DIRECTIONS IN DEVELOPMENT

Wastewater Treatment in Latin America

Old and New Options

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Cover photograph: Detail of low-cost wastewater treatment in Tenjo, Colombia. Courtesy of the Inter-American Development Bank.

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Foreword

Municipal water supply and wastewater systems are typically made up of four major components: water production, water distribution, wastewater collection, and wastewater treatment. There is little doubt that in Latin America and the Caribbean wastewater treatment has lagged far behind the other three components. Although the share of the urban population connected to public water supplies and sewerage systems in Latin America and the Caribbean is about 80 and 50 percent, respectively, less than 5 percent of municipal wastewater is treated at any level whatsoever.

Many large cities in the region, such as Bogotá, Buenos Aires, Lima, Mexico City, and Santiago, discharge almost all their wastewater into the environment virtually untreated. The once pristine rivers on which many Latin American cities were founded are now polluted with domestic and industrial waste. The rivers that at one time represented a source of beauty and pride have turned into health hazards, with their contaminated waters used for domestic water supply, irrigation, or recreation downstream of major wastewater discharge points. Mexico City and Santiago in particular are known for practicing large-scale irrigation of agricultural crops using river water containing large amounts of untreated sewage.

This unhealthy and unsustainable situation has largely resulted from the low priority given to wastewater treatment. More urgent needs of the population, such as the provision of potable water and the sanitary collection of sewage, prevail, and wastewater treatment is invariably deferred.

Undoubtedly, the debt crisis of the 1980s also played a role. Public austerity forced the postponement of wastewater treatment plants, whose construction often involves large capital investments. The construction of a conventional secondary wastewater treatment plant for a population of 1 million requires a capital investment of about

$100 million, and its subsequent operation and maintenance demand an additional steady and substantial expenditure. Such costs have in the past been difficult to recover through user charges when consumers do not perceive the benefits associated with such investments.

In addition, decisionmakers are usually faced with the difficult task of selecting the most adequate wastewater treatment method among a wide array of options. The large variety of old and new methods can be confusing even for the professional, let alone the nontechnical policymaker. This difficulty is compounded by the complex and variable nature of municipal wastewater, which contains both domestic and industrial wastewater, and by the continuous evolution of the standards established for the disposal and reuse of effluent.

The inability of public providers of water and sanitation services to respond to the growing threats to public health and environment has spawned a search for new alternatives. The most promising is the emergence of public/private partnerships, whereby the public sector redefines its traditional role of constructing wastewater treatment plants and providing water supply and sewerage services. While limiting its role to creating enabling legislative and regulatory frameworks, the public sector can encourage private firms to assume much of the responsibility for financing, building, operating, and maintaining wastewater treatment plants and water supply and sewerage systems in general.

The Technical Department of the Latin America and the Caribbean Region of the World Bank, together with host countries in the region, organized a series of seminars in 1995–96 to explore viable options to speed up wastewater treatment. The first such seminar took place in Santiago, Chile, in May 1995 and was cosponsored by EMOS, the municipal water supply and sewerage company of Santiago. The seminar was attended by professionals representing eight Latin American countries. A second seminar was organized in December 1995 in Campinas, Brazil, and was cohosted by the Secretaría de Política Urbana. A third seminar took place in Medellín, Colombia, in December 1996 and was cohosted by Empresas Públicas de Medellín.

These seminars focused on the technological and financial options available for municipal wastewater treatment and reuse. Invited speakers from the United States, the United Kingdom, Israel, and Latin American countries described traditional and innovative wastewater treatment and reuse schemes. In addition, a number of participants presented case studies of their own cities in Latin America. These included Buenos Aires and Mendoza (Argentina), Cochabamba (Bolivia), São Paulo (Brazil), Antofagasta and Santiago (Chile), Bucaramanga and Medellín (Colombia), Mexico City (Mexico), and Lima (Peru). Also discussed was the World Bank's technical and financial support of the wastewater sector development in Latin America.

The keen interest generated by these seminars within the Bank and in Latin America prompted the Technical Department of the Latin America and the Caribbean Region to prepare this publication. It reviews old and new technological as well as financial and implementation options available for wastewater treatment and reuse.

The general, simplified description of the available wastewater treatment technologies and implementation methods should interest both the professional and the nonprofessional, who will be obliged to devote more attention to wastewater treatment over the coming decade. We hope that this publication will clarify the debate and pave the way for investments in wastewater treatment to make up for the decades of neglect.

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Acknowledgments

Emanuel Idelovitch is presently an independent consultant. He was previously a staff member in the Latin America and the Caribbean Regional Office of the World Bank. He is now teaching a postgraduate class on wastewater treatment and reuse at the Faculty of Engineering of the Tel Aviv University in Israel. Klas Ringskog is the principal water specialist in the Technical Department of the Latin America and the Caribbean Regional Office of the World Bank.

A number of publications—too many to be listed—were used as general documentation for this report. However, one outstanding book deserves mention and has been consulted by many generations of sanitary engineers (including the authors of this publication) either as a textbook or for reference purposes: Metcalf and Eddy, Inc., *Wastewater Engineering: Treatment, Disposal, and Reuse* (1991).

The authors are grateful to all the speakers and participants who contributed to the World Bank wastewater treatment seminars held in Santiago, Chile (May 1995), in Campinas, Brazil (December 1995), and in Medellín, Colombia (December 1996).

Acronyms

BAYESA	Biwater Aguas y Ecología S.A.
BOL	build, own, lease
BOO	build, own, operate
BOOT	build, own, operate, and transfer
CTAPV	Compañía Tratadora de Aguas Negras de Puerto Vallarta
EMOS	Empresa Metropolitana de Obras Sanitarias [municipal water supply and sewerage company of Santiago, Chile]
ESSAN S.A.	[public company in charge of water supply and sewage disposal in Antofagasta, Chile]
GDP	gross domestic product
MERCOSUR	Mercado Común del Sur
NAFTA	North American Free Trade Agreement
RBC	rotating biological disks
SEAPAL-PV	Servicio de Agua Potable y Alcantarillado de Puerto Vallarta

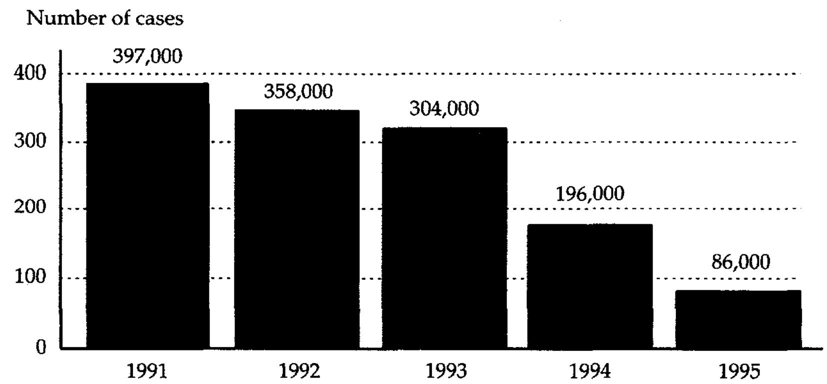
1
Introduction

After an absence of more than a century the scourge of cholera returned to Latin America in 1991. The detection of *Vibrio choleræ* in coastal Peru in January 1991 and the subsequent explosive epidemic throughout Peru proved to be only the start. Subsequently, cholera marched across Central and South America and has now become firmly established in a number of countries. It has appeared in all countries of the American continent with the exception of Canada and Uruguay.

The cholera epidemic did not occur because sanitary standards had suddenly deteriorated. It only proved what public health professionals had known all along: the deficiencies in potable water quality, public sanitation, and general hygiene were such that any water-related disease could establish itself overnight and then spread quickly. The decades of complacency and slow progress in increasing the coverage of water supply and sanitation came to fruition. The region was forced to acknowledge that more than 20 percent of the urban population was not connected to safe public water supply, that some 50 percent was not connected to public sewerage, and that virtually all municipal wastewater was disposed without treatment into natural water recipients.

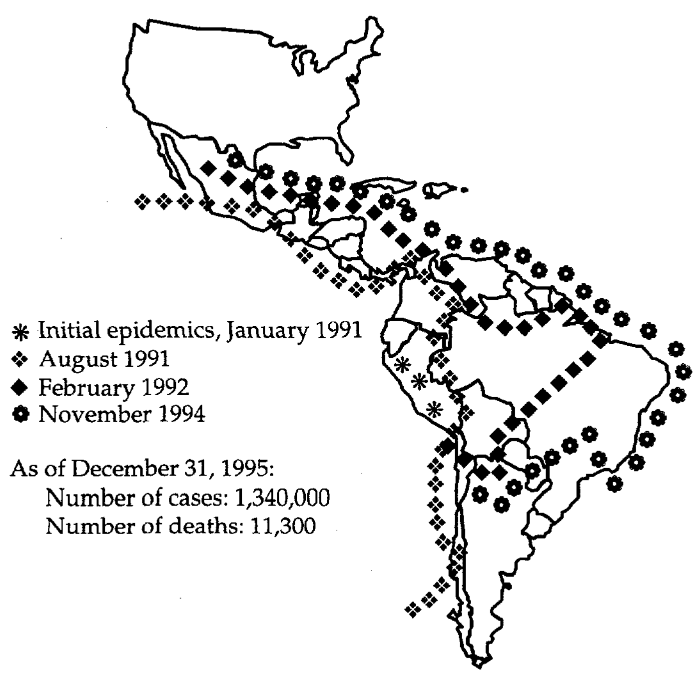
Like many other water-related diseases, cholera tends to be underreported. Even so, it is well documented that the epidemic has been costly for Latin America. From the start of the outbreak in 1991 through 1995 more than 1.3 million cases of cholera were reported, and total mortality was 11,300 deaths, about 1 percent of reported cases. The epidemic phase of the disease slowly receded, to be replaced by an endemic phase. From an annual high of nearly 400,000 cases in 1991, the incidence gradually dropped to less than 100,000 in 1995 (figure 1.1). Although the total number of cases is decreasing, the disease continues to spread geographically (figure 1.2).

Figure 1.1. Reported Cases of Cholera in the Americas, by Year, 1991–95



Source: Pan American Health Organization and World Health Organization 1996.

Figure 1.2. The Geographic Spread of the Cholera Epidemic in the Americas, 1991–95



2
Economic Aspects of Wastewater Treatment

The recent cholera epidemic serves as a grim reminder of the importance of wastewater treatment in the control and prevention of certain water-related diseases. Cholera and typhoid fever are both transmitted in a similar fashion through the "long cycle": *an infected individual* spreads the disease via *sewage,* which, if untreated and disposed inadequately, results in *water pollution.* Farmers often use polluted waters to irrigate food crops, such as in the arid areas around Lima, Mexico City, and Santiago. The long transmission loop is closed when individuals eat *food* that has been contaminated with polluted irrigation water or drink *water* that has been contaminated by sewage. More individuals fall sick, and the cycle is repeated.

The construction of sewerage systems alone cannot break this long cycle. Collecting the sewage of a city is of major benefit because it removes a potential health hazard from populated areas where the risk to public health is the greatest. But the threat to the population remains as long as the untreated wastewater is disposed into water recipients and then used to supply potable water or to irrigate food crops that are eaten raw.

Alternative on-site disposal systems such as dry latrines, cesspools, or infiltration wells used in conjunction with septic tanks do not remove the danger to public health either. Sewage from septic tanks may infiltrate the shallow groundwater from which potable water is extracted, resulting in groundwater pollution. In the short term, sewerage systems can even degrade the environment because piped collection and interception concentrate the sewage in a few disposal points. The end result is the deterioration of natural water recipients, such as rivers and lakes, whose natural purification capacity is exceeded.

The failure to treat wastewater is unsustainable. This was presumably evident in Western Europe and North America when these countries instituted large-scale wastewater treatment programs. Some 40 years later, Latin America is now facing the same situation: What is the optimal degree and technology of treatment? And how can the substantial financing needs be met at a time when pressing demands are threatening to crowd out funding for the wastewater treatment sector?

The Constituency of Wastewater Treatment

Large programs of wastewater treatment will not be implemented until a political constituency has been built to promote them and to secure the financial resources necessary for the first round of large-scale treatment works. Only recently has such a constituency begun to emerge in Latin America. Three groupings of opinion makers and lobbying groups favor sharply expanded wastewater treatment. The first group comprises officials and practitioners in the water supply and sewerage sector and public health officials who are fully aware that diseases are transmitted by the lack of wastewater treatment. The second group consists of related international businesses (agricultural exporters, contractors, and equipment manufacturers) that have a direct economic interest in wastewater treatment. The third group is formed by advocates of a sustainable environment, both individual consumers and representatives of government and nongovernmental organizations.

In recent years these three groups have been strengthened by the wave of democratization and the gradual opening of the region's economies, supplemented by regional trade agreements such as the North American Free Trade Agreement (NAFTA) and the Mercado Común del Sur (MERCOSUR) in the South. NAFTA in particular represents a determined effort to make major improvements in the environment.

The Public Health Costs of Water-Related Diseases

The 1991 cholera epidemic provided evidence of the very substantial costs associated with such explosive outbreaks. The direct and indirect costs of the Peruvian epidemic were particularly striking because they were so large in relation to the size of the economy. In Peru alone the costs were well in excess of the large number of cases registered. The economic impact was considerable. The country had to spend sharply more than usual in both curative and preventive health care. The high morbidity and the mortality of close to 3,000 persons implied a loss of economic production in addition to the suffering and hardship of the sick and their families. The losses affected the production destined for both domestic and external markets. Exports declined because of a temporary ban on imports of Peruvian food products and a drop in tourism.

Two available studies estimate the costs in Peru during 1991, the first year of the epidemic. The first study assesses the economic damage at about $500 million, while the second estimates losses at about $180 million (table 2.1; Petrera and Montoya 1991 and USAID 1993; all dollars are U.S. dollars). The estimates differ in how they quantify the economic losses due to higher morbidity and premature mortality and the losses in the tourism industry. The average of the two estimates yields a figure of about $340 million for the first year alone, or about 1.5 percent of Peru's gross domestic product (GDP).

The level of economic losses of 1.5 percent of GDP merits comparison with the level of investment in the Peruvian water supply and sewerage sector. Over the period 1971–78, Peru invested annually only $1.3 per capita in water supply and sewerage, equivalent to 0.18 percent of GDP. During 1985–89, at the height of the debt crisis of the 1980s, investments dropped further to only 0.15 percent of the country's GDP. Such low levels imply that the country was effectively disinvesting, because the annual investment was well below the level of capital stock depreciation. In addition, the sector agencies were chronically short of funds for operations and maintenance, which might ultimately have triggered the recurrence of cholera.

Table 2.1. Estimates of Total Economic Losses due to the Cholera Epidemic in Peru, 1991
(millions of U.S. dollars)

Type of losses	*Pan American Health Organization*	*USAID Water and Sanitation for Health Project*
Direct incremental health care	29	41
Lost production (morbidity and premature mortality)	260	85
Lost domestic production	47	27
Lost tourism	147	15
Lost exports	23	8
Total economic losses	506	176

Source: Petrera and Montoya 1991; USAID 1993.

In essence, by failing to invest at reasonable rates and to provide the funds and resources for safe operations, Peru exposed itself to water-related diseases. As a result, in the first year of the cholera epidemic alone, economic damage amounted to at least 10 times the level of sector investment. The achieved "economies" of deferring investment proved in the end to be penny-wise but pound-foolish.

Good Environmental Management and the Global Marketplace

The progressive integration of the Latin American and Caribbean economies with those of the Western Hemisphere and the global marketplace is a positive measure of how far the countries have come in making their exporting industries more competitive. However, in the short run the success of agricultural exports also means that the economies will have to use good environmental management as a competitive asset.

The point has not been lost on the countries in the region that have well-developed agricultural exports. Among others, Chile and Mexico cater to premium-priced off-season markets with high potential exports. Conversely, many years of efforts to develop markets could be lost if water-related epidemics close down exports. Agricultural interests are now pressing for better environmental management, including wastewater treatment.

The concern of agricultural exporters is acute because regional trading agreements such as the NAFTA are linked to improved environmental practices. The economic interests are not restricted to agricultural exports but span a number of exporting sectors, particularly tourism. The groups lobbying for improved environmental practices are not restricted to domestic producer and consumer interests. As the links with markets in industrial countries continue to grow, concerns about the health of agricultural workers in developing countries can be used to influence the consumers' choice of producers.

Growing Domestic Environmental Concerns

Most important, however, is the domestic awareness in all Latin America and Caribbean countries that gross contamination of rivers, lakes, and shorelines is unsustainable and exacts a heavy price on the health of the population and the aquatic ecosystems. Such environmental concerns are in part intuitive and in part based on empirical studies.

Studies are now available that show the impact of better sanitation on key welfare parameters such as infant mortality (Castañeda 1985). Although such studies have typically related health parameters to the coverage of public water and sewerage systems, it stands to reason that wastewater treatment is of considerable importance.

The Municipalization of Water and Wastewater Services

The trend in almost all Latin America and the Caribbean is to assign municipalities a greater role in the provision of a series of services. In recent years the legislation has changed so that, typically, municipalities are legally obliged to provide water supply and sewerage services, either directly or by delegating the responsibility to specialized public or private companies. In the short term the trend toward municipalization has created problems because the transformation has often been enacted overnight and has not allowed municipalities the time to prepare themselves for the added responsibilities.

The case of wastewater treatment is of particular concern because it is a technically sophisticated service for which qualified and experienced operators are scarce. Moreover, a particular municipality may be tempted to dispose its liquid waste in a river or lake without any treatment whatsoever. However, downstream communities suffer, and over time the natural self-purification capacity of recipients is exceeded. With worsening water quality, municipalities abstracting water downstream of the point of untreated effluent discharges incur steadily rising costs to make the water potable, without the certainty that all contaminants of importance have been removed. Under these circumstances it will become more and more cost-effective to treat wastewater and thus avoid the higher costs of treating potable water. It is well known that preventing contamination is a more economical and safer measure than correcting the damage after rivers and lakes have been polluted.

The special problems created by nonpoint-source pollution from agriculture and other diffuse sources are more difficult to address than the point-source pollution of urban wastewater. The nonpoint-source pollution will have to be reduced in parallel, but the measures will be different in nature and will focus more on modified techniques for applying fertilizer, herbicides, and pesticides and, ultimately, on modified methods of agricultural cultivation.

Given the substantial external costs of pollution, the municipalization of wastewater management has put a premium on solutions that are environmentally sustainable for entire river basins. River basin authori-

Table 2.2. Population Served with Public Water Supply and Sanitation in Latin America and the Caribbean, by Country, 1995

	Population (millions, rounded)		*Drinking water (percentage of houses connected)*		*Public sanitation (percentage of houses connected)*	
Country	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*	*Rural*
Argentina	30.3	4.1	68	24	39	42
Bahamas	0.3	..	88	86	16	100
Barbados	0.1	0.2	98	98	4	98
Belize	0.1	0.1	89	51	44	21
Bolivia	4.2	3.0	74	42	41	39
Brazil	124.5	37.2	74	28	35	43
Chile	12.2	2.0	99	47	79	7
Colombia	26.4	10.3	86	32	65	27
Costa Rica	1.5	1.6	100	99	55	95
Dominican Republic	5.2	2.9	56	55	28	68
Ecuador	6.5	4.7	79	10	61	26
El Salvador	2.7	3.4	78	24	60	65
Guatemala	4.2	6.1	84	48	70	50
Guyana	0.3	0.5	77	69	27	28
Haiti	2.2	4.9	29	39	—	16
Honduras	2.8	3.1	77	66	50	71
Jamaica	1.4	1.1	57	53	34	65
Mexico	68.1	22.7	93	57	81	29
Nicaragua	2.5	1.6	86	28	34	28
Panama	1.6	1.4	98	73	64	81
Paraguay	2.6	2.4	59	6	20	44
Peru	16.8	6.6	63	31	59	23
Suriname	0.3	0.1	95	70	2	36
Trinidad and Tobago	0.9	0.4	90	88	32	92
Uruguay	2.7	0.3	90	—	56	—
Venezuela	19.8	1.7	73	79	62	60
Total	340.2	122.4	79	39	52	39

— Not available.
.. Negligible.
Source: World Bank estimates based on survey data from the Pan American Health Organization.

ties are now being considered and set up in a number of countries such as Brazil, Chile, and Mexico. Although embryonic, they offer considerable promise. They are loosely patterned on the German and French models, where the objective is to optimize the sustainable use of water resources in the basin. The key is to implement the "polluter pays" principle, whereby users of water are charged for the water they extract and for the pollution they cause. The experience so far with attempting to optimize the use of water has been mixed. Environmental concerns have been subordinated to the interests of producers of hydro-based electricity and to the interests of agriculture.

Levels of Urbanization, Water Supply, and Sewerage

Latin America and the Caribbean is the most urbanized region in the developing world. In 1994 the urban population was estimated to be about 74 percent and increasing. Such high levels of urbanization drive the need for sewage collection and treatment. Individual wastewater collection and disposal on the premises may be acceptable for some time in low-density rural and urban areas, but as population density and water use increase, the feasibility of individual or on-site disposal systems recedes, and collection and disposal become a public concern.

The sequence of public investments is well known. The coverage of piped water supply service increases, which prompts the need for a sewerage system. The sewage is collected and disposed first in nearby recipients and lakes and then farther and farther away from populated areas. Eventually, sewage has to be treated to remove the polluting substances so that the capacity for natural purification of the recipients is not exceeded.

Water Supply Levels

Latin America and the Caribbean has progressed far toward offering high coverage of both water supply and sewerage. In 1995 about 79 percent of the urban population lived in homes individually connected to piped water. In absolute number this meant that about 270 million out of an urban population of 340 million had piped water. Table 2.2 provides detailed estimates of the level of water supply service for the 26 largest countries in the region.

The service levels reported by the countries should be taken for what they are: estimates of varying quality. In past years individual countries have reported sharp changes from one year to the next, pointing to possible changes in definition. Definitions also may vary between countries and, thus, inter-country comparisons should be treated with caution.

Sewerage Levels

The level of sewerage coverage lags behind the level of water supply service by a wide margin. For the same year (1995), the urban population connected to public sewerage was estimated at about 52 percent. This means that about 180 million of the total urban population of 340 million had public sewerage. Almost 100 million people lived in homes connected to water, but not to public sewerage systems. The estimated level of sewerage service for the 26 largest countries in the region is detailed in table 2.2.

Wastewater Treatment Levels

The treatment of collected wastewater has hardly been initiated in Latin America and the Caribbean. Wastewater treatment plants are few and far between in almost all countries in the region. Few plants are operated properly. One evaluation of existing sewage treatment plants in Mexico estimates that only about 5 percent of the existing plants are being operated satisfactorily.

Less than 5 percent of all wastewater collected receives any form of treatment whatsoever. Because only about half of the urban population has sewerage and less than half of the wastewater generated is collected, a negligible percentage of the total volume of wastewater generated is treated.

Access to Safe Water and Sanitation Services for the Poor

In Latin America, approximately three-quarters of the population inhabit urban areas. Out of these one-third live below the absolute poverty line. This share of the population is growing. The urban poor lag significantly in the availability of safe water and sanitation services. In Latin America, only 18 percent of the urban low-income population has an in-house connection to safe water, compared with more than 80 percent of the urban high-income population. Similar results are found in the access to sanitation services. Improving the situation will be difficult because the urban poor often inhabit squatter settlements located on sites unsuitable for conventional development (steep hillsides, swamps, flood plains).

The skewed provision of services to the urban poor is not just a low-income country phenomenon. Colombia, a middle-income Latin American country, provides a good example. In 1992, 95 percent of the highest-income quintile lived in homes connected to the water supply compared with 62 percent of the lowest-income quintile. The situation was even more skewed for sewerage: an estimated 90 percent of the highest-income quintile was connected to a sewerage system compared with only 35 percent of the lowest-income quintile (Velez 1996).

The unequal access to public water and sewerage has implications for public health as well as for the human suffering that results from higher morbidity. The poor are more likely to have lower levels of sanitary education as well, and the result is a higher incidence of water-related diseases. This incidence will likely only be reduced through a three-pronged effort to improve the provision of potable water, the provision of sewerage, and the provision of extended sanitary education.

Past and Needed Investments in the Sanitation Sector

The return of cholera proved that the water supply and wastewater sector was investing well below what was needed to sustain service, let alone to expand coverage and improve quality. In retrospect the 1960s were dynamic years for the sanitation sector, in which relatively large investments were financed with national savings supplemented by bilateral and multilateral funds.

The trend of relatively high investment activity continued in the 1970s. The Latin America and Caribbean region invested on the order of $4.4 billion annually, in 1993 prices, in both water supply and sewerage. This level of investment constituted approximately 0.4 percent of regional GDP. Very little was invested in wastewater treatment, however. As a result, by 1978 about 68 percent of the total urban population was connected to public water supplies, and 36 percent was connected to public sewerage (Ringskog 1980).

The 1980s bore the consequences of the regional debt crisis. Investments were sharply reduced, and funds for operations and maintenance did not keep up with needs. Regional investments dropped to about $2 billion (1993 prices), equivalent to about 0.2 percent of regional GDP. All the same, the shares of the urban population connected to public water supplies and public sewerage slowly crept up to 79 and 52 percent, respectively, by 1995. In contrast, very little was invested in wastewater treatment.

As part of an initiative to raise the level of operating efficiency and service, the World Bank has estimated that about $12 billion annually would be required to raise water supply and wastewater standards to reasonable levels over a ten-year period (World Bank 1995): $5 billion for water supply and $7 billion for wastewater. Out of the annual wastewater investments of $7 billion, about $4.4 billion would be for sewage collection, $1.2 billion for wastewater treatment, another $1.2 billion for rehabilitation of existing but deteriorated installations, and the balance of $0.2 billion for rural sanitation.

These estimates assume that wastewater would be treated for 60 percent of the persons with public sewerage at an average cost of $70 per capita. These investments would be modest compared with the need for wastewater collection, but they represent a considerable increase from past levels. The construction and operation of wastewater treatment schemes would benefit both from technological advances and from the increased interest of private sector firms attracted to undeveloped markets in Latin America and the Caribbean. Supported at times by financing tied to the sale of equipment, foreign-integrated private firms could play an important role in allowing the region's countries to acquire cost-effective technology.

At the same time, countries need to develop the expertise needed to select between different treatment technologies in such a way as to dovetail with their capacity to pay for and operate the treatment works that will be built over the coming decade. The ability to select optimal treatment technologies requires a better understanding of the technological options available.

3
Technological Options

Selecting the appropriate process for treating a city's wastewater entails a careful process in which technical, economic, and financial considerations come into play. The uniqueness of each situation makes it difficult to define a universal method for selecting the most adequate type of wastewater treatment plant.

Ten Steps for Selecting the Most Appropriate Treatment Scheme

In most situations, the process of planning wastewater treatment involves ten major steps:

1. Determine the flow of wastewater
2. Determine the composition of wastewater
3. Determine standards for disposing or reusing effluent
4. Identify objectives and alternative processes for treating effluent before disposal or reuse
5. Determine the quantity and quality of sludge for each process
6. Determine standards for disposing or reusing sludge
7. Identify alternative processes for treating and reusing sludge
8. Identify alternative sites for treating, disposing, or reusing effluent and sludge
9. Determine the need for pilot studies and industrial pretreatment programs
10. Evaluate the technical and economic feasibility of each alternative and select the most attractive scheme.

Some of these steps are straight-forward, such as determining the flow and composition of wastewater. Others are much more involved and require considerable expertise, such as determining the appropriate standards and examining alternative technologies for treating wastewater and the sludge produced during the liquid treatment. Both conventional and innovative methods should be evaluated. The exception would be where land is so scarce and costly that land-intensive but capital-extensive technologies can be ruled out early on.

Step One: Determine the Flow of Wastewater

Determining the correct flow of wastewater to be treated is fundamental to estimating the scale of investments required. For this reason, the projections of wastewater flow should be based on adequate field measurements and should be linked explicitly to the city's investment program in expanding its water supply and sewerage collection systems.

It is necessary to assess early on whether the existing data on water production and consumption are realistic and whether they will remain valid in future years. Where the pattern of water consumption is wasteful, it is important to manage demand in order to reduce per capita consumption to reasonable levels and then to base the investment in wastewater treatment on the expected results of the effort to reduce wastage. Two variables are key to managing demand. The first is the extent of metering. Experience has taught that consumption is about 40 percent lower with metering than without it.

Similarly, the water tariff has a bearing on the amount of wastewater generated. The so-called price elasticity of demand measures the percentage change in the level of water consumption divided by the percentage change in the tariff. Its value varies with the type of consumption, among other things. Numerous studies have estimated the value of price elasticities (see, for instance, Cestti, Yepes, and Dianderas 1996). Long-term price elasticity of domestic demand has been found to be on the order of –0.4, showing that a doubling in real prices of the tariff can be expected to reduce per capita consumption 40 percent. The corresponding elasticities for different types of commercial and industrial consumers are even more significant, with values ranging from –0.6 to –1.2. These values are significant enough to be taken into account in the projections of future wastewater flows.

The counterbalancing effect of higher income on water consumption should not be forgotten. The analogous income elasticity of water demand measures the percentage change in per capita consumption divided by the percentage change in per capita income. Its value has been estimated at +0.3, showing that consumers are quick to add water-consuming fixtures and appliances as their income levels climb.

The level of the tariff is not the only determinant of the volume of wastewater generated; the structure of the tariff also has a bearing. The environmental impact of industrial effluents depends on their quality, the presence of toxic substances, and the location of the discharge, in addition to their quantity. For this reason pollution charges are often imposed as a binomial, where the total charge varies with the amount of pollution and the volume of wastewater. This gives polluting firms an incentive to reduce both their pollution loads and their volume of wastewater. In three industries in São Paulo, Brazil, the introduction of effluent charges reduced the consumption of industrial water 40–60 percent within two years.

Finally, the determination of wastewater flow will have to be closely linked to future coverage of the wastewater collection system.

Step Two: Determine the Composition of Wastewater

Wastewater comprises the water supplied for domestic, commercial, or industrial uses plus the contaminants added through that use. Wastewater may also contain storm water that has reached the sewerage system as well as groundwater that has infiltrated the underground sewage pipes. Domestic wastewater consists of about 99.9 percent water and 0.1 percent solids; the latter corresponds to a concentration of total solids of about 1,000 milligrams per liter or parts per million, which is typical for medium-strength municipal sewage. The solids in wastewater include settleable solids—large particles, which can be removed rapidly by gravity; suspended solids, which can also be removed by gravity but require longer settling times; colloidal particles, which can be removed from wastewater only by chemical coagulation or biological degradation; and dissolved solids. The concentration of suspended solids is a common parameter used to indicate the general quality of wastewater and level of treatment needed.

Most of the impurities in sewage are organic in nature. They include the main organic groups (proteins, carbohydrates, fats, and oils); some environmentally important substances, such as detergents, pesticides, and phenols; and numerous synthetic chemicals. Contrary to general belief, synthetic chemicals are generated not only by industries but also by households, which are using more and more household cleaning products that contain them.

Because of their great number and large variety, organic substances in wastewater are difficult to identify and measure. Only the concentration of certain organic compounds can be determined, and this requires sophisticated and costly techniques such as mass spectrophotometry, gas or liquid chromatography, and other emerging techniques. Therefore, for practical purposes, surrogate parameters are used to assess the concentration of organic substances in wastewater. The most common of these parameters are biochemical oxygen demand and chemical oxygen demand. Wastewater also contains inorganic substances as well as a large variety of microorganisms, including bacteria, helminths, and viruses, some of which are pathogenic to man.

Municipal wastewater from medium and large cities always contains a certain amount of industrial wastes that must be well known and characterized. If needed, industrial pretreatment should be imposed in order to ensure that the treatment plant will function properly.

Step Three: Determine Standards for Disposing or Reusing Effluent

Wastewater treatment is generally aimed at producing an effluent that complies with standards or guidelines for discharge into water bodies such as rivers, lakes, or oceans. When the effluent is to be reused, its quality must comply with standards set up for a specific purpose (irrigation, industrial, recreation, groundwater recharge).

The main objective of wastewater treatment depends to a great extent on the destination of the final effluent and the quality required by that destination. The common objectives, which are related to both aesthetic and health concerns, are to remove floatable material, suspended solids, biodegradable organic substances, and pathogenic organisms. A more recent objective is to remove nutrients (nitrogen and phosphorus), when the effluent is discharged into lakes or reservoirs. This prevents or limits the growth of aquatic plants and the proliferation of algae, which deteriorate the quality of the receiving water. Another objective is to remove toxic compounds, such as certain heavy metals and refractory organics, which must be treated by advanced methods, especially when the effluent is intended for reuse.

Quality standards are usually set up for industrial wastewater discharged into municipal sewerage systems, in order to ensure that heavy metals or other wastewater contaminants generated by industrial activity do not reach levels that may damage pipes, inhibit the biological treatment processes, remain in the effluent in higher concentrations than permitted, or accumulate in the sludge and limit or even prevent its disposal or reuse. The establishment of industrial discharge standards is important in order to promote industrial pretreatment programs and control certain industrial discharges, which may be critical for the operation of wastewater treatment plants.

The most common parameters used for monitoring the compliance with effluent discharge standards are the biochemical oxygen demand, suspended solids, and dissolved oxygen. As already indicated, biochemical oxygen demand is a surrogate parameter reflecting the content of biodegradable organic matter and the level of treatment achieved. Suspended solids measure the concentration of particulate matter in sewage, most of which is of organic nature. Dissolved oxygen levels are important mostly in connection with bodies of water used for fishing, because minimum levels are required for normal activity of fish.

The adoption of suitable effluent standards for each situation is critical in wastewater treatment in developing countries. Some countries have adopted no official standards at all, whereas others have adopted unrealistic standards established in the industrial world. The complexity of establishing rational effluent standards is best illustrated by the level of dissolved oxygen, which will eventually determine the acceptable level of biochemical oxygen demand in the effluent. First, the minimum level of dissolved oxygen required is not constant: it varies roughly between 2 and 5 milligrams per liter, depending on the fish species involved. Second, it depends on temperature. Fish require more oxygen at higher temperatures, which is when oxygen in water is less soluble. And third, lower concentrations of heavy metals are toxic to fish at lower levels of dissolved oxygen than at saturation levels. The self-purification capacity of rivers and the dilution of the effluent with the flow of natural water in the river must also be considered when setting up discharge standards. The river flow is constant when the river is regulated by an upstream reservoir, but in most cases there is a considerable difference between flows during dry and wet weather.

Step Four: Identify Objectives and Alternative Processes for Treating Effluent before Disposal or Reuse

Alternative treatment processes can be identified based on the quality of influent wastewater and the desired quality of effluent. The large variety of treatment methods include both old, traditional processes still in use as well as new, innovative processes.

Wastewater treatment is generally required to avoid or at least reduce the hazards created by the disposal of untreated wastewater into receiving waters or onto land. These hazards include aesthetic nuisances caused by large, floatable solids; malodorous gases released during decomposition of organic matter; pathogenic microorganisms that represent a public health risk; the growth of aquatic plants in receiving waters caused by nutrients; compounds that are toxic to people, animals, or crops; and adverse conditions such as the lack of oxygen in receiving waters.

It is particularly important to treat wastewater that is discharged into receiving waters used for drinking water downstream of the discharge site. Conventional drinking-water treatment technology cannot remove all the organic contaminants remaining in water after conventional wastewater treatment and after the self-purification and dilution in natural water courses. Some of these contaminants may have short- or long-term adverse effects on human health.

Similarly important is the treatment of wastewater destined to irrigate crops such as vegetables and fruits that are consumed uncooked. Even when waters such as rivers or oceans are used only for recreational purposes, adequate wastewater treatment must be provided. The common practice of discharging wastewater into the sea or ocean may adversely affect not only the use of beaches for recreational purposes but also the production of fish and shellfish consumed as a source of protein by humans and animals.

The particular case of industrial wastewater or of municipal wastewater with unusually high percentages of industrial discharges may require special analyses and the adoption of specific treatment processes for removing certain contaminants. In most cases, however, wastewater treatment methods and objectives are universal and have changed little in the last few decades.

Step Five: Determine the Quantity and Quality of Sludge for Each Process

Sludge—the by-product of almost any wastewater treatment process—must be quantitatively and qualitatively characterized for each process considered. There is a close connection between the treatment of liquid and the treatment of sludge. The optimization of a wastewater treatment plant refers to the treatment of both, which should minimize the quantity of sludge produced and yield a sludge cake of the highest possible quality, meaning as stable (minimal concentration of organic matter and pathogens) and as dry (maximum solids content) as possible.

Step Six: Determine Standards for Disposing or Reusing Sludge

There is growing concern that the standards for disposing sludge safely are as important as the standards for treating effluent. The setting up of sludge standards is a relatively new development even in industrial countries such as the United States. It is the result of the recent ban on dumping sludge in the ocean and growing awareness that global environmental protection can be achieved only by imposing limits on the disposal of both effluent and sludge.

Step Seven: Identify Alternative Processes for Treating and Reusing Sludge

Alternative treatment processes can be identified based on the quantity and quality of sludge produced by the plant and the quality of the sludge cake to be obtained after treatment. A sludge cake (semisolid sludge) is the output of the sludge treatment plant, because dewatering (extracting water from the sludge) is normally included in any treatment scheme. Without dewatering, transporting sludge to the final disposal or reuse site is generally not economical.

Step Eight: Identify Alternative Sites for Treating, Disposing, or Reusing Effluent and Sludge

After determining the specific destination of the treated effluent and sludge (disposal or reuse) and the alternative processes that would be considered, specific sites must be identified for the effluent and sludge treatment plants as well as for the final disposal or reuse of the two products (effluent and sludge).

Step Nine: Determine the Need for Pilot Studies and Industrial Pretreatment Programs

It is then necessary to determine whether laboratory or field studies should be undertaken for some of the processes considered. Such studies are usually needed for evaluating new processes and equipment, for which experience is still scarce but that seem promising for the conditions of the project, as well as for confirming or determining the performance of a certain process under the conditions prevailing in the project area (for example, temperature).

In large cities, where industries contribute a significant amount of wastewater, the enforcement of industrial pretreatment programs is essential for the successful operation of any treatment plant. The importance of such programs cannot be overemphasized in cities with large wastewater treatment programs. The main elements of a successful industrial pretreatment program are the following:

- A discharge inventory and information system
- An industrial discharge permit system establishing limits for discharging into sewers and requirements for presenting a compliance plan
- Self-reporting requirements that involve the use of certified laboratories
- Inspection and monitoring by the wastewater authority
- Sanctions for noncompliance
- Sewer use tariffs based on both the volume discharged and the organic load
- Industrial participation, for example, through a joint water quality council, in all phases of the program, including design, the setting of standards, and implementation
- Some form of technical and financial assistance for industries, particularly small and medium enterprises.
- A training and institutional development program to help the wastewater authority prepare itself in this new area of responsibility
- Close and well-defined coordination with the environmental regulator responsible for ensuring that industrial wastes are not discharged into sewers as well as for the correct disposal of effluent and sludge.

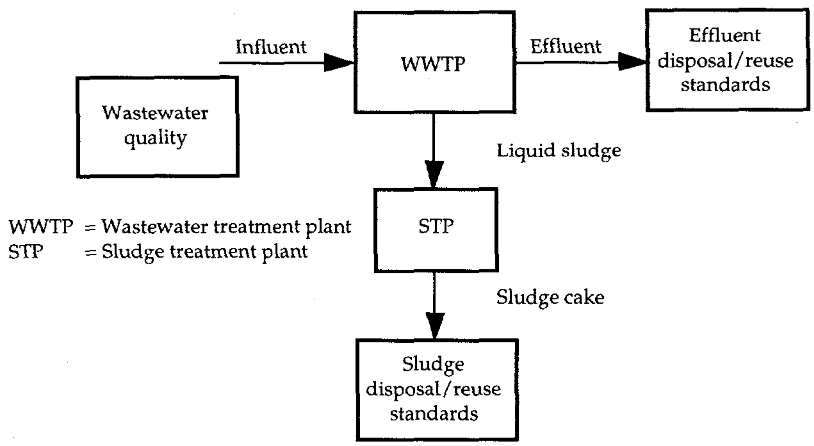
Step Ten: Evaluate the Feasibility of Each Alternative and Select the Most Attractive Scheme

The alternatives considered suitable for the project must be submitted to a full technical and economic feasibility analysis. The most attractive scheme is then selected based on preliminary designs and cost estimates. The present value of both capital investment costs and annual running costs must be taken into account. Other important factors must also be considered such as the environmental impact of the plant, the complexity of its operation, and its compatibility with existing installations.

Wastewater Treatment Methods

In a simplified manner, wastewater treatment should be regarded as two boxes, whose contents must be adequately defined (figure 3.1): the effluent or liquid treatment and the treatment of its by-product, sludge. Wastewater treatment methods are usually classified into four categories, in accordance with the order in which they were developed and applied and the degree of treatment they provide: preliminary or pre-

Figure 3.1. Wastewater and Sludge Treatment



treatment, primary treatment, secondary treatment, and tertiary or advanced treatment.

In the case of conventional methods, this classification is clear and adequate, because each stage of treatment refers to a well-defined technological process or processes. Pretreatment refers to the processes that remove large objects and usually includes at least bar screens and grit chambers. Primary treatment usually consists of primary sedimentation tanks, where particles settle as a result of gravity. Secondary treatment refers to biological methods such as activated sludge or trickling filters. Tertiary or advanced treatment generally refers to chemical methods that remove nutrients or toxic compounds or improve the overall quality of the secondary effluent.

This terminology may be confusing when unconventional treatment processes are used. Recent modifications of the most common secondary treatment method—the activated sludge—include the capability of removing nitrogen and phosphorus by biological processes, whereas chemical precipitation can be used not only as tertiary treatment but also as an enhancement of primary treatment or simultaneously with biological treatment. In such cases, the terminology should reflect the nature of the process, not its sequential order. For this reason, treatment methods are best classified as physical, biological, or chemical processes. Physical processes include screening, mixing, sedimentation, and filtration. Biological processes include all the aerobic and anaerobic processes whereby treatment is carried out by microorganisms. Chemical processes include flocculation, precipitation, and disinfection. A brief review of conventional wastewater treatment processes is given in the appendix. Several innovative wastewater processes developed recently and old natural processes adapted to modern use are described below.

Chemically Assisted Primary Sedimentation

Chemical treatment of wastewater is not a new idea. The process was known before biological treatment methods were developed but lost its popularity with the development of biological treatment methods such as trickling filters and activated sludge. When it became necessary to remove phosphorus at many treatment plants, tertiary chemical treatment (following biological treatment) regained part of its past popularity. Following the success of chemical precipitation in removing phosphorus, chemically assisted primary precipitation was also introduced, either to remove phosphorus or simply to enhance the removal of suspended solids and biochemical oxygen demand (see table 3.1). Numerous plants in Europe and the United States have recently implemented chemically assisted primary sedimentation.

Nitrogen Removal by Biological Methods

Because nitrogen removal by chemical methods such as ammonia stripping following high-lime treatment, ion exchange, or breakpoint chlorination is costly, an important research effort was made in the last decades to develop biological methods for removing nitrogen. These efforts were successful and brought about a series of modifications of the conventional activated-sludge process, which include either nitrification alone or nitrification combined with denitrification.

Although conventional activated sludge removes only the carbonaceous oxygen-demand substances (organics), incorporating nitrification

Table 3.1. Removal Efficiencies of Conventional and Chemically Assisted Primary Sedimentation
(percent)

Parameter	*Conventional*	*Chemically assisted primary sedimentation*
Suspended solids	50–60	80–90
Biochemical oxygen demand	30–40	50–80
Phosphorus	10–20	70–90

Table 3.2. Effluent Qualities of Conventional and Modified Activated-Sludge Processes
(concentrations in milligrams per liter)

Parameter	*Conventional*	*Modified biological nutrient removal*
Suspended solids	20–30	10–15
Biochemical oxygen demand	20–25	10–15
Chemical oxygen demand	80–120	40–60
Total nitrogen	30–50	3–10
Phosphorus	10–20	1–5

into the process (in either a separate or the same tank) can remove noncarbonaceous oxygen-demand substances such as ammonia and organic nitrogen. A small portion of the ammonia is removed, while the remaining ammonia is converted into the less harmful, oxidized nitrogen compound—nitrate (NO_3). The amount of energy consumed and the volume of tank required are higher in the nitrifying activated-sludge process than in the conventional process.

The more sophisticated nitrification-denitrification process includes not only the oxidation of ammonia to nitrate but also the biological conversion of nitrate into nitrogen gas that is released into the atmosphere.

Combined Nitrogen and Phosphorus Removal by Biological Methods

Perhaps the most interesting modification of the activated-sludge process is the simultaneous biological removal of nitrogen and phosphorus. This has been carried out successfully at several plants, where phosphorus is removed by bacteria, where biological denitrification takes place, and where carbonaceous organic substances are removed. There are several proprietary processes for this method and many alternatives, one of which has been applied in the large wastewater treatment and reuse plant in Tel Aviv, Israel. The results obtained with the modified process are compared with those obtained with the conventional activated-sludge process in table 3.2.

Natural Wastewater Treatment Processes

Most wastewater treatment processes are, in fact, man-made developments of natural processes. The two most common examples are the settling of suspended particles due to gravity and the biodegradation of organic substances performed by microorganisms.

Gravity particle settling occurs in almost all wastewater treatment installations. In grit chambers, it removes sand, silt, and those organic particles that settle like sand. In primary sedimentation tanks, gravity settling, assisted by natural flocculation, is the principal mechanism that removes particulate matter. In secondary sedimentation basins, it separates and settles the biological floc formed in the aeration tank. In chemical precipitation processes, it removes the chemical floc formed during coagulation and flocculation. And in all of these installations, as well as in sludge thickeners, it concentrates solids and separates water from solids. All sedimentation processes seek to produce simultaneously a clarified effluent and a concentrated sludge. Grit chambers, primary sedimentation, and chemically assisted primary sedimentation were developed from the natural processes of particle flocculation and gravity settling.

In all biological treatment methods, either aerobic or anaerobic microorganisms degrade organic matter present in wastewater and sludge. The activated-sludge process was developed based on observations of self-purification in rivers, where aerobic bacterial degradation occurs using natural sources of oxygen. Anaerobic sludge digestion was developed based on observations of anaerobic bacterial activity in river sediments. Trickling filters evolved from the disposal of wastewater on land, which was common practice at the end of the last century. And the process of disinfection was introduced after observing the natural decay of pathogenic organisms.

But along with the impressive advances and developments in man-made wastewater treatment processes in the last decades, some natural, old treatment systems are still being used successfully and should be considered as alternatives. However, most of these natural systems require large extensions of land, which may limit their applicability to small and medium-size cities.

Besides soil absorption, which is the natural process used in on-site disposal systems (cesspools and septic tanks), there are three major groups of natural wastewater treatment systems: stabilization ponds, land treatment systems, and aquatic systems. Stabilization or oxidation ponds are used extensively in Latin America and elsewhere. The great variety of pond combinations in use makes any systematic classification difficult. In principle, natural (nonaerated) ponds can be aerobic, facultative, or anaerobic. Aerated ponds—a man-made development of aerobic ponds—reduces the amount of land required by adding artificial aeration.

The great advantage of ponds over other treatment processes is their ability to remove pathogens without the need for chlorination, if the detention time of the effluent in the ponds is sufficient. Other advantages include their low capital investment and operating costs and their simple operation and maintenance. Their main drawback is the large extension of land they require, which makes them less suitable for large cities than for small and medium-size localities. One of the main dilemmas facing some Latin American cities is the choice between a conventional wastewater treatment plant of the activated-sludge type and lagoons, which are cheaper to build but require large extensions of land that may be unavailable or expensive. A relatively new system of natural stabilization ponds used extensively in Israel, and also in Spain, California, and Santiago, Chile, is the deep reservoir treatment, which consists of a deep stabilization pond (8–12 meters deep) used for both seasonal storage and effluent purification.

Land treatment systems are usually classified into three categories. Slow-rate systems refer to vegetation or crop irrigation using effluents; rapid infiltration or soil-aquifer treatment refers to groundwater recharge with effluent via spreading basins; and overland flow consists of spreading the effluent over sloped land covered with vegetation and collecting it at the bottom of the slope as surface runoff.

Aquatic systems usually include ponds with water hyacinth or duckweed, which have the capacity to absorb nutrients, heavy metals, and other sewage contaminants, and natural or man-made wetlands.

Sludge Treatment

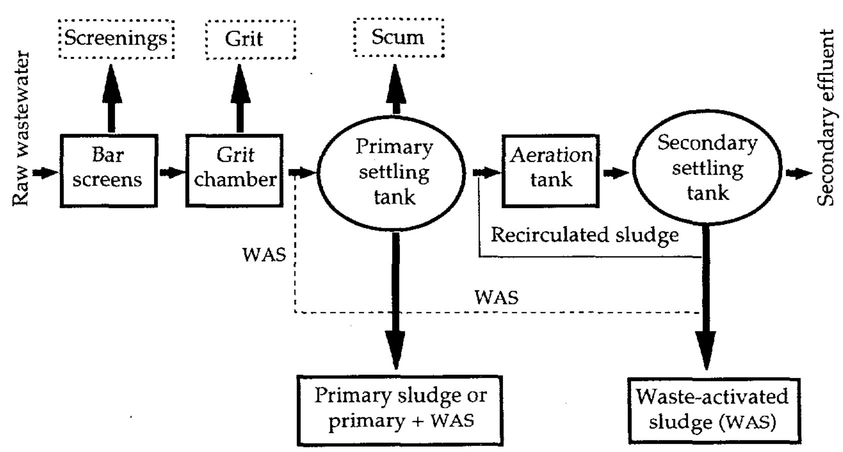
The most neglected aspect of wastewater treatment is the treatment and disposal of its main by-product—sludge. Sludge, which accounts for less than 1 percent of the wastewater flow, represents 50 percent of the treatment cost and 90 percent of the day-to-day problems for plant operators. Indeed, no wastewater treatment is complete without adequate handling and safe environmental disposal of the various types of sludge produced.

Preliminary treatment generates only a small amount of residuals, which include screenings removed from bar screens and grit removed from grit chambers. Primary treatment generates large amounts of primary sludge that are removed periodically from the bottom of the primary sedimentation tanks as well as minor quantities of oil, grease, and scum that are skimmed from the top of the primary sedimentation tanks. Biological treatment by the activated-sludge process generates large amounts of biological sludge that must be removed from the system continuously.

A distinction must be made between the main sludge produced in large quantities and the minor residuals produced in relatively small quantities (figure 3.2). The minor residuals are usually disposed on land in the vicinity of the plant or transported to the municipal refuse disposal site.

Primary and waste-activated sludge are voluminous mainly because they contain large quantities of water in addition to the solids removed during the treatment process. The typical concentration of solids in primary sludge is 4–8 percent. When waste-activated sludge is returned to the plant inlet and settles with the primary sludge in primary sedimentation tanks, the concentration of solids in the combined sludge is slightly lower (3–6 percent). The concentration of solids in waste-activated sludge is much lower—usually between 0.5 and 1.5 percent. When primary sedimentation is excluded from the activated-sludge process (such as in extended aeration systems), the concentration of waste-activated sludge is slightly higher—between 0.8 and 2 percent. These figures explain why the primary goal of sludge treatment is to concentrate the sludge, that is, to reduce its water content and volume. Almost all sludge treatment plants include sludge thickening and dewatering facilities to achieve this goal. Doubling the concentration of sludge solids—for example from 1 to 2 percent or from 3 to 6 percent—reduces the volume of sludge to half.

Figure 3.2. Sludges and Minor Residuals in Conventional Treatment

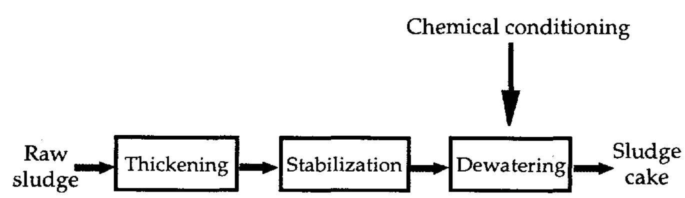


In addition to thickening and dewatering, sludge treatment also includes stabilization, which destroys volatile organic matter to minimize bad odors and reduce the number of pathogens. Stabilization is usually accomplished by biological methods (anaerobic digestion or aerobic oxidation) or by chemical methods such as lime stabilization. Stabilization also reduces the volume of sludge because some of the organic solids are destroyed in the process.

While thickening precedes stabilization, dewatering usually follows it (figure 3.3). Thickening is usually accomplished by gravity or by dissolved air flotation. Thickening is suitable for primary sludge, whereas dissolved air flotation may be efficient for waste-activated sludge, which is less concentrated and consists of lighter particles that may be easier to flotate than to settle by gravity. Thickening the waste-activated sludge, for example, can increase the concentration of solids from 0.5–1.5 percent to 2–3 percent.

Dewatering can be accomplished by natural methods or by mechanical means. Natural methods include sludge drying beds and lagoons. Some of the most common mechanical types of equipment used for dewatering are vacuum filters, pressure filters, belt filter presses, and centrifuges. Mechanical dewatering must be aided by conditioning the sludge chemically prior to dewatering. Chemicals used to improve dewatering include iron salts such as ferric chloride, lime, and polyelectrolytes. Dewatering the sludge with chemical conditioning may raise the concentration of solids up to 35–40 percent.

Figure 3.3. Sludge Treatment Scheme



(Percentage solids)

Type of sludge				
Primary	4–8	6–10	8–12	18–40
Waste-activated	0.5–1.5	2–3	4–5	15–20
Combined	3–6	4–7	5–10	15–30

Sludge heating, which is both a stabilization process and an alternative conditioning process that precedes dewatering, is rarely used because its cost is often prohibitively high.

Wastewater Reuse

In areas where natural water is scarce, municipal effluents are considered an unconventional source of supply that can be used either for local, specific needs or as an integral part of the regional water supply system. Even in areas where water from natural sources is plentiful, reusing wastewater can be the most efficient means of disposal from an environmental viewpoint.

When effluent is reused, its sale can offset the relatively high cost of wastewater treatment. However, institutional and legal problems may limit the sale of effluent to consumers. A distinction is usually made between incidental reuse, which takes place when wastewater is discharged into rivers or lakes from which water is withdrawn for irrigation or for potable supply, and deliberate planned reuse. Another, more important, distinction is made between direct and indirect reuse. In direct reuse, also referred to as pipe to pipe, the effluent from the wastewater treatment plant is supplied directly for irrigation or any other purpose. In indirect reuse the effluent is discharged into a natural water recipient (river, lake, aquifer) and is then reused, after undergoing self- purification and dilution with natural water.

The most attractive and widespread reuse of effluent is to irrigate agricultural crops, pastures, or natural vegetation. The main reasons are the following:

- Where crops need to be irrigated, water tends to be scarce, and treated effluents can substitute for freshwater
- Irrigation needs large amounts of water that are used only once, representing a large portion of total water demand in dry areas
- Agriculture benefits both from the water and the organic matter plus nutrients in the effluent
- The quality of water required by irrigation is relatively flexible, depending on the crops to be irrigated, soil conditions, irrigation method, and harvesting techniques.

An important distinction should be made between two types of irrigation with effluent: restricted and unrestricted. Restricted irrigation refers to the use of low-quality effluents in limited areas and for specific crops only. Restrictions are imposed on the type of soil that can be irrigated, the proximity of the irrigated area to a potable aquifer, irrigation method, crop harvesting technique, and fertilizer application rate. Unrestricted irrigation refers to the use of high-quality effluents, instead of freshwater, to irrigate any crop on any type of soil, which means without limitation.

Restricted irrigation is simple and low cost, but it is generally applicable only to small amounts of wastewater that can be used in specific locations, where areas and crops are well-defined and unlikely to change. The crop limitations imposed must be enforced and controlled. Farmers and agricultural workers must be trained to handle the low-quality effluent so as to minimize health hazards. Few farmers are willing to accept low-quality effluent in equal exchange for freshwater. In unrestricted irrigation, however, contact and even accidental drinking do not pose health risks, and the high-quality effluents should be acceptable to farmers.

Irrigation with sewage effluents is safely and widely practiced in many parts of the world, both in industrial and in developing countries. But at the same time, the dangerous practice of direct or indirect irrigation using untreated wastewater is also common in many of the region's cities such as Lima, Mexico City, and Santiago.

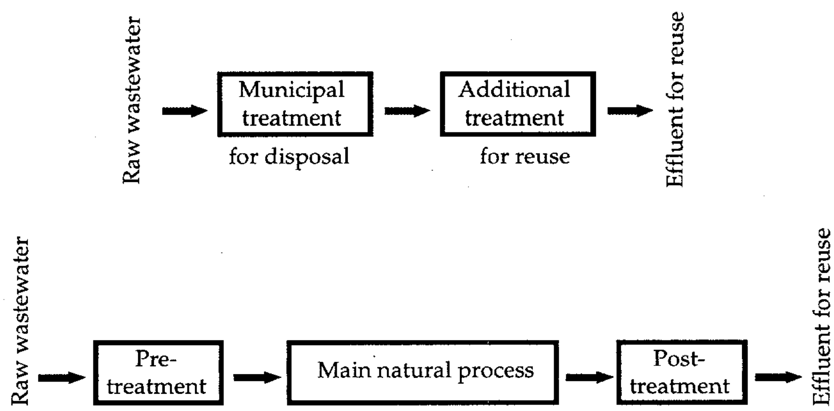
Effluents can also be reused for secondary industrial needs such as cooling water, recreational waters to be used for partial-body contact, municipal nonpotable uses such as landscape and golf-course irrigation, and domestic nonpotable water (flush toilets). The use of effluent for domestic nonpotable water, which has been introduced recently in specific locations in Southern California, implies the construction of a dual urban supply network, which could be economical for new urban areas in water-scarse regions.

Potable reuse of sewage effluents is technically feasible too, because a combination of advanced treatment processes can produce reused water of drinking water quality. However, such reuse is economically feasible only in situations of extreme water scarcity or an emergency. Moreover, the available analytical methods for detecting and measuring organic compounds in water cannot determine whether the residual organic carbon in the final product represents a long-term hazard to human health.

Wastewater Treatment Aimed at Reuse

Few widely known methods have been devised specifically to fulfill the objectives of wastewater reuse. The most common methods, which combine natural and man-made processes, were developed in connec-

Figure 3.4. Wastewater Treatment for Reuse



tion with requirements to control pollution in rivers and lakes. Wastewater treatment for reuse can be approached in two ways (figure 3.4). When conventional wastewater treatment for disposal is already in existence, tertiary treatment processes can be added to achieve a higher quality of effluent. Processes used in such situations include chemical precipitation with alum and polymers plus sand or dual-media filtration; direct filtration, in the case of low-turbidity effluents; lime treatment; and soil aquifer treatment.

When effluent reuse is considered before any wastewater treatment is in existence, special schemes can be devised to fulfill the specific purpose for which the effluent is destined. In most cases, this approach is the most efficient and economical. The most suitable treatment process for reuse, including natural treatment, can be adopted as the core process, preceded by minimal pretreatment and followed by posttreatment, according to needs and the final reuse of the effluent. Two such reuse systems were developed and implemented in Israel and are briefly described here: soil aquifer treatment (figure 3.5) and deep reservoir treatment (figure 3.6).

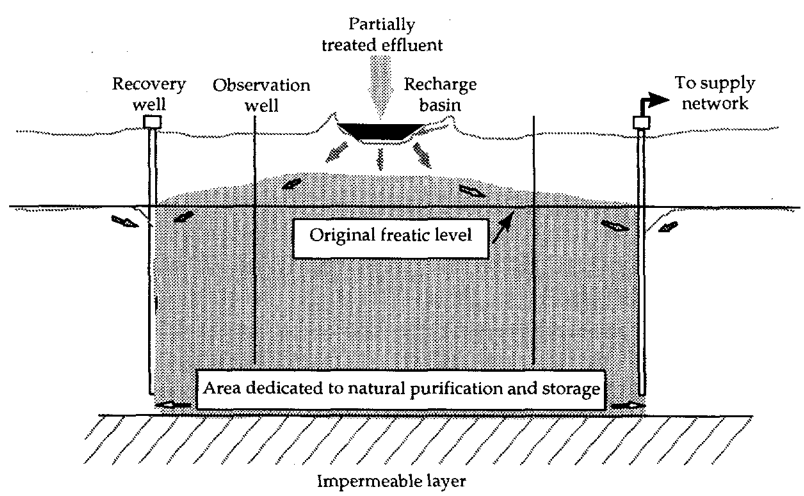
Soil Aquifer Treatment

Soil aquifer treatment is a special system consisting of groundwater recharge through spreading basins of partially treated effluent, which flows vertically through the unsaturated zone until it reaches the aquifer and then flows radially in the aquifer, and a ring of recovery wells surrounding the recharge basins and designed to pump the self-purified, high-quality water from the aquifer. As the name indicates, the purification effect is achieved by a combination of physical, chemical, and biological processes occurring in the soil and the aquifer. At the beginning of the operation, the wells pump native groundwater found in the aquifer. Later, they pump a mixture of native groundwater and increasing amounts of recharged effluent. In the steady-state phase, the wells pump large amounts of recharged effluent from the inner basin, where groundwater flow gradients are higher, and small amounts of native groundwater from the outer basin.

If the recovery wells are adequately spaced, the recharge and recovery facilities can be operated so as to confine the recharged effluent within the groundwater subbasin that is located between the recharge area and the recovery wells. This underground zone is dedicated to the treatment and storage of effluent and represents only a small percentage of the regional aquifer. The remaining groundwater basin is not affected and can continue to be used for potable supply. The reclaimed water, which can be traced and monitored by means of observation wells, is of very high quality and is appropriate for a variety of uses, including unrestricted irrigation. Accidental drinking of the reclaimed water would not involve any health hazard because of its high microbiological quality.

To achieve maximum infiltration and purification capacity, recharge basins must be operated intermittently, that is, flooding periods should

Figure 3.5. Soil-Aquifer Treatment Scheme



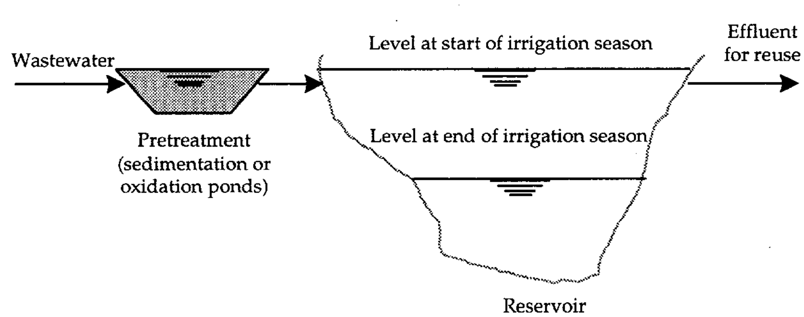
alternate with adequate drying periods. Continuous flooding of the basins would soon reduce the infiltration rates and require more and more land. It would also cause anaerobic conditions to develop in the aquifer, which would adversely affect the purification capacity of the system. This system has been successfully operated since 1977 in Tel Aviv's large reuse project (Idelovitch 1984). It is appropriate in areas where soil and groundwater conditions are suitable for recharge and where sufficient land is available for the recharge basins.

Many features of the soil aquifer treatment system are common to other systems, usually referred to as rapid infiltration. The most similar and well known of these systems has been investigated and applied in Arizona, where recharge basins are located in two parallel rows along the river bank and recovery wells are drilled in the river bed. In other systems, where groundwater is shallow, the effluent is collected by underdrains. In Germany and Holland, many cities use polluted river water after bank filtration, a concept similar to that of soil aquifer treatment. Advanced water treatment to produce drinking water is usually undertaken after bank filtration.

Deep Reservoir Treatment

One of the main components of any irrigation scheme with effluent is a seasonal storage reservoir, which is needed to balance the virtually constant supply of effluent with the great fluctuations in demand for irrigation, which depends on climate as well as crop patterns. Deep reservoirs were originally built in Israel to store effluents to be reused for cotton irrigation during a three-month peak summer season. It was soon observed that the quality of the effluent after several months of storage was significantly better than the quality of the influent to the reservoir, mainly with respect to organic content and number of pathogens.

Figure 3.6. Deep Reservoir Treatment Scheme



Since then, the deep reservoir treatment has been developed as an innovative scheme and been successfully applied in small and medium-size irrigation reuse projects. The reservoir is usually full at the beginning of the irrigation season and almost empty at the end. The depth of the reservoir varies between 8 and 12 meters. Most of the time the reservoir is stratified, with most of its volume acting as an anaerobic reactor and only the upper layer acting as an aerobic zone, from which the final effluent is extracted. The reservoir is totally mixed only during winter or transition seasons.

The pretreatment needed for wastewater before it is stored in the reservoir and the organic load on the reservoir must be carefully determined in order to avoid the creation of anaerobic conditions over the whole volume of the reservoir, which would result in low effluent quality and bad odors that can spread far from the plant.

Sludge Reuse

Sludge treatment and disposal have traditionally been the most neglected aspects of wastewater treatment. Until recently, both in industrial and developing countries, cities located close to the ocean disposed their sludge into the sea by means of more or less adequate sea outfalls. In inland cities in developing countries, sludge is usually discharged into lagoons or landfills. Limited sludge treatment is provided prior to disposal, usually including only gravity thickening and natural dewatering in drying beds (where climatic conditions are favorable).

However, like the liquid effluent, sludge can be treated and reused for a variety of beneficial purposes, without risk to human health and the environment. Anaerobic sludge digestion, which is a popular method of sludge stabilization, can generate methane gas that can be used to produce heat or power. Anaerobic digestion is particularly suitable in warm climates and for primary sludge, but it can also be used for combined primary and waste-activated sludges.

Applying sludge on cropland (agriculture) or forestland (silviculture), which is similar to using wastewater for irrigation, is a feasible alternative to disposal and should always be considered. Because of its high organic and nutrient content, sludge is particularly suited to the reclamation of marginal lands, such as saline or alkaline lands. When sludge is used on cropland, pathogens and heavy metals may be of concern. To reduce the danger of microbiological contamination of the agricultural produce, the sludge must be disinfected. Certain safety guidelines must also be followed. Control of industrial waste discharges is important to reduce the level of heavy metals and other toxic substances that may impair use of the sludge for application on land.

Wide-scale application of sludge on land requires the establishment of clear standards or guidelines, which are lacking in most countries. Even in the United States, where land application is used extensively, standards have been introduced only recently. Application of sludge in silviculture has the advantage of not posing health dangers, because the product does not enter the human food chain. Sludge can be applied to agricultural land either in liquid form (without the need for dewatering) or as sludge cake after dewatering. Suitable equipment for spreading the sludge and incorporating it into the soil or subsoil is required in both cases.

Sludge composting is another attractive reuse of sludge. Dewatered sludge is placed in a pile together with bulking material such as wood chips, straw, or recycled compost and is then aerated and stored for several weeks. During composting the organic matter present in the sludge is degraded and converted to stable end products. During composting, the temperature of the sludge rises to about 50–60 degrees Celsius, which reduces the pathogen content. Although the process is essentially aerobic, anaerobic zones in the sludge pile may cause bad odors—the main environmental problem of composting. To reduce the extent of the anaerobic zones and the danger of bad odors, in some composting systems, the sludge pile is periodically turned and mixed to improve aeration. The systems are referred to as windrow composting and as static pile composting.

The final product is a humus-like material that can be used to condition or fertilize the soil. Composting can be carried out with either unstabilized or prestabilized sludges. The joint composting of wastewater sludge and municipal refuse is also a common practice. The main effect of applying sludge on land is to increase crop production in agriculture and tree production in silviculture.

4
Options for Financing and Implementation

Constructing wastewater treatment plants is capital-intensive. Recent examples of competitively procured plants indicate an investment cost of $100 per capita of the design population. The investment cost per capita of the initial population can easily exceed $200, because it usually takes a number of years before the population actually served matches the design population. Where treatment plants are not bid competitively, the investment cost per capita is likely to be even higher.

To operate efficiently, such plants require competent operators and additional funds for current expenditures such as labor, materials, spare parts, chemicals, and energy. Improperly operated plants cannot ensure a high-quality effluent and a sludge that can be disposed or reused without representing a risk to public health or the environment. Only if such effluent and sludge are produced can the wastewater plant be considered successful and the capital used for its construction well invested.

Conventional Management and Financing of Public Projects

Until recently, wastewater treatment plants in developing countries, like any other component of a municipal water supply and sewage disposal system, were financed by governments or by government agencies. Typically, the public water supply and sewerage agency was responsible for undertaking preliminary studies as well as for designing and constructing the plant. In most cases, the public company contracted the studies and the design with a specialized private engineering firm, the construction with a private contractor, the equipment with one or more suppliers, and the supervision of the project execution with an engineering firm. In some cases, the contractor had to supply equipment as well. Only in isolated cases, and for relatively simple plants, did the public agency carry out the studies and designs in-house. Many contracts included the responsibility of the contractor to operate the plant, but only during a limited period (usually between three months and one year) for running-in the equipment and confirming the capabilities of the process.

In the past, treatment plants were often financed with the help of loans from international and bilateral agencies. Such financing was contingent on explicit or implicit central or local government guarantees that could be called in if the borrower did not service the debt in a timely fashion. In this way both lenders and operators were protected against all kinds of commercial and political risks. Such reassurances can give rise to complacency and even abuse because the government with its taxation and borrowing powers is thought to be able to bail out any shortfalls in the project's debt service. In addition to not promoting the best performance of suppliers, contractors, and operators, such all-inclusive government guarantees also use up too much of the government's limited guarantee capacity. In the process, they could crowd out other projects, for instance in the social sectors where government direct financing or guarantees are a must. Granting guarantees for revenue-generating projects that could well be financed without them does not represent an optimal use of the government's creditworthiness.

As a result of such full-recourse financing and public project management, many of the wastewater treatment plants constructed in developing countries have been plagued by cost overruns, implementation delays, and operation and maintenance difficulties. One of the major deficiencies of this scheme is that responsibility for the process selected is split between the consultant who recommended it and the contractor or equipment supplier who implemented it.

Turnkey Contracts with Government-Recourse Financing

"Turnkey" contracting represents a slightly more advanced conventional method, whereby a consortium of firms is responsible for both designing and constructing the plant. Although such schemes eliminate the possible conflict in responsibility for design, construction, or equipment, they do not guarantee long-range efficient performance of the plant. When such turnkey contracts are financed with full recourse to the government, they invariably suffer from the disadvantages of an unequal sharing of risks. The public sector will continue to bear the commercial risk during the operational stage. This is a weakness given the frequently poor performance of the public sector in the operations and maintenance stage.

Limited-Recourse or Nonrecourse Financing: BOOT Schemes

The difficulty of having the public sector finance such a large current and capital expenditure has made it natural to look at private sector participation as a way to finance water and wastewater projects in developing countries. Governments are keen to identify projects in sectors that have a potential to generate revenue, to become financially self-sustaining, and to be financed without public sector guarantees. The intent is to steer the government toward projects in sectors where there is no alternative to continued public sector management and financing.

The most extreme form is nonrecourse financing, where project sponsors and investors have no assurances from the government but depend entirely on cash generated by the project. This shifting of risk from the government to the private sector is in practice difficult to achieve. A compromise is then struck in which private sponsors and investors have limited recourse to the government, for instance in the form of a guaranteed minimum level of revenue.

A number of schemes exist in which the private sector finances, builds, and operates wastewater treatment plants. One common designation is BOOT, which stands for build, own, operate, and transfer schemes. Under a BOOT contract, a firm or a consortium of firms finances, builds, and operates the plant. The private sector retains ownership of the facility throughout the operations period and is allowed to charge a tariff sufficient to recover the investment. At the end of the operations stage the facility is transferred to the government, free of charge and in good operating order.

A variation is a BOO (build, own, and operate) contract in which private ownership is retained indefinitely. Other variations include BOL schemes where the private firm builds the project with government financing but then stays on to operate the plant while paying an annual lease fee. The gamut of schemes is limited only by the imagination of the parties.

The main objectives for introducing BOOT contracts in wastewater treatment are to make the operation and management of the plant more efficient, to attract new ideas and technologies, which could lower costs, and to finance the investment without public guarantees in any form.

Efficiency Gains of BOOT Plants

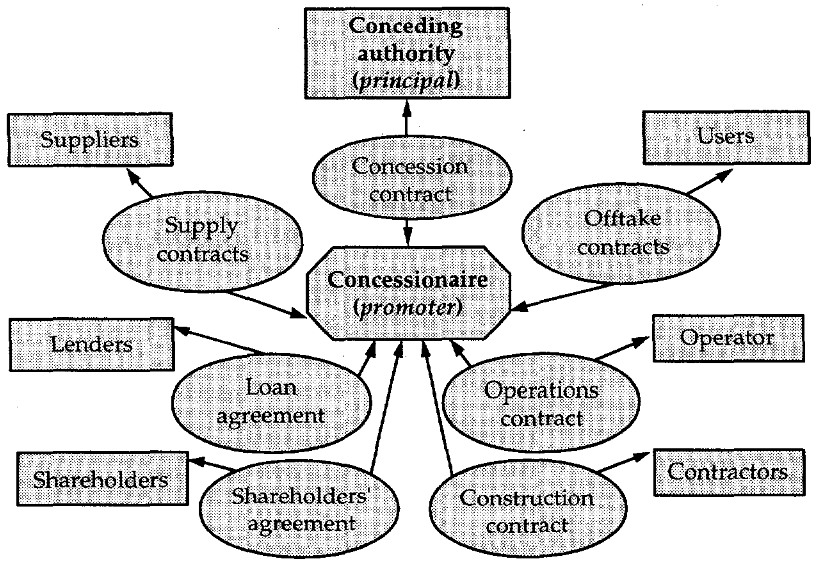
The efficiency targets are likely to be reached as far as the design, construction, and operation of the plant itself are concerned. In contrast, an efficient BOOT plant will not automatically resolve the larger problems of inefficiency in the total cycle of water supply and wastewater treatment. For instance, it is not uncommon to find that the water supply in a city is operated inefficiently, with levels of unaccounted for water as high as 50 percent, compared with efficient levels of 15 percent. In such a case, a BOOT wastewater plant built to treat the wastewater flow will necessarily be too large, at least initially. Similarly, it is not efficient for a city to contract with a BOOT operator to supply more potable water when rationing exists alongside unaccounted for water of 50 percent. In the same vein, a BOOT contract may not be the most efficient solution where consumption is excessive due to, for example, unrealistically low tariffs.

In situations like these, contracting with a BOOT operator should in no way remove the public sector's obligation to increase efficiency in those parts of the system that are not the responsibility of the BOOT operator. Ideally, BOOT contracts should not be bid until the system's efficiency is at a reasonable level. The difficulties are substantial, however, because achieving efficiency involves a combination of incentives for higher efficiency, better management in a number of areas, and also selective investments. Experience has proven that private operators are often more successful than the government in increasing operational efficiency.

General Principles of BOOT Contracts

A BOOT contract is a complex undertaking involving the *promoter*, which is given the right to build-own-operate a facility that provides a service in return for an agreed compensation before the facility is transferred back to the *principal*, which then concedes this right through a concession agreement. In turn, the promoter necessarily interacts with a host of other subsidiary parties during the course of complying with the concession agreement. The promoter, which can often be described as a capable "deal maker," attempts to reduce the substantial risks that it assumes under the concession agreement by entering into a series of subsidiary contracts. The most important of these subsidiary contracts are shown in the schematic representation of a full BOOT contract in figure 4.1.

Figure 4.1. BOOT Contractual Relationships



The first of the six subsidiary contracts may be a *supply contract* with the businesses or individuals that will be served by the facility. In the context of wastewater BOOT contracts, the supply contract will specify the quantity and quality of wastewater that will be supplied for treatment. In these projects the public authority or municipality granting the concession often represents the interests of all consumers. Instead of drawing up a special supply contract, the conditions and obligations of the clients will be included as part of the concession agreement. One such condition may be that consumers who have a supply of water are obliged to hook up to the public sewerage system in order to have their wastewater treated by the BOOT plant.

Under a BOOT contract for a wastewater treatment plant, the public authority is usually responsible for determining plant capacity, based on the estimated flow of wastewater. These estimates are of particular importance, because the public authority may guarantee the private contractor a particular level of wastewater flow to be treated and thus assume the risk of paying for the full service when the plant is used at less than full capacity.

The second type of contract is the *offtake contract*, in which the promoter agrees to supply output from the BOOT installation. Again, if the conceding party is a municipality, it often is in the interests of the community to have the wastewater treated at a certain, agreed level. The quality of effluent will then be specified in the concession agreement. The private operator must supply the quality of effluent defined in the BOOT contract or pay a penalty. To enable the private operator to do that, the public utility must ensure that the influent to the plant is of acceptable quality.

A major issue in municipal wastewater treatment in general, and in BOOT contracts in particular, is the need to control industrial waste. Heavy metals or other toxic elements discharged by some industries may, above certain concentrations, stop the biological treatment process or impair the quality of the final plant effluent or the sludge produced by the plant. In order to ensure uniform quality of the plant effluent, the public authority must ensure that only legal industrial discharges are allowed into the municipal sewerage network and treatment plant. The BOOT contract should establish clear responsibility for monitoring and controlling industrial waste.

A special offtake contract is relevant where water is so scarce that the treated wastewater can be sold for reuse, for instance in agriculture or industrial processing. The promoter can then sign a special contract in which it agrees to supply wastewater of a certain quality and in amounts specified by time period.

The third type of contract is the *loan agreement*, in which lenders commit themselves to finance the construction of the BOOT facility. Often a lead lender will attempt to spread its risks by syndicating the total amount of the loan over a number of lending institutions. The private consortium will usually raise a large percentage of the financing required for the plant from commercial banks, as well as from bilateral and multilateral lenders, such as the International Finance Corporation. The duration of a BOOT contract should equal the period of time needed to allow the consortium to pay back the debt incurred and return the equity investment. BOOT arrangements represent a substantial risk for the private firms involved if there are no assurances that the investment will be recovered during the lifetime of the project.

The fourth type of contract is the *shareholders' agreement*, in which investors agree with the promoter to provide the specified amount of equity needed to construct the BOOT facility. The necessary amount of equity is often a consequence of the demands of either the lenders or the principal. Both have an interest in ensuring that the promoter secures a sufficient proportion of the investment financing as equity to provide a cushion against unfavorable developments in the project's cash flow. At times, the promoter will secure some equity from contractors or equipment suppliers that have an interest in having the facility built.

The fifth type of contract is the *construction contract,* in which the promoter passes on the construction risk to an experienced contractor. The sixth and final type of contract is the *operations contract,* in which the promoter secures the services of a specialized firm to operate and maintain the facility. Through a BOOT concession agreement, the principal actually procures a range of services such as financing, construction, operations, and marketing. Only very large international firms can provide the full range of such services in-house. In other instances the promoter will often form a consortium of firms such as civil works contractors, equipment suppliers, plant operators, and both foreign and local lenders and investors.

Risks of BOOT Wastewater Treatment Projects

A BOOT contract, like any other form of private sector participation, involves certain risks both for the private and for the public sector. A successful BOOT will depend to a great extent on how well these risks can be quantified and mitigated. Careful analysis of the risks involved should be carried out early in the process, and risks should be shared between the private and public sectors following the principle that whoever can control or manage the risk best should assume it and receive adequate compensation for doing so.

The chief planning tool for analyzing the risk associated with a BOOT project is the project's cash flow. Both equity investors and lenders look to cash flow as the main guarantee of a return on their investment and of timely debt service. There is a difference, however. Equity investors are apt to make their decisions on the financial rate of return of the cash flow over the concession period. A high rate of return may result even if the cash flow in certain years is in deficit. In contrast, lenders study the annual cash flow carefully and decide whether to lend or not based on the likelihood that their loan will be serviced in an orderly fashion. Because long-term debt has a fixed remuneration and does not enjoy the upward potential that equity has, it is more difficult to attract. For this reason, cash flow becomes the centerpiece for analyzing BOOT projects.

Illustrative Cash Flow in Wastewater Treatment Projects

Table 4.1 shows a typical cash flow for a wastewater treatment project. Typically, a BOOT concessionaire will commit itself to treat a daily contractual volume of sewage of certain characteristics to comply with

Table 4.1. Cash Flow in a Wastewater Treatment Project

	Volume of wastewater treated
x	Average tariff for wastewater treatment
=	Gross operating revenue
–	Operating expenses
=	Gross internal cash generation
–	Interest payments
–	Amortization of loans
–	Income taxes
–	Complementary investments
–	Dividends paid to investors
=	Surplus for concessionaire/investors

stipulated standards of effluent quality. In return, the concessionaire will be compensated with a wastewater treatment tariff. This tariff is typically the criterion for selecting among BOOT concessionaires that bid for the concession.

The concessionaire will have to pay operating expenses and is then left with a gross internal cash generation. The internal cash generation is likely to be used in a strict order of priority. First, the concessionaire will be obliged to use the internal cash generation to pay interest on any loans contracted to construct the wastewater treatment facility. Second, the concessionaire will have to amortize the loans according to the agreed conditions. Lenders are exceedingly sensitive that debt service be paid on time and will reserve the right to call in the entire loan if the concessionaire or promoters fail to service debt in a timely fashion. Third, the concessionaire will likely be liable to pay taxes. Fourth, the concessionaire will need to invest in complementary works as demand grows over the concession period.

The concessionaire will likely attempt to finance such investments out of the internal cash generation. When complementary investments are so large that they cannot be financed out of retained cash, the concessionaire will likely attempt to borrow additional amounts rather than to contribute any additional equity. Additional borrowings should become easier to secure as the concessionaire establishes a track record and as the regulatory and tariff regimes are successfully tested. Often different borrowings receive different priority claims on the available cash. Senior debt has first claim, mezzanine debt has a lower priority, while subordinated debt of different types has still lower priority. Some subordinated debt approaches equity that has the lowest priority. Only after all kinds of lenders, taxes, and complementary investments have been satisfied will the concessionaire or project sponsor be able to receive dividends on its equity investment.

Risk Analysis

The cash flow of a typical wastewater treatment project is subject to many risks (table 4.2). Each item can vary depending on the magnitude of the risk. Both the public authority and the private operator incur risks under a BOOT contract. The risks will be analyzed from the vantage point of each of the two parties, placing special emphasis on the promoter's risk, which is usually the greatest.

Types of Risk

First, the amount of wastewater to be treated can be different from the amount envisioned in the contract. This type of risk is often referred to as *market risk*. Not only the volume treated but also the quality can be different. For instance, the wastewater may contain substances from industrial effluents that may harm the biological treatment process employed.

Second, the approved tariff actually paid can vary from what was assumed in the original cash flow calculations. For many types of infrastructure projects, the risk of tariff variations is determined by market competition, such as in transportation projects with competing modes

Table 4.2. Types of Risk in a Wastewater Treatment Project Cash Flow

Item	*Type of risk*
Volume of wastewater treated	Market
x Average tariff for wastewater treatment	Market (free competition) Political (under regulation)
= Gross operating revenue	
– Operating expenses	Operational/technical
= Gross internal cash generation	
– Interest payment	Financial
– Amortization of loans	Financial
– Income taxes	Political
– Complementary investments	Construction
– Dividends paid to investors	Political and transfer
= Surplus for concessionaire/investors	

of transportation. In the case of wastewater treatment, where one client, typically a municipality, has committed itself to pay a certain tariff, the risk is *political* in the sense that the concessionaire is relying on the stability and good faith of the methodology and its application in the calculation of tariffs.

There is, of course, always the risk that the client will not be able or willing to pay according to the volume of wastewater treated and the agreed tariff. BOOT contracts are usually signed by the promoter with one client, which could be a utility or a municipality. This *payments risk* can be considerable in the case of municipalities with a poor record of managing their affairs in an orderly fashion. The payments risk of municipalities is a good deal higher in developing than in industrial countries, where municipalities are careful not to endanger their access to credit markets by failing to honor their financial commitments in a timely and orderly fashion.

Third, the level of operating costs can differ from projected levels. Whenever the characteristics of the received wastewater prove to be at variance, operating costs will be higher to enable the operator to comply with the stipulated effluent standards. There is also the risk that the treatment technology employed will not yield the expected results even in cases where the wastewater characteristics are within the contractual parameters.

Fourth, interest payments will fluctuate over the life of the BOOT contract. This can best be described as *financial risk* because it depends on the financial conditions negotiated and on the evolution of financial markets. BOOT projects typically require long contract periods to allow the original investment to be recovered without resulting in such high tariffs that the consumers' capacity to pay is exceeded. However, financial markets in most developing countries are so unstable that few financiers are willing to lend medium-term funds or agree to fixed-interest conditions.

Fifth, an *exchange or currency risk* often arises when borrowings and equity contributions are in foreign exchange. Borrowings in external markets may often be the only way of obtaining reasonable maturities because developing countries often have no medium- or long-term credit market. Foreign borrowings are extremely vulnerable to sharp adjustments in exchange rates. Coverage against such exchange risks is prohibitively expensive or unavailable, except possibly over the short term.

Sixth, there is a risk that the government may modify its tax regime, which could affect the liabilities and cash flow of the concessionaire. Seventh, whenever works need to be built there is a *construction risk*. This risk is true primarily for construction of the initial wastewater treatment plant. Eighth, foreign investors are subject to the risk of not being able to convert their surplus local currency into foreign currency. This *transfer risk* arises because wastewater treatment projects typically earn revenue in local currency but frequently involve foreign investors or operators that wish to be compensated in foreign currency. The risk arises because a country may not be able to attract enough foreign currency to allow all those wishing to purchase foreign currency to do so.

Risks may usefully be grouped into two major categories: global risks that vary with the political and economic situation in the country and project risks that are specific to the BOOT facility.

Level of Risks

The level of risks will vary among the different items of the wastewater treatment project (table 4.3). First, there is the risk that the quantity of wastewater will be different from the projected levels. There could be many reasons for variances. For instance, the amount of water consumed can decrease if water tariffs are raised. This sensitivity of water demand to tariff changes is measured by the price elasticity, which is calculated as the ratio between the relative change in water consumption and the relative change in water price. The price of water will also include the sewerage tariff whenever water and wastewater services are charged as a combined tariff. The short-term price elasticity is around –0.2, which implies that a doubling of the tariff could be expected to reduce the

Table 4.3. Level of Risks in a Wastewater Treatment Project Cash Flow

Item	*Type of risk*	*Level of risk*
Volume of wastewater treated	Market	Medium
x Average tariff for wastewater treatment	Market/political	High
= Gross operating revenue		
– Operating expenses	Operational/technical	Medium
= Gross internal cash generation		
– Interest payments	Financial	High
– Amortization of loans	Financial	Medium
– Income taxes	Political	Low
– Complementary investments	Construction	High
– Dividends paid to investors	Political/transfer	Medium
= Surplus for concessionaire/investors		

consumption 20 percent. In the longer term the price elasticity of demand is higher, or –0.45.

Where the tariff for wastewater is based on the amount of pollution discharged, the amount of wastewater could also change. The level of effective metering has a significant impact on the level of consumption. In the short term, metering can be expected to reduce average consumption around 40 percent—and in the longer term about 50 percent—compared with the situation in which consumption is completely unmetered.

Given the sensitivity of water consumption to price and metering, the level of risk must be rated medium. However, treatment projects are typically built to address a problem that already exists: the environment is polluted by the unsanitary and unsustainable disposal of wastewater. This makes the volume of wastewater to be treated a better-known quantity than in BOOT projects that aim to satisfy a demand to be developed. In addition to the risk that the quantity of wastewater may vary from forecasts, there is the additional risk that the characteristics of the wastewater will be substantially different from the characteristics on which the treatment technology is based.

Second, there is also the substantial risk that tariffs may lag those projected, which could occur for several reasons. Tariff setting is often politicized, and authorities may wish to slow the rise in tariffs in the belief, for example, that this will help slow inflation. Where tariff increases are authorized in line with projections, there is the risk that consumers will not be able to pay them. The risk of tariffs that are driven by short-term political considerations and the payments risk combine to create a high risk that tariffs may lag forecasts.

Third, there are operational risks in the sense that the treatment technology will prove unable to meet the contractual effluent standards or that the level of operating costs will be higher than projected. With an experienced specialized operator, these operational risks are at the most medium, particularly if the operator is part of the promoter consortium and has been involved in designing and constructing the treatment facility.

Fourth, the financial risks associated with volatile interest rates are high. The promoter faces a dilemma in trying to reduce these. If much of the financing is sought in domestic financial markets, interest rates will be considerably higher and more volatile than they are in international capital markets. If much of the financing is sought on the international capital markets, which have lower interest rates and less volatility, a foreign exchange risk is created. If exchange rates are realigned substantially, the impact on the BOOT project's cash flow can be severe and swift.

Fifth, the construction risk must be rated as high.

Mitigation of Risks

Risks are inimical to economical and efficient project construction because all parties require compensation to assume risks. It is therefore natural to attempt to reduce risks from the outset because lower risks will reduce the level of compensation demanded by project sponsors, operators, and lenders. Table 4.4 illustrates ways to mitigate or reduce risks.

First, market risk in the form of lower-than-expected wastewater flows can typically be reduced through judicious coordination of the investment programs that connect customers to the sewerage system. Failure to do so may result in underutilized treatment facilities. Even with good coordination between wastewater collection programs and the BOOT treatment plant, the promoter will often try to obtain a guaranteed level of income through a take-or-pay contract in which the principal, often a municipality, commits itself to pay a minimum amount irrespective of the volume of wastewater treated.

Second, the high risk for the concessionaire of not being able to charge and collect adequate wastewater treatment tariffs can be reduced con-

Table 4.4. Reduction of Risk in a Wastewater Treatment Project Cash Flow

Item	*Type of risk*	*Reduction of risk*
Volume of wastewater treated	Market	Sewerage connections
x Average tariff for wastewater treatment	Market/political	Explicit regulation
= Gross operating revenue		
– Operating expenses	Operational/technical	Prequalification of operators and simple technology
= Gross internal cash generation		
– Interest payments	Financial	Fixed interest through swaps
– Amortization of loans	Financial	Long-term loan refinancing guarantees
– Income taxes	Political	Explicit contracts
– Complementary investments	Construction	Hiring of qualified contractors
– Dividends paid to investors	Political/transfer	Guarantees of repatriation
= Surplus for concessionaire/investors		

siderably by establishing a transparent and rational legislative and regulatory framework. Tariffs should cover both investment and operating costs as well as compensate sponsors adequately for assuming risks. The risk that consumers will not be willing to pay the higher charges always remains, of course. As a rule, however, the concessionaire will sign a contract with the municipality and will then assume municipal risk. This municipal risk can be mitigated through the establishment of escrow accounts that will serve as a buffer for payments to the concessionaire in case the municipality's capacity to pay slips.

Third, the risks of unexpectedly high operating costs or effluent standards that do not meet the contract can be reduced in several ways. For example, the risk that operating costs will be unexpectedly high can be reduced by requiring the use of simple or well-tried technologies rather than accepting experimental or untried ones. The risk that contractual effluent standards will not be met can be reduced by requiring operators to be prequalified.

Fourth, financial risks can often be reduced by using risk management instruments such as interest swaps. However, such financial instruments can become prohibitively expensive in high-risk countries with poorly developed financial markets. Fifth, contracts should be explicit about the income tax obligations of investors and concessionaires in order to avoid unexpected taxation. Sixth, the substantial construction risk can partially be controlled through careful pre- and post-qualification in order to ensure that only experienced contractors are used.

Allocation of Risks

After risks have been reduced through a series of judicious measures, any remaining risks have to be allocated between the different parties on the public and private sides of the BOOT contract. In a simplified form the two main sides are that of the private concessionaire and that of the government, meaning either the national government or provincial or municipal governments, as dictated by the constitution or administrative legislation of the country. Table 4.5 suggests ways to allocate risks following the principle of assigning risk to the party best able to manage the particular kind of risk.

The (medium) risk of not having a sufficient volume of wastewater to be treated could be assigned to the concessionaire. The concessionaire, in turn, may attempt to share this risk with the government by demanding a take-or-pay arrangement in which the client pays for a given volume of wastewater treated whether it is delivered to the plant or not. The concessionaire will also typically demand a release from meeting

Table 4.5. Allocation of Risk in a Wastewater Project Cash Flow

Item	*Type of risk*	*Allocation of risk*
Volume of wastewater treated	Market	Concessionaire
x Average tariff for wastewater treatment	Market/political	Government
= Gross operating revenue		
– Operating expenses	Operational/ technical	Concessionaire
= Gross internal cash generation		
– Interest payments	Financial	Concessionaire/ lenders
– Amortization of loans	Financial	Concessionaire/ lenders
– Income taxes	Political	Government
– Complementary investments	Construction	Concessionaire
– Dividends paid to investors	Political/transfer	Investors
= Surplus for concessionaire/ investors		

the contractual effluent standards if the characteristics of the incoming wastewater are substantially different from what has been stipulated.

The (high) risk of being able to charge adequate tariffs will need to be assigned to the government. This is a risk that the private concessionaire is unable to control. After all, it is the prerogative of the government to establish and ensure that tariff legislation is implemented and adequately regulated. The concessionaire should assume the (lower) risk that the client, often a municipality, will not pay the billings. However, in practice the concessionaire will often seek to pass this risk along to the central government because the payments risk in developing countries is high given the low and unreliable revenue base of many municipalities.

The fact that the government needs to guarantee the policy and implementation of the tariffs charged does not mean that it guarantees a certain level of revenue. The concessionaire should still be responsible for the commercial risk of not being able to capture a sufficient volume of wastewater to treat and for the risk that it will not be able to collect the corresponding charges. In practice, investors and operators often seek to transform the government guarantee of a tariff policy into a de facto government guarantee of a minimum level of revenue.

The (medium) risk of controlling the level of operating costs should be assigned to the concessionaire, which possesses superior experience in managing this risk. In turn, the concessionaire may involve, as part of a consortium of concessionaires or through subcontracting, an experienced operator in order to pass on the technical operating risk. The risk of receiving wastewater of different characteristics than contracted will likely be passed on to the client through the BOOT contract, with stipulations that free the concessionaire from the risk of any resulting damages or the failure to meet contractual effluent standards.

The financial risks related to the level and profile of interest payments and amortization of borrowings should be borne directly by the concessionaire and indirectly by the lenders to the project. The government should not bear this risk because the prime rationale for involving the private sector under a BOOT contract is precisely to avoid using the government's limited room for extending guarantees.

The risk that changes in tax legislation will adversely affect the project's cash flow is political in nature. Only the government can manage this risk and should logically bear it. Tax legislation should be clearly spelled out in the BOOT contract in the interest of both parties.

The construction risk should clearly be borne by the BOOT concessionaire. Often, the concessionaire will pass on this risk to an experienced construction company that is contracted to build the treatment plant under a turnkey arrangement. The construction risk is substantial for water supply and sewerage projects. A review of 120 World Bank–financed water supply and wastewater projects reports that the average expected cost overrun for these projects was 25 percent (World Bank 1992). These projects were implemented by public water and sewerage agencies, for the most part with private contractors. The public sector's poor record of controlling construction risk is a major reason in favor of switching to private BOOT contracts. Logically, the entire risk should then be borne by the private concessionaire in order to provide an incentive for timely, efficient, and within-budget construction.

Finally, the transfer risk that foreign investors or operators may not be able to change local currency to foreign currency should be borne by the government, which is in the best position to implement macroeconomic policies that will enable investors and operators to repatriate equity and profits. In turn, foreign investors could purchase insurance from bilateral and multilateral agencies (such as the World Bank Group's Multilateral Investment Guarantee Agency) against the risk that the government's macroeconomic policy will fail.

5
BOOT Examples in Latin America

This chapter describes and analyzes several BOOT projects that have been implemented or are being prepared in Latin America: two in Chile, two in Mexico, and one in Argentina (figure 5.1). In Chile, after long debates over the modality of constructing the much-needed wastewater treatment plants in Santiago, as well as in other cities, initial preparations have begun for contracting, via a BOOT contract, the first large wastewater treatment plant for Santiago. At the same time, the treatment and disposal of wastewater in Antofagasta have recently been contracted as a BOOT venture. Mexico has become active in the last couple of years in contracting BOOTs for wastewater treatment plants and, at this stage, is undoubtedly the leader in this field in Latin America. In addition to the two projects described here (Cuernavaca and Puerto Vallarta), many others are at different stages of preparation, negotiation, or implementation. In Argentina, a wastewater treatment plant for the city of Mendoza was recently completed by a BOOT contract. These projects demonstrate the feasibility of allowing the private sector to participate in water and wastewater treatment using the "new" options for financing and implementation.

Antofagasta, Chile

Antofagasta is a port city in the north of Chile, with a population of about 250,000. It is located in a desert area with little or no rainfall. Water has to be transported to the city from a distance of several hundred kilometers, and costly potable water treatment is required to remove arsenic from the water. Most of the wastewater collected from the city is disposed in the Pacific Ocean via seven short sea outfalls, which pollute the

Figure 5.1. Location of BOOT Projects in Latin America

beaches. A small amount of wastewater (about 120 liters per second) has been treated in an old activated-sludge plant, and, after chlorination for disinfection, has been reused for industrial needs in the vicinity of the plant and, after pumping to an elevated storage tank, also for crop irrigation some 10 kilometers from the plant. The wastewater treatment plant was operated by ESSAN S.A., the public company in charge of water supply and sewage disposal in the region, whereas the pumping station, storage tank, and distribution system were operated by the farmers' association. The farmers paid only for the power required to pump the wastewater. The wastewater treatment plant was poorly maintained, and only one of the two treatment modules was in operation lately.

Following a bid issued by ESSAN, a new wastewater disposal and reuse system was contracted by BOOT with an Anglo-Chilean consortium (BAYESA—Biwater Aguas y Ecología S.A.). The system consists of pumping stations and collectors, a pretreatment plant to remove large solids, grit, oil, and grease, and a single, long sea outfall. Construction of the system should be completed by the end of 1997. BAYESA will operate and maintain the facilities during a period of 30 years. BAYESA will also own the facilities for the first 20 years of the contract (until they are fully depreciated in accordance with Chilean accounting practice), when they will be handed over to ESSAN. The BOOT contract also includes rehabilitation and operation of the existing activated-sludge plant and the effluent distribution system.

Although effluent reuse is not the main component of the system, the sale of effluent affects the financial feasibility of the project. Financial evaluations showed that the long-run price of the treated effluent delivered at the treatment plant would be much higher than the current price. The existing agricultural consumers of treated effluent initially received a discount of 44 percent on the long-run cost, which was to be reduced gradually every four months until the end of 1996, when all users would begin paying the full cost. The increase in cost was intended to coincide with improvements in service, which was not reliable in the early months of operation. Meters were also provided free of charge to agricultural consumers. In contrast, industrial consumers paid the full price of the effluent from the beginning, including the cost of installing the connection and a meter. Starting in 1997, when all consumers are paying the full cost and the main investments are complete, BAYESA will begin transferring part of the payments received to ESSAN.

Santiago, Chile

A total flow of about 15 cubic meters per second of wastewater produced by about 5 million people living in the Santiago metropolitan area is collected by an extensive sewerage network covering more than 7,000 kilometers of pipes and discharged virtually without treatment into three watercourses crossing or bordering the metropolitan area. These watercourses feed numerous canals that supply irrigation water to various areas totaling about 130,000 hectares, on which a variety of crops are grown all year round, including high-value vegetables for fresh consumption and fruits for export. In summer, wastewater is the only source of irrigation water in some of these areas.

indexed to inflation. At the end of the 17-year period, the facility will be transferred to SEAPAL free of charge.

The plant was designed to be constructed in two phases: in the first and completed phase the capacity of the plant is 750 liters per second, and in the second stage (to be constructed 10 years later) the capacity will be increased to 1,000 liters per second. The cost of the first stage was about $33 million in 1993, and the additional cost of the second stage will be an estimated $5 million. Financing for the first phase of the project was provided by equity from Biwater and loans from the government-owned BANOBRAS, Biwater, and the International Finance Corporation, which provided $5 million as senior debt and another $2 million as subordinated debt.

The Puerto Vallarta plant illustrates many of the benefits but also the market, operator, and financial risks of BOOT contracts. The plant was inaugurated in February 1995, a few months after the serious Mexican macroeconomic "tequila" crisis in December 1994.

The market risks have become very much a reality because the plant is receiving an average wastewater flow of 450 liters per second, which is well below the 750 liters per second that could be treated. This represents a loss of revenue for the BOOT contractor. At the same time, the Puerto Vallarta municipality has continued to operate another wastewater treatment plant, Norte I, that existed when the Biwater plant was contracted. The capacity of Norte I is about 175 liters per second, or less than the excess capacity of the Biwater plant (Norte II).

In addition, many of the hotels and condominium buildings catering to tourists were equipped with small wastewater treatment plants when the Biwater plant was contracted. These plants are under no obligation to close, although they do not produce effluents of the high standards that the Biwater plant does. This represents a second unrealized market for the Biwater plant that might develop in the future.

A third source of unrealized revenue for the Biwater plant is represented by those areas in Puerto Vallarta and neighboring Nayarit state that are not connected to sewers or do not have collectors that could carry wastewater to the Biwater plant. The reduced public investments in the aftermath of the Mexican balance-of-payments crisis in December 1994 have so far prevented the necessary sewerage systems from being built.

The BOOT contractor, CTAPV, receives a payment per cubic meter of wastewater treated. This tariff was negotiated when the contract was signed and contains an indexation formula that automatically increases the tariff as soon as the monthly change in the price index exceeds a certain level. The contractual tariff level has been honored in spite of the macroeconomic difficulties since the December 1994 crisis.

In order to guarantee payment, a credit line, guaranteed by the state of Jalisco, was established with the fiduciary agent, the government-owned BANOBRAS. The credit line provides for payments to Biwater in cases where SEAPAL might suffer liquidity problems. It is uncertain to what extent SEAPAL is able to pass on to its own consumers the wastewater treatment fee that it pays to Biwater.

The financial risks to the operator materialized when the plant was still under construction. The fact that the Mexican peso fell from a rate of Mex$3.1 per U.S. dollar to Mex$8.0 per U.S. dollar (November 1, 1996) in the course of about two years obviously reduced the value of the equity and increased the debt service on any foreign borrowings.

The BOOT plant has produced effluent of a quality that has consistently exceeded the contractual standards. The plant has even served as a demonstration plant for visitors from other wastewater treatment plants in Mexico. To this extent, the plant has amply fulfilled the objective of bringing well-tested plant design and operation to Mexico.

Mendoza, Argentina

The greater Mendoza metropolitan area has a total population of 700,000, which is estimated to grow to 1 million by 2010. Sewerage coverage is projected to increase from 75 percent at present to 95 percent by 2010. Mendoza is located in an arid region in the foothills of the Andes in the western part of Argentina. The city's wastewaters have by tradition been used indirectly for irrigation.

Two wastewater treatment plants are in operation: Campo Espejo, a primary treatment plant with an average flow of 1.6 cubic meters per second and serving a population of about 310,000, and Paramillo, a lagoon treatment plant treating an average flow of 1.2 cubic meters per second.

To upgrade the quality of the effluent, the public water company (Obras Sanitarias de Mendoza) recently bid and awarded a 20-year BOOT contract to operate and maintain the existing installations, as well as to design, construct, and operate a lagoon system consisting of 12 modules, each including three lagoons in series (two facultative and one polishing), which should produce an effluent of a quality acceptable for unrestricted irrigation according to World Health Organization standards. The lagoons cover a total area of about 320 hectares.

The treated effluent will be conveyed to a 1,900-hectare irrigation area, where the quality of the agricultural produce and the health of the agricultural workers will be monitored. The possibility of charging farmers part of the cost of treatment is being considered. About one-quarter of the irrigated area is devoted to the production of grapes, another quarter to the cultivation of tomatoes and squash, and the remaining area to the cultivation of alfalfa, artichokes, garlic, peaches, pears, and poplar biomass.

The bidding process was straight-forward. Bidding documents were drafted and reviewed by the Procurement Committee of the Province of Mendoza under the Provincial Concession Law no. 5507/90. The bidding documents specified criteria for the quality of effluent, such as a maximum of 1,000 coliform per 100 milliliters, a maximum of one helminth egg per liter, removal of at least 30 percent of biochemical oxygen demand, and removal of at least 70 percent of suspended solids. The bidding documents defined a certain level of fines for failure to produce an effluent of the standard specified. The Province of Mendoza guaranteed a minimum wastewater flow of 3 million cubic meters per month. The selection criterion used was the wastewater treatment charge per cubic meter demanded by the BOOT bidders.

Five contractors submitted bids. The bid wastewater treatment charges varied from a $0.05 to $0.11 per cubic meter plus value added tax. The negotiated contract price was below $0.05 per cubic meter treated. Subsequently, the first phase of the oxidation ponds was constructed and is now in operation.

Appendix. Conventional Wastewater Treatment Processes

A brief review of sewage treatment history indicates that many of the so-called new developments are not new and have been known for a long time. Sewage has been used to irrigate land since early on. The First Sewage Commission of England and Wales recommended in 1857 that municipal sewage be applied continuously to the land in order to avoid pollution of rivers. Another Royal Sewage Commission reiterated the recommendation in 1884 that sewage be applied to the land before it is discharged into a stream. However, it was also realized that applying sewage to land requires large areas, which makes land application impractical for big cities.

In 1884, before biological treatment was discovered, the Royal Sewage Commission recommended chemical precipitation to remove organic matter from sewage. This was long before the recent interest in using chemical precipitation to remove phosphorus from effluents in order to control eutrophication of lakes. Similarly, discovery of the "fill-and-draw" activated-sludge process at the beginning of the twentieth century preceded that of the conventional, continuous flow activated-sludge process. Today there is renewed interest in a rather similar process (sequencing batch reactors) for certain applications.

The major man-made, intensive wastewater treatment processes in use today were developed at the beginning of this century, when population growth and industrialization of large cities in Europe and the United States started to limit the application of natural treatment methods that were in use in the previous century.

No historic note on sewage treatment would be complete without referring to the establishment in 1915 of the Royal Commission's standard of 20/30 for the disposal of sewage effluent into rivers (biochemical oxygen demand of 20 milligrams per liter and suspended solids of 30 milligrams per liter). This standard remains largely valid today, despite the need to improve quality.

Preliminary and Primary Treatment

Preliminary or pretreatment is the first step in most wastewater treatment schemes and aims at removing coarse solids. It includes as a minimum bar screens and nonaerated or aerated grit chambers. Primary treatment consists in most cases of primary sedimentation, which is probably the most widely used unit in wastewater treatment. In some cases—before secondary treatment facilities are built—it is used for a certain period of time as the only treatment prior to disposal. In most cases, primary treatment precedes biological treatment and is aimed at reducing suspended solids and organic load. Typically, primary sedimentation can remove 50 to 60 percent of the influent suspended solids and 30 to 40 percent of the influent biochemical oxygen demand.

Primary sedimentation occurs simply because solids reaching the primary sedimentation tanks are susceptible to natural flocculation, which is aided by the motion of the fluid within the tanks. The main factors affecting the performance of primary sedimentation tanks are hydraulic surface loading, or overflow rates, and hydraulic detention time. Primary treatment removes settleable solids, floating materials, oil, and grease and reduces the organic load on the subsequent treatment units.

When lagoons are used for biological treatment, neither preliminary nor primary treatment is essential, because the first lagoons can fulfill their functions and act as a deposit for coarse suspended solids. In some modifications of the activated-sludge process, such as extended aeration, primary sedimentation is not required prior to biological treatment.

The main problem of primary sedimentation is that only relatively large particles (larger than 0.01 millimeter in diameter), which include gravel, coarse and fine sand, and silt, can settle within the practical range of detention times provided by these tanks (around two hours). Particles such as colloids of smaller size and bacteria (0.001 millimeter in diameter) take much longer to settle—hours, days, or even years. Such smaller-size particles can be removed only if flocculating chemicals are added to the primary sedimentation tanks. This process—referred to as chemically assisted primary sedimentation—is gaining renewed popularity.

Secondary Biological Treatment

Biological treatment, which is the nucleus of almost any conventional wastewater treatment plant, is aimed at removing or stabilizing, by means of microorganisms, the colloidal and soluble organic matter present in wastewater. The process requires adequate environmental conditions for the growth of microorganisms, such as pH, temperature, oxygen (for aerobic bacteria) or lack of oxygen (for anaerobic bacteria), and nutrients. Aerobic biological treatment processes are essentially of two types:

- Attached-growth processes, such as trickling filters, where the bacteria performing the treatment are attached to rock or plastic media, or rotating biological contactors, where the bacteria grow on the surface of a plastic rotating disk
- Suspended-growth processes, such as activated sludge, where the bacteria are suspended in the wastewater.

The most widely used biological treatment is the activated-sludge process, presumably because it can produce high-quality secondary effluent. It is usually preceded by primary sedimentation, although this may not be necessary in some of its variations. The activated-sludge process consists of an aeration tank, where wastewater and recirculated sludge are mixed and aerated to form a thick liquid biomass (known as mixed liquor), and a secondary sedimentation tank, where this biomass undergoes gravity separation, in which the clear liquid is separated from the sludge solids. The aeration tank must provide sufficient retention time for the bacteria to grow. Air or oxygen-enriched air provided by a suitable source must be introduced by adequate equipment to maintain aerobic conditions in the aeration tank. Mixing equipment is also necessary to maintain aerobic conditions in the entire aeration tank. A certain amount of excess activated sludge must be continuously wasted from the system.

A successful activated-sludge plant is one in which both the aeration tank and the secondary sedimentation tank perform their tasks. This happens only when the colloidal and dissolved organic matter is converted into a biomass that settles easily by gravity. In many instances, however, the biomass does not settle well because of the so-called bulking-sludge phenomenon, which is caused by uncontrolled growth of filamentous-type bacteria.

Along with its many advantages, such as the relatively limited area required by large plants, activated sludge is a complex process that requires careful and knowledgeable operation, can be upset by industrial shock loads, and does not improve the bacteriological quality of the effluent, unless heavy chlorination (with its disadvantages) is provided to the final effluent.

One of the complexities of the activated-sludge process, which is an additional cause of confusion for the design engineer, even after the decision has been made to select activated sludge among all the alternative biological processes available, is the great number of alternative processes and modifications available:

Process	*Modifications*
Conventional	
Plug-flow	Contact stabilization
Tapered aeration	Oxidation ditch
Step-feed aeration	Extended aeration
	Sequencing batch reactor
	Pure-oxygen
Advanced	
Nitrification	
Nitrification-denitrification	
Nitrification-denitrification and phosphorus removal	

Anaerobic Treatment

Anaerobic biological treatment, which has been traditionally used for sludge treatment as well as for certain high-strength organic industrial wastes, has been used lately for municipal wastes, too. Anaerobic treatment has some advantages, along with disadvantages, when compared with aerobic treatment. The advantages are:

- It allows high organic loading rates and thus reduces the amount of area required (this is particularly important in the case of anaerobic ponds compared with aerobic or facultative ponds)
- It does not require costly oxygen
- It produces less sludge, because only about 5–10 percent of the organic carbon is converted to biomass (about 50 percent in aerobic processes)
- It produces a useful gas (methane), which can be burned on-site to provide heat for digesters or to generate energy for use within the plant.

The disadvantages of anaerobic treatment are:

- Anaerobic digestion is a slower process than aerobic oxidation
- It is more sensitive to upsets by toxic substances
- Its unstable end products may generate bad odors
- A long start-up period may be needed to acclimate the anaerobic bacterial population
- It requires energy for heating, mainly in cold climates.

Anaerobic treatment cannot completely stabilize organic matter and must be followed by aerobic treatment if a high-quality effluent is desired. The combination of anaerobic and aerobic biological treatment has the advantage of being able to deal with a wide variety of organic compounds, some of which are degradable by aerobic bacteria and others by anaerobic bacteria.

The main operational difficulty of anaerobic reactors is due to the fact that the anaerobic process is a two-stage process, each stage being carried out by a different group of bacteria, with the second-stage bacteria being more sensitive than the first to environmental conditions such as pH. In the first stage, acid-forming or nonmethanogenic bacteria convert the organic matter present in sewage to organic acids, whereas in the second stage, methane-forming bacteria or methanogens convert the organic acids to methane gas and carbon dioxide. For efficient performance, the methanogens require a pH in the range 6.5–7.5, and they cannot develop at all below a pH of 6.2. However, if too many acids are produced by the acid-forming bacteria, which develop and multiply easily, the result is a low pH, which may impede the production of methanogens. In the presence of high concentrations of sulfates, the methanogens also compete with the sulfur-reducing bacteria. The main consequences of such a situation are the appearance of unpleasant odors and a reduction in the efficiency of the anaerobic process. Although the problem can be corrected by adding lime or other chemicals to raise the pH, it is preferable to prevent it by controlling the pH and the volatile acids concentrations.

The anaerobic process usually requires artificial heating, because the optimum temperature for both groups of bacteria (nonmethanogens and methanogens) is at least 35 degrees Celsius.

Although the complete-mix process is still the most widely used anaerobic digestion process, mainly for primary or combined sludges, other anaerobic treatment processes have been used for industrial (concentrated) as well as municipal (diluted) wastewaters. These include attached-growth processes, such as the anaerobic filter (the anaerobic equivalent of the trickling filter) and the upflow packed bed, and suspended-growth processes, such as the anaerobic contact (the anaerobic equivalent of the activated sludge) and the upflow anaerobic sludgeblanket or UASB process. The latter has been used in several plants in Brazil and Colombia.

Advanced Treatment

Advanced treatment includes processes required to remove various contaminants remaining in the effluent after primary and secondary biological treatment.

Phosphorus Removal

When effluents are disposed into lakes or reservoirs, nutrients such as nitrogen (N) and phosphorus (P) are of concern, because they stimulate the growth of algae, causing eutrophication of lakes and deterioration of water quality. Phosphorus, which is the only nutrient not readily available from the atmosphere or the natural water supply, is the limiting factor—it was found to correlate well with the concentration of chlorophyll (algae).

Postprecipitation is the conventional method of removing phosphorus, that is, tertiary chemical treatment following biological treatment, using alum (aluminum sulfate), iron salts (mainly ferric chloride), or lime. Less conventional methods of removing phosphorus are preprecipitation or chemically enhanced primary sedimentation (prior to biological treatment) and coprecipitation or simultaneous precipitation (the addition of chemicals for removing phosphorus in the biological process itself).

Lime Treatment

Lime treatment is perhaps the best example of an old wastewater treatment process, which was abandoned in favor of biological treatment processes and then readopted as an advanced treatment to remove phosphorus and heavy metals and toxic substances. A clear distinction should be made between low-lime treatment that raises pH to 9.0–9.5 and high-lime treatment that raises pH to 11.0–11.5. Low-lime treatment can remove phosphorus, suspended solids, and some heavy metals such as lead and zinc that form low-solubility carbonates. High-lime treatment can remove phosphorus, suspended solids (including algae), organics, calcium and magnesium hardness, bacteria, viruses, and a variety of metals and toxic elements that form low-solubility hydroxides such as cadmium, copper, iron, manganese, lead, zinc, boron, and fluorine.

High-lime treatment thus has the capability of softening as well as disinfecting water. In addition, at high pH, most of the ammonia present in wastewater is converted to free ammonia (NH_3), which can then be removed by air stripping that takes place in ammonia stripping towers or ammonia stripping ponds (nonaerated or aerated). High-lime treatment usually requires high dosages of lime to raise the pH above 11. The process is particularly efficient if sufficient magnesium is present in the wastewater to precipitate as magnesium hydroxide at high pH values. To raise the pH, either quicklime (CaO) or hydrated lime $Ca(OH)_2$ can be used. Because of the large amounts of lime added in the process, high-lime treatment produces large quantities of sludge. The lime sludge, however, is more readily dewatered than other chemical sludges such as alum sludge.

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