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Sustainability of least cost policies for meeting Mexico City's future water demand

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Abstract. Meeting future water demand without degrading ecosystems is one important indicator of sustainable development. Using simulations, we showed that compared to existing policy, more sustainable water supply options are similar or cheaper in cost. We probabilistically forecasted the Mexico City metropolitan zone population for the year 2015 to be 23.5 million and total required water supply to be 106 m^3 s^{-1}. We optimized existing and potential supply sources from aquifers, surface water, treatment/reuse, and efficiency/demand management by cost to meet future supply needs; the applied source supply limits determined the degree of sustainability. In two scenarios to supply 106 m^3 s^{-1}, the business-as-usual scenario (zero sustainability) had an average relative unit cost of 1.133; while for the most sustainable scenario (it includes reducing potential supply basins' exploitation limits by 50%), the value was 1.121. One extreme scenario to supply the forecast's 95% confidence value (124 m^3 s^{-1}) showed little unit cost change (1.106). The simulation shows sustainable policies can be cost-effective.

1. Introduction

A United Nations special session recently recommended to "strengthen the capability of governments and international institutions to collect and manage information, including scientific, social and environmental data, in order to facilitate the integrated assessment and management of water resources" (United Nations, Earth Summit +5 Programme of Action adopted by the Assembly, Special Session of the General Assembly to Review and Appraise the Implementation of Agenda 21, United Nations Department of Economic and Social Affairs, New York, 1997, http://www.un.org/esa/earthsummit/). A shortfall of the Ecological Society of America's *Lubchenco et al.* [1991] report is that underlying problems of population growth and excessive resource exploitation, though recognized, were left unaddressed by research initiatives.

One definition of sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [*World Commission on Environment and Development*, 1987]. We defined sustainable water supply as a relative state, not an absolute one, improving according to the degree to which the following sources are used: nondepleting groundwater withdrawal; nonexcessive surface water withdrawal, savings from demand management and efficiency measures; local rainfall capture; and reuse of treated wastewater.

Environmental economic models place two limitations on the goal of sustainable development, "sustaining the economy as a source of improved standard of living" [*Pearce and Turner*, 1990, p. 44]. The two rules are as follows: (1) Always use renewable resources in such a way that the harvest rate is not greater than the natural regeneration rate. (2) Always keep waste flows to the environment at or below the "assimilative capacity" of the environment. Rule 2 is, and will continue to be, highly contentious because it is difficult to determine the response of complex ecological systems to perturbation and achieve scientific consensus to guide policy [*Hilborn and Ludwig*, 1993]. However, rule 1 is a common sense rule: it makes sense ecologically and economically; it is a primary operational criterion for pursuing sustainable development and for defining what it implies in policy terms. Without sufficient water supply and sanitation the development of any settlement will be constrained and the discussion of other development issues becomes secondary (T. J. Downs, Report on final discussion session: The human face of the urban environment, internal document, World Bank, Washington, D. C., 1994).

We chose Mexico City as a case study since it is among the three largest cities in the world [*World Resources Institute*, 1994]; the others, Tokyo and Sao Paulo, also exist under extreme resource pressures. Water supply has been described as the "most serious problem" facing Mexico City [*Mazari Menzer*, 1996, pp. 58–59]. The problem is that the city is growing faster than present water supply capacity, and the supply is unsustainable. We addressed the following questions: How much water will the city need in 2015, how can it be supplied in a way that is comparable to or cheaper than the cost of existing policy, and how can the water supply be more sustainable? Our objective was to investigate the following hypothesis: Least cost water supply policies are also more sustainable.

We forecasted water demand for the year 2015 for domestic, agricultural, industrial, commercial, and energy-generation sectors using a probabilistic model. We characterized current local groundwater supply sources with estimates of recharge and withdrawal, while existing surface water sources outside the city's hydrological basin were characterized using historical runoff data from monitoring stations. We used these data to

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Table 1. Existing Water Supply: Sources and Withdrawals

	Reference and Year				
	A	B	C	D	E
Water Source	1981	1987	1990	1995	1996
Surface waters in Mexico City Basin	4.7	1.0	4.0	4.7	1.5
Groundwater in Mexico City Basin	51.9	44.0	49.5	43.0	42.0
Water exchanges/reuse	···	···	2.0	···	···
Total local supply	56.6	45.0	55.5	47.7	43.5
Groundwater in Lerma Basin	···	···	10.0	5.3	6.0
Cutzamala System (first and second stages)	···	···	10.0	10.6	13.5
Total external supply	11.5	19.0	20.0	15.9	19.5
Total supply	68.1	64.0	75.5*	63.6	63.0

References are as follows: *Secretaría de Agricultura y Recursos Hidráulicos* (*SARH*) [1981]; B, *SARH* [1987]; C, *Ramírez-Sama* [1990]; D, *National Research Council et al.* [1995]; and E, *Ezcurra and Mazari* [1996]. Numbers are average withdrawal rates given in m^3 s^{-1}. Ellipsis indicates no data.

*Broken into 67.0 urban use and 8.5 agricultural use.

estimate less depleting withdrawal rates. We optimized alternative water resource management scenarios to minimize cost, applying supply constraints and unit costs for all available sources, including treatment and reuse of wastewaters.

1.1. Water in the Mexico City Basin

The history of human settlement in the Basin of Mexico is tied to water. Mexico City lies in a basin located within the Tertiary rocks of the central volcanic axis. The basin is delineated by volcanic mountains which surround a central lacustrine plain of average elevation 2240 m (7350 feet) above sea level. Over the centuries, Aztec tribes settled the southern part of the basin around lake shores and islands. This settlement expanded with the establishment of an ingenious agriculture using raised parcels of land on the lake edges. Canals and flood gates completed a highly efficient water management system based on this chinampa irrigation method, providing the food surplus that drove the rise of the Aztec culture and the founding of its capital city, Tenochtitlan, on a shallow lake island in 1325 A.D. In 1519, 600 Spaniards led by Hernán Cortez and helped by neighboring tribes conquered the city and founded modern Mexico City. It is only during this century, though, that population has grown rapidly from an estimated 0.70 million in 1910, which demanded water at an equivalent average rate of 1.7 m^3 s^{-1}, to 5.2 million (water demand 20 m^3 s^{-1}) in 1960 and 17 million (water demand 63 m^3 s^{-1}) in 1990 [*Ezcurra and Mazari*, 1996].

Tenochtitlan used groundwater from artesian wells to satisfy demand. Mexico City began withdrawing groundwater from well fields in the mid nineteenth century, and this sufficed until the mid-1960s when demand exceeded 30 m^3 s^{-1}. To meet excess demand, water has been withdrawn from two external basins, starting with groundwater from the Alto Lerma Basin well field and aqueduct system built in 1952 and followed in 1982 by the more ambitious surface water transport scheme of the Cutzamala System. Official estimates of supply rates are fuzzy; historical average supply estimates from Lerma vary from 5 to 10 m^3 s^{-1}, while currently 4–5 m^3 s^{-1} is likely, while Cutzamala in its first two stages supplies about 11.0 m^3 s^{-1}, with an additional 13 m^3 s^{-1} planned. Table 1 shows several estimates of current withdrawal rates for local and external sources.

1.2. Water Politics in Mexico

Sustainable water resources development and use are key goals of both the National Economic Development Plan 1995–2000 [*Secretaría de Hacienda y Crédito Público*, 1995] and the Hydraulic Development Plan 1995–2000 [*Secretaría de Medio Ambiente, Recursos Naturales y Pesca*, 1996]. Master plans for water management have been proposed for the Mexico City metropolitan zone (MCMZ) during different administrations under the jurisdiction of multiple agencies, causing institutional conflicts. Only recently, in 1996, a Basin Council (Consejo de Cuenca) was created for the Valley of Mexico [*Jaime*, 1997] to do the following: (1) promote an integral administration of water in the basin; (2) develop a common responsibility between the three government levels (national, regional, and local) and the users for administration, exploitation, use, and conservation of water quantity and quality; and (3) establish an effective mechanism of coordination.

Any water policy change must be transmitted through institutions: the National Water Commission (CNA) is leading an initiative to improve water cycle sustainability which develops and integrates four essential components to achieve the Basin Council's goals in the MCMZ and nationwide: (1) education and training (community, professional, and institutional); (2) monitoring and information; (3) regulations, compliance, and resource management; and (4) water sector products and services [*Comisión Nacional de Agua et al.*, 1999]. Table 2 summarizes the roles of the many organizations involved in water resources management in Mexico.

In theory, each organization has its distinct role, but in practice, there is duplication, overlap, and sometimes conflict. The various governmental institutions responsible for water management in the MCMZ have generated relevant information about different aspects of water resources, and it is beginning to be made more public.

2. Methods

2.1. Study Region

The study region consists of the Federal District (Distrito Federal (DF)) and its 16 delegations together with 27 municipalities of the surrounding State of Mexico Conurbation (Estado de México-Conurbación (EMC)) described as such in an official population and water report [*Consejo Nacional de Población and Comisión Nacional de Agua*, 1993]. The DF has an area of 1499 km^2, and the EMC has an area of 2982 km^2. Together these 43 political areas constitute the Mexico City Metropolitan Zone (MCMZ) (Figure 1) with an area of 4481

Table 2. Water Responsibilities in Mexico

Organization	Level	Responsibilities
National Water Commission (CNA) (part of Ministry of Environment, Natural Resources, and Fisheries (Secretaría de Medio Ambiente, Recursos Naturales y Pesca (SeMARNaP))	federal	all nationwide water management tasks: supply, drainage, flood control, wastewater handling, hydrologic monitoring, and irrigation, and legislation compliance with General Ecological Balance and Environmental Protection Law, National Public Health Law (Water), National Water Law, and Federal Water Rights Law
Health Ministry (Secretaría de Salud (SS))	federal	drinking water quality certification
Treasury Ministry	federal	management of water rights revenue and budgeting
Federal District Government (Gobierno del Distrito Federal (GDF)) through its General Directorate for Waterworks, Construction and Operation (Dirección General de Construcción y Operación Hidráulica (DGCOH))	Distrito Federal (DF)	receipt and distribution of water to DF and purification and treatment plants, supply of groundwater, wastewater stormwater drainage system, operation, maintenance, administration, and regulation and legislation compliance as CNA above plus local bylaws
State of Mexico Commission for Water and Sanitation (Comisión de Agua del Estado de México (CAEM))	state	supply and distribution of water, wastewater collection, treatment and reuse, operation, maintenance, administration, and regulation and legislation compliance as CNA above plus state ecology and water laws
Federal District Government (GDF) via Federal District Water Commission (Comisión de Aguas del Distrito Federal (CADF))	DF	installation and maintenance of meters, maintaining users' database, establishing and maintaining plans for water distribution and drainage networks, and issuing water bills and also supervision of the four private concession companies which signed a general contract with the GDF in 1993
DF Concession Companies: Servicios de Agua Potable (Mexico-France), Industrias del Agua (Mexico-United Kingdom), Tecnología y Servicios del Agua (Mexico-France), and Agua de México (Mexico-United Kingdom)	DF	identification and registration of customers, installation of meters, production of network plans, reading and maintaining installed meters, designing and implementing customer billing systems, calculating, printing, and distributing water bills, set up of new connections, operation, maintenance, and rehabilitation of water distribution and drainage networks
Municipal governments (not DF)	municipal	operation and maintenance of the secondary water distribution and drainage networks and enforcement of local bylaws
GDF (CADF or DGCOH) since 1997	DF delegation	operation and maintenance of the secondary water distribution and drainage networks

km^2. The total area of the hydrologic basin is 9600 km^2, but population densities outside the MCMZ are at least 1 order of magnitude less than the city [*Consejo Nacional de Población* (*CONAPO*), 1994] with relatively low water demands that we accommodated within the error bounds of the analysis. It is important to consider the MCMZ as a whole; DF estimates and data alone do not provide a basis for integrated regional water resource management.

2.2. Total Water Supply

Equation (1) is a mass balance equation for water supply, showing illustrative percentages for the supply of domestic water.

$$\text{input water supply } (100\%) = \text{consumption } (18\%) + \text{wastewater return } (42\%) + \text{losses } (40\%) = \text{demand} + \text{losses}. \quad (1)$$

For example, if the domestic demand by an individual were 200 L d^{-1}, this would be made up of 60 L of consumption and 140 L of wastewater return. To supply this amount in a system with 40% distribution losses, the input flow would need to be 333 L d^{-1}. Distribution losses in Mexico City are generally thought to be between 25% and 45% by water professionals. An unpublished study (Departamento del Distrito Federal, Estadística de los cobros desde 1996, Mexico City, internal report, 1997) of water losses for each delegation of the DF shows that they vary greatly (Figure 2). We assumed a loss value of 35% ± 5% for the MCMZ supply forecast.

Equation (2) shows the six components considered in the model, assuming water is used only once since no reuse is active. We forecasted values of each demand for each of the 43 political areas and for the DF, EMC, and MCMZ aggregate regions. We obtained total demands by summing the five demands for the DF, EMC, and MCMZ and estimated losses from these totals to give total required supply. This requirements approach was the most practical at this exploratory stage given the limited water data for the city and an order of magnitude variability in domestic demand per capita (see section 2.3). Econometric regression models of demand versus water price, demographic variables, price of output products, etc. cannot be estimated because data are insufficient.

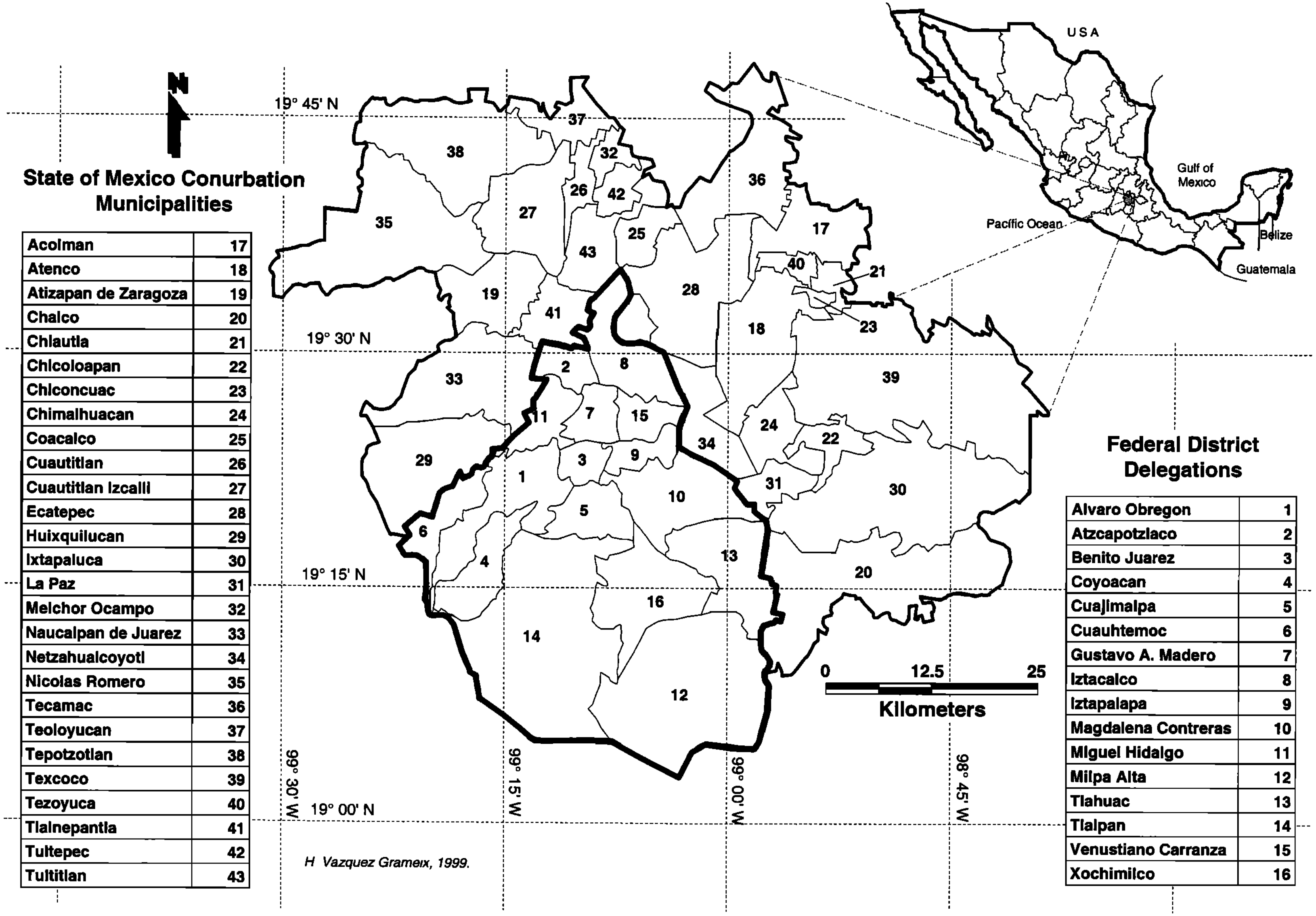
$$S = D_{\mathrm{DO}} + D_{\mathrm{AG}} + D_{\mathrm{IN}} + D_{\mathrm{C/S}} + D_{\mathrm{EN}} + L, \quad (2)$$

where

S	total required water supply, m^3 s^{-1};
D_{DO}	domestic demand, m^3 s^{-1};
D_{AG}	agricultural demand, m^3 s^{-1};
D_{IN}	industrial demand, m^3 s^{-1};
$D_{\mathrm{C/S}}$	commerce and services demand, m^3 s^{-1};
D_{EN}	demand for energy generation, m^3 s^{-1};
L	distribution losses, m^3 s^{-1}.

2.3. Population Change and Domestic Demand

We modeled domestic water demand for a population as the total number of people withdrawing water multiplied by the demand rate per person, as given in (3). Population and demand projection requires a probabilistic approach. We used the method of Monte Carlo simulation to represent the variabilities and uncertainties in our demand model. Using histor-



State of Mexico Conurbation Municipalities

Acolman	17
Atenco	18
Atizapan de Zaragoza	19
Chalco	20
Chiautla	21
Chicoloapan	22
Chiconcuac	23
Chimalhuacan	24
Coacalco	25
Cuautitlan	26
Cuautitlan Izcalli	27
Ecatepec	28
Huixquilucan	29
Ixtapaluca	30
La Paz	31
Melchor Ocampo	32
Naucalpan de Juarez	33
Netzahualcoyotl	34
Nicolas Romero	35
Tecamac	36
Teoloyucan	37
Tepotzotlan	38
Texcoco	39
Tezoyuca	40
Tlalnepantla	41
Tultepec	42
Tultitlan	43

Federal District Delegations

Alvaro Obregon	1
Atzcapotzlaco	2
Benito Juarez	3
Coyoacan	4
Cuajimalpa	5
Cuauhtemoc	6
Gustavo A. Madero	7
Iztacalco	8
Iztapalapa	9
Magdalena Contreras	10
Miguel Hidalgo	11
Milpa Alta	12
Tlahuac	13
Tlalpan	14
Venustiano Carranza	15
Xochimilco	16

Figure 1. Mexico City metropolitan zone (MCMZ) consisting of the Federal District (DF) and the State of Mexico conurbation (EMC).

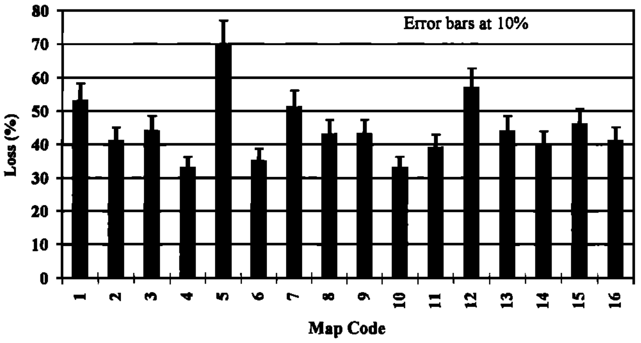


Figure 2. Distribution losses in the DF delegations (see Figure 1 for map codes).

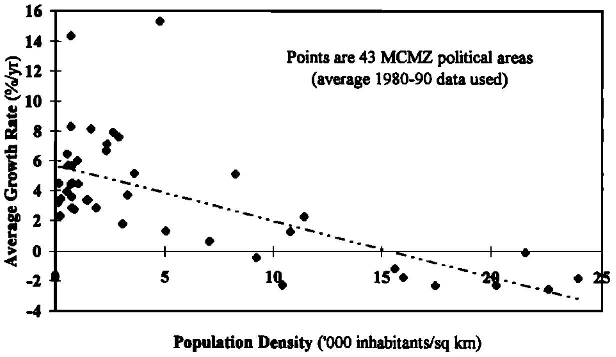


Figure 4. MCMZ population density-dependence effect.

ical population data [*CONAPO*, 1994] for the decades since 1950 for each of the 43 MCMZ political areas, we described the future growth of each one using three normal probability distribution functions (pdfs) of average annual growth rate (r_N, percent/year) for the decades 1990–2000, 2000–2010, and 2010–2020. We chose the pdf means and standard deviations for each political area by carefully analyzing its historical growth trends. A recent report [*Ezcurra and Mazari*, 1996] stated that official population data from the latest official census (1990 value at 15 million) was underestimated by 12%. We assumed a 6% underestimate for 1990 and increased baseline values for the forecast.

$$D_t = N_0(1 + r_N)^t w \tag{3}$$

where

D_t water demand by population at time t, volume per unit time;
N_0 initial population at time zero, number of people;
r_N population growth rate per unit time, decimal fraction;
t number of time units, time;
w per capita water demand, volume per person per unit time.

Variables r_N and w were treated probabilistically in the model using a normal distribution described by mean and standard deviation.

According to *Shryock and Siegel* [1976] a logistic (S shaped) curve best predicts long-term population growth; exponential growth is but one stage of this model before density dependence is evident. Validating this model, MCMZ historical growth in the number of inhabitants (N) over time (t) follows a logistic curve which showed a slow start (dN/dt low and positive), experiencing an exponential growth period (dN/dt high and positive), decreasing in slope toward zero and peak N, sometimes dropping off with depopulation (negative dN/dt). The model curve used for each political area and the MCMZ as a whole is shown in Figure 3.

Density dependence is evident: we plotted growth rate versus density for the MCMZ (Figure 4) to guide our assumption of means and standard deviations to describe future growth rate uncertainty for each political area. The assumptions were made using *CONAPO* [1994] data, combining eyeballing, logistic curve fitting, and the condition to keep future densities to realistic levels. For areas that experienced depopulation in the decade 1980–1990, which were all in the DF, we assumed that the future growth trend would follow a decelerating negative gradient, leveling off toward zero. Mean growth rates and standard deviations were increased as the timeline progressed: For assumed values of mean growth rate below about 2% yr^{-1}, standard deviation values were assumed to be 0.33% yr^{-1} for 1990–2000, 0.66% yr^{-1} for 2000–2010, and 1% yr^{-1} for 2010–2020. We gave larger assumed growth rates slightly larger standard deviations, but they did not exceed about 1.5% yr^{-1} to accommodate uncertainties without rendering the forecast too uncertain to be useful.

Unit domestic demand is measured in liters per person per

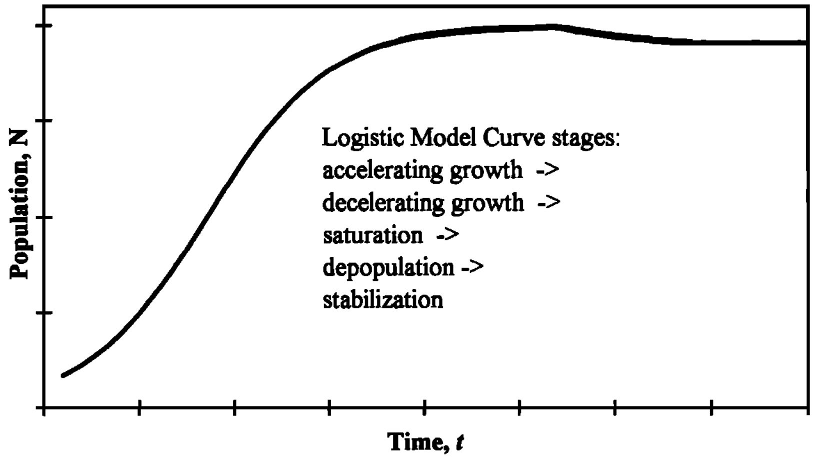


Figure 3. Growth model curve.

Table 3a. Socioeconomic Groups I–V

DT	1	2	3	4	5
A	III	III	IV	V	V
B	II	III	III	IV	IV
C	II	III	III	III	IV
D	I	II	II	II	III
E	I	I	II		

Abbreviations are as follows: DT, dwelling type; A, single-family home; B, apartment in a complex; C, apartment in a building; D, poor neighborhood multifamily home; and E, very poor neighborhood multifamily home. Number scheme is as follows: 1, very low relative family income (<1.0); 2, low relative family income (1.0–2.9); 3, middle relative family income (3.0–6.9); 4, high relative family income (7.0–10.9); and 5, very high relative family income (>11.0). Numbers in parentheses are normalized income sizes. Table 3a is after *DGOCH* [1982].

day. In Mexico City this parameter (w) has been found empirically to be a marked function of socioeconomic criteria; we used a previous study [*Departamento General de Construcción y Obras Hidráulicas* (*DGCOH*), 1982] for the Miguel Hidalgo DF delegation that related family income and dwelling type to water demand for five socioeconomic groups. Using this baseline study and extrapolating to the MCMZ as a whole, we defined five socioeconomic groups for the MCMZ population using combinations of criteria for family income and dwelling type (Table 3a). Unit demand for five random individuals from each of the socioeconomic groups was described using a normal distribution; mean unit demand ranges from 40 L person^{-1} d^{-1} (L p^{-1} d^{-1}) for the lowest socioeconomic group I to 450 L p^{-1} d^{-1} for the highest group V (full range 16–654 L p^{-1} d^{-1}) (Table 3b). For simplicity, each of the 43 political areas was classified by its predominant socioeconomic group, and the group's statistics were used in the Monte Carlo Simulation.

Monte Carlo simulation of population and domestic water demand was carried out using 1000 iterations, Latin hypercube sampling, and sensitivity analysis (estimation of input variables' contribution to uncertainty of outputs) for each one of the 43 MCMZ political areas and for the aggregate DF, EMC, and MCMZ regions. Latin hypercube sampling is a more accurate method that samples values from the probability function at a rate proportional to probability, taking, for example, proportionally more values close to the mean of a normal distribution than at the tails; that is, it is nonrandom. Crystal Ball® version 3.0 [*Decisioneering*, 1993] running in Excel 5.0® on a Pentium® 75 MHz computer was used to run the simulations and compute sensitivities.

2.4. Agricultural Demand

Agricultural water demand for each political area was modeled as the total surface area under irrigation multiplied by the demand rate per unit area. Baseline data on irrigated surface area for the 43 MCMZ areas were taken from the most recent official data [*Instituto Nacional de Estadística, Geografía e Informática* (*INEGI*), 1994, 1996]. Lacking data on crops and crop-dependent demand, we assumed a national average annual irrigation demand per hectare of 11,120 m^3 (±20%) [*Domínguez-Mora*, 1996]. Since historical data were sketchy, we used the simplifying assumption that irrigated land area in the Federal District would not change significantly because of the DF saturated growth state, while in the EMC the change in area would be half the rate of population growth modeled for each of the 27 areas. This is a reasonable assumption: During city growth, competition exists between land area for agriculture and area for settlement. We estimated the error in unit demand to be ±20% and the error in area values to be ±10%.

2.5. Industrial Demand

We modeled the industrial water demand for each political area as the total production for each industrial subsector multiplied by the demand rate per unit of production for that subsector. We used nine industrial subsectors to model the demand, applying different unit demands for each one (Table 4). We estimated the error in unit demand to be ±20% and the error in production values to be ±10%. We took baseline 1993 production data from industrial censuses for the DF and EMC [*INEGI*, 1995a, b] and applied the same growth assumptions that were used in the agricultural model.

2.6. Commercial/Services Demand and Energy Generation Demand

Commercial and service sector water demand for each political area was modeled for eight subsectors as the total number of people employed in the subsector (and for subsectors 92 and 93 an adjustment for operating activities) multiplied by the demand rate per employee. Table 4 shows the activities of the subsectors and their unit demand rates. We took baseline 1993 employment data from economic censuses for the DF and EMC [*INEGI*, 1995a, b] and applied the same simplifying growth assumptions that were used in the agricultural model. The effect of future labor and wage and water price changes on water demand were neglected since historical econometric data are insufficient to estimate it. (Note that previous studies have included "commercial" demand in the "industrial" category). Energy generation was the simplest to model. Only two power stations exist in the MCMZ, one in the DF withdrawing 0.007 m^3 s^{-1} and one in the EMC withdrawing 0.022 m^3 s^{-1}. Being so small, we assumed these values to be constant over the forecast window.

2.7. Assumptions, Sensitivity, and Uncertainty Analyses

Following the recommendations of *Morgan and Henrion* [1992] for policy analysis under uncertainty, we identified significant assumptions (Table 5), quantified uncertainties (Table 6), and performed systematic sensitivity analysis. A major assumption of the model was that people in each socioeconomic group would stay in that group (inequalities are marked and constant) and their unit demand would not change over time. Water pricing is not yet culturally accepted (adjustment to the user's ability to pay will help) and therefore is ineffective at demand management. The model assumption implies a subtle but very important distinction between growth and development; development requires an upward shift from poorer to

Table 3b. Unit Water Demand

SG	Mean	SD	Range
I	40	8	16–64
II	100	20	40–160
III	210	42	84–336
IV	330	66	132–528
V	450	68	246–654

Demand is given as liters per person per day. SG is socioeconomic group from Table 3a; SD is standard deviation. Table 3b is after *DGOCH* [1982].

Table 4. Industrial and Commercial/Service Subsectors and Unit Demands

Subsector	Activities	UD	UDp	UDm
	Industrial Sector			
31	food, drink, and tobacco	18.90		
32	textiles and leather	0.84		
33	timber and wood furniture making	4.37		
34	paper and printing	12.46		
35	chemicals, petrochemicals, and plastics	16.76		
36	nonmetallic, nonpetroleum mineral products (e.g., glass)	8.62		
37	basic metal working	12.84		
38	metal products, equipment, and instruments	1.17		
39	other manufacturing industries	2.44		
	Commercial and Service Sector			
82	rental of immobile goods		30	
83	rental of mobile goods		100	
92	social services, education, research, and health		30	309
93	restaurants and hotels		100	525
94	arts, recreation, and sport		100	
95	professional and technical		30	
96	repair and maintenance		100	
97	agriculture, construction, transport, finance, and commerce		30	

UD is unit demand in cubic meters per year per N$1000 (N$ is Mexican new pesos) of 1993 produced value. UDp is unit demand in liters per worker per day. UDm indicates addition for maintenance. Source is R. Domínguez-Mora (Identificación de usuarios de aguas nacionales, Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico City, internal report, 1996).

richer socioeconomic groups. In this way our forecast is conservative.

In order to judge the adequacy of the forecast for the year 2015, we ranked input variables by their contribution to output uncertainty. Using the uncertainties from Table 6, the sensitivity analysis computed Spearman rank correlation coefficients between each input and output. For 2015 domestic demand, 172 input uncertainties were involved in the calculation (three growth rates and unit demand for 43 areas), and sensitivity analysis identified the main contributors to output uncertainty for the DF, EMC, and MCMZ aggregates. For the 2015 nondomestic demand DF, EMC, and MCMZ we first calculated aggregates for each consumptive variable (agricultural hectares, nine industrial subsector productivities, eight commercial/services subsector activities, and energy) then specified uncertainties for each one. We specified the uncertainties in unit nondomestic demands before running the summation for total 2015 demand using the mean and standard deviation of the domestic demand. We ran final sensitivity analysis on the summation for total demand.

2.8. Supply Characterization of Groundwater Sources

Since between 60 and 70% of water for Mexico City still comes from the ground reserve first tapped by the Aztecs, understanding local groundwater flows and qualities is vital. The current average 60% overexploitation condition (discharge:recharge equal to 1.6:1) effectively sets groundwater as a nonrenewable (or more accurately net depleting) resource with sustainability rule 1 broken (see section 1). Groundwater recharge is a complex function of the hydrologic cycle, ground surface, vegetation, and hydrogeology. Recharge estimates vary between 23 and 27 m^3 s^{-1} [*Ramírez Sama*, 1990; *Ezcurra*, 1991; *Secretaría de Agricultura y Recursos Hidráulicos* (*SARH*), 1981, 1987]. A recharge value of 24 m^3 s^{-1} (±3 m^3 s^{-1}) was assumed to set conservative near-steady-state withdrawal at 20 m^3 s^{-1} as a sustainability condition for the optimization model.

In Mexico City, studies have shown that the groundwater is at risk from contamination [*Mazari and Mackay*, 1993], and the quality of well water has been reported to be deteriorating [*Ezcurra and Mazari*, 1996]. The visible sign of the Mexico City

Table 5. Significant Model Assumptions

Assumption	Description
Policy concern	existence of unsustainable water resource policy
Evaluation criteria	magnitude of component water demands and losses; unit supply costs; scope and bounds of 43 political regions of MCMZ; 20 year forecast period; and 4 decades of historical average population growth rates
Intangibles	effects of pricing, leak repair, and demand management equivalent to "efficiency" saving of 0.5% total supply per year when applied over forecast window
Aggregation	input variables defined on spatial scale of delegations and municipalities; timescale of annual rates of change up to year 2015
Value judgements	reasonable withdrawal rates; unit supply costs (include capital and running costs over lifetime)
Objective functions	minimization of total supply cost to meet 2015 total demand plus losses
Growth model form	population growth curve of logistic type; domestic demand following population growth rate (r_N); DF agricultural, industrial, and commercial demand at zero growth; EMC growth at 1/2 r_N

Table 6. Uncertainties in Model Variables

Variable	Description	Uncertainty Value (Data Source)
S	total water supply	from sensitivity and uncertainty of inputs
r_N	population growth rate	standard deviation (empirical data)
w	unit domestic demand	standard deviation (empirical data)
D_{DO}	total domestic demand	from sensitivity and uncertainty of inputs
H	hectares under irrigation	±10% (expert opinion)
h	unit agricultural demand	±20% (expert opinion)
D_{AG}	total agricultural demand	from sensitivity and uncertainty of inputs
P_{j}	productivity industrial subsector j	±10% (expert opinion)
p_{j}	unit industrial demand subsector j	±20% (expert opinion)
D_{IN}	total industrial demand	from sensitivity and uncertainty of inputs
Q_{k}	activity of commercial subsector k	±10% (expert opinion)
q_{k}	unit commercial demand subsector k	±20% (expert opinion)
$D_{\mathrm{C/S}}$	total commercial/services demand	from sensitivity and uncertainty of inputs
D_{EN}	total energy generation demand	±10% (expert opinion)
L	total supply losses	losses at 35% ± 5% of total supply (empirical data and expert opinion)
U	unit supply costs for optimization	±20% (expert opinion)

mining of groundwater is significant ground subsidence as observed by the tilting buildings and undulating pavement in the center. The subsidence is caused by overpumping of groundwater, reducing hydraulic head in the aquifers below the thick, compressible lacustrine clay upon which the city is built. Pore water in the clay layer drains down to the layer of lower pressure, and the clay compresses. The center of the city has suffered an average 7.5 m of subsidence over the past 100 years [*National Research Council et al.*, 1995], and rates of settlement in outer parts such as Xochimilco and Xico reach 40 cm yr^{-1} [*Murillo Fernández*, 1990]. Piezometric levels of existing wells are said to be dropping an average of 1 m yr^{-1} [*Birkle et al.*, 1995]. Water and sewage pipes crack with differential settlement, causing high losses of water and cross contamination. To make matters worse, settlement compromises the stormwater/wastewater drainage system's ability to evacuate, and flooding in the rainy season (May to October) is a constant and increasing threat. It may be this settlement rather than dropping water table levels that eventually places an unavoidable absolute limit on the groundwater withdrawal rate. In 1982 the city's water authority, the General Department of Construction and Hydraulic Works (DGCOH), published a recommendation to reduce withdrawal to 15 $\mathrm{m}^3\ \mathrm{s}^{-1}$ [*DGCOH*, 1982]. Despite this the current withdrawal stands at over 40 $\mathrm{m}^3\ \mathrm{s}^{-1}$ (Table 1). Groundwater is also supplied from the external Alto Lerma Basin.

2.9. Characterization of Surface Water Sources

The exploitation of external basins is a common supply strategy for many urban centers. Surface water is pumped from the external Cutzamala Basin (Table 1). The main costs associated with external basin exploitation are the direct economic costs of construction, operation (pumping over large distances, see Table 7), and maintenance, plus the ecological and indirect socioeconomic costs borne by the external basin with the removal of water from the local hydrological cycle. We crudely estimated the potential impacts of Mexico City water supply on the local water cycle by characterizing local river flows using statistical confidence intervals and comparing these flows with official withdrawal rates of Table 1. Existing and potential supply basins are shown in Figure 5.

We delineated hydrologic basins using maps of surface water hydrology [*INEGI*, 1983a, b, c]. To characterize flows statistically, we collected historical hydrometric flow data for selected monitoring stations located in and around the withdrawal points of Alto Lerma and Cutzamala. The main sources of data were official hydrological bulletins from the years 1920–1980 [*Secretaría de Agricultura y Recursos Hidráulicos/Comisión Federal de Electricidad*, 1920–1980a, b]. The data of interest were the total monthly streamflow volumes expressed in thousands of cubic meters. The two regions are both characterized by marked dry and wet seasons, the latter usually lasting from June to September.

We modeled the monthly variability in flow as a lognormal probability distribution, often used to describe hydrological parameters in semiarid regions [*Dunne and Leopold*, 1978]. For each of four stations in Lerma and eight in Cutzamala, we transformed monthly volumes into their natural logarithms

Table 7. Distances and Elevations of Existing External Basin Water Supply Sources

Scheme	Reservoirs/Lake	G/S	Rate, $\mathrm{m}^3\ \mathrm{s}^{-1}$	Distance,* km	Elevation,* m
Upper Lerma	Jose Antonio Alzate	G	4.0–5.0†	45	−180
Cutzamala I	Villa Victoria	S	4.0†	160	−1100
Cutzamala II	Valle de Bravo, Chilesdo	S	7.0†	170	−1050
Cutzamala III(P)	El Bosque	S	8.0	180	−1000
Cutzamala IV(P)	El Tule	S	5.0	180	−1150
Total			28–29		

G is groundwater; S is surface water. Cutzamala III(P) and Cutzamala IV(P) are planned expansions.
*Distance and elevation relative to Mexico City are estimated from maps [*INEGI*, 1983a, b, c].
†Current is estimated 1998 exploitation (differs from Table 1).

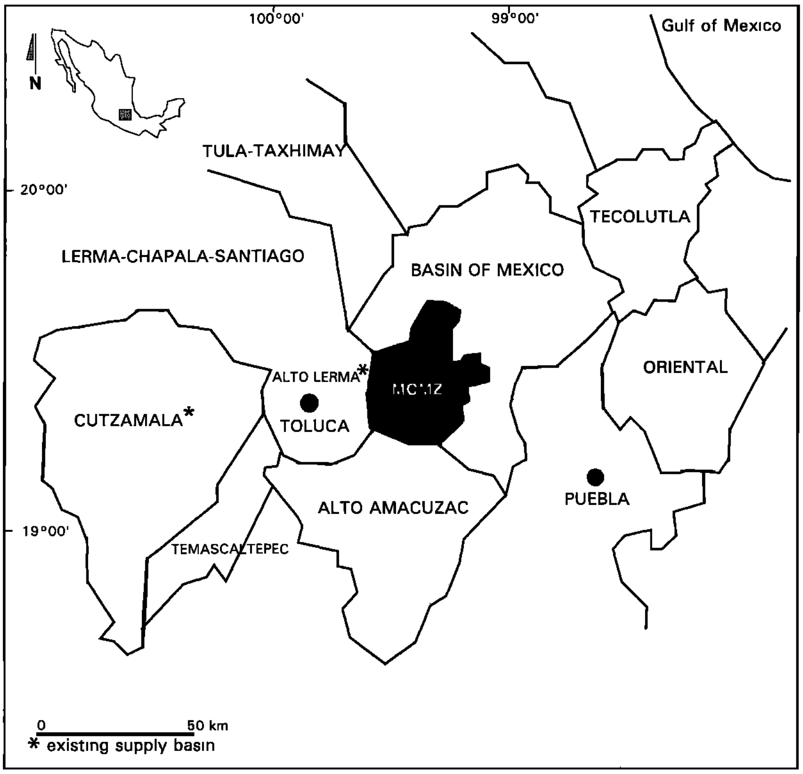


Figure 5. Existing and potential supply basins.

and calculated the monthly geometric mean and standard deviation. We used these statistics to calculate the 90%, 50%, 25%, and 10% probability bounds for the lognormal distribution. In this way we characterized monthly flows for each station by the probabilities that a random flow would be less than the bound. The resulting annual hydrographs are convenient to compare withdrawal rates with natural flows for an assessment of impact.

2.10. Wastewater Flow and Reuse

MCMZ wastewaters consist of domestic, agricultural, and industrial waste, together with storm water runoff during the rainy season. The wastewater is collected and evacuated by three main collectors: the Gran Canal, the west collector, and the central collector. We plotted the combined wastewater outflow by progressively adding three levels of wastewater infrastructure data as new tunnels and/or collectors were built. Currently, about three quarters of the urban wastewater is reused in the irrigation districts 03 and 100 in the State of Hidalgo, 80 km north of the city in one of the largest schemes of its type in the world [*Siebe and Cifuentes*, 1995]. The wastewater receives no formal treatment and is used for the flood irrigation of fields growing crops as diverse as maize, wheat, alfalfa, oats, chiles, lettuce, and tomatoes, although the latter two are officially prohibited for health reasons because they are consumed raw.

To determine wastewater flows available for recycling in the optimization scenarios, we estimated wastewater yields from domestic, industrial, and agricultural sources using a government hydrologic balance [*SARH*, 1981] and applied a conservative reclamation efficiency of 80% to the yields (in developed countries efficiencies of 90–95% are common).

2.11. Rainfall Capture

The option of rainfall capture is attractive from the point of view of sustainability. Critics of the option cite seasonal and spatial variability in rainfall as the obstacles to its use. In water-scarce regions of the world a statement that rainfall in Mexico City cannot be captured and used would be viewed as wasteful. Optimists view the basin as a natural capture zone for rainfall which averages 700–750 mm yr^{-1} over the full basin, reaching 1200–1500 mm yr^{-1} in the southern and western mountain zones. According to a study by *Ramírez-Sama* [1990] the rainfall resource represents an annual volume of the order of 6850×10^6 $\mathrm{m}^3\,\mathrm{yr}^{-1}$ (equivalent to 217 $\mathrm{m}^3\,\mathrm{s}^{-1}$), and 1300×10^6 $\mathrm{m}^3\,\mathrm{yr}^{-1}$ (41 $\mathrm{m}^3\,\mathrm{s}^{-1}$) is runoff, of which about 790×10^6 $\mathrm{m}^3\,\mathrm{yr}^{-1}$ (25 $\mathrm{m}^3\,\mathrm{s}^{-1}$) recharges groundwaters, leaving part of the rest available for human use. Currently, storage of excess runoff is 130×10^6 $\mathrm{m}^3\,\mathrm{yr}^{-1}$ (4.1 $\mathrm{m}^3\,\mathrm{s}^{-1}$) in several small reservoirs, leaving 12 $\mathrm{m}^3\,\mathrm{s}^{-1}$ unused. The same study suggests that the renovation of the two ancient lake bodies of Zumpango and Texcoco could provide the necessary storage volume for the excess runoff. Another study [*Murillo-Fernández*, 1990] estimated about 11 $\mathrm{m}^3\,\mathrm{s}^{-1}$ is unused. In optimization scenarios we conservatively set supply from rainfall capture to 2 $\mathrm{m}^3\,\mathrm{s}^{-1}$.

2.12. Water Supply Optimization

For integrated water resource management all existing and potential surface water, groundwater, and wastewater supplies should be considered. We carried out an optimization of all possible MCMZ water supply options to meet 2015 demand using linear programming to minimize total supply cost subject to supply constraints, as described by the algorithm below

Table 8. Optimization Scenarios, Conditions, and Degrees of Sustainability

Condition	A	B	C	D	E	F
Local aquifer withdrawal, $m^3\ s^{-1}$	20	20	20	20	40	40
Lerma Basin withdrawal, $m^3\ s^{-1}$	4	2	2	2	4	2
Local rainfall capture, $m^3\ s^{-1}$	0	2	2	2	0	2
Local deep aquifer withdrawal, $m^3\ s^{-1}$	0	4	4	4	0	4
Major treatment/reuse exists?	no	yes	yes	yes	no	yes
Savings from efficiency measures, (percent $year^{-1}$)	0	0.5	0.5	0.5	0	0.5
New external basin supply (percent of official limits)	100	100	100	50	100	100
Forecasted supply goal, $m^3\ s^{-1}$	106*	106	124†	106	106	106
Relative degree of sustainability	low	medium	medium	high	zero‡	zero

Scenario columns A–F.

D and E are opposite extremes.
*Mean of forecast is indicated.
†Upper 95% confidence interval of forecast is indicated.
‡This is "business as usual" approach.

$$\text{minimize} \sum_{i=1}^{n} SC_i,$$

subject to the following two sets of constraints, the first that supplies be limited and the second that total withdrawal meet total required supply:

$$EV_i \leq SL_i, \qquad \sum_{i=1}^{n} EV_i \geq S_{\text{total}}$$

where

SC_i supply cost for source i, with $SC_i = EV_i \times RUC_i$;
n number of sources;
EV_i withdrawal from source i;
RUC_i relative unit cost for source i;
SL_i supply limit for source i;
S_{total} total required supply from forecast.

To optimize supply, it is only necessary to obtain reasonable estimates of relative unit costs. For convenience, we chose local groundwater to have a relative unit cost of 1.0 and normalized all other supply costs to it. The unit cost of efficiency measures (changes in habits and technology substitutions that save water) was assumed to be 1.0 since although no comparative unit cost data exist to compare it to the existing sources, it has generally been shown to be a very cost-effective intervention for medium to high consumers, though limited by effective pricing. Unit cost estimates assumed, where appropriate, capital, operation, and maintenance costs spread over the lifetime of the supply option, discounted at the same rate. We estimated the unit supply and treatment costs from three publications [*Barocio et al.*, 1991; *Ramírez Sama*, 1990; *Moreno*, 1987] using a combination of treatment technologies: for domestic reuse the cost of two advanced treatment processes was averaged; for industrial reuse secondary and tertiary treatment unit costs were averaged; for agricultural and energy reuse primary treatment unit cost was used; and for services reuse an average of tertiary and advanced treatment unit cost was used. To account for the costs of new infrastructure to incorporate recycled water into the distribution system (different water qualities for different uses require differential collection and redistribution), we increased the base treatment costs by 50%. It is worth noting that in Mexico and other developing countries reliable estimates of any unit treatment cost is difficult to obtain, and it is important to be sure how and when the unit cost was calculated for comparisons between regions and projects (T. J. Downs, Unit wastewater treatment costs for developing countries, internal report, Water and Sanitation Department, The World Bank, Washington, D. C., 1994).

We considered six supply scenarios to meet forecasted demand in the year 2015. For comparability and as a baseline sustainability criterion, local groundwater withdrawal was limited to 20 $m^3\ s^{-1}$ in scenarios A–D, while scenarios E and F used the current overexploitation value of 40 $m^3\ s^{-1}$; scenario E is the "business as usual" approach. Table 8 shows the conditions we applied.

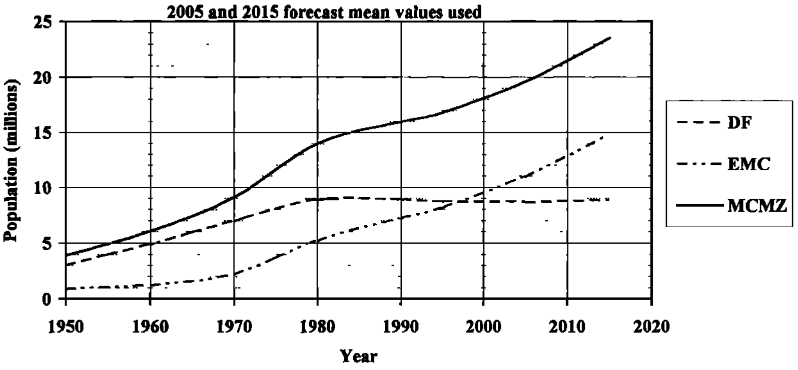


Figure 6. Population growth for DF, EMC, and MCMZ (data to 1990 from *CONAPO* [1994]).

Table 9. Population and Density Trends 1980–2015

Region	1980	1990*	1995†	2005‡,§	2015‡,§
			Numbers (millions)		
DF	8.831	8.825	8.680	8.631 (0.126)	8.798 (0.260)
EMC	5.165	7.153	8.074	10.93 (0.213)	14.73 (0.603)
MCMZ	14.00	15.98	16.75	19.56 (0.245)	23.53 (0.651)
			Densities‖ (inhabitants km^{-2})		
DF	11000	9800	9300	8500	8300
EMC	2400	3200	3500	4600	6100

*The 1990 census data are modified to account for assumed 6% underestimate.

†The 1995 estimates used modified 1990 values as baseline and were not forecasted probabilistically.

‡Population means with standard deviation in parentheses are forecasted.

‖The 1990 land areas are assumed. Values are arithmetic means of the densities of each political area of the region.

§Forecasted population means are assumed.

3. Results

3.1. Population and Water Demand Forecasts

Figure 6 shows the historical [from *CONAPO*, 1994] and forecasted population trends for the DF, EMC, and MCMZ. Since the DF and the EMC are at different stages on the logistic curve, the MCMZ is a composite curve consisting of the sum of early and later phases of a logistic curve. Table 9 shows trends in numbers of inhabitants and densities, with average densities at plausible levels. Figure 7 shows forecast output for 2015 MCMZ population and domestic demand, while Figure 8 shows total demand. Forecast mean 2015 MCMZ population and domestic demand are 23.5 million and 56.7 m^3 s^{-1}, respectively, while the DF values are 8.80 million and 26.0 m^3 s^{-1}, and the EMC values are 14.7 million and 30.7 m^3 s^{-1}. The 95% confidence intervals for MCMZ population and total required supply are 22.3–24.9 million and 90.7–124 m^3 s^{-1}, respectively. The mean 2015 MCMZ value of required supply (106 m^3 s^{-1}) and the upper 95% bound (124 m^3 s^{-1}) were both used in the optimization exercise. Table 10 summarizes the population statistics and water demand statistics for 2005 and 2015 forecasts. For all forecasts the coefficients of variability were ≤0.09, and standard errors of means were low. In all cases the skewness was small, indicating a near-normal distribution, as expected from normal inputs.

These data illustrate the inadvisability of projecting populations much beyond 2 decades; many publications, including those of the "global development" type, tend to project populations by extrapolating current growth rates or by assuming exponential growth and not accounting for density dependence or quantifying intrinsic uncertainty. In 1986 the United Nations Population Fund [*United Nations*, 1986] unrealistically projected Mexico City population would be 26.3 million by the year 2000 (unofficial 1999 estimates are 18.0–19.0 million).

Table 11 summarizes the components of required supply (demands plus losses). The split between MCMZ domestic, agricultural, and industrial/commercial/service demands was 84%, 12%, and 4%, respectively, for 1995 and was 83%, 14%,

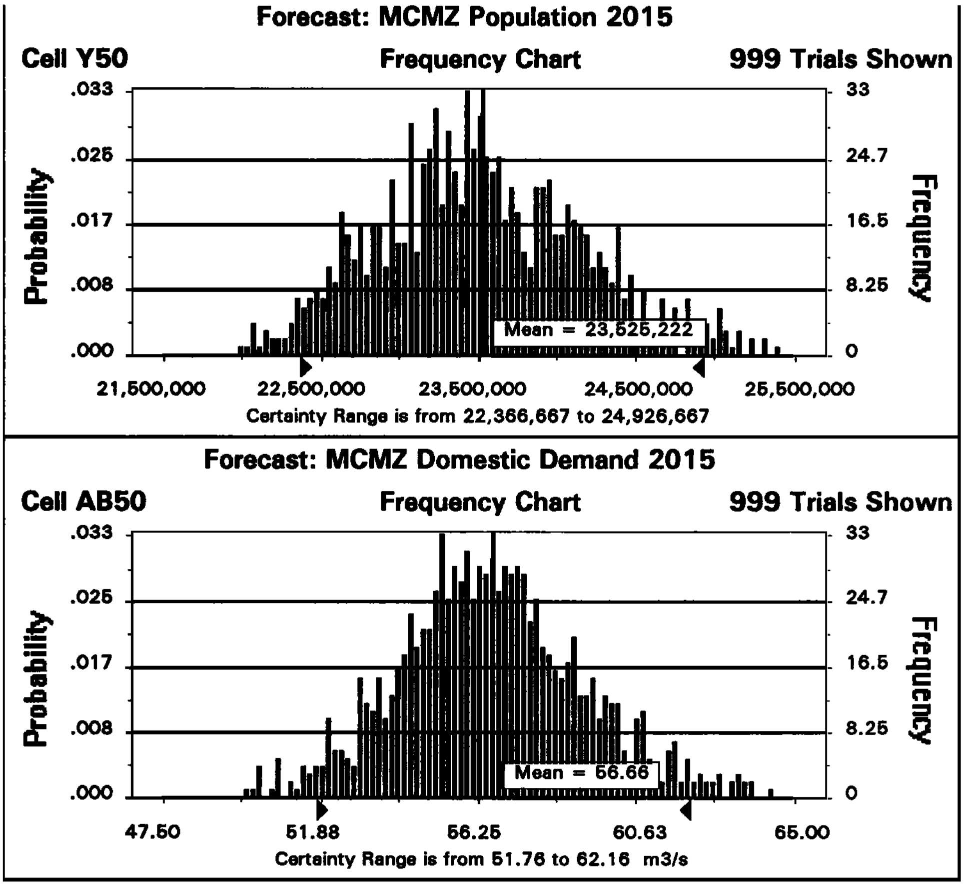


Figure 7. The 2015 forecasts of population and domestic water demand.

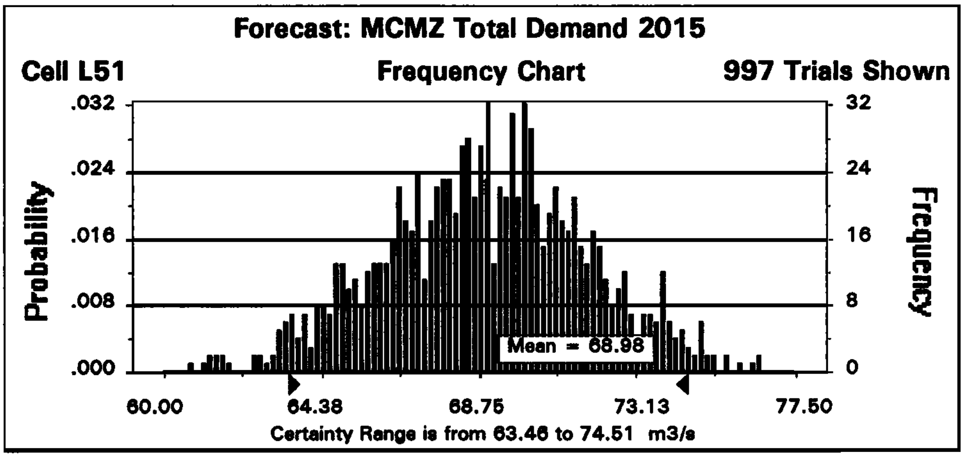


Figure 8. The 2015 forecast of total demand.

and 4%, respectively, for 2015 remaining almost the same. Figure 9 shows the relative size of total supply components. The DF demand shows minor growth in all categories because its population lies at saturation in most delegations, while the EMC demand is forecasted to grow markedly and dominate the MCMZ growth trend (Figure 10).

3.2. Shortages

Shortages (demand minus supply) have been estimated at 15% in the past [*Departamento del Distrito Federal/Gobierno del Estado de México*, 1989]. If we estimate current supply at 70 m^3 s^{-1} and compare this to the 1995 estimated required supply of 83 m^3 s^{-1} (Table 11), the shortage is now at least 15%. Even with planned Cutzamala expansion of 13 m^3 s^{-1} (Table 7), unless alternative sources are developed, the 2015 shortage may be at least 23 m^3 s^{-1} (106 − 70 − 13) or 22%, since it is uncertain whether the local aquifer can continue to yield 43 m^3 s^{-1}. This shortage will be borne most heavily by already impoverished areas such as Iztapalapa in the DF and Ecatepec in the EMC. Such areas experience no piped water service during prolonged periods, and as in the marginal areas, the population must buy from water trucks at a higher price, exposing a poverty trap and serious environmental justice issues. Arguably, sufficient water supply and sanitation improves the quality of life of a society and its cultural and economic development more than any other intervention.

3.3. Comparisons with Existing Studies

Comparing data from this study with other water demand estimates is problematic because government data are often difficult to obtain, and when data are made available, "demand," "use," "consumption," and "supply" terms are often used synonymously. Also, how numbers were calculated is unclear, for example, whether or not losses were included and which per capita demands were assumed. A recent government report (Gerencia de Aguas del Valle de Mexico, Use of water, internal memo, Mexico City, 1995) states 1990 water "usage" at 63 m^3 s^{-1}, with "Mexico City" comprising the same 16 DF delegations used in this study but only 17 municipalities of the EMC instead of 27. In another government report [*SARH*, 1981], domestic and commercial demand together was estimated at 44.8 m^3 s^{-1}, industrial demand was estimated at 15 m^3 s^{-1}, and agricultural demand was estimated at 12.8 m^3 s^{-1}. *Ezcurra* [1992] forecasted that by the year 2000 the city will need to pump 100 m^3 s^{-1} from "outside" the basin to meet demand. A DF water authority report [*DGCOH*, 1982] estimated "demand" for the year 2000 could range from 50 to 72 m^3 s^{-1}, assuming per capita rates from 250 to 360 L p^{-1} d^{-1}.

3.4. Sensitivity

Tables 12a and 12b summarize results of the sensitivity analyses for the DF, EMC, and MCMZ 2015 forecasts. For the MCMZ population forecast the most important contributors

Table 10. Forecast Statistics for Population and Water Demand for 2015

	Population, millions			Domestic Demand, m^3 s^{-1}			Total Demand, m^3 s^{-2}		
Statistic	MCMZ	EMC	DF	MCMZ	EMC	DF	MCMZ	EMC	DF
mn	23.52	14.73	8.80	56.66	30.66	25.99	68.98	41.09	27.87
md	23.55	14.55	8.74	55.28	30.04	25.20	70.16	39.75	27.50
sd	0.651	0.603	0.260	2.57	1.91	1.78	2.88	2.25	1.77
sk	0.30	0.31	0.15	0.22	0.16	0.16	0.02	0	−0.01
cv	0.03	0.04	0.03	0.05	0.06	0.07	0.04	0.05	0.06
ci95	22.3–24.9	13.6–16.0	8.3–9.3	51.8–62.2	27.1–34.5	22.5–29.5	63.5–74.5	36.7–45.5	24.4–31.4
sem	0.021	0.019	0.008	0.08	0.06	0.06	0.09	0.07	0.06

Abbreviations are as follows: mn, mean; md, mode; sd, standard deviation; sk, skewness; cv, coefficient of variability; ci95, 95% confidence interval; and sem, standard error of mean.

Table 11. Components of Required Supply for 1995, 2005, and 2015

Parameter	Year	DF	Percent	EMC	Percent	MCMZ	Percent
Population (millions)	1995	8.68	74	8.10	69	11.68	100
	2005	8.63	44	10.93	56	19.56	100
	2015	8.80	37	14.73	63	23.53	100
Domestic demand (means)	1995	26.72	93	18.63	73	45.35	84
	2005	25.92	93	23.91	74	49.83	83
	2015	25.99	93	30.66	75	56.66	83
Agricultural demand	1995	0.04	0	6.20	24	6.24	12
	2005	0.04	0	7.70	24	7.74	16
	2015	0.04	0	9.77	20	9.81	14
Industrial demand	1995	0.03	0	0.02	0	0.05	0
	2005	0.03	0	0.03	0	0.05	0
	2015	0.03	0	0.03	0	0.06	0
Commercial-services demand	1995	1.81	6	0.53	2	2.33	4
	2005	1.81	6	0.57	2	2.38	4
	2015	1.81	6	0.62	2	2.43	4
Energy generation	1995	0.01	0	0.02	0	0.03	0
	2005	0.01	0	0.02	0	0.03	0
	2015	0.01	0	0.02	0	0.03	0
Total demand	1995	28.60	100	25.40	100	54.00	100
	2005	27.80	100	32.23	100	60.03	100
	2015	27.87	100	41.11	100	68.99	100
Losses	1995	15.40		13.63		29.08	
	2005	14.97		17.35		32.32	
	2015	15.01		22.13		37.15	
Required supply	1995	44.0		39.1		83.1	
	2005	42.8		49.6		92.4	
	2015	42.9		63.2		106	

All demands are in m^3 s^{-1}. Percent is percentage of population or total water demand for that region.

to its uncertainty were growth rates in Chalco (58% contribution to output variance) then Iztapalapa (7%), Ecatepec (3%), and Cuautitlán Izcalli (2%) (Table 12a). The MCMZ domestic water demand forecast was most sensitive to the unit demand variable (w) in Iztapalapa (11%), Cuautitlán Izcalli (10%), Tlalpan (8%), and Naucalpan (6%). The MCMZ total demand forecast was most sensitive to domestic demand (71%), unit agricultural demand (14%), and areas under irrigation (4%) (Table 12b).

3.5. Characterization of External Supply Basins

Hydrographs constructed for the Alto Lerma monitoring stations suggest that a nondepleting groundwater withdrawal at this location should not exceed 2.0 m^3 s^{-1} (Figure 11a). Current withdrawals from the region are reported to be about 4.5 m^3 s^{-1}, on average, but it is unclear how official withdrawal rates are decided and varied over the year according to demand and natural seasonal hydrology. Our estimate of acceptable withdrawal at 2.0 m^3 s^{-1} is first order and crude; improved estimates require a more exhaustive water balance characterization of the region, especially the relative size of surface runoff and groundwater recharge. Nevertheless, we conclude that withdrawal is excessive and may represent an overexploitation of 100%. Overexploitation has a direct impact on groundwater levels and an indirect impact on surface water levels in rivers and reservoirs, on vegetation, crop cultivation, and ultimately local economy and microclimate.

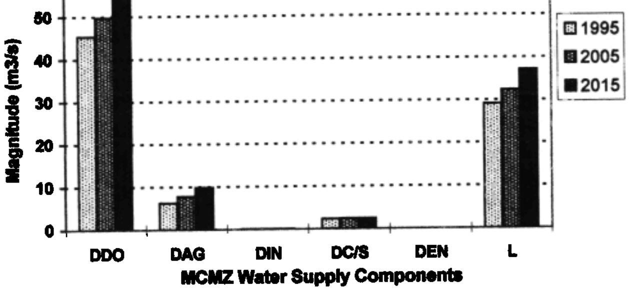


Figure 9. Components of MCMZ required supply for 2015.

In the Cutzamala Basin, current anthropogenic withdrawals in several stages take place in the region of the Villa Victoria and Valle de Bravo reservoirs. Figure 11b shows results from one station San José Malacatepec downstream of the Villa Victoria reservoir and upstream of Los Colorines reservoir. Except for the 90% threshold, seasonality is moderate, with a dry season from December to June and 50% flows around 2.0 m^3 s^{-1}. The wet season shows 50% flows around 6.0 m^3 s^{-1}. Using the seven hydrographs constructed from other stations and reviews of ongoing hydrological studies, the withdrawals appear acceptable, not adversely changing the storage levels of the main reservoirs, which is the main concern of the local residents and the tourist economy. Also, withdrawals are varied so as to ensure the minimum required runoff for downstream farms. Exactly how the alterations in the water cycle affect the local basin remain to be studied, but it may be hypothesized that changes in evapotranspiration and infiltration accompany any major change in runoff. Unlike the case of Alto Lerma, withdrawal constitutes direct diversions of surface runoff and seems conditional on hydrological criteria as well as MCMZ demand.

In the short term any reductions in reservoir storage levels and aquifer storage levels are good indicators of overexploitation, with longer-term monitoring of vegetation and microclimate complicated by the difficulty in distinguishing natural

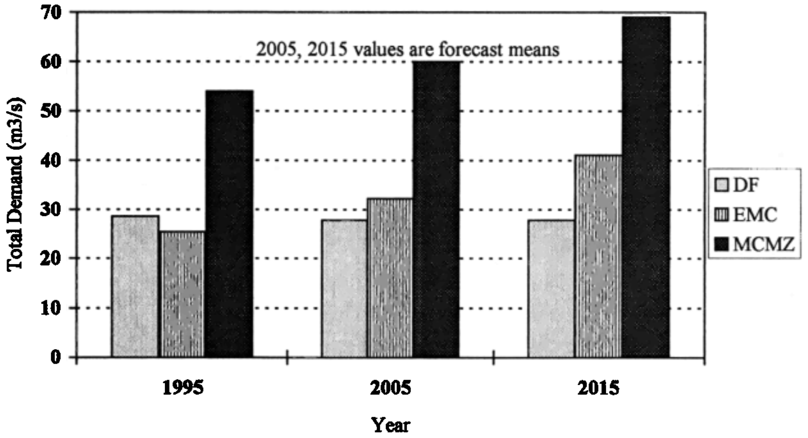


Figure 10. Total water demands for 1995, 2005, and 2015.

from anthropogenic variability. The value-based question needing more research is the following: What is an acceptable water cycle alteration?

3.6. Wastewater Flow

Figure 12 shows combined wastewater flows from 1927 to 1987 of progressive combinations of collectors as they came on-line. There is a general rise from around 6 m^3 s^{-1} in the late 1920s to around 10–12 m^3 s^{-1} in the 1930s and 1940s, to 15–25 m^3 s^{-1} in the 1950s, to 17–27 m^3 s^{-1} in the 1960s, peaking at 33 m^3 s^{-1} in 1973. From these data the importance of storm water as a seasonal contributor to annual wastewater flow may be observed, this component superimposing a higher-frequency variability upon the gradual, decade by decade rise in the anthropogenic wastewaters. The available data did not include the central collector which has measured outflows of about 22 m^3 s^{-1}. Together these flows are of the order of 40–45 m^3 s^{-1}.

3.7. Optimization of Supply

Existing supply sources cannot meet the supply need for 2015; new sources must be developed to achieve this. Table 13 shows details of scenarios A–D, while Table 14 summarizes results for scenarios A–F. Scenarios A and B meet required 2015 supply with average relative unit costs of 1.165 and 1.103, respectively. Scenario B was not only cheaper but was more sustainable by the selected decision variables (see Table 13 supply limit columns). Scenario A supply consists of about 77% surface water and 23% groundwater, while scenario B consists of about 62% surface water, 19% groundwater, 12% wastewa-

Table 12a. The 2015 Forecast Sensitivities of Population and Domestic Demand

Output		Population			Domestic Demand		
Number*	Political Area	MCMZ	EMC	DF	MCMZ	EMC	DF
1	Alvaro Obregon	nt	nr	r2(3)	w(4)	nr	w(6)
2	Atzcapotzalco	nt	nr	nt	nt	nr	w(4)
5	Coyoacan	nt	nr	r2(2)	nt	nr	w(5)
8	Gustavo Madero	nt	nr	r2(7)	w(4)	nr	w(8)
8	Gustavo Madero	nt	nr	r3(6)	nt	nr	nt
10	Iztapalapa	r2(4)	nr	r2(21)	w(11)	nr	w(27)
10	Iztapalapa	r3(3)	nr	r3(16)	nt	nr	r2(3)
10	Iztapalapa	···	nr	r1(3)	nt	nr	···
14	Tlalpan	nt	nr	r2(5)	w(8)	nr	w(15)
15	Venustiano Carranza	nt	nr	nt	nt	nr	w(4)
19	Atizapan	nt	nt	nr	w(3)	w(6)	nr
20	Chalco	r2(32)	r2(35)	nr	nt	nt	nr
20	Chalco	r1(15)	r1(19)	nr	nt	nt	nr
20	Chalco	r3(11)	r3(14)	nr	nt	nt	nr
25	Coacalco	nt	nt	nr	nt	w(3)	nr
27	Cuautitlan Izcalli	r3(2)	r3(2)	nr	w(10)	w(18)	nr
27	Cuautitlan Izcalli	nt	nt	nr	nt	r2(2)	nr
28	Ecatepec	r2(2)	r2(2)	nr	nt	w(17)	nr
28	Ecatepec	r3(1)	r3(2)	nr	nt	···	nr
33	Naucalpan	nt	r3(1)	nr	w(6)	w(11)	nr
34	Netzahualcoyotl	nt	r2(2)	nr	nt	w(2)	nr
41	Tlalnepantla	nt	nt	nr	nt	w(2)	nr

*See Figure 1 for code.

Abbreviations are as follows: nt, not in top eight for region; nr, not in region; r1( ), growth rate 1990–2000 (percent contribution to forecast variance); r2( ), growth rate 2000–2010 (percent contribution); r3( ), growth rate 2010–2020 (percent contribution); and w( ), unit domestic demand (percent contribution).

Table 12b. Forecast Sensitivities for Total Demand

Input*	Total Demand Output: MCMZ	EMC	DF
D_{DO}†	71	63	89
h	14	22	···
H	3.6	5.6	···
$p32$	0.6	···	···
$P33$	···	···	···
$P34$	···	···	···
$P38$	0.6	···	0.7
$q82$	···	···	···
$Q83$	···	···	···
$q93$	0.6	···	···
$Q93$	···	···	0.8
$Q95$	···	0.5	···
$Q96$	···	···	···
$q96$	···	···	···
Total	90.4	91.1	90.5

Numbers are percent contribution to forecast variance. Ellipsis indicates value <0.5%.

*Refer to Table 6 for variable name.

†See domestic demand sensitivities (Table 12a).

ter (all designated for agricultural reuse), and 7% savings from efficiency.

The two extreme scenarios C and D covering the upper 95% bound of the forecast (124 $m^3 s^{-1}$) did not show significant unit cost changes, the increased supply was met by proportional increases in wastewater reuse and efficiency. Scenario D, decreasing new surface supply limits by 50%, only increased unit cost slightly and was the most "environmentally sustainable" for the multiple hydrological basins of the region. Scenario C meets the higher supply goal at a negligible increase in unit cost compared to B (1.106 versus 1.103), while scenario D incurred a small increase (1.121). Figure 13 shows the contributions of sources to optimal solutions.

For scenario E (local aquifer overexploitation), optimal supply consists of 62% surface water and 38% groundwater at an average unit cost of 1.133. For scenario F, optimal supply was 43% surface water, 38% groundwater, 12% reuse, and 7% efficiency measures at average unit cost of 1.076. However, continued overexploitation of the aquifer makes these scenarios undesirable and unsustainable. Although sufficient water exists, more work is needed to determine ecological withdrawal limits for external basins.

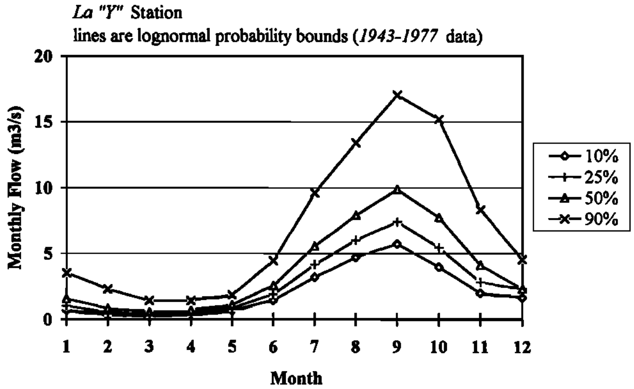


Figure 11a. Hydrograph in Alto Lerma Basin.

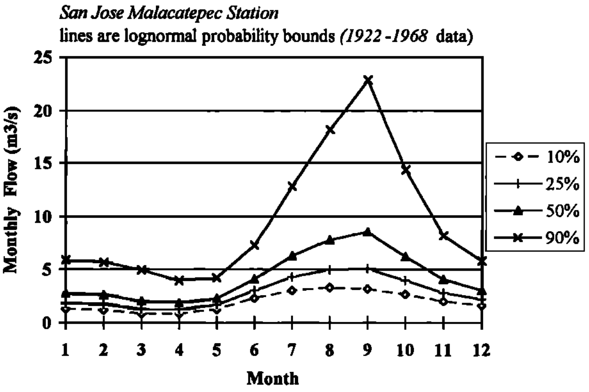


Figure 11b. Hydrograph in Cutzamala Basin.

4. Discussion and Recommendations

An unsustainable water management practice currently exists: Of urban demand 60% is currently met by overexploiting groundwater at 1.6 times the recharge rate, and less than 10% of wastewater is treated and reused inside the local basin. Controlling for sustainability, optimized supply scenarios show that water resource practices which are more sustainable are comparable in supply cost (or cheaper) than existing policy. Since major initiatives and financing are already on the table for further external basin exploitation and wastewater treatment, we recommend that a scenario D type of integration should be used as the basis for a 15–20–30+ year plan, with vigorous, progressive groundwater substitution as new sources are brought on-line and major local recycling. Though not considered here, the detection and repair of distribution system leaks is a strategic intervention, even though leakage does recharge groundwater. However, detection of major leaks is made difficult by low system pressure.

Increasing anthropogenic coupling of hydrological basins requires a multibasin context to integrated water resource management. For example, according to a recent British Geological Survey study (Hidalgo groundwater study–Phase I report, unpublished, 1995) the infiltration of MCMZ wastewater over decades of wastewater irrigation in the neighboring basin of

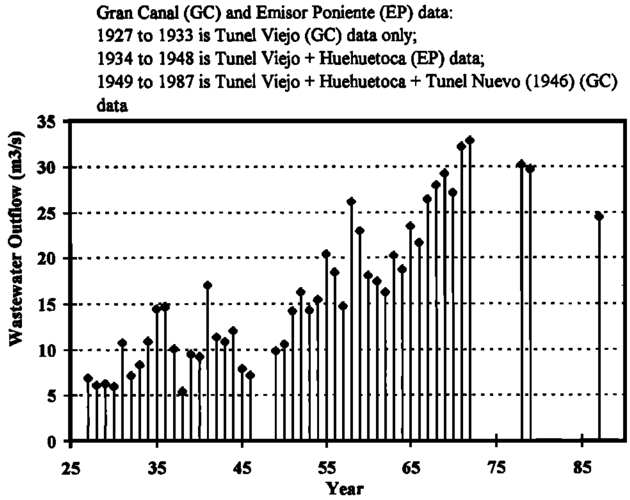


Figure 12. MCMZ wastewater outflow trend (excludes central collector data).

Table 13. Optimization of Supply Sources to Meet 2015 MCMZ Forecast

	Scenario A					Scenario B					Scenario C					Scenario D				
Supply Source	EV	TS, %	SL	RUC	SC	EV	TS, %	SL	RUC	SC	EV	TS, %	SL	RUC	SC	EV	TS, %	SL	RUC	SC
Surface waters																				
Mexico basin local basin runoff	0.0	0.0	0.0	0.87	0.00	2.0	1.9	2.0	0.87	1.74	2.0	1.6	2.0	0.87	1.74	2.0	1.9	2.0	0.87	1.74
Cutzamala I	4.0	3.8	4.0	1.30	5.20	4.0	3.8	4.0	1.30	5.20	4.0	3.2	4.0	1.30	5.20	4.0	3.8	4.0	1.30	5.20
Cutzamala II (Chilesdo)	7.0	6.6	7.0	1.43	10	7.0	6.6	7.0	1.43	10	7.0	5.6	7.0	1.43	10.0	7.0	6.6	7.0	1.43	10.0
Cutzamala III (El Bosque)*	8.0	7.5	8.0	1.43	11	8.0	7.5	8.0	1.43	11	8.0	6.5	8.0	1.43	11.4	8.0	7.5	8.0	1.43	11.4
Cutzamala IV (El Tule)*	5.0	4.7	5.0	1.43	7.15	5.0	4.7	5.0	1.43	7.15	5.0	4.0	5.0	1.43	7.15	5.0	4.7	5.0	1.43	7.15
Nuevo Temascaltepec	1.0	0.9	7.0	1.18	1.18	0.0	0.0	7.0	1.18	0	0.0	0.0	7.0	1.18	0.0	3.5	3.3	3.5	1.18	4.13
Nuevo Tecolutla	0.0	0.0	15.0	1.28	0	0.0	0.0	15.0	1.28	0	0.0	0.0	15.0	1.28	0.0	0.0	0.0	7.5	1.28	0.00
Nuevo Medio Amacuzac	30.0	28.3	30.0	1.17	35	13.0	12.2	30.0	1.17	15	25.9	20.9	30.0	1.17	30.3	15.0	14.2	15.0	1.17	17.6
Nuevo Alto Amacuzac	15.0	14.2	15.0	1.10	17	15.0	14.2	15.0	1.10	17	15.0	12.1	15.0	1.10	16.5	7.5	7.1	7.5	1.10	8.25
Nuevo Oriental	7.0	6.6	7.0	1.04	7.28	7.0	6.6	7.0	1.04	7.28	7.0	5.6	7.0	1.04	7.28	3.5	3.3	3.5	1.04	3.64
Nuevo Taxhimay/Tlautla/Rosas	5.0	4.7	5.0	1.00	5.00	5.0	4.7	5.0	1.00	5.00	5.0	4.0	5.0	1.00	5.00	2.5	2.4	2.5	1.00	2.50
Subtotal	82.0	77.4	103			66.0	62.2	105			78.9	63.6	105			58.0	54.7	65.5		
Groundwaters																				
Mexico basin local aquifers	20.0	18.9	20.0	1.00	20	20.0	18.9	20.0	1.00	20	20.0	16.1	20.0	1.00	20.0	20.0	18.9	20.0	1.00	20.0
New deep local aquifers	0.0	0.0	0.0	1.22	0.00	0.0	0.0	4.0	1.22	0.00	0.0	0.0	4.0	1.22	0.00	4.0	3.8	4.0	1.22	4.88
Lerma aquifers	4.0	3.8	4.0	1.17	4.68	0.0	0.0	2.0	1.17	0.00	2.0	1.6	2.0	1.17	2.34	2.0	1.9	2.0	1.17	2.34
Subtotal	24.0	22.6	24.0			20.0	18.9	26.0			22.0	17.7	26.0			26.0	24.5	26.0		
Reuse and treatment																				
For domestic	0.0	0.0	0.0	1.26	0.00	0.0	0.0	56.7	1.26	0.00	0.0	0.0	64.9	1.26	0.00	2.0	1.9	56.7	1.26	2.48
For industry	0.0	0.0	0.0	1.04	0.00	0.1	0.1	0.1	1.04	0.06	0.1	0.1	0.1	1.04	0.07	0.1	0.1	0.1	1.04	0.06
For agriculture	0.0	0.0	0.0	0.74	0.00	9.8	9.3	9.8	0.74	7.26	11.2	9.1	11.2	0.74	8.31	9.8	9.3	9.8	0.74	7.26
Commerce/services	0.0	0.0	0.0	1.00	0.00	2.4	2.3	2.4	1.00	2.43	2.8	2.2	2.8	1.00	2.78	2.4	2.3	2.4	1.00	2.43
Energy generation	0.0	0.0	0.0	0.70	0.00	0.0	0.0	0.0	0.70	0.02	0.0	0.0	0.0	0.70	0.02	0.0	0.0	0.0	0.70	0.02
Subtotal†	0.0	0.0	0.0			12.3	11.6	32.6			14.1	11.4	37.3			14.3	13.5	32.6		
Efficiency	0.0	0.0	0.0	1.00	0.00	7.7	7.3	0.5%	1.00	7.70	9.0	7.3	0.5%	1.00	9.00	7.7	7.3	0.5%	1.00	7.70
Total	106	100			123.5	106	100			117.0	124	100			137.1	106	100			118.8
Average RUC					1.165					1.103					1.106					1.121

Abbreviations are as follows: EV, extraction value ($m^3 s^{-1}$); TS %, percentage of total supply; SL, supply limit ($m^3 s^{-1}$); RUC, relative unit cost; and SC, supply cost.
*Values are major sustainability criteria.
†Subtotal limit is based on 80% recovery of estimated wastewater returns from demand flows (demand equals consumption plus return).

Table 14. Simulations and Optimization Results

Optimized Supply Results	Scenario A	B	C	D	E	F
Required supply goal year 2015, $m^3\ s^{-1}$	106	106	124	106	106	106
Supply from groundwaters, %	22.6	18.9	17.7	24.5	37.7	37.7
Supply from surface waters, %	77.4	62.2	63.6	54.7	62.3	43.4
Supply from treatment/reuse, %	0	11.6	11.4	13.5	0	11.6
Supply from efficiency savings, %	0	7.3	7.3	7.3	0	7.3
Average relative unit supply cost, per $m^{-3}\ s^{-1}$	1.165	1.103	1.106	1.121	1.133	1.076

See Table 8 for conditions. The relative degrees of sustainability are as follows: A, low; B, medium; C, medium; D, high; E, zero; and F, low.

Hidalgo created and "superrecharges" the local central aquifer such that now it shows signs of saturation. The result has been rapid accumulation of groundwater and a rise in the water table. This has profound implications for Hidalgo and MCMZ water balance since local groundwater may be able to supply more irrigation needs, especially with improved irrigation efficiency, substituting for the current inefficient flood irrigation with other methods. The benefits of this would be to free up a significant quantity of Mexico City wastewater for treatment, reuse, and lake rehabilitation within the Mexico City Basin of origin and may afford the following benefits for the irrigation district:

1. Use of less contaminated local groundwater instead of raw wastewater would have a lower impact on human and environmental health.
2. Use of the local groundwater would prevent the saturation of the local aquifer system by wastewater recharge, a scenario with serious health implications given the current reliance on soils, reservoirs, and rivers as "natural treatment" systems for the wastewater [*Downs*, 1999]. Saturation would magnify the bioavailability of contaminants and therefore exposure for humans, grazing animals, and crops.
3. Use of higher-quality local groundwater may allow higher-value crops to be grown.

Akin to this assumption of required irrigation water quantity lies one of required quality. The soils of the irrigation district have accumulated organic matter over decades. The hypothesis that soils are now sufficiently fertile without further nutrient input is under investigation. A plan by the National Water Commission for advanced primary treatment (sedimentation plus disinfection) of about 35 $m^3\ s^{-1}$ of Mexico City wastewater (Comisión Nacional del Agua, Proyecto de Saneamiento del Valle de México, Federal District of Mexico, internal report, 1995) mainly seeks to remove helminth eggs, while preserving the chemical "nutrient value" of the wastewater. This assumption led to a technology choice that was controversial, with concerns about other pathogens, disinfectant byproducts, sludge handling, and lack of major local reuse [*Downs*, 1997]. Since 1996, despite a presidential mandate and assigned loans from Japan and the Inter-American Development Bank, the prerequisite sustainability evaluation, and thus the whole plan, has been stalled by political wrangling. Meanwhile, Mexico pays interest to do nothing, an unethical, extreme example of political barriers. Compared to the original centralized treatment design ("megaplants"), alternative municipal-scale wastewater plants are much more sustainable. Economically viable with Mexican technology, they would permit compliance with ecological law effective January 2000, stimulating a market for products and services, including recycled water for all uses below the existing unsubsidized supply cost.

The exploitation of external hydrologic basins to supply water to Mexico City is unavoidable even with recycling of wastewaters. Though no panacea, recycling reduces the burden on these external basins. One of the external basins currently in service, Alto Lerma, appears to be overexploited perhaps by as much as 100%, while the other, Cutzamala, is better managed.

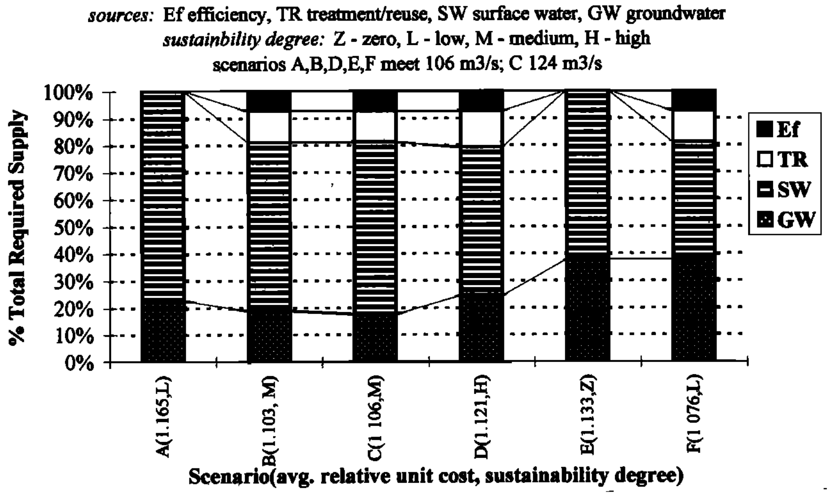


Figure 13. Contributions of sources to optimal solutions (see Table 14).

Integrated water resource management plans must also include protection and enhancement of aquifer recharge areas, especially the control of deforestation and the initiation of systematic reforestation of the mountain slopes.

An important distinction exists between growth and development: Growth implies a change in population size, while development implies a change in life quality. With growth and development happening together, even higher water supplies would be needed than those predicted from this growth model. A city may appear to sustain its needs while slowly declining in the quality of life it offers its inhabitants; care must be taken to set sustainability criteria to maintain an acceptable quality of life, for example, provision of sufficient clean drinking water (and sanitation) to the population continuously over time. For a 2015 mean MCMZ population of 23.5 million the mean domestic demand of 57 m^3 s^{-1} is equivalent to an average per capita demand of 209 L p^{-1} d^{-1} (100 L p^{-1} d^{-1} is a rule of thumb minimum for health requirements), but the actual supply and demand stratification is extreme. The poorest two groups (I and II) are forecasted to account for 29% of 2015 population but to account for only 8.8% of domestic demand (equivalent to 63 L p^{-1} d^{-1}). Average per capita values are often quoted in political discourse, often calculated from total supply not domestic demand alone, and can thus be very misleading. An applied research priority is to refine unit cost estimates of supply sources and compare options using cost, technical, sociopolitical, public health, ecological, and sustainability criteria, requiring a cross-disciplinary, multistakeholder approach.

The current pricing and metering policy is a step toward demand reduction and should be equitably extended to all users. However, such policy needs to be accompanied by increases in utility company service quality (supply and sanitation) to foster user willingness to pay that finances the water sector, removes dependency on subsidies, and promotes willingness to comply with pollution regulations. We suggest that while the pricing policy target groups III, IV, and V (who we forecast will account for about 90% of 2015 domestic demand), all users should pay according to consumption and ability to pay, so water becomes a recognized economic good. Future shortages in supply will most severely, affect poor people, who already suffer from inadequate supply, with consequential effects on health and life quality. As resource management fails to be sustainable, allocation of scarce resources is further controlled, and social tensions between rich and poor classes become heightened; the demographic effect may be an expanding poor class, shrinking middle class, and smaller still ruling elite. As water shortages threaten the security of households, they will undoubtedly become one of the most conflictive problems facing the next generation in many parts of the world; resource sustainability is more a sociopolitical challenge than a technical one.

The main political instrument for controlling future urban resources demand is a vigorous decentralization policy, where economic and fiscal incentives can be cost-effective. Such policy requires a vision of development that spans the next 50 years, integrating urban, industrial, and resource planning and pursued as a long-term national imperative that survives changes in government. Positive sociopolitical changes such as community participation in decision making, federal institutional decentralization, community-lead support for infrastructure, and voluntary compliance with regulations are beginning to be recognized and promoted. Still, the main intellectual tools for implementing more sustainable resource practice are in large measure common sense and imagination. Compelling objective arguments, supported by focused research data, must be clearly presented to policy makers and the public to stimulate the practical pursuit of more sustainable resource management, recognizing its far-reaching implications for human culture.

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