic and industrial)	▪ Metering; and ▪ Differentiation of water quality for various uses
Consumption	▪ Technologies available at the domestic level; ▪ Water pricing policies (domestic and industrial); and ▪ Attitudes toward water consumption
Wastewaters (domestic and industrial)	▪ Types of wastewater as a consequence of water consumption attitudes; and ▪ Types of wastewater from industrial processes
Treatment of wastewaters	▪ Type of treatment (technological aspects); ▪ Cost; and ▪ Health issues
Reuse of wastewaters	▪ Safe treatment systems; ▪ Double supply systems; and ▪ Urban and peri-urban irrigation
Disposal of wastewaters into natural systems	Whole system ▪ Protection of surface water bodies; and ▪ Protection of aquifers System elements ▪ Management of natural systems for water supply and irrigation; ▪ Water policies; ▪ Management of water systems; ▪ Water-demand issues; ▪ Social, economic, and environmental sustainability; ▪ Maintenance of the systems; and ▪ Administration (public versus private, centralized versus dispersed)

- Past investments (generally repayment of loans);
- Future investments;
- Environmental costs (due to water withdrawal from and wastewater disposal into the geosystems and ecosystems);
- Health costs because of inadequate service;
- Social costs because of inadequate service; and Loss of productivity because of inadequate service.

Causes of water supply problems in urban areas

During the last few decades, providing water to Latin American cities has become more and more difficult. Reasons for the problems are numerous: insufficient knowledge and lack of properly trained professionals, political influence on technical decisions, bureaucracy in water management and supply institutions, and corruption in administrative and political systems (Biswas and Kindler 1989). These and other contributing factors are discussed in,the following sections.

Lack of financial resources

At the root of the environmental, health, and social problems that have developed in Latin American cities during the last few decades has been a lack of financial resources. Before 1982, although financial resources were scarce, credit was extended by funding agencies, transnational banks, and financial institutions. However, when the debt crisis in these countries became apparent, the situation deteriorated considerably.

During the 1970s, when money and credit were readily available, many Latin American countries were under the control of right-wing military governments. These regimes felt little accountability to electoral constituencies; political parties were outlawed or weakened; and elections were either not held or were a sham.

Argentina has been governed, on and off, by military or authoritarian governments since the 1950s. In 1975, a particularly bloody and authoritarian junta seized power and remained in control until 1983. During that period, most of Argentina s debt was contracted.

In Brazil, the military took power in 1964 and remained in charge during the Brazilian miracle, in which Brazil experienced one of the most sustained (and wildest) growth periods ever known. In the early 1980s, when the economic situation worsened, the military withdrew from government, mainly because growing popular resentment and the weaker economy made control of the country risky and less profitable. The bulk of the Brazilian debt was also contracted during the military regime.

In Chile and Uruguay, coups d état, mainly organized with outside help, took place simultaneously in 1973 after almost a century of democracy in these countries. These military dictatorships, which lasted until the late and early 1980s, respectively, were responsible for most of Chile s and Uruguay s foreign debt. Other countries affected by this political infection were Bolivia, Paraguay (which has suffered long military dictatorships during much of its history), and Peru (whose military government had a more nationalistic orientation). These countries also developed large foreign debts during the late 1970s.

In Mexico, which has not had a military government for a long time, the practices of the Partido Revolucionario Institucional precluded accountability. In Venezuela, the main problem was widespread corruption of the political elite during the years of easy money resulting from high petroleum prices.

The availability of huge amounts of money in the financial markets and the corruption and unaccountability of most governments in Latin America contributed to the borrowing spree encouraged by the banks. Within a few years, Brazil increased its debt from less than US$10 billion to more than US$100 billion. Mexico managed to borrow US$100 billion while its petroleum income increased 10-fold. Argentina borrowed more than US$40 billion. Venezuela, which enjoyed an excellent credit rating because of its oil reserves, borrowed US$30 billion. Chile, Colombia, and Peru borrowed about US$15 billion each, and even the smaller countries, Uruguay and Costa Rica, managed to contract sizable debts of US$5 and 4 billion, respectively.

The borrowed money was invested in odd ways: some never left the banks coffers; some was transferred to secret (and not so secret) accounts of the local leaders and their political appointees or representatives; probably the largest portion was used to pay for weapons for the military and for unneeded luxury items. A significant amount was used to support rapidly sinking local currencies for a few weeks longer (to the delight of insiders and speculators). A relatively small amount was invested in infrastructure and a fraction went into professional training.

Even good investments of this borrowed money were often counterproductive. Many mammoth projects were environmentally damaging, e.g., the trans-Amazonian highway project that opened vast areas of vulnerable wilderness. The effects of some of these investments were suffered, directly or indirectly, by the whole planet. In the worst cases, these projects were genocidal, as a number of so-called developmental initiatives resulted in elimination of entire tribes of indigenous people.

Among the productive investments, a few hundred million dollars were used to modernize water-supply systems in a number of cities. Treatment plants were established, storage structures repaired, water-distribution and sewerage systems installed, and reservoirs and conduction lines to the urban centres built.

However, these investments only partially improved the situation. The cities kept growing and new investment almost completely stopped in the early 1980s. During the last few years of the 1980s, little money was available for development of water resources or water-supply and sanitation systems in the urban areas and the situation is not expected to change during the 1990s. The main consequences of the lack of financial resources are:

- Inadequate investment in maintenance of existing water-supply networks;
- Inadequate investment in water and sewage treatment, in spite of increasing risk of contamination;
- Less investment in replacement of obsolete systems; Little expansion of networks;
- No replacement of old reservoirs that have become unusable because of silting, etc.;
- Inadequate investment in new reservoirs; and

- Increased cost of water services for users, because of elimination of subsidies and other reasons.

In brief, less water is available, the water is of poorer quality, and the cost is higher.

Structural adjustment and the need for self-financing

As a result of increasing debt, Latin American governments have been forced to negotiate agreements with financing agencies and banks to postpone and reschedule repayment of their loans. The International Monetary Fund (IMF), which is the main financial agency coordinating these agreements, has traditionally promoted structural adjustment to deal with the excessive foreign currency requirements that are mainly the result of foreign debt, but have also resulted from repatriation of profits by foreign companies, payment of foreign royalties, and other transfers.

The IMF s conditions for rescheduling normally include strong recommendations for radical decrease of the fiscal deficits, as well as promotion of a positive balance of trade. The IMF recipe for reducing the fiscal deficit includes decreasing the size of the public service, self-financing public services, eliminating subsidies, and taxes and price increases.

Trade surpluses are achieved by increasing exports and reducing imports. One way to reach this objective is by devaluating the local currency, which automatically reduces workers salaries and other production costs making goods more competitive in international markets. Exports can be increased either by increasing production of some items or, more commonly, by decreasing consumption, i.e., reducing the purchasing power of the population. The lower earnings of the workers also translate into fewer imports, because people are no longer able to buy these items. As can be seen, the cost of obtaining foreign currency to meet debt obligations is borne by the population at large, especially those on a fixed income.

Water management, water supply, and sanitation institutions are usually strongly affected by these structural adjustments. First, their expenditures are reduced. This means laying-off personnel or reducing salaries; reducing operational expenses, including maintenance; delaying, postponing, or canceling new projects, e.g., replacement or expansion of old systems or building new ones; and limiting purchases of required parts, for example.

Second, the requirement for self-financing and elimination of subsidies has forced many water companies and institutions throughout the continent to increase their billings to users. As a result, the price of water services has increased considerably, when calculated as a proportion of actual incomes. These increases usually apply to both water consumption and connection of the service for new users.

Frequently, the poorer members of the population cannot afford to pay these higher prices. As a consequence, many homes in Latin American cities do not have access to municipal water, because they cannot afford the cost of connection or their service has been discontinued because of lack of payment. These policies have resulted in different standards of service for different neighbourhoods. The poorest people in Latin American cities are forced to obtain water from public faucets, trucks, or from water carriers *(aguateros).*

Finally, the need to reduce imports has made it difficult for water companies to buy new machinery or spare parts, fuel, and lubricants required for normal operation of their systems. The result of the structural adjustments has been an increase in cost of water services for the population (measured in working time required to pay for them) and a decrease in the quality of the service (both from the administrative and engineering points of view).

Population growth

Population growth of the continent has been high during most of the 20th century, partly because of decreasing death rates achieved through advances in medical science. Vaccines and antibiotics now control some of the most deadly infectious diseases, such as tuberculosis and typhus. At the same time, birth rate has remained high throughout the Third World and specifically in the LAC region.

The birth rate is not uniform in these countries. During the last few decades, there has been a significant decline in birth rates in urban areas, because additional children mean additional responsibilities and expenses that are difficult to meet in the urban environment. The availability of contraceptive devices and information. and access to abortion has also had a differential influence on birth rate. In rural areas, where children contribute to the household from an early age, birth rate has remained high. Combined rates for urban and rural areas have resulted in sustained growth.

Paradoxically, while reproductive growth was much higher in rural areas, actual population growth was greater in urban areas, because of migration from the countryside to the cities during this century. Latin American cities grew at an accelerated pace, mainly because of this migration, which is continuing in most Latin American countries at various rates. In Argentina, Chile, and Uruguay, it is less significant; in Brazil, Colombia, and Mexico, however, it remains intense. During the last 20 years, birth rates have begun to decrease gradually, even among the rural population and urban growth has begun to slow throughout the continent.

However, the sheer numbers of people in Latin American cities are still considerable. In the year 2000, 2 cities will contain more than 25 million people, 10 will hold more than 5 million, about 50 will have more than 1 million, and 350 will have a population above 0.1 million inhabitants. The annual growth of some cities is staggering. Mexico City and São Paulo gain 0.7 0.8 million residents every year. Guadalajara, Monterrey, Recife, and Rio de Janeiro increase their populations by over 0.3 million people annually. These new residents require the normal array of urban services and considerable additional financial investment is needed to supply them.

Like other service requirements, water needs also increase as the population grows. However, additional water is often not readily available and, even when it is, new distribution networks must be built to bring the water to these new urban residents. In both cases, financial resources are (and will continue to be for some time to come) insufficient.

Lack of protection of water resources

In the largest cities of the continent, there is little control over the disposal of wastes. Sources of pollution can frequently be found upstream of the intake area for surface water or in the recharge areas of aquifers used for water supply. A typical example is Buenos Aires, which draws water from the Río de la Plata just downstream from the outlets of untreated urban sewage wastewaters. In Mexico City, leakage from the main sewer can enter the aquifer and the wells supplying the city s water. In Lima, Guatemala City, and Cochabamba, among other cities, the recharge areas of working aquifers are unprotected.

In São Paulo, waste disposal sites are next to one of the main local rivers (Pinheiros), whose water is pumped into the Billings reservoir. This reservoir supplies water to the 1 million inhabitants of Santo André. To protect the water supply, an earth dam was built to separate the contaminated water from the clean. However, as well as the constant risk of leakage through the dam, pollution sources in the catchment area of the reservoir are probably also affecting the quality of the consumed water.

The hydrological systems of catchment and recharge areas can be affected by the unregulated activities of farms, industries, and city developers. Eliminating forests increases run-off and soil erosion, which in turn cause silting of reservoirs. Increases in the amount of suspended material can also increase the cost of water treatment and cause changes in the hydrological regime of the river. Farming wastes, fertilizers, pesticides, urban domestic wastes, and industrial wastes are produced in large volumes in or near urban areas. Water resources must be protected from these potential contaminants.

Pollution of unprotected reservoirs or streams may result in eutrophication (the result of depletion of dissolved oxygen) with extensive algal development and radical changes in the ecosystem, including death of organisms in the water. However, toxic effects may be felt by humans before these extreme developments take place. Although careful and sophisticated controls and analysis are required to monitor the quality of urban supply water, in most Latin American cities, only routine and often insufficient monitoring is carried out.

Inadequate knowledge of existing resources

To make long-term decisions about management of urban water supplies, accurate information must be available on:

- Types of local water resources, actual and potential;
- Available volumes;
- Present and future renewability of the resources;
- Vulnerability of the resources to degradation; and
- Measures required to develop, manage, and protect the resources.

Acquiring this information requires the input of qualified professionals and the financial resources to carry out the needed studies. Most Latin American cities do not have complete information even about the water resources they are currently using, because of lack of trained hydrological scientists, funds, and understanding on the part of management authorities themselves.

A few cities have obtained reports on the hydrology of some or all surface basins that are or could be of use for their water supply. Less common are studies on contamination of those waters. Analysis of groundwater reservoirs is rare. In many cases, the geometry of the aquifer is unknown or only partially assessed and, in most cases, the water budgets of the aquifers are only estimated or completely unknown, making it difficult to make appropriate decisions about their use.

The following examples, which are not completely hypothetical, illustrate a few of the costly mistakes that can be made when technical knowledge is insufficient or decisions are not made according to sound technical criteria:

- A new reservoir is built at a cost five times that of 20 wells that could have provided the same volume of water and of higher quality;
- New wells are built in the coastal portion of an aquifer, where saline intrusion results in their closure after a short time;
- New wells are drilled next to a sewage canal or waste dump, but closed when leakage from these sources is confirmed; and
- A surface reservoir is constructed in a permeable formation (e.g., limestone, conglomerates, or fractured bedrock), but water does not remain in it, making it useless for storage.

Inadequate management of water resources

One of the consequences of poor knowledge of available water resources and lack of qualified technical personnel is inadequate management practices. Systems are poorly designed, often to save money, but frequently having the opposite effect.

In many cases, coordination is lacking between people responsible for making critical decisions (e.g., opening or closing reservoir gates and establishing pumping rates) and the technical experts who have information about impending floods, sources of pollution, etc. that would allow quick and sound decisions. In other cases, short- and medium-term management decisions are made without sufficient background information. For example, pumping is increased or suspended in a given well, without considering the effect of this decision on neighbouring wells and the recharge from or discharge to nearby streams.

Management decisions require a comprehensive analysis of all aspects of the situation, and this is frequently not done. The results of poor management decisions affect both the quantity and quality of the water, as well as the cost of operations.

Wasteful practices

In most LAC countries, and particularly in the social sector that has easy access to water, consumption practices are highly wasteful. There is a lack of awareness of the value of water, water-saving technology is inadequate, and pricing policies do not promote conservation, as is the case in Buenos Aires where lack of metering is one of the main causes of its very high consumption patterns.

Inefficiency, politics, and bureaucracy in water management

Managing the water resources of an urban region and providing water to its population are difficult tasks, requiring the direction of one or more large organizations involving many people. Technical people from many professions are needed, as well as administrative and manual workers.

People are needed to manage the reservoirs, wells, and treatment plants at the intake end. In the distribution section of the system, numerous personnel are required to deal with the complex storage and pumping systems, distribution networks, installation of new lines, maintenance of old ones, and connections to the system. Most water companies also deal with sanitation and are responsible for maintenance and management of sewers and storm-water systems.

Because of the large number of users, water companies are usually in a stronger financial position than other public institutions. As a result, governments often divert their funds to other projects, not necessarily related to water supply.

Throughout the LAC, water companies have been used to provide employment to the supporters of the politicians in charge. Most of these political appointments are in the administrative sectors, rather than technical positions. As a result, the number of administrative personnel has increased continuously. In many cases, the shortage of financial resources of a water institution is related to the large amounts of money spent on salaries for these appointees.

When a political appointee is hired, commonly new administrative procedures or steps are implemented to provide work for him or her. Put in charge of a new procedure (or a step in that procedure), the appointee may be tempted to inflate its significance (to protect his or her job), making it more complicated or adding new steps that may require the hiring of even more people, who in turn may propose and implement new procedures with more steps, and so on. Once there is a strong bureaucratic lobby in the institution with free time, it feeds itself on available financial resources, reducing the amount that should be used for technical purposes.

The growth of the administrative departments is often paralleled by shrinking of the technical sectors. The shortage of money available to the latter results in lower professional salaries, to a point where the most experienced people prefer to leave the company for more rewarding employment opportunities. The politically appointed managers seldom have adequate professional background and experience to be able to make the right decisions in this complex field. Many crucial decisions are made with insufficient or inappropriate technical knowledge or input and, as a result, strategic decisions can be wrong and costly (Yepes 1990).

Corruption

Corruption in water companies is similar to that in other public institutions, although they may provide better opportunities for illegal practices, because they collect large amounts of money and purchase expensive materials. Theft of materials and charging purchasing commissions to suppliers are common ways of profiting from positions in some public water companies. In addition, the many tedious administrative procedures required for connection or maintenance of the water service may promote the use of bribes to speed up the process.

At a higher level, contract commissions may be charged, under the table, to companies contracting with water institutions. These bribes may be relatively frequent in some countries and add to the total cost of the service. Because such contracts are not awarded according to technical merit, the quality of the service or of the materials used may be inferior. These practices are difficult to prove and still more difficult to evaluate, but they are common in some bureaucratic environments of the continent.

Shortage of trained professionals

As mentioned above, many experienced professionals prefer to leave the water companies for positions offering better salaries and professional opportunities. This contributes to the basic problem of lack of technical know-how in water technology in the LAC region.

In many LAC countries, as many as 10 to 50 times more students may be in the liberal arts than in disciplines more directly related to production (engineering or agronomy). This results in a shortage of sufficient professionals in some key fields to meet actual and potential needs.

Another problem is the lack of proper training in a number of subjects in some Latin American universities. This may be due to low salaries and insufficient incentives for professors to remain in their universities. Quality of professional training is also affected by the scarcity of equipment, the unavailability of current technical literature, and the obsolescence of curricula and programs.

The field of water technology is affected by these problems. Only a few engineers specializing in sanitary engineering or hydraulics graduate from all Latin American universities. Probably no more that a few hundred per year from the over 500 institutes of higher education must serve the needs of 600 million people. There are even fewer hydrologists or hydrogeologists, mainly because there are few undergraduate or graduate programs in these fields. Most people dealing with water resources have studied another subject at university, but have been propelled toward this profession by the pressing needs of the society in which they work.

Despite the lack of formal training, many experienced and knowledgeable professionals are doing a good job in their areas of expertise. However, some of them have chosen to leave the public water companies to work in the private sector and some have emigrated to seek higher salaries and professional opportunities. This loss of expertise also has a negative impact on the future of water management in urban Latin America.

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Sustainable development of water systems

Factors affecting demand for water

The purpose of any water supply system is to satisfy the needs of communities. The suitability of any water resource to meet the demand hinges on the specific requirements of the communities that will use it.

The amount of water consumed by a community depends on many factors. External factors include climate: more water is needed in hot weather than in cold. Some factors may be cultural, e.g., the restriction on water during Ramadan in Muslim countries, or behavioural, e.g., washing practices. These patterns are not unrelated to water availability, but they do not necessarily reflect the level of actual or potential supply. For instance, although hot weather during the summer season tends to increase demand, requirements may actually decrease if most people go on vacation during that period. This situation is often found on hot summer weekends in cities; the fewer people in town compensate for increased consumption per person.

Water demand also depends on water availability. People adapt to available volume and, although there is some inertia involved in modifying habits, increasing supply volumes usually produce some increase in consumption level (other factors being equal). This is probably one of the reasons why the rate of consumption is high in Buenos Aires, i.e., proximity to the large fresh water Río de la Plata (another reason is the lack of metering).

The single most important factor affecting water demand is the existing infrastructure for its supply, i.e., conduction, treatment, storage, and distribution systems. A key element is the ratio of service connections to the number of households. Households without connections normally (but not necessarily) consume much less water, and consumption per person increases with the number of connections. In Latin America, the number of new connections lags behind the number of new households, especially in the fastest growing cities in the poorer countries (Lima, Managua, and Port-au-Prince).

Leakage of water from the distribution systems artificially inflates the rate of consumption. Although leakage occurs in any system On the order of 10 20% of the water in the system), in obsolete systems this proportion can increase to 30 40% or more, e.g., in Lima and Recife, leakage is estimated to be as high as 50%. As discussed in Chapter 9, this problem is serious in Latin America and the Caribbean (LAC) at this time of budgetary restraint. It would be difficult to find any large city on the continent not experiencing this problem. In some cities, leaked water is lost; in others, it finds its way into aquifers and may be at least partly retrieved (at a cost), as is the case in Lima.

Policies of the water management authorities can be used to regulate use as well. Metering and pricing policies are probably the most important in affecting consumption and demand. Water companies should ask themselves a number of questions:

- Is there adequate control (metering) of consumed water?
- Are pricing policies equitable for all neighbourhoods?
- What are the policies for different uses (domestic, industrial, agricultural, etc.)?
- Does cost differ with different levels of consumption?
- Are there different prices for peak periods? and
- What policies address leisure use of water, e.g., swimming pools and watering gardens?

Finally, the technological efficiency of water use can affect demand. Appliances and fixtures designed to provide water are a factor to be considered. To a large extent, "water-using technology and not the user's behaviour, determines the amount of water used" (Brooks and Peters 1988). In Latin America, most water-using appliances are copied from models used in developed countries. In most cases, regulations and controls of appliance efficiency are absent, inadequate, or not enforced. (Recently, new policies have been introduced in some countries, e.g., Mexico, where 7-L flush toilets have been promoted as replacements for 20-L ones.)

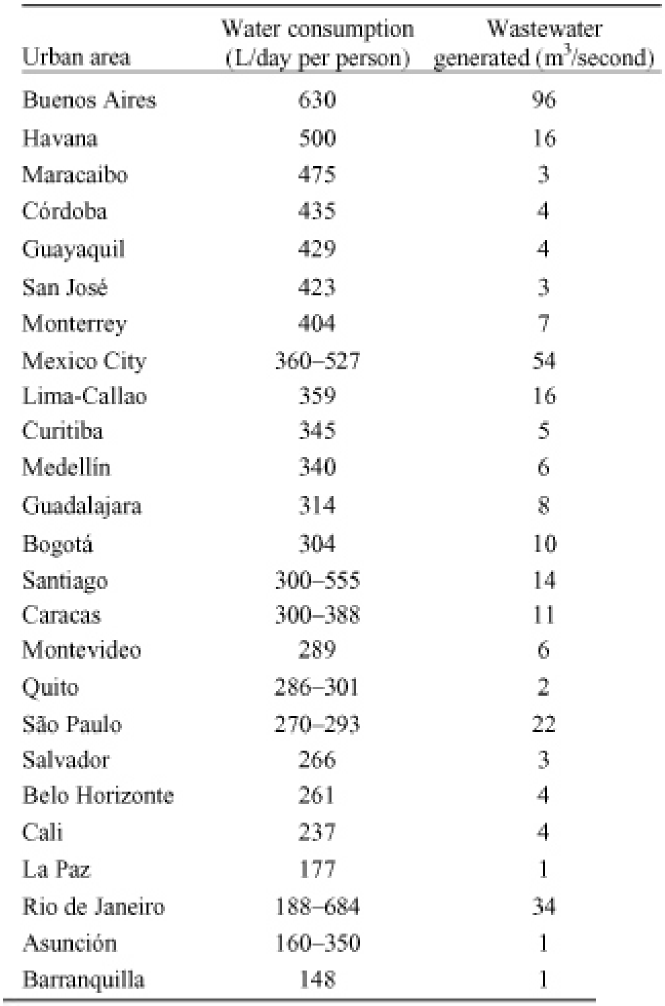
In spite of the importance of reducing unnecessary or wasteful water consumption, little is done in this regard. Although water can be expensive for people at the lower income levels, the price charged to consumers is still below the cost of supplying it when capital investments, maintenance, and other expenses are considered. Well-off urban residents of the LAC region take for granted their access to large volumes of water at a low cost, even when wasting water may mean inadequate supply to less-affluent neighbourhoods. In Lima, "leisure lakes" are fed through the municipal La Atarjea system, while more than 300 000 households have no service. However, wastage is not an exclusive practice of the urban upper classes; waste occurs throughout the social spectrum, including the urban poor.

Water is a valuable resource and its true economic worth must be recognized by decision-makers and consumers alike. Only with this awareness will it be possible to bring demand levels in line with the actual and reasonable needs of the populations.

Level of demand in Latin American cities

Consumption levels in Latin American cities vary from slightly more than 100 L/day per person to more than 500 L/day (Table 4). These figures include total demand from the water company divided by the population. However, in many cases, they also include industrial or agricultural usage, obtained from the municipal service but not always computed as such. In some cases, they do not include considerable volumes of water obtained from domestic wells.

Table 4. Municipal water consumption and wastewater production in large metropolitan areas of Latin America.



Urban area	Water consumption (L/day per person)	Wastewater generated (m^3/second)
Buenos Aires	630	96
Havana	500	16
Maracaibo	475	3
Córdoba	435	4
Guayaquil	429	4
San José	423	3
Monterrey	404	7
Mexico City	360–527	54
Lima-Callao	359	16
Curitiba	345	5
Medellín	340	6
Guadalajara	314	8
Bogotá	304	10
Santiago	300–555	14
Caracas	300–388	11
Montevideo	289	6
Quito	286–301	2
São Paulo	270–293	22
Salvador	266	3
Belo Horizonte	261	4
Cali	237	4
La Paz	177	1
Rio de Janeiro	188–684	34
Asunción	160–350	1
Barranquilla	148	1

However, water demand cannot be measured only by the level of consumption. Consumption is always below potential demand because of interruptions to the service, low pressure, insufficient connections, etc. On the other hand, if conservation measures were applied, consumption could be significantly reduced. Methods to bring about a reduction include:

- Reducing leakage to eliminate up to 20 30% of false consumption;

- Introducing water-saving technology, such as smaller toilet tanks and low-volume shower heads; and
- Changing water-consumption patterns, e.g., through adequate pricing policies or voluntary life-style changes, to stop wasteful practices or decrease consumption during peak periods (systems are overdesigned to meet infrequent but critical peak loads).

Actual consumption could be reduced by more than 50% in many LAC cities, simply through adequate maintenance, appropriate policies, and greater public awareness. Conservation alone could probably compensate for current deficits and a portion of future expansion in many cities of the region for a few years. However, conservation efforts cannot bring more water into the systems. There is still a need to protect present water sources and find new ones, both natural and artificial, i.e., recycled wastewaters.

Water resources and the use of wastewater

Water systems include inputs (e.g., natural sources and used water), the system itself, and outputs resulting, directly or indirectly, from the functioning of the system (e.g., water for recreation, homes, industries, and irrigation and electrical energy) (Sewell and Bawer 1968).

Inputs

Although the primary input (natural water sources) has been dealt with extensively in this publication, the potential of wastewater as an input has been only briefly mentioned. Its importance cannot be overestimated, as has been shown in same countries of the Middle East, such as Israel and Jordan. In the LAC region, used water is considered a problem rather than a resource. It is usually disposed of after little or no treatment, with the result that streams and other water bodies near cities are highly polluted. Currently, some use is made of wastewaters for irrigation, e.g., in Mexico and Peru. The Tietê River near São Paulo and the Mapocho River in Santiago, both of which contain considerable amounts of waste, are used for irrigation and by industries.

The amount of water used for irrigation and industrial purposes in most countries is larger, sometimes by an order of magnitude, than the amount used domestically; The quality standards for this water are frequently less strict than those for drinking water or other domestic uses, although some types of irrigation require water of high quality. Industrial water standards can vary substantially. Some processes require pure water or water with specific characteristics. However, in other cases, industrial water may be relatively impure and even contaminated without affecting its use, e.g., water for cooling machinery. Some of these requirements can be met by reusing wastewater. With effective treatment, wastes can even be turned into good-quality drinking water.

Although plants that treat water for reclamation are more expensive to build and operate than more common treatment plants, the additional costs are often lower than those needed to develop new water resources. Reclamation plants differ from normal treatment plants in several ways (Okum 1990):

- Their location is more influenced by the market for reclaimed water;
- The sludge can be disposed of elsewhere and even returned to the sewage system;

- The volumes reclaimed can be geared to need, i.e., it is not necessary to treat all the water; and
- The product is sold and, therefore, must be reliable in terms of quantity and quality.

In the United States, several water-reclamation systems have been in operation almost from the beginning of this century: Baltimore's Back River plant (1942) and Grand Canyon Village in Arizona (1926), which has a dual system for potable and nonpotable output. In the Irvine Ranch Water District, the cost of reclaimed water was found to be one-third less than that of water from the usual system.

Reclamation of used water has also been initiated in Israel, Singapore, the petroleum--producing countries of the Middle East, and some islands of the West Indies. Other examples can be found in the Beijing-Tianjin area in China, which started operation in 1988, and North Africa. Studies are under way in São Paulo to explore the possibility of reusing water from a secondary treatment plant for industry.

Water reuse is gradually going to gain importance as a source of nonpotable water. Dual systems are a potential tool for better water use in countries where the risk of misuse is high. In any case, developing countries and particularly urban areas of the LAC region cannot afford to ignore this resource, which often represents the best option for meeting the crucial need for more water.

The system

Water systems are designed to obtain water from a natural or artificial source and deliver it to the various users. Normally the water macrosystem includes:

- A regulating system at the source, Le., a system of dams for storage and regulation of stream flow;
- An intake system, i.e., dams, pumps, canals, and various pools, which may also include a conduction system leading to the treatment plant;
- A treatment system, i.e., filtering, sedimentation, and chemical-treatment pools and canals, and pumps;
- A conduction system from the treatment plant to the consumption areas;
- Various storage structures, almost always near the consumption sites, but also in intermediate locations; and
- A distribution system, Le., a network of pipes and canals, pumps, associated storage structures, and household connections.

Because of the complexity of water management in urban areas, water systems require material, technical, economic, administrative, and legal support for everyday operation. In addition, they require continuous monitoring and maintenance as well as heavy investment in replacements for obsolete elements and expansion. In the LAC, this support is normally provided by one or more public enterprises, although in several cases services have been provided by a private company.

Outputs

The main output of the system should be water in a condition that is compatible with its destined use: drinkable water for homes; water with various levels and types of dissolved solids for industries; and uncontaminated water for irrigation and leisure use.

However, this is not always the case in the LAC region. The potability of the water is often doubtful due to contamination of the sources and inadequate treatment. In many cases, monitoring of quality is unreliable. In many cities, the concentration of heavy metals and toxic organic material is not monitored properly.

Economic analysis

One of the key problems in the evaluation of any proposed method or scheme for urban water supply is the relation between expected results and estimated costs. Although, the calculation of costs should be a relatively straightforward exercise if all necessary scientific and engineering information were available, this is often not so. Hydrological and hydrogeological investigations are essential before decisions about alternative methods of water supply can be made.

Other important factors must also be considered to balance the various possible options. One of these is the ability of governments and communities to pay for construction, operation, and maintenance. It is also important to fit water projects into urban-planning strategies. However, we are concerned not only with water and engineering issues, but also with the environmental, social, political, and administrative aspects of the problem. Factors that must be carefully evaluated before an urban water-supply project is supported include:

- The current situation, i.e., present consumption; population; breakdown of household, industrial, commercial, and institutional consumers; number of connections and public standpipes; unsupplied consumers; presence of gardens and swimming pools; and number of breakdowns, leakage, and disruptions;
- Environment and geography, i.e., climate, area covered by the water service, topography, and seismicity;
- Cost of exploration, identification, and characterization of the water source (most research costs are included here);
- Cost of induced or artificial recharge of aquifers;
- Cost of water-extraction structures;
- Cost of water-treatment facilities;
- Cost of water-conduction structures;
- Cost of storage structures;
- Cost of distribution networks, including metering devices; Cost of operating and maintaining all equipment;
- Cost of lost water resources (for other purposes or for other communities);
- Cost of fisheries affected (if any);

- Environmental cost;
- Other environmental effects (short- and long-term, positive and negative);
- Effects on job creation or elimination;
- Other social effects, both positive and negative; Availability and cost of credit or funding;
- Ability of communities or governments to pay all of these costs; Technical feasibility of the project;
- Availability of qualified personnel to carry out the work and operate the installations;
- Administrative and political framework to manage the scheme during construction and operational phases;
- Future demand, according to expected growth of the population and the system's ability to expand; and
- Ease of access to water by different socioeconomic groups, in the volumes that are needed and at the required pressure.

Along with the analysis of costs, a qualitative assessment of the benefits can be carried out. Convenience, reliability, accessibility, health advantages, and increased social productivity (through reduction of the time required to obtain the water) should all be measured.

This checklist applies to specific projects designed to solve well-defined problems or to take care of specific needs after the main research issues have been addressed. In projects involving unknown elements, scientific research is required before a complete assessment of these factors can be carried out. However, to implement the results of the investigation successfully, these issues should be kept in mind and an economic evaluation provides a good starting point for comparing various options.

Economic evaluations of water projects must be carried out in a global context. Included in the bill will be the cost transferred to future generations if the environment is damaged, and the ethical aspects of distribution of the resource among the different social groups, sectors, or classes. (Updated information on administration of water resources in Latin America and the Caribbean can be found in ECLAC (1991).)

11

Quenching the urban thirst

Water and poverty

Shortages of water and poverty are frequently linked. When nature does not provide easily accessible water, communities do not thrive and their development can be limited. When people have access to abundant water, they can spend their financial resources on other necessities. However, supplying water to communities has become expensive and water companies of Latin America and the Caribbean (LAC) seldom give priority to poor neighbourhoods.

City slums are often located in marginal areas, where installation of water systems presents engineering problems. For example, several such areas are on steep slopes at a higher elevation than the storage reservoirs. Water must be pumped up to them, resulting in additional cost. Another common location for poor areas of the cities is on flood plains, where installation of drainage systems and water mains is difficult and costly. As a result, 40 million people in LAC cities lack water and most of them live in the poorest sections of the cities.

Water problems in more affluent parts of the cities may also affect the urban poor, directly or indirectly. In Santa Marta and Recife, for example, shortages of water in the hotels have reduced the number of tourists staying in the city and at nearby resorts. The thousands of people who depend on tourism for their livelihood, many among the poor sectors of the population, are seriously affected by this situation.

Water, health, and quality of life

Whether shortages are a result of lack of service in the area or loss of pressure in the whole system when volumes are insufficient, the urban poor are usually the first to suffer the effects. Poor hygiene, resulting from inadequate education, exacerbates the problems of people living in slum areas. Scarce water is not always used in the most efficient manner leaving poor urban neighbourhoods defenseless against infectious diseases, such as hepatitis and cholera, and putting additional strain on poorly funded and overextended health systems.

Unregulated dumping of garbage can lead to direct contamination of surface water of indirect contamination of groundwater.

The recent cholera epidemics, which started in Peru, later spread to most Latin American countries. Peru reported 200 000 cases of cholera and many neighbouring countries are in a similar situation. Cholera is widespread in the Amazon region and outbreaks occur as far north as Mexico and as far south as Argentina. The only cities where the disease did not establish a foothold are those with the largest sewage and water-supply systems, e.g., Montevideo. The possibility of fighting an aggressive disease like cholera, as well as other waterborne diseases like amoebiasis, diarrhea, typhus, and hepatitis, is closely related to the condition of the water systems in the cities.

Water is not only a defence against sickness, it is also a basic element in the quality of life. In communities not served by municipal systems, considerable effort is required to bring water to the homes: carrying heavy containers from trucks, wells, or streams, waiting in line, walking the distance to the source, and using precious fuel to boil the water. Many hours are spent by members of the household in this daily chore. Children miss school, women and men cannot take care of their infants properly, and people are frequently late for work because getting water is so difficult. Obtaining water at home represents a significant leap forward toward a better life.

Scarcity of water

Water problems of cities in this increasingly urbanized world are not always due to shortage of water at a regional level. Large cities consume relatively large volumes of water. Buenos Aires, Mexico City, and São Paulo, the three largest cities of the LAC region, consume 50 80 m^3/second but this is a very small volume when compared with the total resources of the region. Even with the growth expected during the next decade, this volume will not exceed 100 m^3/second in each city. However, the flow of water in the major rivers of Latin America is hundreds or even thousands times greater. The Amazon's output into the Atlantic Ocean is about 150 000 m^3/second, i.e., 2 000 times the water consumption of the largest city on the continent, the Paraná carries 20 000 m^3/second into the Río de la Plata, and the volume of many other rivers is over 1 000 m^3/second at their outlets, e.g., the Magdalena, Orinoco, San Francisco, Uruguay, and Usumacinta rivers.

This apparent abundance of water does not reflect the actual situation. Significant portions of the basins of these rivers lie in areas of high rainfall. Many other rivers contain much less water. Second, the figures quoted above reflect the flow at the mouths of those rivers. In their upper stretches or in their tributaries, the flow is much smaller in relation to the size of the upstream basin and the local rainfall. Third, few large cities are located at the mouth or in the lower reaches of the large rivers or their tributaries where the flow is at a maximum. Some cities, such as São Paulo, Brasília, Guatemala City, and Bogotá, are close to divides; water there is limited and frequently insufficient to meet the growing needs of their metropolitan populations.

Groundwater is abundant and volumes are several-fold larger than surface water resources (perhaps between one and two orders of magnitude larger). However, the critical measure of these sources is not their volumes, but their renewability. When groundwater sources are tapped beyond their capacity for renewal, water levels drop, pumping costs increase, and sooner or later the resource is depleted.

Considering only renewal volumes of aquifers, the available water is about the same order of magnitude as surface resources or even less. In addition, groundwater availability and urban distribution do not coincide. There. are large aquifers in sparsely populated areas or where there is plenty of surface water and large urban areas with little groundwater in their proximity.

The demand side of the equation

The water problem has two sides: supply and demand. Many of the supply problems in LAC cities would be solved, or would be less acute, if more sustainable policies and strategies were implemented. Consumption is much greater than required to simply provide water for urban activities and dwellings. Wastage takes place at all levels in the water systems: leakage from the pipelines, wasteful attitudes encouraged by lack of metering or inadequate pricing policies, inappropriate water-appliances, etc.

To improve the situation, therefore, both sides of the problem must be attacked: increase supply and reduce demand. In both areas, improved management strategies are needed.

Sustainability and equity

Management strategies must weigh the required investments against returns within the context of sustainability and equity. For every one of the large metropolitan areas of the continent, several possible sustainable and equitable water-supply options are possible. Once these factors are assured, the main criteria for choosing among the various alternatives can be the actual costs of the proposed systems.

Urban water systems should not affect the viability of the water resources themselves, as has been the case where overuse has resulted in a drop in water level, salinization, or contamination. Second, sustain ability includes the protection of other natural resources in the region, Le., fluvial or lacustrine ecosystems.

In addition to ecological sustainability, water systems must be socially sustainable. The establishment of any water system has socioeconomic implications, not only from the perspective of satisfying the needs of the whole population in an equitable way, but also in other ways. Water services create employment, they can promote some types of industries, and they can even be an effective element to support urban planning, e.g., the availability of water will stimulate the development of some neighbourhoods at the expense of others.

Unsustainable models in the LAC region

The solutions discussed above represent only one aspect of the problem, however, and not even the most important one. The main reason for the lack of sustainability of the water systems has less to do with the water policies or strategies themselves, than with the development models that have flourished in the LAC region. When their size and rate of growth are considered, it is clear that the Latin American megacities are not sustainable.

One cannot help wondering what is going to become of Mexico City and its 20 million people. Water is becoming insufficient; huge sums of money and energy are being spent to produce larger and larger volumes of water, pumping up millions of cubic metres every day, but the city and surrounding urban centres are still growing. The development model for the country must be reviewed, the growth must be curtailed, and the country s economy and administration must be decentralized. If these steps are taken in an intelligent manner, there is a real possibility that the water problem will disappear on its own or at least be significantly reduced.

The development model for Brazil is also clearly unsustainable. Hydrologically, São Paulo is in the wrong location and, with further growth of the city, the suitability of the site will not improve. A new model promoting the relocation of commercial and industrial activities, emphasizing local control and decentralization, may be the only real long-term solution to many of the city s problems, including its water supply. The same argument could be applied to almost any other large Latin American city. Bogotá, Buenos Aires, Caracas, Lima, Montevideo, San José, and Santiago have similar problems at different degrees of magnitude (Olivera 1991; Pírez 1991; Santana 1991).

Conclusions

The water supply and environmental problems of large cities result from a complex array of circumstances that include not only the availability of water resources and the characteristics and vulnerability of the environment, but also demographic, legal, administrative, political, and behaviour issues. Although the problems may seem to be solved when water is made available, this is often not the case.

In terms of providing a sustainable water supply to a city, the first element to consider is the availability of safe surface water, preferably at the same altitude or higher than the city. If a source is below the elevation of the city (e.g., Mexico City), costs may be appreciably increased. Bringing water from a higher level is less costly (e.g., Lima), but distance is also a factor in estimating cost. The cost of bringing water from a remote site at a lower altitude may be prohibitive.

When a large, regularly flowing river is close by, a water system requires only intake, adequate treatment, storage, and distribution structures. However, if flow in adjacent streams or rivers is irregular, upstream dams or reservoirs may be needed to stabilize the flow and store water for dry periods. These structures increase the cost of water.

Water quality also varies. It may contain large concentrations of suspended sediments (clays, silts, and sand), organic matter or organisms, or various contaminants. The cost of treating such water to make it potable may be high.

Rate of growth of the city must also be considered. A city may outgrow its original water sources. Larger reservoirs, located further away, and longer, more complex conduction systems may be necessary, multiplying costs. As illustrated earlier, increasing populations are also usually associated with increasing pollution of water sources and the need for more intensive treatment.

Demand constitutes one of the key variables in any water supply scheme. Reducing demand can provide a short- or medium-term solution to water scarcity and help define long-term strategies for the cities of the LAC region. Demand can be regulated through adequate pricing policies and the use of water-saving devices, for example. If wastage can be significantly reduced, the need for new water resources (and consequently for new investment) can be substantially lowered.

Cost comparison of surface and groundwater resources

Surface water and groundwater alternatives require different approaches, from both the economic and systematic points of view. Comparison of the costs of these options may shed light on what strategies will be most suitable for the specific conditions in the urban region under consideration.

In general, water supply costs are of two types: initial investment or capital costs and operating or maintenance costs. In addition, water companies have other costs that do not relate directly to construction and operation: administrative costs of various types, including salaries and benefits, interest on loans, rental costs of land and buildings not directly related to water supply and sanitation, taxes, and even transfers of funds to other governmental institutions.

Operating and maintenance expenditures are ongoing and, although they are relatively low in the short term, they can amount to large sums of money when considered on a long-term basis. Operational costs are normally built into the public or water company s budget and are frequently recovered through water fees or taxes. They are calculated in local currencies and, therefore, are affordable in most LAC countries.

On the other hand, capital investments may be considerable, often measured in tens or hundreds of millions of dollars. In exploiting surface water, investment costs are usually high, e.g., construction of dams, expropriation of land for reservoirs, intake systems, long conduction mains, treatment plants, and storage tanks. A substantial portion of infrastructural investments may be required in hard currencies, which are difficult to obtain in the LAC region. New capital investments for developing surface water sources in the LAC can only be made if external credit or grants are obtained. Underground water provides a possible alternative. In most cases, tapping groundwater requires much smaller initial investment and can be planned with a modular approach.

When an aquifer is close to a city, water conduction can be inexpensive and the cost of water supply affordable. To assess the feasibility of a groundwater-supply project, several other initial costs, such as exploration studies, drilling, well construction, pumps, and water treatment, must be evaluated. However, as a rule, these costs are much smaller than required for large surface-water supply projects and, as a result, groundwater projects may be carried out without borrowing or subsidies. For example, water companies or geological institutes often have unemployed drilling rigs and crews that can be used at a relatively low cost, payable in local currency. Groundwater also usually requires less treatment than surface water, further reducing costs.

Assessment of water resources and development options

Assessing both groundwater and surface-water resources requires a thorough understanding of the natural and artificial systems in the urban region and surrounding areas. This implies a network of observation stations and wells, accurate and updated thematic maps, accurate calculation of water balance, and a capable, well-trained, experienced research team to carry out the collection, processing, and interpretation of the information.

A well-documented assessment of the long-term feasibility of water projects must also be carried out. This should include not only technical and economic elements, but also environmental, social, political, and administrative aspects. Some of the questions that must be answered are:

- Is the project technically feasible? How much will it cost?
- Who is going to pay for it? How will it be financed?
- What will be the overall effect on the environment, short- and long-term?
- Who is going to build, operate, maintain, and administer the proposed systems?
- What effect will the project have on communities living next to reservoirs, structures, and plants?
- Who is most likely to benefit from the project?
- Will new jobs be created or will existing jobs disappear?
- Who will receive the water available as a result of the project?
- Will all or most of the water be used in affluent neighbourhoods or will it also
- serve the poor sections of the city? and
- How will the project affect (or be affected by) the legal, administrative, and political systems?

Cities in the LAC region rely on various combinations of groundwater and surface sources for their municipal supply. Many that rely mainly on surface water, supply groundwater to the industries and communities located far from the source. Others depend almost exclusively on groundwater, but could change to surface water. Still others do not have many options. Solutions to water-supply issues are as varied as the cities themselves and depend on specific local conditions. Only appropriate research will allow an informed decision.

Research efforts must be carried out with the participation of the beneficiaries, because they have first-hand information about field conditions. Their input is necessary not only in defining the research themes, but also at the planning and implementation stages. Community participation has also been shown to increase the chances of success of water projects.

The current situation and future potential

The limitations on water resources, financial constraints, and unabated demographic growth in the LAC region are not going to disappear. In many cases, improvements to water-delivery systems will not be carried out for some time and some sectors of the urban populations will suffer shortages. Over 15% of people in these countries (30 million) do not have access to water in their homes and another 40 50 million are using water of doubtful quality. Some 60% suffer frequent disruption of water service, sometimes depending on systems that only operate a few hours each day.

At the same time, structural adjustments are pushing water prices up, making the service less affordable for poor communities. In affluent areas, the consumption of drinkable water remains disproportionately high because of inappropriate pricing policies and wasteful practices. However, when a choice must be made between various neighbourhoods needing new connections, the more politically influential or affluent people are likely to receive the service or the improvement.

Water supply is a social issue. Throughout its history, the LAC region has been characterized by social inequalities and the current scarcity of water mainly affects those with lesser means to pay for alternative solutions. People living a precarious existence in environmentally hazardous neighbourhoods, with low incomes and large families, are the ones who are most affected by poor decisions about the choice of water supply and sanitation alternatives. Solving the problem of water supply by research, therefore, not only resolves a critical general issue involving the health and well-being of the population at large, but also constitutes a giant step toward providing the most important material need of the poor in cities of the LAC region.

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Glossary

agglomerate	sediment (unconsolidated) made up of rock fragments 20 30 mm in diameter or larger
albedo	proportion of the solar radiation reflected by a nonluminous body
albite	see feldspar
alluvial	processes, materials, or landscapes related to streams or rivers
altiplano (Spanish)	plateau, high-altitude flat or undulating surface
andesite	volcanic rock consisting mainly of oligoclase feldspar (medium term of the isomorphous series of plagioclase feldspars) and frequently including pyroxenes and magnetite (normally without or with very little quartz)
anfractuosity	irregularity on a rock surface, intricate path
anorthite	see feldspar
aquiclude	very low permeability rock stratum obstructing the passage of groundwater
aquitard	low permeability rock layer that slows down the passage of groundwater
argillization	processes of transformation of nonclayey minerals and rocks into clayey ones (i.e., feldspar into smectitic clays)
artesian	pressure condition of an aquifer allowing free flow of water to at least ground level
basalt	volcanic rock consisting mainly of labrador feldspar (plagioclase feldspar rich in calcium) and frequently including pyroxenes and magnetite (normally without or with very little quartz)
bomb	rounded block of lava that is ejected from a volcanic crater during eruptions
breccia	volcanic?r sedimentary rock consisting of large angular pieces in a fine-grained matrix

conglomerate	sedimentary rock (consolidated) mainly consisting of rock fragments larger than 20–30 mm in diameter (gravels, pebbles, and boulders)
cratonic	tectonically stable
dacite	volcanic rock composed of oligoclase feldspar and other associated minerals: the volcanic equivalent of granodiorites
diagenetic	changes in mineral composition and texture that take place in a sediment, mainly as a result of conditions created by burying under new layers of sediments or recent lava flows (such as increased pressure and temperature)
dolomite	a calcium and magnesium carbonate mineral; also the rock chiefly composed of this mineral
epeirogenic phenomena	large scale changes in the level of the earth crust due to which the surfaces of the continents are elevated or depressed with relatively little fracturing or folding
feldspar	group of silicate or aluminum minerals, with a three-dimensional crystalline structure (tectosilicates). The main subgroups are the plagioclases (calcium-rich term is anorthite, sodium-rich term is albite, intermediate terms are labrador and oligoclase) and the orthoclases (potassium feldspars)
ferrallitic	soil rich in iron and aluminum due to washing of other cations as a result of the long action of a humid climate. Ferrallitic soils are composed of aluminum and iron minerals such as gibbsite (aluminum hydroxide) and goethite (iron hydroxide). Kaolinite can also be present.
fersiallitic	soil rich in iron and aluminum but still conserving a substantial amount of silica. Fersiallitic soils consist mainly of smectitic clays (such as montmorillonite)
flysch	fine detritic (silty, clayey, or occasionally sandy) sedimentary rock formed during the medium stages of orogenesis in shallow coastal waters or on continental plains
gelifraction	processes of fracturing of rocks fragments by the action of ice
gibbsite	see ferrallitic
gneisses	metamorphic rocks consisting of granite-type minerals (essentially feldspar, frequently associated are also quartz, micas, and amphibols, among others). Gneisses are formed in medium or deep metamorphic geological environments as a result of the metamorphism of clayey sedimentary or granitic rocks
goethite	see ferrallitic
graben	depressed section of the earth's crust bounded by faults and generally much longer than wide
horst	elevated section of the earth's crust bounded by faults
hydraulic conductivity (K)	capacity of a geological material for allowing the flow of water
hydrological basin	area drained by a river and its tributaries

hyperpluvial zones	zones of very intense rainfall (i.e., higher than 3 000 mm/year)
kaolinite	nonexpansive clay; see also ferrallitic
karstic	geological and geomorphological processes or features related to dissolution of carbonate minerals by water in limestone environments (main processes include enlargement of fractures and cave formation)
labrador feldspar	see basalt
lacustrine	processes or features occurring or developed in lakes or surrounding areas under the influence of these water bodies .
lahar	mud flow of ash and water on the sides of a volcano
lapilli	small rock fragment ejected by a volcano
lentic	relating to still water
llanos (Spanish)	plains; normally used for the Colombian-Venezuelan savanna plains
lava	see magma
magma	underground molten material, it is mainly found in volcanic regions (when it is spilled or ejected to the surface without solidification it is called lava)
massif	principal mountain mass
mica schists	see schists
migmatites	metamorphic rocks formed by widespread injection of quartz and feldspar in the form of small dykes and formed as a result of partial and differential melting and local remobilization of molten materials
molasse	coarse-grained sedimentary rocks (chiefly conglomerates) formed in a subaerian, continental environment during the late stages of the orogenesis
montmorillonite	see fersiallitic
oligoclase	see feldspar
orogenesis	mountain-forming processes
orography	related to .relief
orthoclases	see feldspar
palustrian formations	wetlands formations
pampas (Spanish)	South American grasslands of Argentina, Uruguay, and southern Brazil
phreatic eruption	stearn or hot water eruption, or a combination
phyllites	low-grade metamorphic rocks made up of mica-type minerals (such as sericite, illite, muscovite, chlorite, etc.) see also schists
plagioclases	see feldspar

pyroclastic	generic term used to designate volcanic rocks that are formed as a result of the accumulation and consolidation of volcanic fragments, ashes, or dust, due to gravity, gas ejection, wind, water transport, etc.
rhyolite	silica-rich volcanic rock (normally consisting of orthoclase feldspar and quartz)
sabana (Spanish)	savanna
saline intrusion	encroachment of salty water into a fresh-water aquifer
savanna	tropical grasslands
schists	low- or medium-grade metamorphic rocks composed of mica-type minerals (mainly muscovite and biotite but also sericite, illite, and chlorite). The term schist includes phyllites, mica schists, and several other metamorphic rock types
scoria	extremely vesicular lava formed as a result of eruption in the presence of gases
smectitic clays	expansive clays; see also fersiallitic
steppe	semi-arid ecosystems characterized by low density of vegetation, normally grasses and shrub communities
syenite	see trachyte
tuff	volcanic rock formed as a result of the consolidation of volcanic ash and dust
tectonic	internal processes moulding the various features of the earth crust
trachyte	volcanic rock made up of potassium feldspars; other minerals such as plagioclase feldspars and quartz can also be present (the igneous homologue is called syenite)
thalweg	line followed by a stream in a valley
tillite	glacial conglomerate
watershed	boundary zone between river systems, headwaters
well screen	perforated tube used to allow water to flow into a well