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Research Report

Urban-Wastewater Reuse for Crop Production in the Water-Short Guanajuato River Basin, Mexico

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IWMI

International Water Management Institute

Research Reports

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Summary

Overview

As is the case with most water management practices, there are significant trade-offs associated with irrigation using untreated urban sewage. From a river-basin perspective, wastewater irrigation is an important form of water and nutrient reuse; however, there are important water quality, environmental, and public health considerations. This report explores the advantages and risks of urban wastewater reuse for crop production in the water-short Guanajuato river basin in west-central Mexico. Through a selective literature review, we demonstrate how common this practice is throughout the world and in Mexico specifically. Finally, we apply and validate the Interactive River Aquifer Simulation (IRAS) model, developed by Cornell University and Resource Planning Associates, and evaluate the outcomes of several alternative water management scenarios for water and soil quality in the study area.

Summary of Results

Wastewater irrigation is a critical component of intensive water recycling in the Guanajuato river basin, based primarily on the value of the water resource and the nutrients it transports. The 140 hectares of land irrigated with raw wastewater downstream of the city of Guanajuato serve as *de facto* water treatment with significant retention of contaminants. However, recycling does tend to concentrate salts in the flows leaving the study area. Measured coliform levels where high did not, however, show significant evidence of direct health impacts of wastewater irrigation. Heavy metal concentrations in bed sediments and in irrigated fields are within Mexican, EU, and US norms. Under current irrigation practices, the buildup of heavy metals in soils is within EU and US norms. Based on simulation modeling of flow and nutrient transport, the annual gross values of the wastewater and wasteload to farmers in the Guanajuato river basin, Mexico were estimated at US$252,000 and $18,900, respectively. As part of its plan to install a wastewater treatment plant and sell the water to commercial interests, the city would need to consider how to recover this foregone economic benefit.

Urban-Wastewater Reuse for Crop Production in the Water-Short Guanajuato River Basin, Mexico

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Introduction

Background

The need to understand water management from a river basin perspective has been recognized for many years, and attempts have been made to translate this understanding into action. Some of these attempts have been successful, and many others failures. Within the past few years, there has been a resurgence of interest in regional authorities and basin councils, reflecting increased recognition that it is impossible to effectively manage water resources without considering management in a basin context (Molden 1997). This context explicitly acknowledges that the productivity and equity of water use cannot be understood by considering the various uses and users as if they were independent (Seckler 1996). There also is increasing recognition that productivity and equity are functions of the path of use of the water from its source to a sink, where it is no longer available for use. This sink may be the atmosphere, a saline water body—subsurface aquifer, lake, or the ocean—that cannot be used for productive purposes (including environmental), or a level of pollution that renders the water unusable.

Changing the path of water through the watershed or river basin can alter the utility of the water by shifting its use to a higher-value use, by increasing the output per unit of water consumptively used, i.e., water that is not usefully recycled within the basin, and/or by reducing the degradation in water quality. This last has been of significant concern to the agricultural community for many years, particularly in relation to salinization. In recent years, however, concern has broadened, both in relation to the nature of the contamination, and in terms of the communities affected. Within the agricultural community, there is increasing recognition that agricultural activities contribute to the degradation of water quality—through erosion and through contamination of surface water aquifers with residues of agricultural chemicals and microorganisms. There also is growing concern about the quality of water available for irrigation (as well as for domestic water in rural areas).

This concern has grown, in significant part, as a result of the increased importance of wastewater in the hydrology of many river basins. As urban populations grow, and as industrial development expands, the volumes of wastewater produced increase at a rapid rate, and their composition becomes more complex. The waste streams often include industrial wastes, such as heavy metals, acids, and derivatives of plastics, in addition to the organic components characteristic of human wastes. Thus, the safe discharge of wastes to the environment is increasingly recognized, both in terms of implications for public health, and for the environment more generally. Less well-recognized are the potential benefits from this discharge.

Applied Action Research

Adequate treatment of wastewater prior to use is undoubtedly a good principle; however, in most developing countries, limited financial resources severely constrain wastewater treatment options, making land application an appealing alternative. The need for low-cost sanitary disposal of wastewater has resulted in its widespread use for agricultural and aquacultural purposes. While reuse occurs widely, and guidelines for that use are available (Khouri, Kalbermatten, and Bartone 1994; WHO 1989), these generally identify the water treatment required for different uses. In the case of land application of wastewater, there is little specific reference to the composition of the wastewater as it is used at the field level. In part, this is because composition is not often measured, even at the source. Even in those situations where the composition is measured at the source, i.e., at the sewer outfall, use frequently takes place at a substantial distance. In these cases, the composition of the wastewater can change significantly, especially if transport is through a natural channel subject to aeration and/or sediment deposition. To evaluate the appropriateness of the use of wastewater for irrigation in individual situations, information about the composition at the field level is necessary. Given the cost of sample collection and analysis, there is a major need for a procedure that would predict, with appropriate precision, the pollutant composition of the waste stream as it moves downstream to points of use. The study reported here evaluates the utility of the IRAS model developed for this purpose, and illustrates its application in a water-short area in Mexico where urban wastewater is being used for irrigation.

Wastewater Irrigation as a Global Practice

How Pervasive Is It?

Wastewater irrigation, night soil use in agriculture, and the land application of sewage treatment residues (sludge or biosolids) are traditional practices around the world. Efforts to quantify the location and magnitude of wastewater reuse are fraught with methodological problems (Khouri, Kalbermatten, and Bartone 1994). China and India make significant reuse of wastewater (Bartone 1991). An estimated 80 percent of wastewater in developing countries may be used for irrigation (Cooper 1991). Untreated wastewater is used to irrigate at least 500,000 hectares in Latin America (Moscosco 1996) with over half of this area in Mexico (Rodríguez, Oyer, and Cisneros 1994).

The literature search for the present study turned up several hundred citations in the internationally referenced AGRICOLA© scientific database. To show the wide geographic distribution of wastewater reuse, we use table 1 to list the countries for which research was cited and the number of references, followed by a summary of the major findings of selected articles. The data reported in this table should not be construed to represent the actual distribution of wastewater irrigation as a practice; instead, they are included here to show how pervasive a practice it actually is.

Wastewater as a Valuable Water Resource under Conditions of Scarcity

The most significant wastewater reuse takes place in arid regions where other sources of water are

TABLE 1.
Number and geographic distribution of research citations on wastewater reuse.

Country	No. of references	Country	No. of references	Country	No. of references	Country	No. of references
Australia	25	France	9	Libya	2	Saudi Arabia	2
Austria	1	Germany	19	Lithuania	1	Slovenia	1
Azerbaijan	2	Greece	1	Malaysia	3	Spain	15
Bangladesh	1	Europe	9	Mexico	16	Sudan	3
Brazil	4	Hungary	5	Morocco	1	Sweden	10
Byelarus	1	India	25	Netherlands	10	Switzerland	1
Canada	8	Iran	3	New Zealand	1	Syria	1
Chile	2	Ireland	1	Oman	3	Taiwan	1
China	5	Israel	56	Peru	2	Thailand	2
Cyprus	4	Italy	9	Poland	1	Tunisia	2
Czech Rep.	5	Japan	10	Portugal	4	Turkey	2
Denmark	1	Jordan	8	Qatar	1	Turkmenistan	1
Egypt	13	Kuwait	5	Romania	35	United States	24
Finland	1	Latvia	1	Russia	42	Venezuela	2
						Total	423

not available. Israel is at the forefront of wastewater reuse, with fully 70 percent of the total agricultural demand for water in 2040 projected to be met by effluent (Haruvy 1997). Similarly, a review of water resources in Palestine identified recycled wastewater as the primary water source for future irrigation demand (Sbeih 1996).

Where other water sources are scarce, wastewater is often a contested resource. Bell, Cox, and Fielder (1983) present a number of interesting historical cases of legal battles over the right to existing wastewater flows in the western United States. Generally, little interest was expressed in water quality, although the Clean Water Act has brought water quality to the forefront of water reuse concerns. The city of Lubbock, Texas presents an interesting case study (Fedler, Borrelli, and Ramsay 1987), with increasing commercial demand for wastewater that had originally been land-applied as a disposal mechanism.

Beneficial Use

Along with reuse of a valuable water resource, the appropriate use of the nutrients found in wastewater has been a primary objective of most wastewater reuse systems. Nutrient cycling has been the predominant objective of wastewater irrigation for centuries. In China, night soil and wastewater reuse in agriculture is a traditional practice. However, as wastewater treatment capacity is increased, greater quantities of sludge are being generated with a new set of land application challenges (Wang 1997). With industrial discharges, the heavy metal content of sludge has increased dramatically in China, posing a human health risk (Yediler et al. 1994).

Raw sewage used for irrigation in India over a 15-year period was reported to have improved the soil structure (Mathan 1994). At a separate site, wastewater irrigation over 15 years increased soil nutrients and organic carbon content without increasing heavy metals to toxic levels (Gupta, Norwal, and Antil 1998). Even in cases where wastewater is treated at the primary level (e.g., stabilization ponds) for subsequent discharge into the environment, the nutrients may be beneficially used. Several researchers have described the aquacultural benefits of wastewater ponds (Bartone 1991). Calcutta handles approximately 3 m^3/s of wastewater in 3,200 hectares of ponds to produce 2.4 T/ha/yr. (metric tons per hectare per year) of fish. In a departure from the prevailing 'beneficial use' perspective, particularly valid for developing countries with significant budgetary pressures, is a study of wastewater management in Bangkok, Thailand that recommended the highest cost/lowest uncertainty option of incineration (Stoll and Parameswaran 1996).

Biosolids application to forestland may be an appealing option. Largely as the result of an intense local organizing campaign, the city of Seattle, Washington now makes use of its biosolids in this manner (Touart 1998). Schoppmann (1996) reports on the development of eucalyptus and casuarina stands established with treated wastewater from the city of Pisco on the arid Peruvian coast.

Nutrient Impairment of Water Quality

The percolation of nutrient-rich waters through the soil (as is the case with wastewater irrigation) can lead to the degradation of groundwater quality. With perhaps the most ambitious national policy on wastewater reuse, Israel has major nitrate contamination problems—over half of all wells have nitrate limits higher than the 45 mg/l EU and US drinking water standards, while 20 percent reached beyond the 90 mg/l Israeli standard (Haruvy 1997). Of particular concern are sandy, porous aquifer strata with shallow water depths, as is the case in the Nile delta, parts of which Egypt is attempting to reclaim with wastewater from Cairo (Hall and Smith 1997; Farid et al. 1993).

Generally speaking, the retention of pollutants is strongly correlated to soil or aquifer media texture. Tanik and Comakoglu (1996) describe experimental results that relate nitrogen and phosphorus removal efficiencies to soil texture. Bouwer (1991) reports on the effectiveness of injection- and recovery-well systems for groundwater recharge.

Public Health Risks

The public health risks associated with wastewater reuse include increased exposure to infectious diseases, trace organic compounds (Cooper 1991), and heavy metals. Wastewater contains the full spectrum of enteric pathogens endemic within a community. Many of these can survive for weeks when discharged on the land. Notwithstanding the presence of infective organisms, however, epidemiological studies have shown that the mere presence of pathogens does not necessarily increase human diseases. The establishment of the World Health Organization (WHO) guidelines on wastewater use in 1989 effectively ended the international debate (with some strident objections, e.g., Armon et al. 1994) on how stringent bacteriological standards need to be, to safeguard public health. Earlier, the 1968 California State Department of Public Health standards had been widely adopted. From an epidemiological perspective, these were viewed as excessively restrictive (Shuval 1991a); to meet these standards would require considerable additional treatment capacity at increased cost. Nevertheless, typhoid and cholera transmission was linked to wastewater irrigation of vegetables and salad crops in the vicinity of Santiago, Chile (Shuval 1993).

Of particular concern, from a public health perspective, are the helminths (*ascaris* and *trichuris*), which have both a relatively long persistence and a small infective dose. As a result, the risks of intestinal nematodes (and bacteria at high levels) in untreated wastewater are recognized as important, both for consumers and irrigators (Shuval 1991b). In general, however, viruses are considered to present minimal risk (WHO 1989). Experimental results indicate that soil acts as an effective filter for polio virus (Oron 1996). Sinton et al. (1997) report on bacteriophage and bacteria transport through a shallow aquifer experimentally irrigated with primary treated wastewater. In addition to direct transmission of infectious diseases through wastewater, the ponds and canals used for its handling may serve as habitats for disease vectors, such as mosquitoes and snails.

While most studies on the public health impacts of fecal contamination have focused on wastewater irrigation, the pollution of coastal waters may pose risks to swimmers as well as to the consumers of shellfish. E. coli have been reported to remain culturable in marine and freshwater sediments for several months (Davies et al. 1995).

Heavy Metal Accumulation

Environmental accumulation of heavy metals resulting from wastewater irrigation and sludge is a contentious issue. With legally mandated wastewater treatment increasing worldwide, the amount of annually generated sludge is staggering. In the US alone, the total is estimated to be 5.3 x 10^6 T/yr. (Krauss and Page 1997). Among the countries and regions that have passed regulations on the use of wastewater and its byproducts (principally the sludge), Scandinavia and the Netherlands have set the most restrictive norms. Based on evidence that sludge application at agronomically determined rates will build up heavy metal concentrations in the soil to levels that will take thousands of years to reduce (under present agronomic practices), Sweden has set zero accumulation of metals as a policy (Witter 1996). Other European Union member states have established less stringent norms based on the EU Urban Wastewater Treatment Directive, specifically Spain (Sala et al. 1998; Salgot and Pascual 1996) and the UK (Davis 1996).

In the United States, the Environmental Protection Agency's CFR 503 regulations on the accumulation of heavy metals from land-applied sewage sludge are based on an environmental risk assessment approach. Distinct from most countries that view wastewater and its derivatives as an environmental risk management issue, Australia regulates wastewater use through the Department of Health and Community Services (Eden 1996; Kayaalp 1996). These regulations cover third-party effects including runoff that transports pollutants to neighbors' land or to environmentally sensitive areas. There is concern in Australia over heavy metal accumulation from wastewater irrigation, even though it is treated at the secondary level (Smith, Hopmans, and Cook 1996).

Heavy metal accumulation is a major concern in Mexico. The century-old practice of irrigation with untreated wastewater from Mexico City (see below) has resulted in significant accumulation of at least four metals (cadmium, copper, chromium, and lead) as documented by Mendoza, Cortes, and Muños (1996). A related study (Cortes, Mendoza, and Muños 1996) reports that "serious ecological damage" has occurred, which represents a human health hazard. Heavy metal accumulation was found to be highest in the organically bound fractions with a pronounced decrease in concentrations with depth in the soil profile (Flores et al. 1997). The management factor exerting the greatest influence on metal concentrations was the proportion of raw to sedimented wastewater used for irrigation.

Hansen, León, and Bravo (1995) estimated the heavy metal input into the waters of the Lerma-Chapala basin (where the site of the present study is located). Industrial production, principally in tanning, feedlots, and textiles was the principal source of metals studied. Mining, prevalent in the study subbasin in the seventeenth and eighteenth centuries, is no longer considered to exert a significant influence on heavy metal concentrations. In a related study, Hansen (1992) found that heavy metal accumulation in the lake aquatic system was correlated to the distribution of sediments.

Wastewater Irrigation in Mexico

Institutional Framework

Mexico is committed to increasing the effectiveness with which its limited water resources are used. As a base for this effort, it has adopted the principle of river basin planning and management. To implement this principle, the country has been divided into thirteen Regional Water Authorities, under the Comisión Nacional de Agua (CNA). Within eight of these regions, River Basin Councils (*Consejos de Cuenca*) have been created to ensure user participation in the critical decision making associated with river basin management. Additional councils are to be established in the remaining areas. Fundamentally, the councils will have the responsibility to ensure that the scarce water resources will be used productively, efficiently, with equity, and with due consideration for the impacts on the natural environment.

In recognition of the increasing importance of wastewater in river basin hydrology, Mexico has established water quality norms for the different types of water uses. In addition, it has mandated different levels of wastewater treatment for significant waste streams—industrial as well as municipal—many of which are untreated, i.e., there is no process for reducing the contaminant load before discharge into the environment. The two primary foci of wastewater irrigation research within Mexico are environmental impacts and treatment options. Interestingly, despite the widespread use of untreated wastewater for irrigation there is little research on beneficial use.

At the basin level, the basin councils serve a planning and coordination role for integrated water resources management including environmental protection with significant implications for water quality. IWMI is undertaking research on the attributes, organization, and accomplishments of the Lerma-Chapala Basin Council, which was instrumental in reducing aquatic pollution (Mestre 1997).

Legal Framework

Earlier laws regulating the use of water dealt strictly with volumes, amounts, and concessions. It was not until the 1971 Federal Law for the Prevention and Control of Environmental Contamination *(Ley Federal para Prevenir y Controlar la Contaminación Ambiental)* that water quality was regulated. Interestingly, oversight was given to the health authorities, although the concept of waste load limits to receiving water bodies was the basis for these regulations. The approach was modified by the 1988 General Law on Ecological Equilibrium and Environmental Protection *(Ley General del Equilibrio Ecológico y Protección al Ambiente),* which established concentration limits by categories of water (re-) use for the following receiving bodies: rivers, lakes and reservoirs, coastal waters, soil, and wetlands. The relevant selections of the applicable norms are presented in annex 1 of this report.

Finally, the 1992 Law of the Nation's Waters *(Ley de Aguas Nacionales)* strengthened the enforcement of the existing norms through a system of fines for water quality impairment. Fines are to be levied by invoking two additional federal laws, resulting in an extremely cumbersome application process. The authority to enforce the 1992 Law (and by extension, the norms) rests with the CNA, an agency that is charged with all aspects of water management; as a result, water quality enforcement has not been at the forefront of their mandate. Furthermore, a separate institution—the Federal Legal Office for Environmental Protection *(Procuraduría Federal de Protección al Ambiente)*—must actually take legal action.

Tradeoffs of Wastewater Irrigation in Mexico

Wastewater reuse is a prevalent practice in Mexico. Rodríguez et al. (1994) estimate that 370,000 hectares are irrigated with wastewater in Mexico, although this estimate appears unreasonably high. Of the 7.3 km^3 (231 m^3/s) of wastewater generated annually in Mexico, 5.5 km^3 (174 m^3/s) are sewered while only 0.53 km^3 (17 m^3/s) are adequately treated; the remaining 6.8 km^3 (214 m^3/s) are discharged into the environment without treatment (CNA 1997). An estimated 91 percent of this volume is generated inland in arid to subhumid conditions, indicating that 200,000–250,000 hectares may be a more reliable estimate of total wastewater irrigation in Mexico.

The practice of wastewater reuse has grown around a number of Mexican cities and towns. Cirelli (1998) reports on the social and political dynamics of wastewater irrigation outside of San Luís Potosí. As the city has grown to surround wastewater-irrigated fields, the productive value of the resource has come into conflict with the olfactory and optical sensibilities of the citizens because of the piles of rotting refuse dredged from the canals, and the black pestulant water flowing in uncovered canals near residential neighborhoods. However, wastewater users have secured rights through a series of presidential decrees and the practice will only expand with the growing population.

Mexico City has the largest urban population in the world living in a closed hydrologic basin, i.e., with no natural outflow to the sea. It is also the largest single user of wastewater in the world. Of the raw sewage from Mexico City 1.5 km^3 are estimated as being reused for irrigation every year (approximately 45 m^3/s), far and away the largest single user in the world (Khouri, Kalbermatten, and Bartone 1994). Over the years, attempts to control flooding, changes in watershed land uses, and increased water use have resulted in drastic changes in the hydrology of the basin. Texcoco Lake, a shallow freshwater lake located in the outskirts of Mexico City disappeared as a result of flood control, and overpumping of the underlying aquifer (Cruikshank 1998). In addition, tunnels—both historical and modern—are used to reduce flood risks and to carry wastewater out of the basin. These changes have now caused increased concern for the general ecology in the area.

To reduce the problems now evident in the basin, a lake reclamation project is being implemented that makes use of the wastewater from Mexico City. Three types of water treatment are being evaluated: primary treatment, using a 65-hectare lagoon; primary and secondary treatment; and tertiary treatment resulting in drinking water quality. The wastewater used in this demonstration/research project is approximately 3 percent of the total effluent from Mexico City. Table 2 lists the breakdown of the approximately 45 m^3/s of wastewater flow generated in Mexico City.

Of particular interest to the present study is the experience with wastewater irrigation in the Tula and Alfajayucán irrigation districts. Tula (approximately 100,000 ha of official and unofficial command area, and growing) is considered the largest contiguous area of wastewater irrigation in the world. Historical records indicate that by the late nineteenth century, Mexico City wastewater was already being used for irrigation in this area. As the city grew, so did its waste volumes, and by extension, the area irrigated in Tula. Table 3 illustrates the characteristics of the districts.

Most of the wastewater enters the Endho reservoir before being distributed to the irrigation districts. The detention time in the reservoir allows for some natural remediation. However, to avoid potential health problems, farmers are constrained in their cropping options by regulation: no vegetables or fruit can be irrigated with wastewater, leaving maize and alfalfa as the major crops. The area experiences some problems identified explicitly with the use of

TABLE 2.
Wastewater flow and its uses, Mexico City.

Source/Fate	Flow (m^3/s)	Comments
Wastewater generated in Mexico City	45	194 l/day/capita. At 70% return rate, water supply is 260 l/day/capita.
Primary treatment for irrigating parks/green areas within Mexico City	10	Could irrigate up to 10,000 ha of land, but may be used to maintain wetlands and "floating gardens."
Primary and secondary treatment for Texcoco Lake Reclamation	1.0–1.5	Reclamation of sodic soils, reforestation, and Nabor Carillo Lake.
Tertiary treatment for animals and/or groundwater injection, Texcoco Lake	0.05	Sedimentation, flocculation, filtration (sand, activated carbon), and chlorination.
Untreated wastewater	34	Discharged to Tula Irrigation District (Hidalgo State) through a network of tunnels whose longest tunnel is over 60 km.

TABLE 3.
Characteristics of Tula (No. 003) and Alfajayucán (No. 100) irrigation districts.

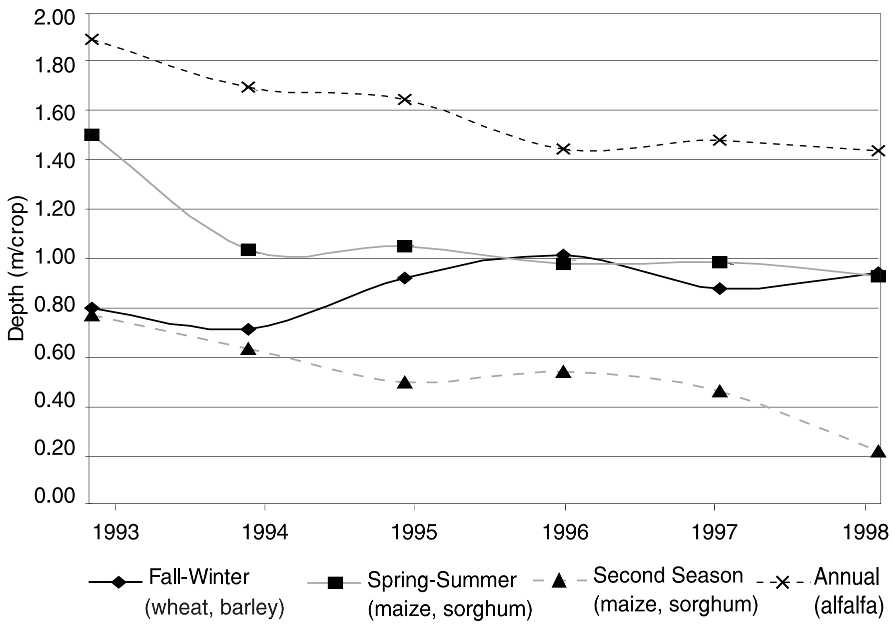
	Tula	Alfajayucán
Total command area (ha)	45,125	33,051
Number of water users	31,316	19,540
Water source	Mexico City wastewater, plus reservoirs with a combined capacity of 278.12 million m^3	Mexico City wastewater, plus reservoirs with a combined capacity of 254.7 million m^3
Area irrigated with drainage return flows (ha)	10,000	Unknown

wastewater. The reservoir has no surviving fish, and the potential growth of aquatic weeds is such that a major program of control is necessary to maintain the use of the outlet structures. Waterlogging and salinity affect a relatively small area of approximately 500 hectares. Information on health problems experienced by the water users is not readily available, though informal discussions with users did not reveal major concerns.

On the positive side, the wastewater provides an abundant source of irrigation water, though this is reducing as Mexico City uses more of the water internally. Figure 1 shows the irrigation depths used in the area, which are substantially higher than irrigation depths in other districts. The wastewater provides plant nutrients not present in non-sewage water, and the farmers use little, if any, purchased fertilizer. Several studies have been carried out in the district, including one on water quality. Figure 2 shows pronounced head-tail effects on water quality. It is clear that nutrients and Biological Oxygen Demand (BOD) are retained in the soil, while salinity gets worse from head to tail.

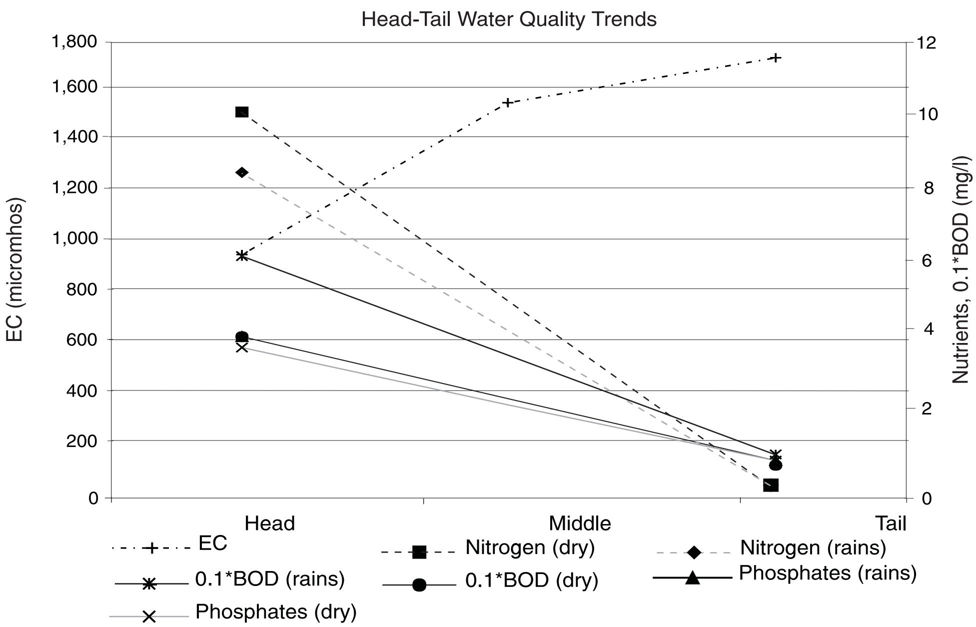
As indicated previously, Mexican legal norms (annex 1) specify the standards for the use of wastewater in irrigation, and these limit the use of untreated wastewater to basic grains (maize, sorghum, and wheat) and fodder (alfalfa). While some clandestine irrigation of higher-value crops undoubtedly takes place, the crop restrictions clearly limit the agricultural profitability. As a result, although this may not be the only reason, the Tula and Alfajayucán irrigation districts are among the few in the country that have not accepted

FIGURE 1.
Irrigation depths by cropping season, Tula Irrigation District.



Source: CNA 1999.

FIGURE 2.
Water quality trends in the Tula Irrigation District.



Source: CNA 1999.

responsibility for operation and maintenance under the irrigation management transfer program. The processes and trends associated with wastewater irrigation reported above were observed firsthand during extensive field research in the Guanajuato river basin, in west-central Mexico.

Field Research Program

The City of Guanajuato has water management interests that span the watershed. Its basic water supply includes both surface water, impounded in two principal reservoirs located in the upper part of the watershed, and groundwater pumped from one main aquifer in the central part of the watershed. It releases wastewater to the downstream part of the watershed, ultimately reaching the Purísima reservoir, which serves as the water source for part of Irrigation District 011 (where IWMI has been undertaking research since 1994). Given the water-short conditions in the basin (annual precipitation of 500 mm, potential evapotranspiration exceeding 1,500 mm, and significant urban and agricultural demand for water), storage levels in the reservoir are chronically low.

Since the groundwater costs approximately six times as much as the gravity surface water, the city has a strong interest in maintaining the water-producing characteristics of the watershed as well as in the potential for use of the wastewater to reduce demands on the city water supply. Similarly, the current users of the wastewater have interests in the future availability of wastewater. These users are small-scale irrigators, organized in *unidades,*[1] whose water sources include the wastewater, flows from natural rainfall, and groundwater. The wastewater represents a significant part of their water supply, especially during the dry season. Irrigation is practiced by rotation, with individual irrigators determining the duration of their turns. In this sense, water applications are relatively high when compared to other countries, or areas within Mexico. The typical crops are forage (alfalfa) and grains (sorghum and wheat). Soils are alluvial in nature with moderate to high permeability.

This combination of circumstances raises a number of questions specific to the location. The Guanajuato City water authority (SIMAPAG) has special concern for the following:

- What level of treatment is mandated under Mexican law?

- What monetary value would this treated water have?

- What are the legal implications of reducing the outflows to the downstream irrigators?

In addition to these specific questions, however, the situation in Guanajuato provides an opportunity to address some generic questions of broader applicability:

- Land application of wastewater through irrigation serves as a waste treatment process, with benefits and problems for the irrigators. What is an appropriate basis for charging or compensating the wastewater users?

- Irrigators using untreated wastewater discharged into natural streams, over time in many situations, acquire a *de facto* right to the water. How should the *de facto* water right be addressed when water treatment reduces wastewater outflows?

- Wastewater application to the land uses the land as the sink for nondegradable contaminants, e.g., heavy metals. How should this environmental externality be valued? What are the most significant risks posed by the complex interrelationship among wastewater, soil, crops and groundwater?

The research reported here addresses the foregoing, in the context of the specific situation in the Guanajuato Basin.

[1]Unidades are organizations of irrigators that are user-managed, often with some governmental oversight.

Methods and Materials

Field-Data Collection

To identify the major hydrologic features of the river between the city and the Purísima reservoir, IWMI staff, accompanied by the SIMAPAG Operations Engineer, walked the 12-km reach prior to developing plans for field-data collection (see figure 3). This reconnaissance served to locate the principal wastewater and natural stream discharges into the river as well as irrigation diversions. Subsequent fieldwork allowed us to pinpoint flow gauging and water quality sampling points on 1:50,000 topographic maps and a digitized air photo. The irrigation areas show up clearly in red on the false color composite Landsat TM image taken on 19 April 1999 (figure 4). Contact was also made with farmers who irrigate with the wastewater, to understand the rules governing water allocation and sharing both among and within the peri-urban communities of San José de Cervera and Santa Catarina. These were selected because they utilize raw wastewater that may be subject to water quality changes based on return flow, and because they have the largest areas irrigated with wastewater.

Field research activities were designed to address three objectives as indicated in table 4. The data collection strategy adopted in each case, the date of fieldwork, and numbers of samples collected are also presented. It should be noted that in general, samples were collected in triplicate at the same point, with sampling points located at and below identified inflows, while seeking to maintain a maximum distance of 800 m between sampling points.

Flow Measurement

Flow in the river and irrigation canals was measured using the velocity-area method at the time water quality was sampled (no continuous flow measurement). The channel cross-section was divided into subsections at least 0.30 m wide (or a maximum of 10 subsections for wider sections). The average depth and width were recorded. Three velocity readings per subsection were made using pre-calibrated Global Flowprobe® current meters (horizontal propeller type). At the request of the SIMAPAG, IWMI

TABLE 4.
Field research design.

Objective	Strategy	Sampling dates	Total no. of samples (no. of points)
1. How are the major water quality constituents transformed during instream transport?	Sample single slugs of wastewater as they flow down the reaches (main river channel and one irrigation canal).	16 Nov. 1998 4 Dec. 1998	87 water samples (29 points)
2. What temporal variations exist for the constituents in the source wastewater?	Sample multiple slugs distributed throughout the day (one irrigation canal from the river diversion to the irrigated field).	19 Feb. 1999	48 water samples (16 points)
3. What residual contamination is present for wastewater-irrigated soils and shallow groundwater?	Compare soil and water quality for wastewater-irrigated plots v fresh (groundwater)-irrigated plots.	15 May 1999	36 water samples (12 points) 12 soil samples (12 points)

FIGURE 3.
Schematic map of the study site.

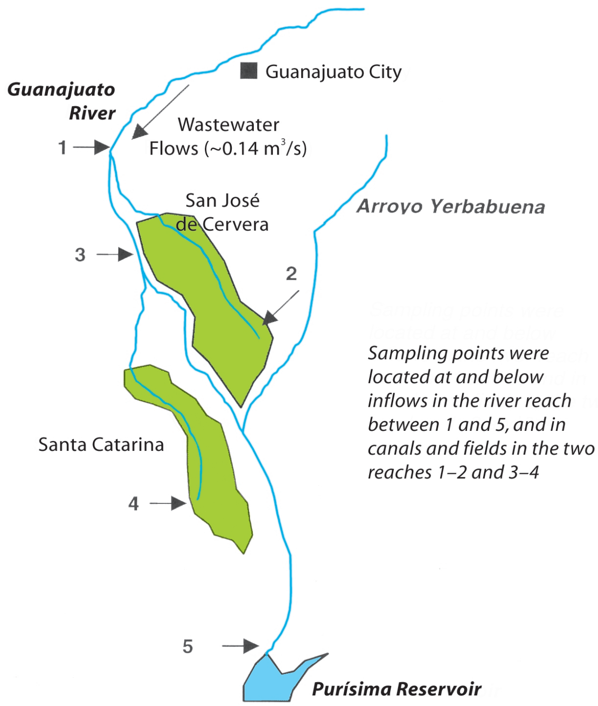
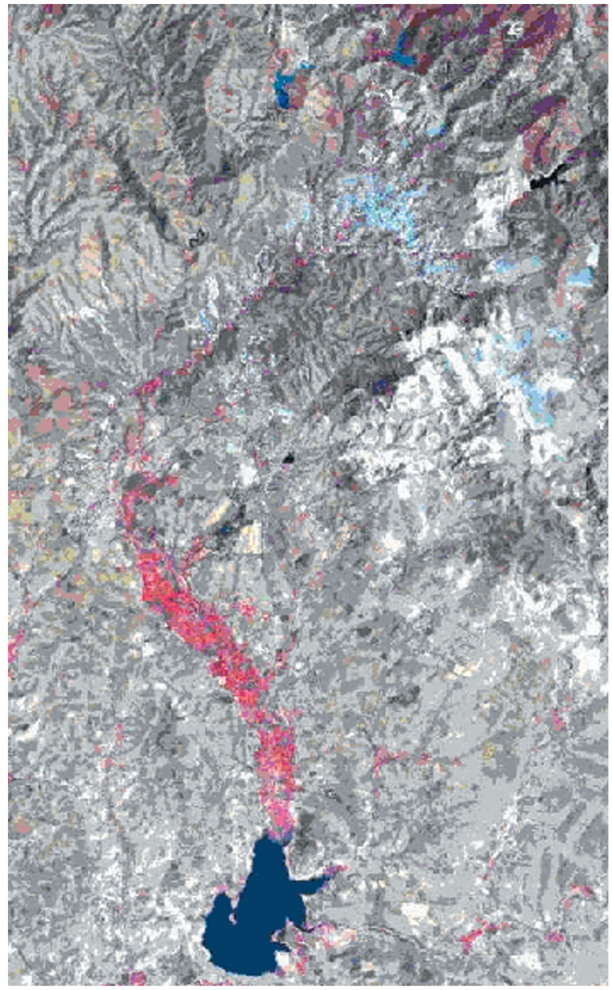


FIGURE 4.
False color composite (Landsat TM) of the study area.



assisted in instrumenting a V-notch weir with a depth sensor and datalogger for continuous measurement of the City's wastewater discharge. This operated for one month in March–April 1999 until an early rainy season storm washed out the weir's wingwalls. One month of hourly flow data were sufficient, however, to determine the daily and weekly cycles generated by water use patterns in the City. These data were subsequently used to simulate both flow and water quality behavior of the system as described below.

Sample Analysis

In all cases, water samples were collected in triplicate (every 10 minutes over a 20-minute time span) to characterize the natural variability that occurs under environmental conditions. Temperature, pH, and electrical conductivity (EC) measurements were made in the field, and the samples were put on ice for subsequent transport to the laboratory where they were refrigerated until analysis. The analytical methods used to determine parameter values are described in annex 2.

Results and Discussion

The flow and quality data indicate that there is significant water recycling in the basin. The measured flows in the Guanajuato river and the principal irrigation channels clearly show considerable return flows resulting from percolation and lateral seepage (we comment below on the likely effect these have on water quality). The unlined, run-of-river diversions flow through permeable soils with some evidence of conduction losses. However, the data strongly indicate that irrigation return flows are responsible for much of the flow in the lower reaches of the study area. The irrigation area is 5–15 m higher than, and 100–700 m set back from, the main river channel. Based on flow measurements of a single slug of water (i.e., timed, based on average velocity and transport time), figure 5 indicates the river reach and estimated magnitude of return flows that enter the channel. The original sources of the upstream return flows are diversions further upstream and wells, which are used to irrigate high-value crops including alfalfa and vegetables.

It should be noted that of the total river discharge of 0.305 m^3/s flowing out of the study reach, over half (0.162 m^3/s) comprised return flows.

In the basin, the urban supply in Guanajuato City is the first use of water; irrigated lands lower in the basin are the second use. However, there is also significant recycling within the irrigation area, as shown in figure 5, which represents a simple mass balance with return flows (portion of diverted or percolated water that comes back to the stream) calculated on the basis of measured inflows and outflows. An upstream diversion is the first irrigation use, the San José de Cervera Canal (SJC, 1 in figure 5) is the second, Santa Catarina (SC, 2) picks up return flows from (1) and is the third use, and the Purísima reservoir and irrigation area downstream of the study area form the fourth recycled use. Thus, even within this relatively small basin (less than 20 km of river reach) there are multiple recycling loops, shown schematically in figure 6.

FIGURE 5.
Return flow replenishment of the river.

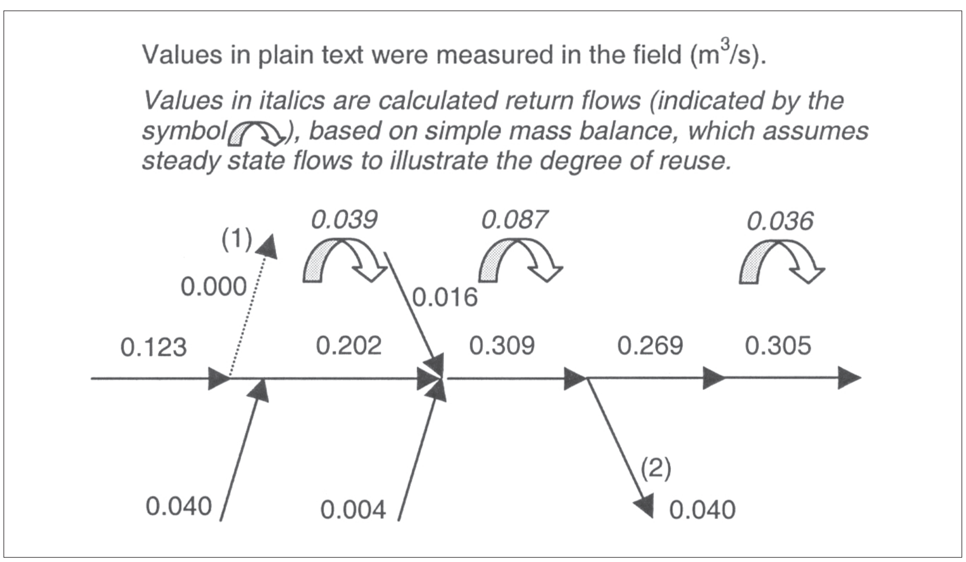
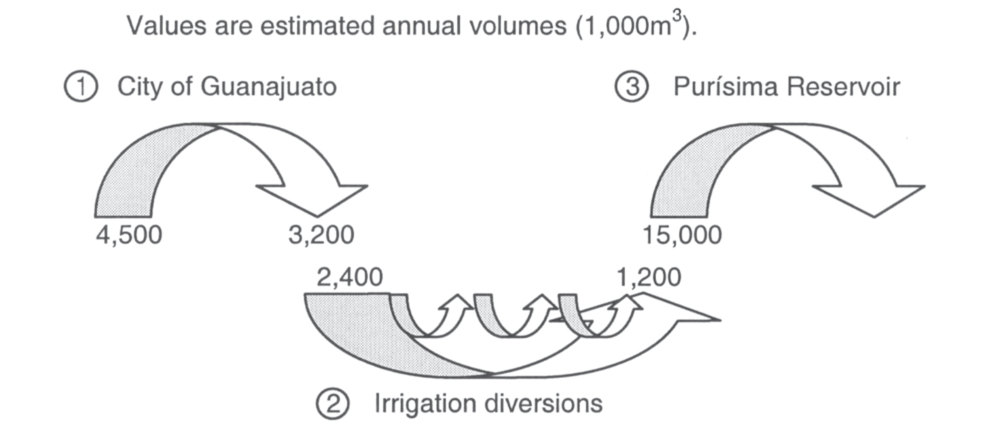


FIGURE 6.
Estimated magnitude of basin water recycling.



The water quality constituents showed marked spatial variability; however, contrary to what was expected, there was little temporal variability. These observations suggest that for short time periods, changes in water quality are largely a result of mixing (dilution and concentration), and will simplify the modeling process (described below). As indicated in the Methods section, the parameters and constituents analyzed include temperature, pH, EC, BOD, total phosphorus (TP), total nitrogen (TN), coliforms (total and fecal), solids (total, dissolved, and suspended), and heavy metals (Hg, As, Pb, Cr, Se, Fe, and Mn). The complete dataset is too extensive to be presented in this report. Instead, we limit our comments to the most notable trends in water quality.

The results of tracking a single slug of wastewater indicate that nutrients, both TN and TP—see figures 7 and 8, respectively—are assimilated (in irrigation areas or bed sediments) and parameter values decrease with distance down the main river channel. By contrast, EC increases with distance down the river (figure 9), a process caused by the concentration of salts through evaporation on irrigated land and the resulting high-EC return flows. It should be noted that for all three figures, the discharge increases with distance downstream due to natural or wastewater inflows, as indicated in figure 5 that presents the flows observed on the same day. While nutrient removal is not at the 90 percent level to be achieved by the proposed wastewater treatment plant (see below), the reductions are considerable. The trends noted here are similar to those reported for the Tula Irrigation District, above (figure 2). It should be noted that TN levels frequently exceeded the Mexican norm of 40 mg/l.

Monitoring temporal changes in parameter values at the same points down a canal provided insight into diurnal cycles. The total coliforms and fecal coliforms (TC and FC) exhibited erratic behavior both for measurements in the river channel where additional sources (animal and human excreta) might be assumed and for the relatively isolated SJC canal (figures 10 and 11, for which flow varied in the range of 0.040–0.090 m^3/s). Although the TC and FC did not display the same temporal changes, the second measurement point, 560 m from the diversion, exhibited consistently high values for these parameters for all times sampled.

FIGURE 7.
Total Nitrogen with distance down the main river channel.

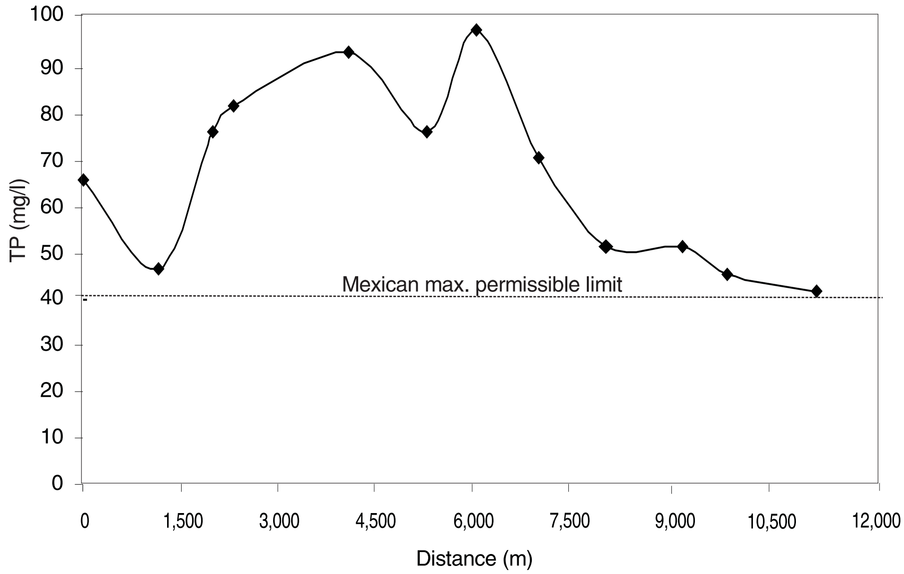


FIGURE 8.
Total Phosphorus with distance down the main river channel.

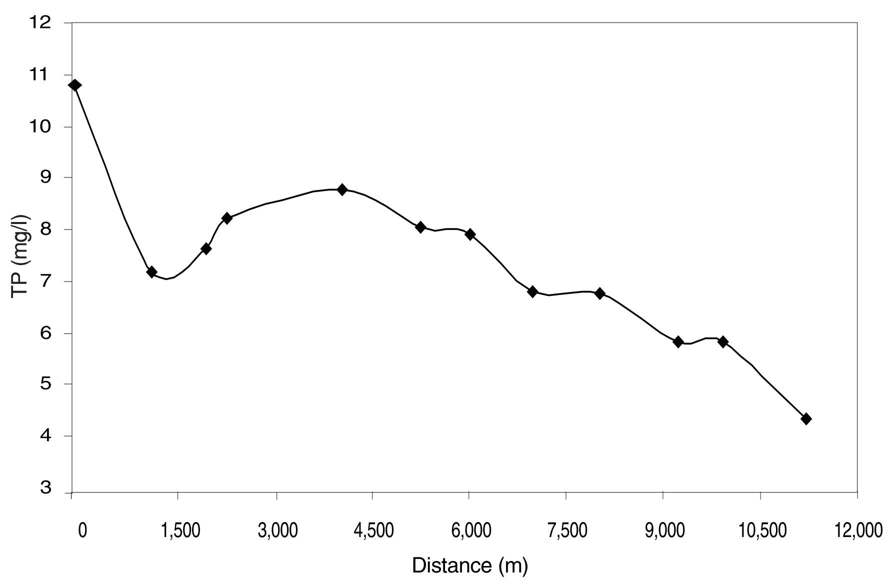


FIGURE 9.
EC with distance down the main river channel.

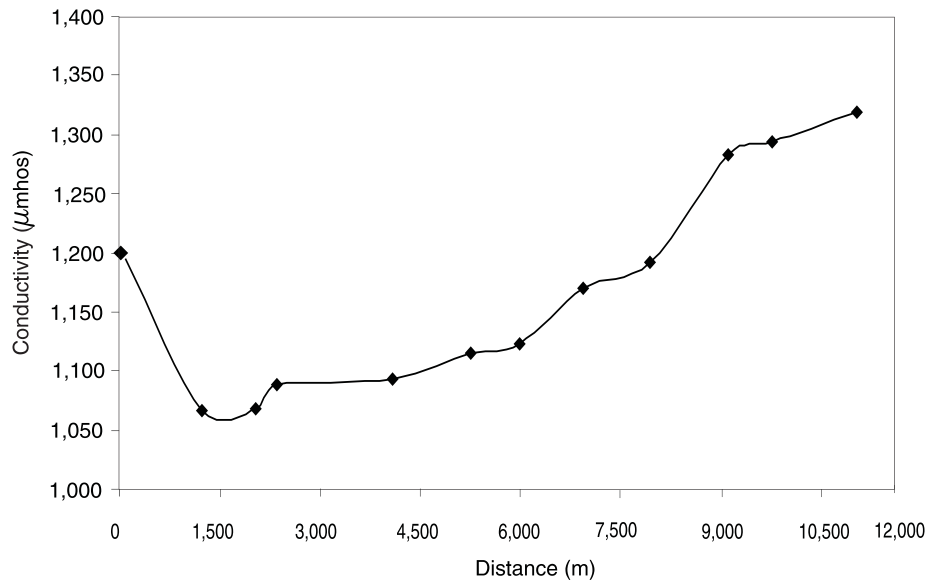


FIGURE 10.
Total coliforms with distance down the SJC canal.

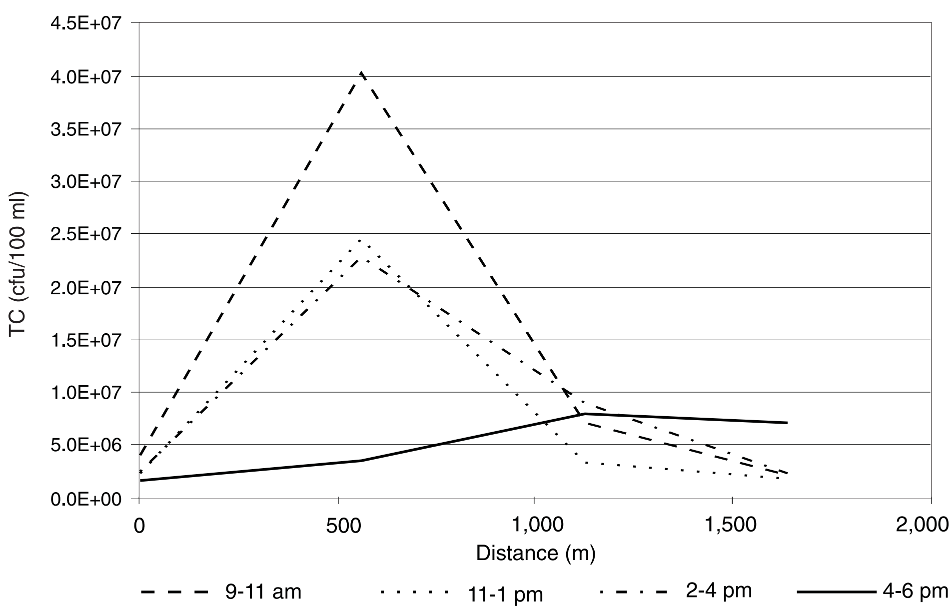
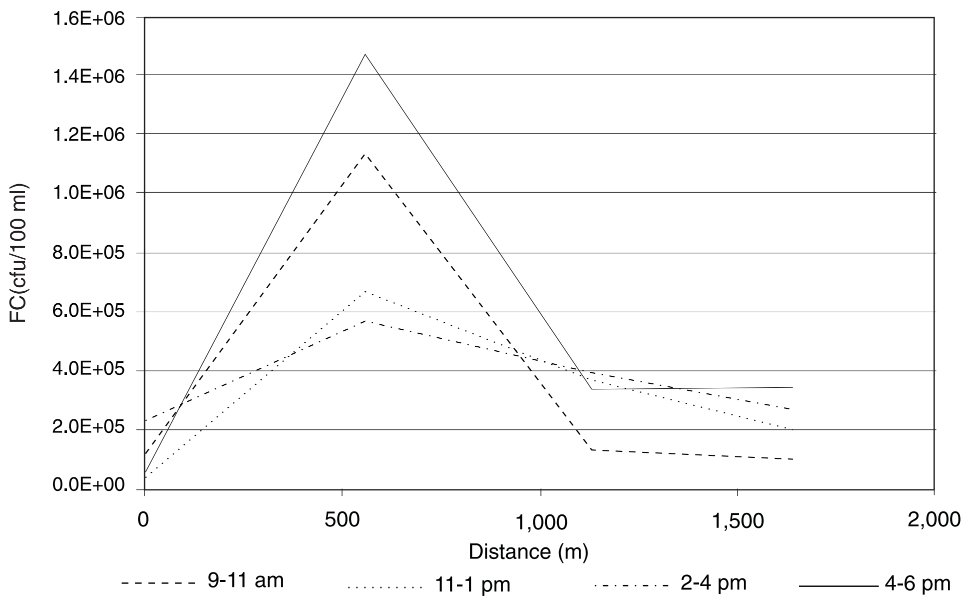


FIGURE 11.
Fecal coliforms with distance down the SJC canal.



Based on the limited sample of fields and wells that our informants identified as having been irrigated with or without wastewater, we were not able to assess the accumulation of contaminants. The results showed higher soil concentrations of TN, TP, TC, and FC for fields said to be irrigated by wells than those irrigated by wastewater. This component of the study did, however, indicate that TN levels measured in drinking water wells were within acceptable levels (0.81–7.28 mg/l as N). It is likely that a significant portion of the N applied in excess of crop demand is simply volatilized.

Finally, the analysis of heavy metals in the sediments of the riverbed and canals, and within the irrigated fields, did not result in levels above either EU or US norms (for Pb and Hg). Arsenic was somewhat elevated in only two locations. This is possibly linked to past silver mining activities (Wrobel and Wrobel 1998).

Water Quality Simulation

To understand the outcomes of alternative water management practices (particularly resulting from the City's plan to install a treatment plant), a variable timestep mass-balance accounting model was set up using the IRAS water quality model, which has been tested around the world. The IRAS computes water and constituent mass balances sequentially for the flow network, and allows the user to define fixed or variable demand schedules. Output may be viewed on-screen or converted to spreadsheet format for further tabulation and presentation. At the level of sophistication employed here, IRAS requires no calibration. Clearly, for applications that account for water quality parameter decay and growth, or for inter-parameter interactions, additional data would be required for calibration. As a result, we use this section to describe only model development, validation and prediction. Sensitivity analyses were not performed given that the simulation assumes linear response of parameter values to discharge, i.e., simple mixing resulting in dilution or concentration.

A link-node network was digitized for the river reach in which flow and water quality measurements were made (the same schematic as for figure 5 above, which we used to calculate return flows). Inflows were the City's principal wastewater discharge, two smaller wastewater discharges, a natural stream, and irrigation return flows. The SJC and SC canals were the demands. The resulting flow and constituent loadings were assumed to enter the Purísima reservoir.

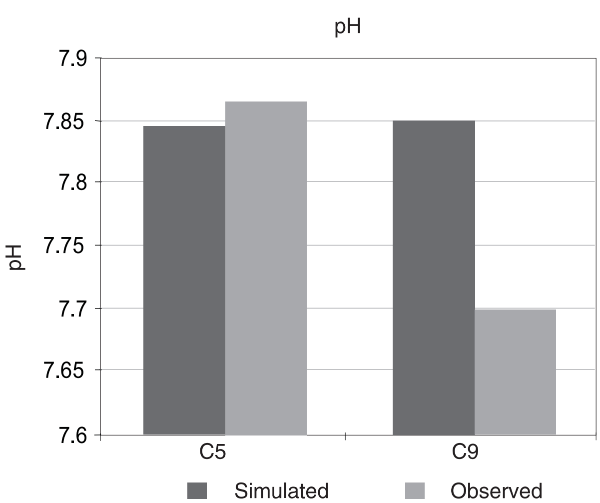
The first simulation was solely for verification purposes and it used a daily timestep covering the period 1 Nov. 1998–30 Dec. 1998. Altogether eight constituents were simulated (pH, EC, BOD, TN, TP, TC, TSS, TDS). Results of the simulation model were compared for two control points (C5 and C9) on the main river channel for the specific day on which water quality measurements were made. The simulated flow and quality values for these points were compared with values observed in the field. Figures 12a–12h compare simulated and observed constituent values at these points.

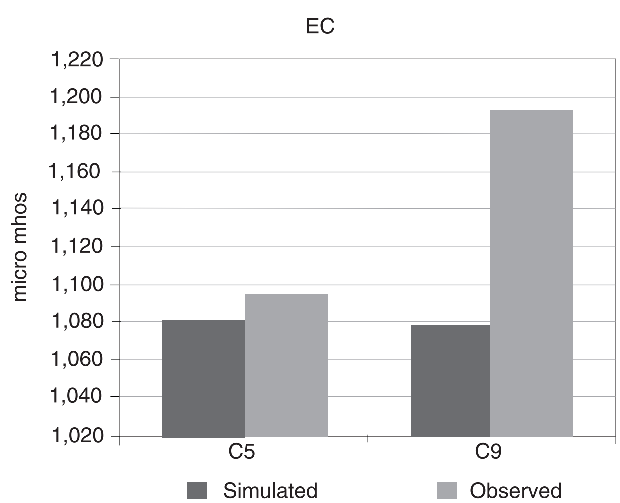
The results of the model verification run indicate the following:

- The model simulated the behavior of BOD and total phosphorus with a high degree of correlation with observed values.
- The model simulated total nitrogen and total dissolved solids with an acceptable degree of correlation with observed values.
- The model did not simulate pH, EC, total coliforms, or total suspended solids with appreciable correlation with observed values.

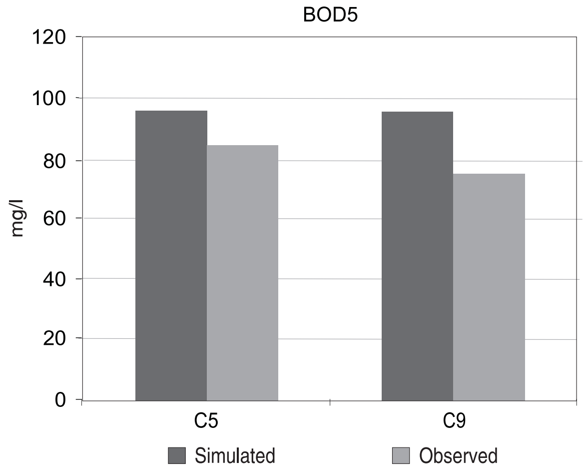
Based on the highly erratic behavior of coliforms in field measurements and in the simulations, it was decided to drop the coliforms parameter from the list of simulated parameters. This observation is corroborated by Gleeson and Gray (1997, 56–57) who found that "Studies of coliforms in tropical climates found that *E. coli* comprised on average 14.5 percent of the total coliforms isolated… [I]t would appear there is no

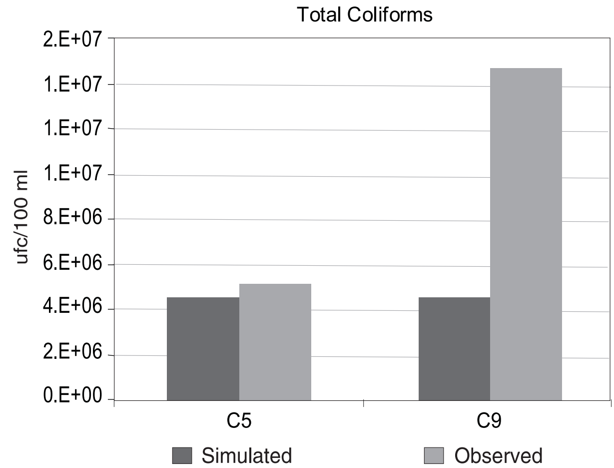
FIGURES 12 a and b.
pH and EC, simulated and observed.



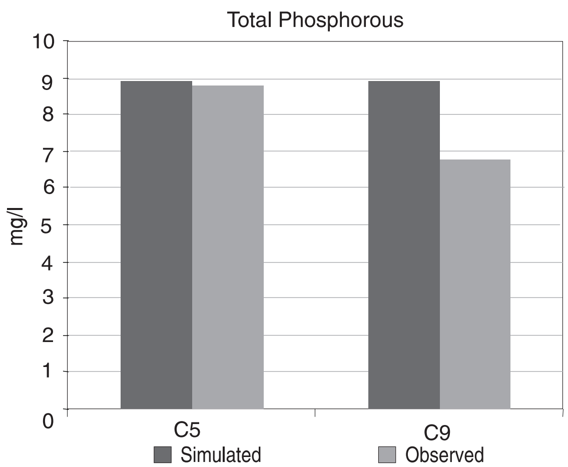


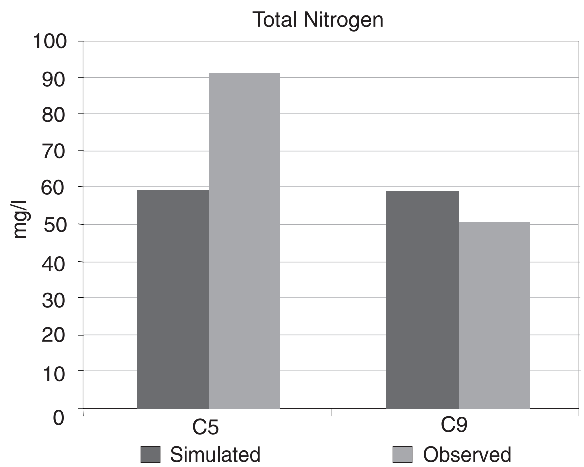
FIGURES 12 c and d.
BOD and total coliforms, simulated and observed.



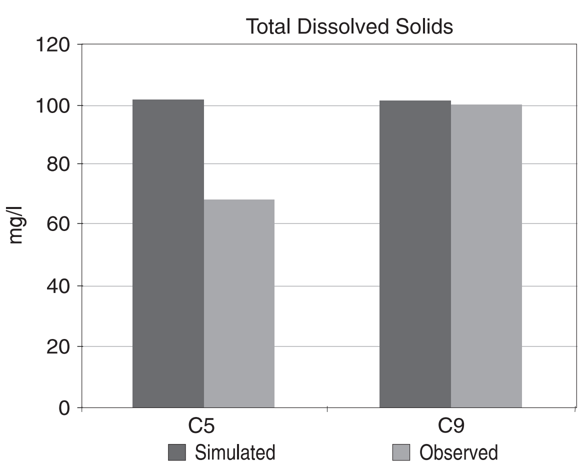


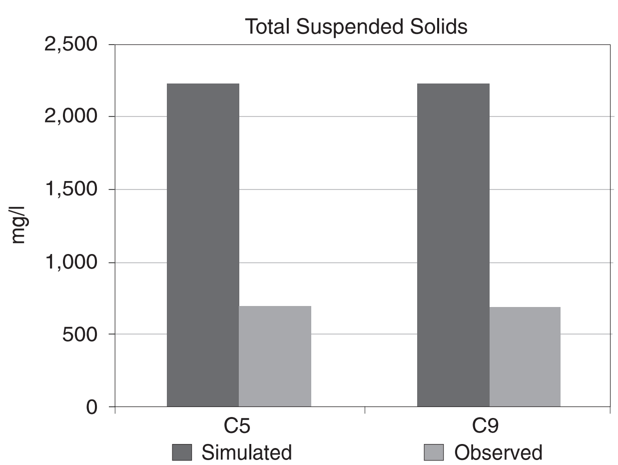
FIGURES 12 e and f.
Total Phosphorus and total Nitrogen, simulated and observed.





FIGURES 12 g and h.
Total dissolved solids and total suspended solids, simulated and observed.





benefit in using faecal (*sic*) coliforms as opposed to total coliforms as both groups give equally inaccurate results… [T]here are considerable doubts about the validity of using coliforms as indicator organisms in tropical countries."

Untreated and Treated Discharges

Based on the verification run just presented, the second simulation was run on a semiweekly timestep based on the following information: a) wastewater discharge from the City is higher during the week (Tuesday–Friday) than over the weekend (Saturday–Monday), and b) SJC and SC alternate irrigation turns for half a week each. On this basis, the second simulation covered the period 1 Nov. 1998 to 26 May 1999, equivalent to the fall winter irrigation season and bracketing the dates of field data collection.

Two sets of wasteload inputs were simulated, corresponding to untreated and treated wastewater discharged by the City. This reflects the City's plan to treat and sell its wastewater to commercial interests, specifically a proposed golf course. However, under the assumption that treated wastewater will be released down the natural river channel to be used by the customary SJC and SC irrigators until such time that the commercial buyer actually acquires the water, we have simulated the difference in (loss of) nutrient delivery for irrigated cropping. Table 5 lists the treated effluent quality to be released by the activated sludge treatment plant scheduled for construction in 2000–2001.

TABLE 5.
Untreated and design treated effluent quality projections.

Parameter	Untreated level (mg/l)	Treated level (mg/l)
BOD	358	5–15
TN	80	5
TP	10	1
SST	220	<10

Nutrient Replacement Value

The second run simulated the volume of flow as well as the TN and TP loads delivered to SJC and SC under untreated and treated conditions as shown in table 6. Subsequently, data on fertilizer costs and the N and P contents of different formulas were assembled from local commercial suppliers. These are listed in table 7 (they compare closely with values reported for the United States by Faust and Oberst 1996). The foregone annual economic benefits of loss in

TABLE 6.
Total N and P deliveries to irrigated fields using untreated and treated wastewater.

	Untreated		Treated		% Change	
Canal	N (kg)	P (kg)	N (kg)	P (kg)		
San José de Cervera (SJC)	45,483	7,553	3,556	711		
Santa Catarina (SC)	63,865	10,308	11,397	1,698		
	N (kg/ha)	P (kg/ha)	N (kg/ha)	P (kg/ha)	N (%)	P (%)
San José de Cervera	455	76	36	7	-92.2	-90.6
Santa Catarina	1,597	258	285	42	-82.2	-83.5
Alfalfa requirements	88	115	88	115		

TABLE 7.
Unit costs of N and P fertilizers.

Source of N	% N	Cost (N$/50 kg)	Cost (US$/kg N)
Urea	46.0	87.50	0.40
Ammonium Nitrate	33.5	82.50	0.52
Ammonium Sulfate	20.5	36.50	0.37
Average			0.43
P Source	% P	Cost (N$/50 kg)	Cost (US$/kg P)
Super Triple	46.0	112.50	0.51
Simple Sulfate	18.0	47.50	0.56
DAP	46.0	137.50	0.63
MAP	52.0	140.00	0.57
Average			0.57
Application cost (combined N+P) (US$/ha)			31.58

Note: N$=Mexican pesos.

nutrient deliveries to the combined irrigated area of SJC and SC are calculated at US$21,900 and US$27,500, respectively. Nevertheless, table 6 also indicates that the N requirements for alfalfa, the principal crop in the study area, are greatly exceeded in the untreated wastewater case. P requirements are approximately met with untreated wastewater; however, P application would not take place every year given its slow release.

Given that nutrients are delivered in excess of demand, a more robust indicator of the nutrient value of the waste stream is the saved cost of commercial inputs. Including the application costs, the total annual value (SJC+SC) is US$18,900, or US$135/ha/yr. Based on the volume of irrigation water delivered, the agronomically utilizable nutrient value represents US$0.02/m^3.

Public Health Risks

Data were collected from the public health offices for the Municipality of Guanajuato on the incidence of diseases related to wastewater irrigation for the period January–August 1999. From the data reported, it would appear that the overall infection rate in the wastewater irrigation sections is 980 cases/100,000 inhabitants, while in the sections without wastewater irrigation it is 5,457 cases/100,000. Such a large discrepancy can only be attributed to problems in reporting and not the real incidence of disease. Hence, we cannot conclusively determine the health impacts of wastewater irrigation in the study area. However, this does emphasize the real methodological challenges associated with using reported data for public health analyses. Further fieldwork would be required to establish the specific epidemiological linkages between wastewater use and disease in the study area.

Eutrophication Potential

The nutrient loadings delivered to the Purísima reservoir as a result of wastewater irrigation in the study area were simulated. It is assumed that wastewater return flows enter the reservoir during the irrigation season from 1 Nov.1998 to 26 May 1999, while wastewater is delivered directly to the reservoir during the remainder of the year (mixed with natural runoff). Furthermore, the City's wastewater accounts for an estimated 9 percent of the annual volume flowing into the reservoir. Under these conditions, untreated wastewater would produce mean TP and TN concentrations of 1.3 mg/l and 8.7 mg/l, respectively. Treating the wastewater would reduce TP and TN concentrations to 0.2 mg/l and 1.6 mg/l, respectively. Given that algae growth leading to eutrophication becomes accelerated above 0.1 mg/l TP (assuming sufficient nitrogen is present), there is significant cause for concern. Some algae growth (although not abundant) was noted in the reservoir in May 1999.

Conclusions

Benefits from Wastewater Irrigation

Water Value

The water used for irrigation represents a recycling of urban wastewater in a basin context. Data from IWMI studies in the Lerma-Chapala river basin (Kloezen and Garcés-Restrepo 1998) indicate that irrigation has a gross value of output per hectare of irrigated land[2] of approximately US$1,800, and per cubic meter of water of US$0.16 (1994 dollars). For the 140 hectares of land irrigated by the wastewater of the City of Guanajuato, this implies a water value of US$252,000 per year. *The water value of wastewater used for irrigation represents a significant monetary benefit to both society and the water users*.

Nutrient Value

The proposed treatment plant is designed to remove approximately 90 percent of both the N and P in the waste stream. This represents a annual nutrient value of US$95,900. Using the recommended level of N and P for the crops planted, the foregone nutrient benefit has a value of US$18,900 per year. While the value of these nutrients to society is included in the gross value cited above*, the loss of these inputs to the farmers is such that their net incomes would be reduced by the cost to replace the nutrients lost. While nutrient deliveries to the irrigated fields are a function of the amount of water used, and the concentrations of the various nutrients, and both of these variables change with the seasons, there are higher uses and higher concentrations occurring during the dry season.*

Reduced Cost of Wastewater Treatment

In accordance with national policy, the City of Guanajuato is in the process of contracting for an activated sludge wastewater treatment plant. The estimated investment cost for the plant is US$2.6 million with an annual operating cost of US$200,000. While the field study and analyses were limited, they strongly suggest that *continued application of the wastewater to the land would be a much more economical form of wastewater treatment.* This conclusion is drawn with the caveat that the potential for serious negative impacts for health and the environment should be evaluated in an ongoing monitoring program.

[2]This was based upon a crop mix of wheat and maize, with a relatively small percentage of vegetables. The cropping pattern in the wastewater-irrigated area includes wheat, barley, and alfalfa, the last being a relatively high-value crop.

Even this would be much less than the operating costs of the treatment plant.

Drawbacks of Wastewater Irrigation

In spite of the short-term benefits received from wastewater irrigation, there are considerable medium- and long-term costs associated with this practice. In the study area, N was found in excess of the 40 mg/l Mexican norm for receiving waters. There is also indication that elevated N levels in irrigation water may contaminate wells with nitrate. However, the limited well-water-quality sampling performed as part of this study did not find levels above the 10 mg/l (as N) US drinking water standard.

The potential adverse health and environmental impacts were not addressed systematically in this study. The potential for adverse health impacts of irrigation with wastewater has been reported in a number of articles, but there was no obvious indication of adverse health impacts in the area of study. The successive reuse of the wastewater in this particular basin suggests that these adverse effects may be smaller than in situations without reuse. The passage through field vegetation and/or the filtration that accompanies irrigation and subsequent runoff and drainage would be expected to reduce the level of parasites and other microorganisms, in addition to the observed changes in chemical concentrations.

The major environmental impact that could be anticipated is increased eutrophication in the Purísima reservoir, due to the P inputs from the wastewater. While the concentration of P in the water is relatively high, the flow from the wastewater path represents a small percentage of the total annual flow into the reservoir. Despite the dilution of TP, the reservoir's trophic status has produced some algal problems. Similarly, the salinity contribution from the wastewater source, while at a higher level due to the reuse upstream, is not likely to represent a significant problem.

The extended use of wastewater for irrigation carries with it the potential for accumulation of heavy metals. The available information did not permit the determination of rates of accumulation because of potentially large changes in wastewater composition resulting from historic changes in mining in the region, as well as changes in the urban population. Notwithstanding this, the levels found in our limited field study suggest that heavy metals do not represent a significant problem. The composition of the waste stream is likely to vary tremendously from city to city depending on the type and number of industries. We have noted that the City of Guanajuato may not be representative with respect to heavy metals.

Finally, although we have identified and described a number short-term benefits associated with wastewater irrigation, the longer-term tradeoffs associated with the practice must be considered carefully, chiefly for reasons of irreversibility. Nevertheless, the difficulty of financing adequate wastewater treatment in developing countries makes land application an attractive alternative. Further research is needed to identify the conditions under which the substantial benefits of wastewater irrigation can be captured while minimizing the risks and associated costs for public health and environmental quality.

Mexican Regulations on Wastewater Irrigation

The following are excerpts, translated from Spanish by the authors, of the relevant sections of the Mexican Water Regulations pertaining to wastewater irrigation.

Secretariat for the Environment, Natural Resources, and Fisheries
(Secretaría de Medio Ambiente, Recursos Naturales y Pesca, SEMARNAP)

Mexican Official Regulation

NOM-001-ECOL-1996

NOM-001-ECOL-1996 establishes the maximum allowable contaminant limits for wastewater discharge in national (public) water bodies or property.

Having followed the procedures established in the Federal Law on Methodology and Regulations to formulate Mexican Official Regulations, the National Consultative Committee on Environmental Protection Regulations, on 30 October 1996, passed the Mexican Official Regulation NOM-001-ECOL-1996.

Objective and Application

This Official Regulation establishes the maximum allowable contaminant limits for wastewater discharged in national (public) water bodies or property, with the aim of protecting their quality and allowing for their use. It is binding on those responsible for such discharges. This regulation does not apply to the discharge of independent storm water discharge.

3. Definitions *(only selected items translated)*

3.2 National waters

The waters belong to the Nation, as defined in the fifth paragraph of Article 27 of the Constitution of the United Mexican States.

3.3 Wastewater

Those waters of varied composition resulting from the discharge of the following uses: municipal, industrial, commercial, services, agricultural, animal husbandry, domestic including residential, and in general, any other use, as well as the mix of such waters.

3.5 National property

That property which is administered by the National Water Commission (CNA) as defined in Article 113 of the Law of the Nation's Waters.

3.6 Contaminant load

The quantity of contaminant, expressed in units of mass per time, delivered in wastewater discharge.

3.8 Basic contaminants

Those compounds and constituents found in wastewater discharge, which may be removed or stabilized through conventional treatment. For these regulations, only the following are considered: grease and oil, floating matter, sedimentable solids, total suspended solids, biochemical oxygen demand 5, total nitrogen (the sum of Kjeldahl nitrogen, nitrites and nitrates, expressed as mg/l of nitrogen), total phosphorus, temperature and pH.

3.9 Pathogenic and parasitic contaminants

Those microorganisms, cysts, and eggs of parasites that could be present in wastewater, and that represent a risk to human health, or flora or fauna. For these regulations, only the following are considered: fecal coliforms and helminth eggs.

3.11 Discharge

The act of spilling, infiltrating, depositing, or injecting wastewater in a receiving water body, continuously, intermittently, or fortuitously, when the receiving body is national property.

3.16 Maximum allowable limit

The value or range assigned to a constituent that may not be exceeded in the wastewater discharge.

3.17 Heavy metals and cyanides

Those compounds which, at concentrations higher than the limits determined, may produce negative effects on human health, flora or fauna. For these regulations, only the following are considered: arsenic, cadmium, copper, chromium, mercury, nickel, lead, zinc, and cyanides.

3.21 Daily average (DA)

That value based on a composite sample. For grease and oils, daily average is the flow-weighted average; for coliforms, it is the geometric average of the individual samples that form the composite; for pH, no individual sample may be outside the allowable range.

3.22 Monthly average (MA)

That value which results from the flow-weighted average of the values of at least two composite samples.

3.23 Unrestricted irrigation

The unlimited use of wastewater for purposes of planting, cultivating and harvesting of agricultural products such as forage, grains, fruits, vegetables and greens.

3.24 Restricted irrigation

The use of wastewater for purposes of planting, cultivating and harvesting of agricultural products, except vegetables and greens, which are consumed raw.

3.28 Agricultural irrigation use

The use of water for purposes of planting, cultivating and harvesting of agricultural products, and for primary processing, particularly where the products have not been subjected to any [agro-] industrial processing.

3.29 Urban public use

The use of national water for population centers or human settlements, which is for purposes of human use and consumption, with previous treatment for drinking water.

4. Specifications

4.1 The concentration of basic contaminants, heavy metals and cyanides in wastewater discharges to national water or property, may not exceed the value indicated as the maximum allowable limit in annex tables 1 and 2 of these regulations. The allowable range for pH is 5 to 10 units.

4.2 To determine pathogenic contamination, fecal coliforms will be used as the indicator. The maximum allowable limit in wastewater discharges to national water or property, as well as wastewater application to soils (for agricultural irrigation) is 1,000 and 2,000 (most probable number, MPN) of fecal coliforms per 100 ml, for monthly average and daily average, respectively.

4.3 To determine parasitic contamination, helminth eggs will be used as the indicator. The maximum allowable limit in wastewater application to soils (for agricultural irrigation) is one helminth egg per liter for restricted irrigation, and five helminth eggs per liter for unrestricted irrigation, following the technique established in annex 1 of these regulations.

(The remainder of the regulations set forth time frames for compliance. In the case of urban areas, deadlines for wastewater treatment are set according to the population, with complete national coverage decreed by 2010. In the case of nonurban discharges, deadlines are set according to water quality).

ANNEX TABLE 1.

Maximum allowable limits for basic contaminants.

Parameter	Rivers						Natural and artificial reservoirs				Coastal waters						Soil			
(mg/l, unless otherwise specified) (A)	Agricultural irrigation use (B)		Urban, public use (C)		Aquatic life protection (B)		Agricultural irrigation use (C)		Urban, public use		Fishing, navigation and other uses (A)		Recreation (B)		Estuaries (B)		Agricultural irrigation use (A)		Natural wetlands (B)	
	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA
Temperature °C (1)	NA	NA	40	40	40	40	40	40	40	40	40	40	40	40	40	40	NA	NA	40	40
Grease and oils (2)	15	25	15	25	15	25	15	25	15	25	15	25	15	25	15	25	15	25	15	25
Floating matter (3)	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab	ab
Sedimentable solids (ml/l)	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	NA	NA	1	2
Total suspended solids	150	200	75	125	40	60	75	125	40	60	100	175	75	125	75	125	NA	NA	75	125
Biochemical oxygen demand$_5$	150	200	75	150	30	60	75	150	30	60	100	200	75	150	75	150	NA	NA	75	150
Total nitrogen	40	60	40	60	15	25	40	60	15	25	NA	NA	NA	NA	15	25	NA	NA	NA	NA
Total phosphorus	20	30	20	30	5	10	20	30	5	10	NA	NA	NA	NA	5	10	NA	NA	NA	NA

(1) Instantaneous.

(2) Simple weighted-average sample.

(3) Absent by test method defined in NMX-AA-006.

MA=monthly average; DA=daily average; ab=absent; NA=Data not available.

ANNEX TABLE 2.

Maximum allowable limits for basic contaminants.

Parameter*	Rivers						Natural and artificial reservoirs				Coastal waters						Soil			
(mg/l, unless otherwise specified) (A)	Agricultural irrigation use (B)		Urban, public use (C)		Aquatic life protection (B)		Agricultural irrigation use (C)		Urban, public use		Fishing, navigation and other uses (A)		Recreation (B)		Estuaries (B)		Agricultural irrigation use (A)		Natural wetlands (B)	
	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA	MA	DA
Arsenic	0.2	0.4	0.1	0.2	0.1	0.2	0.2	0.4	0.1	0.2.	0.1	0.2	0.2	0.4	0.1	0.2	0.2	0.4	0.1	0.2
Cadmium	0.2	0.4	0.1	0.2	0.1	0.2	0.2	0.4	0.1	0.2	0.1	0.2	0.2	0.4	0.1	0.2	0.05	0.1	0.1	0.2
Cyanide	2.0	3.0	1.0	2.0	1.0	2.0	2.0	3.0	1.0	2.0	2.0	2.0	2.0	3.0	1.0	2.0	2.0	3.0	1.0	2.0
Copper	4.0	6.0	4.0	6.0	4.0	6.0	4.0	6.0	4	6.0	4	6.0	4.0	6.0	4.0	6.0	4	6.0	4.0	6.0
Chromium	1	1.5	0.5	1.0	0.5	1.0	1	1.5	0.5	1.0	0.5	1.0	1	1.5	0.5	1.0	0.5	1.0	0.5	1.0
Mercury	0.01	0.02	0.005	0.01	0.005	0.01	0.01	0.02	0.005	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.005	0.01	0.005	0.01
Nickel	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4
Lead	0.5	1	0.2	0.4	0.2	0.4	0.5	1	0.2	0.4	0.2	0.4	0.5	1	0.2	0.4	5	10	0.2	0.4
Zinc	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20

*Measured as total.

DA = Daily average.

MA = Monthly average.

(A), (B) and (C): Type of receiving body as per Federal Law of Rights.

Analytical Methods

Biochemical Oxygen Demand (BOD)

The samples were diluted in autoclaved vials and incubated at 20 °C for 5 days. Dissolved oxygen (DO) was measured using the Winckler method, before and after incubation. BOD was determined as the difference between the initial and final measurements of DO.

Total Phosphorus (TP)

Colorimetry was used to determine TP (converted to orthophosphates $H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}) using ammonium molybdate under acidic conditions to form ammonium phosphomolybdate. All calibration curves had correlation coefficients of 0.95 or higher.

Total Nitrogen (TN)

TN was measured using the Kjeldhal method, in which nitrogen-containing organic compounds are digested in sulfuric acid in the presence of potassium sulfate and a copper sulfate catalyst. Organic matter is digested to form CO_2 and H_2O, thereby releasing ammonium, which in the acidic digestion medium, is immobilized as a nonvolatile salt such as ammonium sulfate. The digested solution is alkalinized and ammonia nitrogen in the distillate is absorbed in boric acid, which is finally measured by titration.

Total Coliforms (TC)

TC was measured using the viable count method. 1-ml dilutions were inoculated in Petri dishes with agar and subsequently incubated at 45–48 °C for 24–48 hours. Dark red colonies measuring 0.5 mm or greater with a precipitation halo were counted and reported as cfu/100 ml.

Fecal Coliforms (FC)

FC was measured using the same viable count method as just described for TC, with the exception that the incubation temperature was 44.5 °C.

Solids

Total solids (TS) were measured by weighing the residual material after evaporating water from a completely mixed sample in a porcelain crucible at 100–105 °C. Total suspended solids (TSS) were measured by weighing the residual on a micropore filter, dried at 100–105 °C . Total dissolved solids (TDS) were measured as the difference TS-TSS.

Metals

Mercury (Hg) and arsenic (As) were measured by atomic absorption with a hydrogen generator. Lead (Pb), chromium (Cr) and selenium (Se) were measured by atomic absorption with a graphite oven. Iron (Fe) and manganese (Mn) were measured by atomic absorption with flame detection. All acid digestions were performed by microwave heating.

Soil samples were collected in plastic bags, with a portion stored in sterile containers for microbiological analyses.

Organic Matter (OM)

OM was measured as the oxidizable fraction of a pre-weighed sample, using potassium dichromate in strong acid as the oxidizing agent. The unconsumed oxidant was measured with ferrous sulfate (oxidized to ferric sulfate), with OM calculated as the difference in mass and expressed in percent.

Texture

Clay, silt, and sand contents were measured using differential sedimentation and a Bouyoucus hydrometer. These are expressed in percent.

EC

EC was measured using a YSI Model 35 EC© meter, and is reported in µmhos for saturated soil solution and 10 percent distilled water solution.

Sodium Adsorption Ratio (SAR)

SAR was determined by measuring Na^{+}, Ca^{2+}, Mg^{2+} in solution and calculating SAR (in meq/l) as:

$$SAR = \frac{Na^{+}}{\sqrt{[(Ca^{2+} + Mg^{2+})/2]}}$$

Cation Exchange Capacity (CEC)

CEC was measured by saturating a soil solution with Ca^{2+}, and measuring the exchange with K^{+} using EDTA. CEC is expressed in meq/kg.

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