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Improving Wastewater Use in Agriculture

An Emerging Priority

Susanne M. Scheierling
Carl Bartone
Duncan D. Mara
Pay Drechsel

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Abstract

Wastewater use in agriculture is a growing practice worldwide. Drivers include increasing water stress, in part due to climate change; increasing urbanization and growing wastewater flows; and more urban households engaged in agricultural activities. The problem with this trend is that in low-income countries, but also in many middle-income countries, it either involves the direct use of untreated wastewater or the indirect use of polluted waters from rivers that receive untreated urban discharges. This poses substantial risks, in particular microbial risks to public health. To address these risks, the World Health Organization in 2006 issued new guidelines for the safe use of wastewater.

This paper aims to highlight the growing importance of improving wastewater use in agriculture across the spectrum from lower to high-income countries. It presents an innovative approach linking key issues related to different aspects of wastewater irrigation to a country's level of economic development. Based on data presented in the World Bank's World Development Report, it differentiates between four country income levels to create a typology for analyzing current issues, trends, and priorities for improving agricultural wastewater use with a focus on reducing the risks to public health. It also presents the basic principles of the new 2006 World Health Organization Guidelines, and how to apply them. Beyond regulatory aspects, the paper also discusses other aspects that are important for achieving a more integrated approach to agricultural wastewater use, including institutional/planning, technological, economic/financial, and social issues. Finally, the paper provides recommendations for moving the wastewater irrigation agenda forward.

This paper—a product of the Energy, Transport and Water Department, Water Anchor—is part of a larger effort in the department to assess the feasibility of interventions for improving wastewater use in agriculture.. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at sscheierling@worldbank.org.

Produced by the Research Support Team

Improving Wastewater Use in Agriculture: An Emerging Priority*

Susanne M. Scheierling
The World Bank

Carl Bartone
Consultant

Duncan D. Mara
University of Leeds, UK

Pay Drechsel
International Water Management Institute (IWMI)

* Contact information: sscheierling@worldbank.org. We are grateful to following colleagues at the World Bank for helpful comments and guidance during the discussion of the concept note, the presentation of initial study results, and the review meeting: Mohammed Benouahi, Marjory-Anne Bromhead, Julia Bucknall, Alexander Danilenko, Daniel Hoornweg, Peter Kolsky, Paul Kriss, Abel Mejia, and Halla Qaddumi. The authors also wish to acknowledge constructive comments from the peer reviewers Alexander Bakalian, Menahem Libhaber, and Jamie Bartram (University of North Carolina at Chapel Hill), Further comments were received from Blanca Jimenez (Universidad Nacional Autónoma de México, UNAM), Mark Redwood (International Development Research Centre, IDRC), and Takashi Asano (University of California at Davis). Alexandra Evans (International Water Management Institute, IWMI) contributed to the materials on urban agriculture, and Bénédicte Augeard (World Bank) to the portfolio review. The paper received financial support through the Water Partnership Program (WPP). It is based on Economic and Sector Work carried out in the Water Anchor, Energy, Transport and Water Department. A more detailed report is available at http://siteresources.worldbank.org/INTWAT/Resources/ESWWastewaterAg.pdf.

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Chapter 1. Introduction

Wastewater use is a growing practice worldwide.[1] As freshwater sources become scarcer, wastewater use has become an attractive option for conserving and expanding available water supplies. Wastewater use can have many types of applications, including irrigation of agricultural land, aquaculture, landscape irrigation, urban and industrial uses, recreational and environmental uses, and artificial groundwater recharge (Asano *et al*., 2007). Principally, wastewater can be used for all purposes for which freshwater is used, given appropriate treatment and reliable operation. With a few exceptions worldwide, wastewater use applications are restricted to nonpotable uses, or at most to indirect potable uses.

Wastewater use in agriculture is by far the most established application, and the one with the longest tradition. In most cases the irrigated lands are located in or near the urban areas where the wastewater is generated. Estimates on wastewater use worldwide indicate that about 20 million hectares of agricultural land is irrigated with (treated and untreated) wastewater (Jiménez and Asano, 2008). Especially in lower income countries and in arid and semi-arid high-income countries, wastewater irrigation is the most prominent and also the most rapidly expanding wastewater use. Besides increasing water stress, drivers for the expansion include increasing urbanization, growing urban wastewater flows due to the expansion of water supply and sewerage services, and more urban households engaged in agricultural activities that could be intensified with additional sources of irrigation water.

The problem with this growing trend toward more agricultural wastewater use is that in low-income countries, but also many middle-income countries, the practice either involves the direct use of untreated wastewater or the indirect use of polluted waters from rivers and streams. With freshwater either unavailable or too expensive, and wastewater treatment not keeping up with urban growth, urban farmers often have no alternative but to use highly polluted water. Many of them belong to the urban poor who depend on agricultural activities as a source of income and employment generation as well as food security (UNDP, 1996; World Bank, 2000).

Especially when untreated wastewater is used for crop irrigation, it poses substantial risks to public health, not only to the farmers, but also the surrounding communities and the consumers of the crops. The biggest risk to health is microbial risk which arises due to pathogens, i.e. disease-causing organisms that are usually present in untreated or partially treated (and to some level also in treated) wastewater (Feachem *et al*., 1983). Many excreta-related diseases can be spread by wastewater use in agriculture to those working in the wastewater-irrigated fields and those consuming wastewater-irrigated foods, especially when eaten uncooked. However, the consumption of wastewater-irrigated foods is only one possible route of transmission, and this route may or may not be of local public health importance.

The 1989 World Health Organization "Guidelines on the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture" have long been the standard reference for regulating the most common water use (WHO, 1989). Later research and results from practice have stressed that they needed to be broadened to better accommodate local conditions and, therefore, should be complemented with other health interventions, such as hygiene promotion.

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[1] This refers to intended wastewater use. However, most wastewater use is unintended. Once discharged to the aquatic environment (treated or untreated), effluents are recycled to the natural water flows from which they are withdrawn again for diverse purposes.

In 2006 the WHO issued new guidelines which consider addressing wastewater use issues as only one component of an integrated risk management strategy (WHO, 2006). The 2006 Guidelines now include health-based targets, which correspond to the 'tolerable' burden of disease that would result from agricultural wastewater use. Models were used to calculate the required levels of pathogen reduction to meet the targets for different types of irrigation scenarios and employing different degrees of wastewater treatment and/or even non-treatment options. For different health protection control measures, their potential to reduce the amount of pathogens on the crop has been determined. In this way, it is possible to predict the pathogen reductions achievable with each combination of different health protection control measures, and risk management strategies can be chosen based on the targeted pathogen removal. The 2006 Guidelines are intended to provide a framework that supports the establishment of national standards and regulations for agricultural wastewater use that can be readily implemented and enforced.[2] Initial applications of the new framework have been made, but the approach needs to be disseminated more widely. This paper hopes to contribute to this effort.

The paper, which is based on Economic and Sector Work carried out in the Water Anchor of the World Bank, aims to highlight the growing importance of improving wastewater use in agriculture across the spectrum from lower- to high-income countries. It presents an innovative approach linking key issues related to different aspects of wastewater irrigation to a country's level of economic development. Based on data presented in the World Bank's World Development Report (World Bank 2010), it differentiates between four country income levels (lower-income, lower-middle income, upper-middle income, and high-income) to create a typology for analyzing current issues, trends, and priorities for improving agricultural wastewater use with a focus on reducing the risks to public health. It also presents the basic principles of the new 2006 WHO Guidelines, and how to apply them. Beyond regulatory aspects, the paper also discusses the other aspects that are important for achieving a more integrated approach to agricultural wastewater use, including institutional/planning, technological, economic/financial, and social issues. Finally, the paper provides recommendations for moving the wastewater irrigation agenda forward. The primary audiences for the paper are water professionals, regulators and decision-makers who help to plan and implement projects for wastewater use in agriculture and to develop a coherent policy and regulatory framework for such activities.

The report is organized as follows: Key issues and trends in wastewater use in agriculture are discussed in chapter 2, supported by the introduction and application of the country typology based levels of economic development. Chapter 3 reviews the benefits and risks of wastewater irrigation, with the main risk being the microbial risk to public health. The microbial risk assessment and management framework of the 2006 WHO Guidelines is discussed in Chapter 4. Based on that, Chapter 5 discusses implementation measures for reducing public health risks, and broader issues for achieving a more integrated approach to planned wastewater use for irrigation and to urban water management. Finally, Chapter 6 summarizes the key messages of the paper and discusses how countries can tailor wastewater interventions to fit their unique circumstances.

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[2] Although outside of the scope of this paper, it should be noted that the framework proposed by WHO for wastewater use in aquaculture is similar to that for wastewater use in agriculture (WHO, 2006).

Chapter 2. Issues and Trends in Wastewater Use in Agriculture

2.1 Wastewater use in agriculture: past and current practice

The use of domestic wastewater for agriculture is not new. The Minoans may have collected wastewater for reuse at Knossos, Crete, some 4000 years ago (Angelakis *et al*., 2005). In East Asia, human excreta have been used to fertilize crops and replenish depleted soil nutrients since ancient times. In his seminal treatise on traditional Asian agriculture, Farmers of Forty Centuries, F. H. King (1911) noted: "One of the most remarkable agricultural practices adopted by any civilized people is the centuries-long and well nigh universal conservation and utilization of all human waste in China, Korea and Japan, turning it to marvelous account in the maintenance of soil fertility and in the production of food."[3] The earliest documented sewage farms—where wastewater is applied to land for disposal and for agricultural use—were operated in the sixteenth and seventeenth centuries in Bunzlau, Germany and Edinburgh, Scotland (Shuval *et al.*, 1986).

With the advent of water-borne municipal sewage in the mid-nineteenth century, sewage farms were increasingly seen as a solution for the disposal of burgeoning volumes of wastewater from many rapidly growing cities of Europe and the United States including London, Paris, and Berlin. The benefits cited included the prevention of river pollution and the provision of water and nutrients to agriculture. With the development around 1913 of biological wastewater treatment processes, such as trickling filters and activated sludge, that require much less land, sewage farms fell into decline in urbanized industrialized countries (Asano *et al.*, 2007). Odors and concerns about public health, such as the possible transmission of disease from vegetables irrigated with raw sewage, also contributed to the decline of sewage farms and their almost complete abandonment in much of the western world (Shuval *et al*., 1986).

After World War II scientific and engineering interest in wastewater treatment and disposal through land application grew in both industrialized and developing countries, particularly in the more arid regions. It was seen as a way to prevent river pollution and to increase the supply of water resources for agricultural development.

Researchers in the United States further investigated the microbiological and public health aspects of wastewater use in agriculture, with the goal of providing a rational basis for evaluating the health risks from the microbial contamination of crops. State health departments established guidelines and regulations to control the sanitary aspects of wastewater irrigation. The State of California was a pioneer; it issued the first regulations in 1918, later modifying them to make them more stringent (Asano and Levine, 1996). The California regulations provided design engineers, public health authorities, and farmers in the United States with a carefully worked out, rational basis for reintroducing wastewater irrigation in agriculture as a socially acceptable and sanitary practice that could meet the strictest public health criteria. They were replicated or used as a basis for similar regulations in many parts of the world, including developing countries.

Shuval *et al*. (1986, p.8) summarized these developments as follows: "During the past 100 years, then, the concept of land application and wastewater reuse has gone through a complete cycle. Starting with official blessing and enthusiastic initiation of land application and sewage farming projects in England, Europe, and the United States, it soon became almost the sole method of disposing of municipal wastewater. In the early years of the twentieth century, however, the projects were often ill-conceived, inadequately funded, and poorly regulated, and thus were eventually

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[3] Cited in e-book http://www.gutenberg.org/etext/5350, p. 51.

abandoned. Subsequently, the concept of reuse fell into disrepute. Today, wastewater reuse is becoming widely accepted once again, except that now it is based on more rational scientific and engineering principles. In some countries it is used to control water pollution, but more frequently it is seen as an economically feasible source of water in water-short areas."

During the past four decades, the use of wastewater in agriculture has become more common, especially in developing countries and in semi-arid and arid areas of industrialized countries. When discussing current practice of wastewater use in agriculture, three issues should be kept in mind: First, wastewater is predominately generated by various urban activities; they are further discussed in Box 2.1. Second, different types of wastewater are used in agriculture; a typology is provided in Box 2.2. And, third, wastewater irrigation is generally limited to agricultural areas near the communities that generate the wastewater; this makes urban and peri-urban areas the target for wastewater use, and irrigated agriculture in and near urban areas the farming system most likely affected.

Box 2.1 Urban Wastewater—The Basics

Urban wastewater usually refers to a combination of one or more of the following flows generated by various urban activities (van der Hoek, 2004):

- Domestic effluent consisting of blackwater (feces, urine and associated sludge, i.e. toilet water) and greywater (kitchen and bathing wastewater)
- Water from commercial establishments and institutions, including hospitals
- Industrial effluent where present
- Storm water and other urban runoff

About 80 to 90 percent of the urban water supply to homes, businesses and industries is not consumed by users but is returned to the urban environment as wastewater (Tchobanoglous and Schroeder 1985; Asano *et al.*, 2007). Because urban wastewater contains human excreta and may also contain hazardous chemicals from industry, households, and other sources, it is polluted and constitutes a serious health hazard to local populations. A common health protection measure is to isolate the hazard from local residents by constructing a sewer system to evacuate the wastewater from the neighborhood.

Where sewerage is provide, it concentrates the wastewater flow and transports the associated pollution and health hazards to a downstream location where both downstream populations and water resources are at risk. If such hazards are significant, they can be reduced or controlled by treating the wastewater up to a defined standard in a wastewater treatment plant consisting of one or more physical, chemical and/or biological processes. If the standard is not achieved, the wastewater is considered at best as partially treated. Wastewater treatment produces sludge, a contaminated byproduct that is also a health hazard and requires safe management and disposal.

Where sewerage is not provided, safe wastewater management can be achieved at the domestic level through on-site sanitation options such as simple pit latrines, ventilated improved pit latrines, dry toilets, non-sewered public toilets and aqua privies, and septic tanks. All of the on-site options remain with the problem of accumulating fecal sludge that must periodically be safely removed and disposed so that it does not constitute a public health hazard. In communities without sewerage, the same care has to be applied to greywater flows which may contain significant amounts of excreta derived pathogens, and usually end up in stormwater drains.

Box 2.2 Wastewater Use in Agriculture—A Typology

Various attempts have been made to provide a broad typology of wastewater reclamation and use in agriculture (e.g., Asano *et al*, 2007) or a more restricted typology for wastewater irrigation in developing countries (e.g., von der Hoek, 2004), but differences persist in the terminology used by professionals in this field. The following definitions and distinctions are used in this paper:

- *Direct use of treated (or reclaimed) wastewater* is the use of reclaimed water that has been transported from the point of treatment or production to the point of use without an intervening discharge to surface water or groundwater body.
- *Direct use of untreated wastewater* is the use of raw wastewater from a sewage outlet, directly disposed of on land where it is used for crop production.
- *Indirect use of untreated wastewater* is the abstraction of usually diluted wastewater (or polluted stream water) for irrigation. This is common downstream of urban centers where treatment plants are limited. Farmers might or might not be aware of the water quality challenge.
- *Planned wastewater use* is the conscious and controlled use of wastewater either undiluted (direct) or diluted (indirect). Most use of untreated wastewater is unplanned and indirect. Within the category of planned wastewater use for irrigation, two subcategories are important:
    - o *Restricted irrigation* is the controlled use of wastewater to grow crops that are not eaten raw by humans; and
    - o *Unrestricted irrigation* is the controlled use of treated wastewater to grow crops that are normally eaten raw.

Source: WHO 2006; Jiménez *et al*., 2010.

Data on current wastewater use in agriculture in different countries worldwide are mostly based on rough estimates. Estimates of the volume of wastewater used in for irrigation are shown in Table 2.1.[4] Estimates on the agricultural areas irrigated with wastewater, both treated and untreated, are shown in Figure 2.1.

Table 2.1 The twenty countries with the largest volume of wastewater used for irrigation

Country	Wastewater used for irrigation (m^3/d)	Country	Wastewater used for irrigation (m^3/d)
Mexico	4,493,000	Iran	422,000
Egypt	1,918,000	Chile	380,000
China	1,239,000	Jordan	225,000
Syria	1,182,000	UAE	200,000
Spain	932,000	Turkey	137,000
USA[a]	911,000	Argentina	130,000
Israel	767,000	Tunisia	118,000
Italy	741,000	Libya	110,000
Saudi Arabia	595,000	Qatar	80,000
Kuwait	432,000	Cyprus	68,000

[a] California and Florida.

Source: Jiménez and Asano, 2008.

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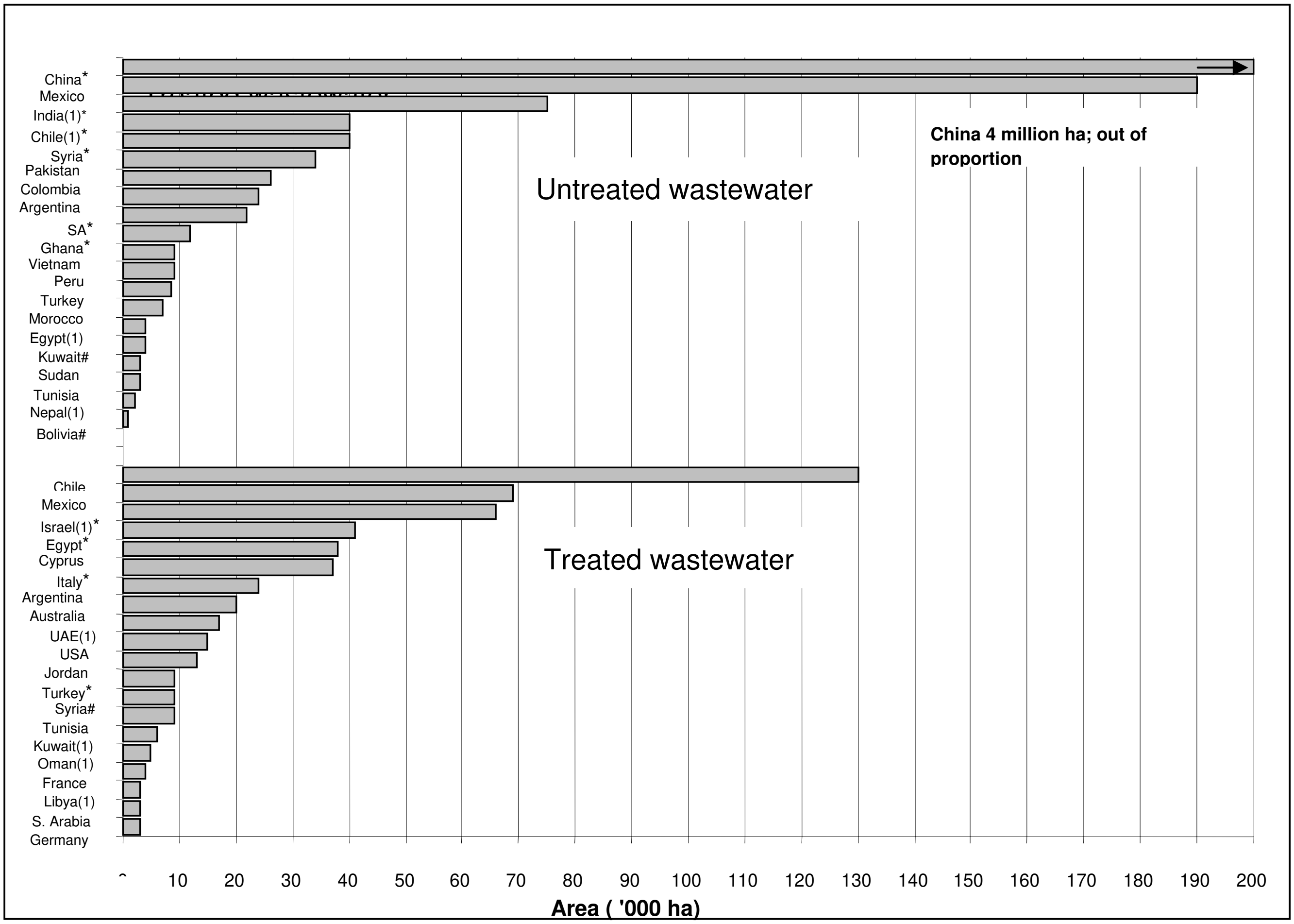
[4] The volume estimates mask the exemplary practices of some of the smaller countries in arid zones. See Table 2.5.

Figure 2.1 Countries with largest areas irrigated by untreated and treated wastewater.



Sources: Scott *et al*., 2010; Jiménez and Asano, 2008; Xianjun *et al*., 2003; Xie *et al*., 2009.
*Data uncertain; (1) Area probably underestimated; + Practice reported (including forestry), but data missing

Jiménez and Asano (2008) report that globally about 20 million hectares of agricultural land is irrigated with polluted water (i.e., direct use of raw or untreated wastewater, direct use of treated wastewater, as well as indirect use of untreated wastewater). According to Pearce (2004), "a tenth of the world's irrigated crops—everything from lettuce and tomatoes to mangoes and coconuts—are watered by sewage, and much of that sewage is raw and untreated, gushing direct from sewer pipes into fields at the fringes of the developing world's great megacities".[5] The estimates suggest that the extent of unplanned wastewater irrigation (with direct and indirect use of untreated wastewater) is an order of magnitude greater than planned wastewater use (with direct use of treated water and some indirect use of untreated water) (Scott *et al*., 2010). In lower income countries, wastewater irrigation is predominantly unplanned and either involves the direct use of untreated wastewater or the indirect use of highly polluted waters from rivers and streams. Farmers seldom have other water sources, and unplanned wastewater use is their only means to irrigate when investments in wastewater treatment

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[5] http://www.newscientist.com/article/dn6297

do not keep pace with urban growth, and/or no other measures are undertaken for a more controlled use of wastewater. In higher income countries where wastewater irrigation occurs, it is normally planned use with treated wastewater.

2.2 Key issues in wastewater use in agriculture

2.2.1 Levels of economic development and wastewater issues

The assessment of current practice in wastewater use in agriculture reveals important patterns between a country's economic status (low-income, lower-middle income, upper-middle income, and high-income) and the types of wastewater issues it faces. Inadequate water supply, sanitation, and unplanned, untreated wastewater use in urban areas are associated with a low level of economic development. Higher levels of economic development are associated with the provision of adequate water supply, sanitation, wastewater treatment for the vast majority of the urban population, and the planned use of wastewater. Based on these patterns, this paper uses an innovative approach that distinguishes four country income levels based on 2008 national GNI per capita data from the World Bank's World Development Report 2010, and relates them to various issues to create a typology for describing and analyzing current issues, trends and, later, priorities in wastewater use in agriculture.[6]

Urbanization and the provision of improved urban drinking water supply and sanitation services increases significantly with income growth, and reaches close to 100 percent in high-income countries (Table 2.2).

The table also shows that the disease burdens for diarrheas and Ascariasis decrease rapidly as development occurs—an important observation since both diseases are linked to irrigation of food crops with untreated wastewater.

While Table 2.2 gives the share of urban population with access to improved sanitation rather than just sewer connections, Locussol *et al*. (2007) have shown that the urban population in developing countries served specifically by sewer connections more than doubled between 1990 to 2004, from 618 million to 1,488 million (an increase of 141%) as urban population grew only 46%.

Countries progress up the treatment ladder from untreated to treated wastewater as per capita incomes increase (Table 2.3). This progression has occurred historically in developed countries and is currently occurring at different paces in emerging countries. It should be noted that there can also be substantial variations among and within the countries that are grouped together in a particular country type. Some countries may be more advanced than others (for example, because of one or more of the drivers discussed in Chapter 2); and within countries, subnational geographic disparities may persist (for example, upper-middle income countries may have pockets with conditions of low-income countries). Nevertheless, the broad typology is useful for assessing key relationships.

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[6] This approach was first developed and applied to assess different urban environmental problems related to levels of economic development (Bartone et al., 1994).

Table 2.2 Urban population, water supply and sanitation coverage, and selected disease burden by level of development

Characteristics by level of economic development	Low-income countries (43 countries) <$975 GNI/cap	Lower-middle-income countries (55 countries) $976-3,855 GNI/cap	Upper-middle-income countries (46 countries) $3,586-11,905 GNI/cap	High-income countries (66 countries, 27 OECD) >$11,906 GNI/cap
Total urban population (millions)	280.4	1,528.3	709.7	812.1 OECD 750.9
Percent of total population that is urban (%)	28.7	41.3	74.8	76.0 OECD 77.3
Urban population with improved drinking-water (%)	86.2	94.6	95.2	99.3 OECD 100.0
Urban population with improved sanitation (%)	49.6	60.3	86.6	99.4 OECD 100.0
Diarrheal disease burden (thousand DALYs)	59,207	11,798	1,309	438
Ascariasis disease burden (thousand DALYs)	661	304	34	6

Sources: Economic and urban population data from World Bank, 2010; improved sanitation data from WHO-UNICEF, 2010; disease burden data from WHO, 2008.
DALY = Disability-Adjusted Life Years, a measure of the burden of disease due to a specific risk factor.
Note: Improved drinking-water is defined by WHO and UNICEF (2010) as using one of the following water sources: piped water into the dwelling, yard or plot; public tap or standpipe; tubewell or borehole; protected dug well; protected spring; and rainwater collection; Improved sanitation is defined by WHO and UNICEF (2010) as using facilities that ensure hygienic separation of human excreta from human contact. They include: flush or pour-flush toilets/latrines that are connected to a piped sewer system, septic tank or pit latrine; ventilated improved pit (VIP) latrines; pit latrines with slab; and composting toilets.

Table 2.3 Urban sanitation and wastewater treatment characteristics by level of economic development

Characteristics by level of economic development	Low-income countries (43 countries) <$975 GNI/cap	Lower-middle-income countries (55 countries) $976-3,855 GNI/cap	Upper-middle-income countries (46 countries) $3,586-11,905 GNI/cap	High-income countries (66 countries, 27 OECD) >$11,906 GNI/cap
Access to basic sanitation services	Low coverage, especially for urban poor; Mainly non-sewered options	Increasing coverage but low access for urban poor; Increasing use of sewerage	Generally acceptable coverage; Higher sewerage levels	Good coverage; Mainly sewered
Wastewater treatment	Virtually no treatment or very few treatment facilities; Severe operational deficiencies; Affordability issues dominate	Some treatment facilities; Often poorly operated and/or design capacity exceeded; Affordability issues persist	Increasing treatment capacity; Continued operational deficiencies; Difficulties in mobilizing needed investments	Generally high treatment levels; Increasing investments over past 20 years in non-OECD countries; Major investments over past 40-50 years in OECD countries
Water pollution issues	Health problems from inadequate sanitation and raw domestic sewage "in the streets"	Severe health problems from untreated municipal discharges	Severe pollution problems from poorly treated municipal and mixed industrial discharges	Primarily concerned with amenity values and toxic substances

Sources: Adapted from Bartone, 1997; income data from World Bank, 2010.

Wastewater treatment in low-income countries. In low-income countries, wastewater treatment plants, if they exist, are minimal or function poorly, and basic sanitation is the primary focus. In Ghana, for example, about 70 mostly decentralized wastewater and fecal sludge treatment plants collect less than 10 percent of the generated wastewater. Of the 70 plants, about 10 function more or less as designed, and most of these belong to larger hotels (Murray and Drechsel 2010). Under these circumstances, the key pollution concern is to protect public health by isolating households from fecal sludge and raw domestic sewage in the streets.

In these countries, policymakers and consumers face financial, institutional, and technical challenges when considering improvements in sanitation and wastewater management. Affordability is a critical issue. Only non-conventional, low-cost sewerage and treatment options are likely to be feasible alternatives to on-site sanitation options except in the city centers and richer neighborhoods of the larger cities.

Two key constraints affecting many wastewater collection and treatment systems in low-income countries are the high frequency of power-cuts and the low volumes of water supply per capita. Frequent power outages can affect pumps as well as treatment plants. Where sewers exist, many fall into disrepair due to temporal or general lack of sufficient water quantities to flush them.

Wastewater treatment in middle-income countries. In middle-income countries, particularly upper-middle-income countries, wastewater management is becoming an increasingly important concern, and more complex regulatory structures are being developed, along with the political will and the financial resources to implement them. Wastewater treatment has advanced, but both operational deficiencies and difficulties in mobilizing needed investments and operating funds still persist. An example of the wastewater treatment experience of Latin America and the Caribbean (LAC) region, a predominantly middle-income region, is provided in Box 2.3. Statistics about wastewater treatment capacity can be misleading since they usually refer to installed capacity rather than real capacity, as is exemplified by a survey of LAC countries (Egocheaga and Moscoso 2004) and a study from China (Xie *et al*., 2009).

Wastewater treatment in high-income countries. Wastewater is generally, but not always, treated in high-income countries. The OECD countries have made major investments over the past 40-50 years to achieve high treatment levels. In North America, over 90 percent of wastewater is treated, generally to secondary, and in many cases, tertiary levels (WHO/UNICEF, 2000). Progress in the United States has largely been the result of a subsidy program in which US$56 billion in federal construction grants were provided to local governments from 1972–1989 to build mandated secondary treatment facilities, but these grants were eliminated and subsequently replaced by state revolving funds for loans to municipalities (Bartone, 1997).

In Europe, driven by the 1991 European Union (EU) Directive on Urban Waste Water Treatment, over 68 percent of wastewater is treated (CEC, 2004). However, performance varies greatly across EU countries and in 2003 only Austria, Denmark, Germany, and the Netherlands fully complied with the directive. In other countries significant amounts of wastewater—from 40 to 60 percent—were still not being treated adequately before being discharged into the surface waters of the Member States. According to the European Commission, the directive represents the most cost intensive European legislation in the environmental sector. The EU estimates that €152 billion were to be invested in wastewater treatment from 1990 to 2010. The EU provides support for the implementation of the directive in the order of €5 billion per year.

The industrialized countries are now placing more focus on how to improve the management of wastewater sludge and biosolids (UN-HABITAT, 2008). Much of this progress in wastewater treatment has been driven by the desire to protect the aquatic environment and amenity values, and to control toxic substances such as trace chemicals, heavy metals, and newly perceived problems of endocrine-disrupting compounds (EDCs), and pharmaceuticals and personal care products (PPCPs).

Many of the non-OECD high-income countries have made substantial investments in wastewater treatment over the past two decades and have implemented more complex and comprehensive regulatory frameworks. Advance treatment systems have been built, particularly in the high-income Mediterranean Basin and Middle Eastern Countries where the investments have been driven by severe water scarcity.

Box 2.3 Wastewater treatment in the LAC region

The Latin America and the Caribbean (LAC) region has the highest rate of sanitation coverage among the developing regions. According to the 2000 global assessment conducted by WHO and UNICEF, 49 percent of the LAC population was connected to a sewer system in 2000 compared to 42 percent in 1990: 68 million people had gained access to a sewer connection over a single decade. Most of this increase had occurred in urban areas; 63 percent of the urban population was connected to sewers. However, less than 14 percent of the urban wastewater collected through sewerage systems is reported to receive some kind of treatment, often by inadequate and poorly operated treatment plants, and the rest is all discharged raw. Of a total of 600 m^3/s of urban wastewater that is collected, it is estimated that only 36 m^3/s (6 percent) receives adequate treatment.

To gain better insight into wastewater treatment in LAC, in 2003 the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS) carried out a regional inventory of urban sewerage and treatment in 11 participating countries,[7] with some 2,333 cities responding to the survey. These cities, with a total population of 43.6 million, reported that 72.5 percent of their population was connected to sewerage networks, and 140.5 m^3/s of wastewater was collected, of which 40 percent received treatment. A total of 1,251 treatment plants were reported by the cities, treating a total of 55.4 m^3/s (see table). The quality of treated effluent was only reported for 114 of the 1,251 plants surveyed (9.1 percent), of which only 27 plants (24 percent) achieved an effluent quality of less than 1,000 fecal coliforms per 100 ml (the WHO 1989 guideline for unrestricted irrigation).

Type of treatment plant	Number of WWTPs	Total volume treated (l/s)
Activated sludge	233	25,031
Aerated lagoon	40	3,849
Stabilization pond	553	10,365
Anaerobic pond	15	120
Combined pond system	29	4,117
Primary treatment	370	11,672
Other	11	215
Total	1,251	55,368

Sources: WHO/UNICEF, 2000; PAHO, 2001; Egocheaga and Moscoso, 2004.

2.2.2 Levels of economic development and wastewater irrigation issues

The different wastewater treatment characteristics discussed above are a significant determinant of the key issues in wastewater use in agriculture, again classified along the four types of countries. Again countries tend to progress from unplanned to planned wastewater irrigation as per capita incomes increase (Table 2.4). But a number of constraints need to be addressed during this progression. They include not only technical issues (e.g., the emerging need to increase wastewater treatment), but also institutional (e.g., coordination among stakeholders), regulatory (e.g., wastewater use guidelines), economic/financial (problems of water pricing), and social issues (e.g., perceptions of safety of wastewater use).

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[7] The countries participating in the survey included: Argentina, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Mexico, Nicaragua, Paraguay, Peru and the Dominican Republic.

Wastewater irrigation in low-income countries. In low-income countries, the direct use of untreated wastewater and fecal sludge in urban and peri-urban agriculture is common, particularly in, but by no means restricted to, drier areas. Box 2.4 provides an example from the city of Kumasi in Ghana.

Wastewater provides a reliable source of scarce water in the dry season, permitting multiple crops throughout the year. Production in the off-season, when larger scale dry farming is limited, gives urban and peri-urban agriculture a competitive advantage. Wastewater also contains valuable plant nutrients: crop yields are higher when crops are irrigated with undiluted wastewater than with freshwater. Where sewerage is provided—often only to city centers and higher income neighborhoods—the untreated or poorly treated effluents are discharged to the nearest drainage channel or watercourse, from which the wastewater is taken by farmers to irrigate communal or peri-urban plots. Where there is no sewerage, wastewater flows end up in gutters and open storm drains where they are often still accessible to urban farmers. When the wastewater enters other surface water bodies used for irrigation, all farmers depending on these water sources in and downstream of the cities are affected. In areas with relatively abundant water, this wastewater is usually diluted by its receiving water body, but in drier regions wastewater can remain virtually undiluted. In urban slums and informal settlements where on-site sanitation predominates, greywater, blackwater and/or fecal sludge are used to irrigate and fertilize household gardens or communal plots.

Urban farmers in low-income countries use wastewater for irrigating their crops because it cannot be avoided; the use of wastewater for irrigation is a reality that cannot be denied or effectively banned (Buechler *et al*, 2002; Drechsel *et al*., 2002; and Scott *et al*., 2004). Properly managed, wastewater irrigation contributes significantly to sustaining livelihoods, food security, and the quality of the environment. Improperly managed, it imposes significant health risks on farmers and consumers leading to a costly burden of diarrheal and parasitic diseases, and of environmental degradation.

Table 2.4 Wastewater use for irrigation by level of economic development

Characteristics by level of economic development	Low-income countries (43 countries) <$975 GNI/cap	Lower-middle-income countries (55 countries) $976-3,855 GNI/cap	Upper-middle-income countries (46 countries) $3,586-11,905 GNI/cap	High-income countries (66 countries, 27 OECD) >$11,906 GNI/cap
Wastewater use practices	Indirect use of untreated wastewater commonplace due to widespread pollution; Direct use of untreated wastewater and fecal sludge commonplace, especially in water short areas	Indirect use of untreated effluents commonplace; Direct use of untreated wastewater still observed; Direct use of treated effluents appearing	Direct use of treated effluents on the increase; Indirect use of untreated effluents still problematic but increasingly regulated	Direct use of reclaimed wastewater commonplace in agriculture and industry
Wastewater use policy framework	Generally non-existent or unenforced; Informal (or unplanned) use predominates	Emerging policies and framework; Enforcement capacity a major concern	Use policies generally defined within water resources management framework; Enforcement capacity increasing	Use policies established and enforced, often within an integrated water resources management framework, especially in water short areas
Wastewater use health issues	High burden of helminthic and diarrheal diseases (both occupational and consumer exposure); Difficult to distinguish cause due to high background levels from lack of basic water and sanitation services	Continued concern with helminthic and diarrheal diseases (both occupational and consumer exposure); Uncontrolled industrial discharges problematic in emerging economies	Observed outbreaks of typhoid and cholera linked to agricultural use of untreated sewage; Increasing concern with industrial discharges into municipal sewer systems	Pathogens under control; Industrial discharges under control; Primarily concerned with amenity values and exotic toxic substances
Drivers of wastewater use	Subsistence agriculture in and around cities in search of water; Livelihood opportunities; Proximity & reliability of supply; Nutrient value of wastewater	Water scarcity or drought; Urban food demand; Proximity & reliability of supply; Nutrient value of wastewater; Exports protection	Water scarcity or drought; Proximity & reliability of supply; Food security; Pollution of traditional water sources; Exports protection	Water scarcity or drought; Pollution prevention; Food security; Exports protection
Key wastewater use countries	Sub-Saharan Africa except South Africa; Vietnam, Yemen	Bolivia, China, Egypt, India, Iran, Jordan, Morocco, Pakistan, Sudan, Syria, Tunisia, West Bank and Gaza	Argentina, Chile, Colombia, Lebanon, Libya, Mexico, Peru, South Africa	Non-OECD: Bahrain, Cyprus, Israel, Kuwait, Malta, Oman, Qatar, Saudi Arabia, UAE OECD: Australia, France, Greece, Italy, Japan, Portugal, Spain, US (e.g., CA, FL, AZ)

Sources: Shuval *et al*., 1986; Bartone, 1997; Scott *et al*., 2004; WHO, 2006; Jimenez and Asano, 2008a; UN-HABITAT, 2008; and Drechsel *et al*., 2010. Income data from World Bank, 2010.

Box 2.4 Wastewater use in a low-income country: Kumasi, Ghana

In Kumasi, Ghana, with a population of about 1.1 million in 2000, and a population growth rate of 6 percent, 80–90 percent of the perishable vegetables consumed in the city are produced on a few sites in the city itself. Farmers take advantage of fertile soils along streams and drains passing the city to grow popular exotic vegetables such as spring onions, lettuce and, cabbage which require frequent watering. Although exotic crops are not part of the traditional diet, they are in high demand in the booming street food sector where the common 'rice and chicken' dish now comes with a raw salad. Since wastewater collection and treatment only covers 4 percent of the city, all streams are heavily polluted with stormwater, grey water, and excreta, resulting in fecal coliform levels on the vegetables of 10^{6-7} at farm gate. As security of land tenure is low, farmers hardly ever invest in irrigation infrastructure except for mobile equipment such as watering cans, small 2-4 KW pumps, or dugouts near or in smaller streams.

Like in most parts of West Africa, the typical urban vegetable farmer is a male 30–40 years old, and very often a migrant from the another region. The land he is farming is likely government-owned, and may be considered unfit for construction. Individual plots are only 0.05-0.1 hectares large but labor-intensive. Lettuce cultivation is especially labour-intensive, requiring twice-daily watering which consumes up to 60 percent of the labor input. Although Kumasi lies in the humid tropics with annual rainfall of 1400 millimeters, crops must be watered every day that it does not rain. The highest profits are obtained in the two short dry (lean) seasons. Over the year, farmers specialized in exotic vegetables might harvest up to 10 lettuce crops, 2–3 cabbage, and 8–9 times spring onions and can earn about US$400-800 which is at least twice as much as their colleagues who depend on rainfed maize and cassava. Rainfed farmers who switch to irrigated vegetables in the dry season can earn about US$300-500 per year. These urban and peri-urban farmers are examples of the booming informal irrigation sector in sub-Saharan Africa and supply nearly all of the perishable produce for urban consumption (about 1,350 tonnes of lettuce and 7,400 tonnes of cabbage per year in Kumasi). Due to the high profits, urban farming is the main and often only occupation of these farmers.

While the total farming area in the city is small (40–50 hectares under irrigation), there are about 11,900 hectares under dry season vegetable production in a 40 kilometer radius around Kumasi, cultivated by about 12,700 households. These plots are larger and have tenure security, farmers tend to be natives rather than migrants and are on average older (37 years) than those on urban plots. Up to 70 percent of the water comes from polluted streams and rivers (10^{3-6} fecal coliforms), 21 percent from shallow dugouts, and 9 percent from other sources. Many dugouts are adjacent to the streams and are equally polluted. As in the city, watering cans are the most common irrigation tool.

The irrigated farming around Kumasi covers more than twice the area than is under formal irrigation in the rest of Ghana where in 22 irrigation schemes only about 5,600 hectares are farmed using irrigation. It is only in 2006, with support from FAO and IWMI, that the irrigation authorities and related ministries recognized the contribution of the informal irrigation sector in Ghana's new national irrigation policy and strategy which was endorsed in 2009. The new policy recognizes the constraints of the informal sector, such as credit access, as well as its challenges, like the use of unsafe water in urban and peri-urban farming. It recommends to identify, evaluate and, where feasible, implement or disseminate promising and affordable technologies (including water treatment options) for making the most of specific local conditions and resource endowments for urban and peri-urban irrigation (Government of Ghana, 2010).

Sources: Obuobie *et al*., 2006, Drechsel *et al*., 2007; Cornish and Lawrence, 2001.

Wastewater irrigation in middle-income countries. In the arid and semi-arid middle-income countries a common transition is observed: wastewater irrigation grows in scale because of increasing levels of sewerage and the gradual introduction of treatment. The unplanned direct use of untreated wastewater still occurs, but the following scenarios assume greater importance:

- The indirect and unplanned use of untreated effluents becomes a growing concern as cities discharge larger volumes of untreated effluents into nearby rivers with the resulting pollution of traditional irrigation sources (e.g., Santiago, Chile).

- In some cases untreated effluent may constitute nearly all the dry-weather flow in rivers used for irrigation, so that indirect use in reality is closer to direct reuse (e.g., Lima, Peru).
- Some countries, including some of the lower-middle-income countries, have introduced the planned use of treated wastewater, both indirect (e.g., Jordan) and direct (e.g., Tunisia).

Case studies (Boxes 2.5–2.8) show that even lower-middle-income countries can make significant improvements in wastewater irrigation schemes when driven by concerns about health, water scarcity and drought, proximity and reliability of water supply, urban food demand and food security, protection of agricultural export markets, and the pollution of critical water sources. It is apparent that the experience of epidemics or acute water shortages can contribute significantly to the formation of political resolve as a critical element to achieve improvements and to drive progress toward coherent wastewater use and water resources management policies and goals. Also, the introduction of wastewater treatment is an essential step toward achieving planned reuse. However, in most middle-income countries emerging wastewater management still coexists with extensive water pollution and wastewater reuse issues.

Box 2.5 Santiago, Chile—indirect use of untreated wastewater

In 1991, the Greater Santiago urban area had a population of 4.7 million and generated 13 m^3/s of domestic and industrial wastewater. The latter was projected to double over the next 30 years. The collected wastewater was discharged in more than 40 spots along three major natural river channels that drain the metropolitan area: the Mapocho River, the Maipo River, and the Zanjon de la Aguada. The resulting pollution of the three water courses in turn polluted the entire network of irrigation canals that derive from them and irrigated some 130,000 hectares of high-producing agricultural lands, including 7,000 hectares used for growing vegetable crops for raw consumption in the Santiago market. The larger area also produces 40 percent of Chile's fruit exports, a major industry for the country, and to a lesser extent vegetable exports.

Endemic typhoid had persisted for decades in Santiago until 1991, with incidence rates in some years reaching hyper-endemic levels in excess of 150 cases per 100,000 population. Epidemiological studies linked typhoid transmission in Santiago to the indirect use of wastewater for irrigation of vegetables via the "long cycle" (infected individual → sewage → water pollution → food → people). The incidence of typhoid in Santiago far exceeded rates in the rest of Chile, and exhibited a seasonal variation with more cases in the dry summer months coinciding with irrigation and vegetable harvesting. Also, the causal agent of typhoid (*Salmonella typhi*) was isolated directly from irrigation water. The appearance of cholera in Santiago in 1991, when a major cholera epidemic broke out in Latin America, raised another serious health threat to the local population since cholera is spread similar to typhoid via the "long cycle." The cholera outbreak also posed a considerable threat to Chile's agricultural export business that was valued at $1.1 billion annually.

How the Chilean authorities confronted and overcame these threats through decisive interventions is described in detail Box 5.3. To briefly summarize, an emergency control program was put into place to improve water quality, change irrigation practices, and change consumer behavior. This was accompanied by health education campaigns and intensive press coverage about cholera and typhoid. The emergency program achieved immediate results, and was later supplemented by development of a sanitation plan in 1998 that will be completed in 2012 when all of Santiago's wastewater will be treated.

Sources: Bartone, 1994; Ferreccio, 1995; Larrain, 2009.

Box 2.6 Lima, Peru—indirect use of untreated wastewater

The Agricultural Zone of San Augustín (ZASA) is an organization of 145 families formed in 1972, who occupy an area of 540 hectares which is completely surrounded by the urban fabric of the Lima-Callao metropolitan region. ZASA annually produces more than 15,000 tons of vegetables that are sold in the markets of Lima (about 20 percent of the vegetables sold in the city). ZASA is irrigated with water from the Rimac River. However, during all but a few months a year, the flow in the river is basically domestic and industrial wastewater discharged just upstream and further degraded by garbage that is illegally dumped in the river. Under increasing pressure from the health authorities because of the significant health risks posed, and the threat of urban encroachment, ZASA is proposing to construct a waste stabilization pond system comprising 30 hectares of ponds in series (anaerobic + secondary + polishing) to achieve 1989 WHO guidelines for unrestricted irrigation. It would treat 400 l/s of raw sewage supplied directly from a nearby interceptor by the Lima water company. The treatment plant would be built by ZASA with a government line of credit (8 years at 8 percent interest). The property owners whose land is occupied by the ponds would be paid the value of their foregone farm profits by the other families. The project would be paid off in 10 years with an estimated financial rate of return of 92.2 percent and a benefit/cost ratio of 2.82, making it appear to be a financially sound and profitable venture.

Source: Egocheaga and Moscoso, 2004.

Box 2.7 Amman, Jordan—indirect use of treated wastewater

Jordan is one of the most water-deprived countries of the Middle East, and has some of the highest groundwater depletion rates. To meet growing water demands, more than 70 million m^3 of reclaimed wastewater, around 10 percent of the total national water supply, is used either directly or indirectly each year. The majority of reclaimed water is generated in the Amman Zarqua Basin. Treated effluent from the As Samra waste stabilization pond systems is discharged to the *Wadi* Zarqua that in turn flows into the King Talal Reservoir. Irrigation water taken from the *Wadi* is considered indirect use of reclaimed wastewater and is controlled as such. Water from the reservoir, however, is blended with other irrigation sources and is no longer considered reclaimed wastewater, and not subject to similar control.

There has been a steady evolution of the wastewater policy framework in Jordan as standards have been adapted to the needs of a severely water-constrained nation. Standards governing wastewater use have gone through four iterations. Initial standards were introduced in 1982 but were replaced in line with the 1989 WHO Guidelines; and in 1995 with a more comprehensive set of standards dealing with wastewater use and environmental discharges. Finally, in 2003 more stringent standards were promulgated following a multi-year consultation process with stakeholders. Under the new standards, groundwater recharge is permitted, but not for potable use. Jordan's experience demonstrates that wastewater use has great potential in water-scarce areas; but that planning for wastewater use must be integrated coherently with water resources planning, environmental management, and financial arrangements.

Sources: McCornick *et al*., 2004; Bahri, 2008a, b; Kfouri *et al*., 2009.

Box 2.8 Tunisia—direct use of treated wastewater

Wastewater irrigation has had Government support since 1975, and since a severe drought in 1989, treated wastewater use in irrigation has been a part of the Government's overall water resources management and environmental pollution control strategies. Water quality standards for wastewater use are based on the 1989 WHO Guidelines. Over 78 percent of the urban population is connected to sewerage, and 83 percent of the collected sewage is treated to adequate standards – about 4.7 m^3/s. However, only about 1.1 m^3/s is currently used for irrigation of 7,000 hectares of fruit trees and fodder. It is estimate that by 2020 about 20,000-30,000 ha, or about 7-10 percent of total irrigated area will be using treated wastewater. Despite strong government support, farmers currently prefer not to use reclaimed wastewater. Among the problems identified are: social acceptance; regulations restricting irrigation of high-value vegetable crops; water quality problems leading to clogging of drip irrigation systems; concerns about long-term impacts of saline wastewater; and inability to match the timing of supply and demand for water due to inadequate storage capacity for treated effluent.

In addition to technical and social concerns, there are institutional and economic issues to be resolved. It is recognized that there is a multiplicity of agencies involved in treated wastewater use, sometimes with conflicting objectives and overlapping responsibilities – efforts are underway to increase coordination and stakeholder involvement. On the economic side, efforts to develop a market-based strategy of treated wastewater should focus on the preferences of intended wastewater users.

Source: Shetty, 2004; Bahri, 2008b; Kfouri *et al*., 2009; Louati and Bucknall, 2009.

Wastewater irrigation in high-income countries. Wastewater reclamation and use in irrigation is a well-developed practice in the high-income countries, or parts of the countries, that are facing water scarcity, rapid urban growth, and water quality problems. Many OECD countries have achieved technological advances in physical, chemical, and biological processing of wastewater, together with the development of a rational regulatory framework controlling wastewater reclamation and use practices. Examples include the United States (especially the States of California and Florida), Australia, and European countries such as Spain and the southern provinces of France and Italy.

In non-OECD countries, there has also been an effort toward wastewater reclamation and use in irrigation in the water-short countries of the Mediterranean Basin and the Middle East, such as Bahrain, Cyprus, Israel, Kuwait, Malta, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (Jimenez and Asano, 2008b). In addition to water scarcity, wastewater use in these countries is driven by the marginal cost of alternative sources of water of sufficient volume and quality. For example, in Bahrain, cost of tertiary treated effluent is about \$0.32/m^3 while the cost of desalinated water is about \$0.79/ m^3 (Bahri, 2008a). These countries also have established regulatory frameworks for controlling wastewater reclamation and use practices, and invested in advanced wastewater treatment technologies.

The volume of reclaimed wastewater used for irrigation and the intensity of wastewater use (in volume per million capita) for key OECD and non-OECD countries is shown in Table 2.5. The data confirms that in response to water scarcity and drought, countries with resources are willing to make the considerable investments required in order to assure water supply augmentation and environmental protection through wastewater reclamation and use.

Table 2.5 Volume and intensity of treated wastewater use for irrigation in selected high-income countries, ranked by intensity

Country	Treated wastewater used for irrigation—volume (m^3/d)	Treated wastewater used for irrigation—intensity of use (m^3/d per million capita)
Kuwait	431,520	225,455
Qatar	80,000	141,593
Israel	767,123	127,007
Cyprus	68,493	87,364
United Arab Emirates	200,000	76,746
Malta	26,000	66,667
Bahrain	27,000	42,188
Saudi Arabia	594,521	29,221
Oman	67,000	26,399
USA, California	814,271	23,745
Spain	931,507	23,340
USA, Florida	300,940	16,390
Italy	741,262	12,885
Australia *	103,000	10,853
Greece	20,030	1,888
France	19,178	324
Japan	35,300	278

Sources: Adapted from Jimenez and Asano, 2008b; California data from SWRCB, 2003; Florida data from FDEP, 2009; Australia data from www.recycledwater.com.au.

* The volume figure corresponds to wastewater irrigation of 4 cities only: Melbourne, Adelaide, Sydney, and Alice Springs. Intensity is calculated utilizing the populations of the four cities (9.49 million).

Operational Involvement of the World Bank

During the last decade the World Bank's operational involvement in improving wastewater use in agriculture has mostly focused on lower-middle-income countries. A portfolio review based on an analysis of Project Appraisal Documents (PADs) approved between fiscal year (FY) 1999 and 2009 identified 26 projects that address wastewater treatment and (possible) use in agriculture. They are listed in Annex 3. Of the 26 projects, 17 include wastewater reuse in agriculture under project components: Eight projects plan the preparation of a reuse strategy, a related feasibility study, or the establishment of pilot sites; and nine projects provide support for treated wastewater use in agriculture. The latter projects are shown in Box 2.9. Overall, lending in direct support for wastewater use in agriculture amounted to less than 0.5 percent of the total lending for wastewater and sewerage projects during FY99-09.

Box 2.9 World Bank-supported projects for treated wastewater use in agriculture (FY99-09)

Projects strengthening institutions and building capacity on wastewater use in agriculture

- Iran: Tehran Sewerage Project, 2000
- Iran: Ahwaz and Shiraz Water Supply and Sanitation Project, 2004
- Lebanon: Ba'Albeck Water and Wastewater Project, 2002

Projects supporting treated wastewater being made available for use in agriculture:

- Tunisia: Tunis West Sewerage Project, 2006
- China: Second Tianjun Urban Development and Environment Project, 2003
- Thailand: Sapthip Wastewater Biogas and Renewable Energy Project, 2009
- Cape Verde: Energy and Water Sector Reform and Development Project, 1999

Project supporting the establishment of irrigation schemes using existing treated wastewater:

- Tunisia: Waters Sector Investment Project, 2000

Project supporting improvements in wastewater treatment and the establishment and rehabilitation of irrigation schemes:

- Tunisia: Second Water Sector Investment Project, 2009

Source: Authors.

2.3 Powerful drivers toward growing wastewater use in irrigation

Four key drivers can be identified that are leading to growing use of wastewater in agricultural activities in and around urban centers. They are expected to become even more powerful in the near future, making improved wastewater use in agriculture in many regions an emerging priority.

Growing water stress. Many parts of the world are experiencing growing water stress and water scarcity.[8] Projections indicate that the population living in water-stressed and water-scarce countries will grow from about 1.2 billion (or 18 percent of the world population) in 2007 to 4.0 billion (or 44 percent of the world population) by 2050 (Comprehensive Assessment of Water Management in Agriculture, 2007).[9] Water stress and scarcity may even become a concern in regions that are generally thought to have abundant water supplies, because of the unequal spatial distribution of water resources. For example, Latin America is generally considered a humid tropical region. Yet the 20 percent of the land that is arid or semiarid, with only 5 percent of the region's water resources, supports 60 percent of the region's population (Bartone, 1990).

The trend toward growing water stress is likely to accelerate due to climate change. The Intergovernmental Panel on Climate Change (2007) predicts that global warming will alter

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[8] A country is considered water-stressed when its annual supply of renewable freshwater is less than 1,667 m^3 per capita, and water scarce when it is less than 1,000 m^3 per capita (Falkenmark and Lindh, 1993).

[9] It should be noted that such figures only provide an impression of the annual average on a country level, disregarding the spatial and temporal distribution of precipitation, groundwater layers and surface flows. Due to a number of reasons, such as the availability of infrastructure, not all of these resources can actually be used. Furthermore, the figures do not consider that many water uses are nonconsumptive, and that return flows can be reused.

precipitation patterns around the world, melt mountain glaciers, and worsen the extremes of droughts and floods. Drought-affected areas are projected to increase in extent, with higher frequency and intensity of drought. In particular, the subtropics and mid-latitudes, where much of the world's poorest populations live, are expected to become substantially drier, resulting in heightened water stress (Meehl *et al*., 2007). Climate change will also affect water quality in water scarce regions, with reduced river flows losing assimilative capacity, and salinity increasing (Sadoff and Muller, 2009). As a result of these changes, the demand for irrigation water and in particular for wastewater as an extremely reliable water resource will rise, and it will need to be increasingly considered an integral component of local water resources.

Growing urbanization. An ever larger share of the world population lives in cities. Particularly in developing countries, urbanization is growing very rapidly. From 2010 to 2030, the population living in urban areas in developing countries is expected to increase from about 2.6 billion to 4.0 billion in 2030; and in lower-income countries the urban population is expected to more than double from 254 million to 539 million (UNDESA, 2008).

Growing urban wastewater generation. Associated with the large growth in the urban population in developing countries will be a growth in urban wastewater generation. As countries' income levels rise, the levels of piped water supply and sewer networks also tend to rise, and lead to further increased wastewater flows.

In the recent past impressive achievements have been made in the provision of improved urban sanitation services, including sewerage. From 1990 to 2006 improved sanitation facilities were provided to some 779 million additional urban residents, a large share of whom are also connected to sewers (WHO/UNICEF, 2008). However, despite these efforts, the provision of these services has barely kept pace with urban population growth, and the urban service deficit only dropped from 23 percent to 22 percent. Achieving the Millennium Development Goals sanitation target of cutting in half the service deficit by 2015 and achieving sanitation for all by 2025, will require significant ramping up of the pace of improvements. At the current rate of investment, the urban service deficit will only drop to 18 percent by 2015. Nevertheless, in absolute terms wastewater flows in urban areas will continue to grow substantially, and make improved wastewater management a necessity.

Growing agricultural activities in and near urban areas. The growth in the urban population in the developing world will not only lead to an increasing supply of urban wastewater, but also to a growing demand for irrigation water for agricultural activities in and near urban areas.

Estimates on the current extent of urban agricultural activities are limited. UNDP (1996) estimated that in the early 1990s more than 800 million people (or a third of all urban households) were involved in some way in urban agriculture, producing about 15 percent of the world's food. More recent estimates for West Africa suggest that about 20 million people—of an urban population of 100 million—live in households engaged in urban agriculture; in many cities they produce 60 to 100 percent of the consumed perishable vegetables (Drechsel *et al*., 2006). Table 2.6 shows the contribution of urban agriculture to food consumption in selected Asian and African cities. Even in high-income cities, such as Singapore and Hong Kong, the share of certain products supplied from urban agricultural activities is relatively high.

Table 2.6 Contribution of urban agriculture in selected cities in Asia and Africa

City and Country	Contribution of urban agriculture
Asia	
Shanghai, China	60 percent of the vegetables consumed, produced on 300,000 hectares administered by the city[a]
Hong Kong, China	50 percent of the vegetables consumed[b]
Jakarta, Indonesia	Squatters produce 20 percent of their food consumption[b]
Singapore	25 percent of vegetables consumed[b]
Africa	
Bamako, Mali	More than 100 percent of horticultural products consumed, including some urban-rural exports[b]
Kumasi, Ghana	80-90 percent of consumed perishable vegetables[c]
Dakar, Senegal	Nearly 80 percent of the country's vegetables are produced in the Niayes zone in suburban Dakar, amounting to about 3 percent of country's land area)[d]

Sources: [a] Yi-Zhang and Zhangen, 2000; [b] Smit *et al.*, 1996; [c] Drechsel *et al.*, 2007; [d] Mbaye and Moustier, 1999.

Main reasons for the involvement in urban agriculture are income and employment generation as well as food security, particularly for the urban poor and unemployed (Smit *et al.*, 1996). The urban environment also provides relative advantages, including direct access to urban consumers and markets; proximity to institutions that may provide market information, credit and technical advice; and availability of cheap inputs such as urban organic wastes and wastewater for irrigation (Veenhuizen and Danso, 2007). The recent rise in food prices is also likely to have contributed to an increased interest from urban households and local and national governments in expanding urban agriculture.

Together, these four drivers will contribute to increased wastewater use in agriculture, and the need to improve that use, especially in the lower- and middle-income countries.

Chapter 3. Risks and Benefits of Wastewater Use in Agriculture

Wastewater use in agriculture has substantial benefits, substantial benefits, but can also pose substantial risks to public health—especially when untreated wastewater is used for crop irrigation. Farmers often have no alternative but to use untreated wastewater because there is no wastewater treatment and freshwater is either unavailable or too expensive. The major risks to public health are microbial and chemical. Wastewater use in agriculture can also create environmental risks in the form of soil and groundwater pollution. However, if properly planned, implemented and managed, wastewater irrigation can have several benefits for the environment, as well as for agriculture and water resources management. Given these risks and benefits, countries seeking to improve wastewater use in agriculture must reduce the risks, in particular to public health, and maximize the benefits.

3.1 Risks to public health

3.1.1 Microbial risks[10]

Wastewater pathogens

At any point in time wastewater contains all the pathogens (disease-causing organisms) being excreted by members of the community from which the wastewater is derived. If no-one in a community is suffering from any excreta-related disease, then the community's wastewater does not contain any excreta-related pathogens. However, even in high-income countries, this hardly ever occurs, and wastewaters always contain at least some pathogens. Pathogen numbers in a community's wastewater reflect the amount of excreta-related disease in the community; in general, the number of pathogens is higher in wastewater in low-income countries than it is in wastewater in high-income countries.

The pathogens present in wastewaters are the agents of excreta-related diseases and so comprise the viruses, bacteria, protozoa and helminths that cause these diseases (Box 3.1). The diseases in the community caused by these pathogens may be endemic—i.e., the diseases are maintained within the community by continuous transmission between community members—or they may occur as epidemics—i.e., they are introduced to susceptible communities by persons from outside the community.

Many excreta-related diseases[11] can be spread by wastewater use in agriculture to those working in wastewater-irrigated fields and/or those consuming wastewater-irrigated foods, especially when eaten uncooked (e.g., salad crops and some vegetables) (Table 3.1). However the consumption of wastewater-irrigated foods is only one possible route of transmission, and this route may or may not be of local public health importance.

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[10] Microbes (or micro-organisms) are the life forms in the domains Bacteria and Archaea. Helminths (worms) are in the domain Eukarya and so, strictly speaking, are not microbes. However, in the context of wastewater use in agriculture, the term 'microbial health risks' includes the health risks due to helminths (see Box 3.1).

[11] Details of all excreta-related diseases are given in Feachem et al. (1983) and in the CDC *A-Z Index* available at http://www.cdc.gov/az/a.html.

Box 3.1 Pathogens in wastewaters

Viruses: Numerous viruses may infect the intestinal tract and be passed in the feces, whereupon they may infect new human hosts by ingestion or inhalation. One gram of human feces may contain 10^9 infectious virus particles, regardless of whether the individual is experiencing any discernible illness. Concentrations of 10^5 infectious particles per liter of raw wastewater have been reported. Although threy cannot multiply outside a suitable cell host, the excreted viruses may survive for many weeks in the environment. Five groups of pathogenic excreted viruses are important: adenoviruses, enteroviruses (including poliovirus), hepatitis A virus, reoviruses, and diarrhea-causing viruses (including norovirus and rotavirus).

Bacteria: Human feces contain large numbers (~10^9−10^{11} per gram) of commensal bacteria of many species; these are non-pathogenic and essential for the proper functioning of the intestinal tract. However, some bacteria cause excreta-related diseases—for example, *Campylobacter* and *Salmonella* (diarrhea), *Vibrio cholerae* (cholera), *Shigella* spp. (bacillary dysentery) and *Salmonella typhi* (typhoid fever). The numbers of these pathogens can be as high as 10^6−10^8 per gram of feces and 10^3−10^5 per liter of wastewater.

Protozoa: Several species of protozoa infect humans—for example, *Entamoeba histolytica* (which causes amebic disentery), and *Giardia lamblia*, *Cryptosporidium parvum* and *C. hominis* (severe diarrhea). Numbers can reach 10^3−10^5 per gram of feces and 10−10^3 per liter of wastewater.

Helminths: Helminths are worms. In wastewater-irrigated agriculture the most important intestinal worms are *Ascaris lumbricoides* (the human roundworm), *Trichuris trichiura* (the human whipworm), *Ancylostoma duodenale* and *Necator americanus* (the two human hookworms) (these four are nematode worms), and *Taenia saginata* and *T. solium* (the beef and pork tapeworms) (these two are cestode worms). The eggs of all these helminths are voided in the feces. *Ascaris* is generally taken as the 'reference' helminth as it is the most common (ascariasis affects ~1.2 billion people, almost exclusively in low- and low-middle-income countries), the female worms produce vast quantities of eggs (~200,000 per day), and the eggs can survive for long periods of time (many months to several years) in the environment. *Ascaris* egg numbers in wastewaters are ~10−10^3 per liter.

Sources: Adapted from Feachem *et al*., 1983; further information in WHO, 2008b.

Table 3.1 Environmental classification of excreta-related diseases important in wastewater-irrigated agriculture

Category	Environmental transmission features[a]	Major examples	Exposed groups and relative infection risks[b,c]
Non-bacterial feco-oral diseases	Non-latent Low to medium persistence Unable to multiply High infectivity	*Viral diseases:* Hepatitis A, E and F Diarrhea due to rotavirus, norovirus and adenovirus *Protozoan diseases:* Amebiasis Cryptosporidiosis Giardiasis Diarrhea due to *Cyclo-spora cayetanensis*, *Enterocytozoon bienusi* and *Isopora belli*	Fieldworkers: + Consumers: +++
Bacterial feco-oral diseases	Non-latent Medium to high persistence Able to multiply Medium to low infectivity	Campylobacteriosis Cholera Pathogenic *Escherichia coli* infections Salmonellosis Shigellosis	Fieldworkers: + Consumers: +++
Geohelminthiases	Latent Very high persistence Unable to multiply High infectivity	Ascariasis Hookworm infection Trichuriasis	Fieldworkers: +++ Consumers: +++

Source: Adapted from Feachem *et al*., 1983.

[a] Latency is the length of time required outside a human host for the pathogen to become infective, and persistence is the length of time the pathogen can survive outside a human host.

[b] +++ = high risk, + = low risk. These risks refer to the use of *untreated* wastewater for crop irrigation; they can be reduced by wastewater treatment and the use of the post-treatment health-protection control measures detailed in Table 4.2.

[c] Note that fieldworkers are often also consumers.

Transmission of microbial disease through wastewater

The available good-quality epidemiological evidence on the health risks due to wastewater use in agriculture was first reviewed by Shuval *et al*. (1986). The main findings from their study were:

- Soil-transmitted helminthic infections[12] represented the major actual (as opposed to potential) health risk (Box 3.2) to both those working in wastewater-irrigated fields and those consuming wastewater-irrigated foods uncooked when untreated wastewater was used for crop irrigation, but not when treated wastewater was used.
- Bacterial feco-oral diseases, such as diarrhea and cholera, can be transmitted to those consuming wastewater-irrigated salad crops and raw vegetables.

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[12] The principal soil-transmitted helminths (also called geohelminths and human intestinal nematode worms) are detailed in Box 3.1. In the context of wastewater use in agriculture, reference is commonly made to 'helminth eggs', rather than 'soil-transmitted helminth eggs' or 'human intestinal nematode eggs.'

Box 3.2 Actual and potential health risks in wastewater irrigation

An *actual* risk to public health occurs as a result of wastewater irrigation when all of the four following conditions are satisfied:

(1) either an infective dose of the pathogen reaches the wastewater-irrigated field or the pathogen multiples in the field to form an infective dose
(2) the infective dose reaches a human host
(3) the host becomes infected
(4) the infection causes disease or further transmission.

Actual risks can thus only be determined from epidemiological studies.
If conditions 1−3 are satisfied but not condition 4, then the risk is only a *potential* risk.

Source: WHO, 1989.

There was less compelling evidence for the transmission of viral and protozoan diseases. Blumenthal and Peasey (2002) reviewed the epidemiological evidence reported after the study by Shuval *et al.* (1986). The main findings of their study were:

- *Unrestricted irrigation*: The use of untreated wastewater to irrigate vegetables led to increased helminth infection (mainly *Ascaris lumbricoides* infection), bacterial infections (typhoid, cholera, *Helicobacter pylori* infection), and symptomatic diarrheal disease in consumers. When wastewater was partially treated, there was evidence that the risk of bacterial and viral enteric infections was still significant when consumers ate some types of uncooked vegetables irrigated by water containing $\geq 10^5$ fecal coliforms per 100 mL (see Box 3.3).
- *Restricted irrigation*: Studies of the risks of viral and bacterial enteric infections related to use of treated wastewater suggested that when sprinkler irrigation was used and the population was exposed to wastewater aerosols, there was an increased risk of infection when the quality of the wastewater was 10^6 total coliforms per 100 mL, but no increased risk of infection when the quality of the wastewater was 10^3−10^4 fecal coliforms per 100 mL. Studies of the risks of symptomatic diarrheal disease and enteric viral infections related to direct contact with treated wastewater through farm work (adults and children) or play suggested that, when flood or furrow irrigation occurs, there was an increased risk of infection in children when the quality of the wastewater was $>10^4$ fecal coliforms per 100 mL. For adults, the threshold level for symptomatic diarrheal disease was 10^5 fecal coliforms per 100 mL, but the threshold level for transmission of a Mexican strain of norovirus was $<10^4$ fecal coliforms per 100 mL where high levels of contact occurred, even in a rural area where there were many other transmission routes for this virus.

Significance of microbial health risks

Feachem *et al*. (1983) considered that the health problems associated with wastewater use in the production of human food could be broken down into a series of questions:

- How many pathogens and of what kind reach the field or crop?
- Are pathogens likely to survive in sufficient numbers and for sufficient time to cause subsequent infection?
- How significant is this infection route compared to all other potential infection routes?

Box 3.3 Total coliforms, fecal coliforms and *Escherichia coli*

Total coliforms are bacteria that can ferment lactose (milk sugar) with the production of acid and gas in the presence of bile salts at 37°C. They exist naturally in the intestines of warm-blooded animals, including man, and so are present in feces in very large numbers ($\sim10^8-10^{10}$ per gram). However, they can also be found in unpolluted environments, so their presence in water does not indicate beyond doubt that the water has been fecally polluted.

Fecal coliforms are coliforms that can ferment lactose at the higher temperature of 44.5°C. They are better indicators of fecal pollution than total coliforms, but some fecal coliforms (especially in tropical and subtropical areas) are not exclusively fecal in origin.

Escherichia coli (generally termed *E. coli*) is currently the only known fecal coliform that is exclusively fecal in origin.

Both fecal coliforms and *E. coli* (as well as total coliforms) occur in the feces of man and animals, so they cannot be used to distinguish between human and animal fecal pollution.

The concept of coliforms as fecal indicator organisms has its origin in the bacteriological examination of drinking waters (Smith, 1895). With wastewater, the fecal origin of which is not in question, fecal coliforms and *E. coli* numbers are used as indicators of bacterial and viral pathogens. They are less than perfect for this purpose, but, given that information on pathogen numbers is scarce, especially in developing countries, they are the best indicators currently available.

The answers to the first two questions depend on the diseases endemic in the affected populations and on the degree of wastewater treatment, if any. Feachem *et al*. (1983, pp. 100–101) answered the third question by describing the following hypothetical, but typical, case study, which refers to crop fertilization with human excreta (‘night soil’) and sewage sludge, but which applies equally to wastewater irrigation:

> Imagine a town of moderately wealthy people who live in houses with water connections and flush toilets. Outside this town is a village where people are extremely poor, houses have earth floors, water is drawn from an open well, and no adequate excreta disposal system exists. The main source of income for the village is the cultivation of vegetables for sale to the town; vegetables are also used by the villagers as subsistence crops. These vegetables are fertilized by night soil collected in the village and by sewage sludge obtained free of charge from the treatment works on the outskirts of the town. The prevalence of [ascariasis] in the town is only 8 percent, and the principal means of entry to the home of viable *Ascaris* eggs is on the vegetables bought from the villagers. Transmission among the wealthy townsfolk does not take place because their excreta are flushed away and high standards of hygiene prevail. The prevalence of ascariasis in the village, however, is 68 percent, and transmission occurs intensively, particularly in the home. The floors and yards of the village houses are contaminated with viable eggs from the feces of infected children. Most transmission is quite unrelated to the contaminated vegetables that the villagers eat. If the supply of contaminated vegetables suddenly ended, the transmission of ascariasis in the town would be reduced very substantially, but transmission in the village would be unaffected.

The same argument applies to poor *urban* communities with inadequate housing, water supplies and sanitation.

From a more rigorous epidemiological perspective the health risks from working in wastewater-irrigated fields and/or consuming wastewater-irrigated foods (especially those eaten uncooked) are only significant—i.e., of public-health importance—if, in the exposed population compared with a carefully matched control group, they result in:

- an excess incidence of disease,

- an excess prevalence of disease,
- an excess intensity of infection, and/or
- further transmission of disease.

"Incidence" refers to the number of new cases of a disease in a community in a specified period of time (usually a week, month, or year), and "prevalence" refers to the number of cases of a disease in a community at a given point in time; incidence is normally used for acute diseases (e.g., diarrheal disease) and prevalence for chronic diseases (helminthiases). In the present context of wastewater use in agriculture, if fieldworkers and/or crop consumers have an excess incidence or prevalence of a disease, or an excess intensity of infection (e.g., a higher worm burden as shown by the number of helminth eggs per gram of feces), compared with a control group, then these excesses are attributable to the use of wastewater in agriculture, which is therefore an issue of public health importance—and this is the only way that this importance can be ascertained.

Shuval *et al*. (1986) showed that, when untreated wastewater was used for irrigation, there was an excess prevalence (and also an excess intensity of infection) of ascariasis and hookworm disease in fieldworkers compared with a control group (Figure 3.1), but not when treated wastewater was used. Blumenthal and Peasey (2002) confirmed this for both geohelminthic and bacterial diseases.

Approaches to microbial risk control

There have been three basic approaches to the control of microbial risks:

- Approaches based on potential risks, such as the very strict Californian standards and the even stricter US EPA/USAID guidelines (State of California, 2001; US EPA/USAID, 2004);
- Approaches based on actual risks, such as the 1989 WHO Guidelines (WHO, 1989); and
- Approaches based on quantitative microbial risk analysis (QMRA), such as the Australian National Guidelines (EPHC/NRMMC/AHMC, 2006) and the 2006 WHO Guidelines (WHO, 2006a) discussed in Chapter 4.

The currently recommended approach is that based on QMRA as it provides greater flexibility in risk management. Risk reduction, for example, can be achieved not just by wastewater treatment, but also by including post-treatment health-protection control measures. This approach also reduces costs. More details are provided in Chapter 4 and Annex A.

3.1.2 Chemical risks

Chemical risks to human health

Health risks from chemicals are caused by heavy metals (e.g., cadmium, lead, and mercury) and many organic compounds (e.g., pesticides). These mostly derive from industrial wastewaters and, if these are discharged to public sewers, they are present in municipal wastewaters. The health effects of prolonged exposure to many of these chemicals are well known (e.g., cancers).[13] There is an emerging class of chemical contaminants, the so-called 'anthropogenic' compounds, which include pharmaceuticals, hormones and endrocrine disruptors, antimicrobials and antibiotics, and personal care products, the long-term health effects of which are less clearly understood (see Bhandari *et al*., 2009).

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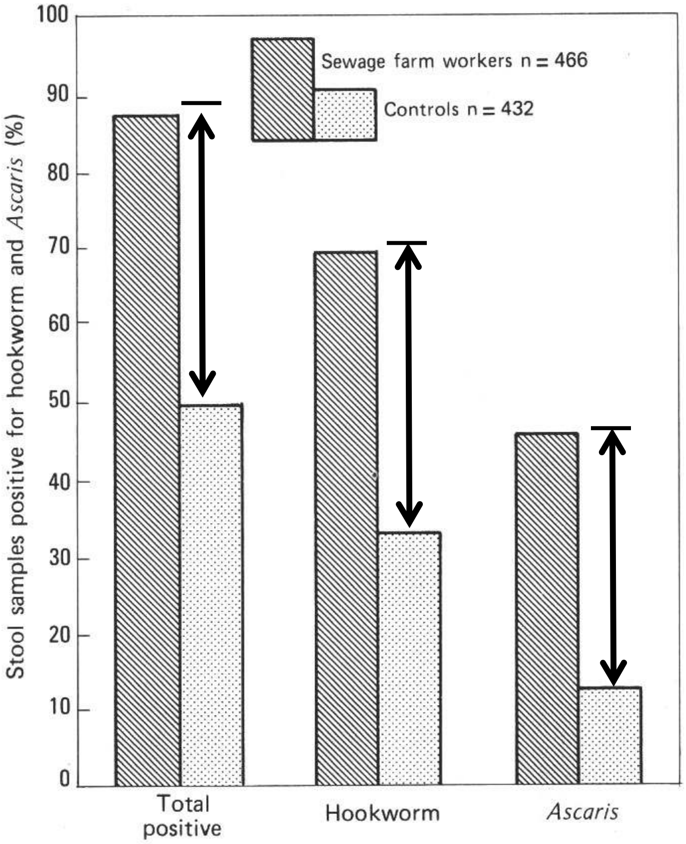
[13] A useful summary is given in WHO (2008c).

Figure 3.1 Prevalence of ascariasis and hookworm disease in 'sewage farm' workers in India using untreated wastewater for irrigation compared with a control group



Source: Shuval *et al*., 1986.
Note: Arrows indicate excess prevalences.

Chang *et al*. (2002) reviewed the principal chemical risks to human health resulting from the consumption of wastewater-irrigated foods. They found that:

- Land application has been a popular option for disposing of municipal wastewater and sewage sludge worldwide for more than a century. While most of the operations appear to be successful, reports from countries such as China suggested that large-scale irrigation of crops with mostly untreated municipal and industrial wastewaters could be harmful to crops and cause injuries to humans because of poorly controlled discharge of toxic and hazardous constituents in the wastes.
- Concentrations of potentially hazardous pollutants in the municipal wastewater and the resulting sewage sludge varied considerably from location to location and, for the same community, were subject to temporal variations due primarily to point-source discharges from industries. The frequency of detection for inorganic pollutants, such as the trace elements in the wastewater, usually ranges from 50 to 100 percent and they are invariably concentrated into the sewage sludge in the course of wastewater treatment. The frequency of detection for organic pollutants was considerably lower. They range usually from 5 to 10 percent and their concentrations, when found, were low. Community-wide industrial

wastewater pretreatment provisions to prevent the discharge of pollutants by industries have been effective in reducing the pollutant concentrations in wastewater and sewage sludge.

Chang *et al*. (2002) developed the following two principles to minimize chemical risks to human health:

- Prevent pollutant accumulation in waste-receiving soils: In land application, if the pollutant input equals the pollutant output, there will not be a net accumulation of pollutants in the receiving soil. Consequently, the pollutant contents of the soil will remain at the background level and the soil's ecological and chemical integrity are preserved. When this requirement is met, the capacity of the soil to sustain any future land uses is guaranteed and the transfer of pollutants up the food chain is kept to a minimum. Numerical limits, therefore, are set to prevent the pollutant concentration of the soil from rising during the course of land application. Guidelines derived from this approach will have stringent upper limits for pollutants and are universally applicable. The cost of implementation will be high, however, as wastewater treatment plants need to employ advanced wastewater treatment technologies to minimize the pollutant levels in the reclaimed wastewater and sewage sludge.
- Take maximum advantage of the soil's capacity to assimilate, attenuate, and detoxify pollutants: Soils possess natural abilities to assimilate, attenuate, and detoxify pollutants. In land applications, this capacity should be fully utilized. In this manner, the agronomic benefits of applying wastewater and sewage sludge may be realized and, when managed properly, accumulation of pollutants in soil can be controlled so that they will not reach levels harmful to human health. Land application guidelines based on this approach set the maximum permissible pollutant loading and provide users the flexibility to develop suitable management practices for using wastewater and sewage sludge within the boundary. However, under this scenario, pollutant levels in the soil will rise eventually to levels considerably higher than the background levels, and future land uses may be restricted. Furthermore, the technical data needed to define the pollutant transfer parameters of the exposure pathways are not always available.

Chang *et al*. (2002) also derived tentative health protection guidelines for common inorganic and organic pollutants by considering the food-chain transfer of pollutants (i.e., wastewater → soil → plants → people) from the consumption of grains, vegetables, root/tuber crops, and fruit (which, together, account for about 75 percent of the daily global average adult diet) (Table 3.2). The exposure scenario used assumed that (1) most exposed individuals were adult residents with a 60-kg body weight; (2) their entire consumption of grains, vegetables, root/tuber crops, and fruit were produced in wastewater-irrigated fields; and (3) their daily intake of pollutants from consumption of grain, vegetable, root/tuber, and fruit foods accounted for 50 percent of the acceptable daily intake (ADI), with the remaining 50 percent of the ADI being credited to background exposure.

Chang *et al*. (2002, iv) note that where there are "effective industrial wastewater pretreatment programs, the pollutant discharge into the wastewater collection and treatment systems is effectively regulated and pollutants incompatible with land application may be screened out. The reclaimed wastewater from these communities may be used for crop irrigation without undue restrictions, provided the [microbiological] quality of the water is acceptable and the volume of water applied does not exceed the normal water requirement for a successful crop harvest. In this manner, the pollutant input to the receiving soil, realistically, may be balanced by the outputs through plant absorption when the reclaimed wastewater is used for irrigation."

However, effective industrial wastewater pretreatment programs are not the norm in developing countries and therefore special attention has to be paid to chemical risks in such circumstances. Even if they do exist there is always the additional problem of household chemicals, such as soap and detergent residues, cleaning fluids, personal care products (e.g., deodorants), and pharmaceutical residues, all of which are discharged as part of the greywater into the household wastewater.

Table 3.2 Tentative guideline values for the maximum permissible concentrations of selected inorganic and organic pollutants in wastewater-irrigated soils

Maximum permissible concentrations (mg per kg soil)					
Inorganic compounds					
Antimony	36	Arsenic	8	Barium	302
Beryllium	0.2	Boron	1.7	Cadmium	4
Fluorine	635	Lead	84	Mercury	7
Molybdenum	0.6	Nickel	107	Selenium	6
Silver	3	Thallium	0.3	Vanadium	47
Organic compounds					
Aldrin	0.48	Benzene	0.14	PAH[a]	16
Chlorodane	3	Chlorobenzene	211	Chloroform	0.47
Dichlorobenzene	15	2,4−D	0.25	DDT	1.54
Dieldrin	0.17	Dioxins	1.2×10^{-4}	Heptachlor	0.18
Hexachlorobenzene	1.4	Lindane	12	Methoylchlor	4.27
Pentachlorophenol	14	PCBs	0.89	Pyrene	41
Tetrachloroethane	1.25	Toluene	12	Toxophene	0.0013
2,4,5−T	3.82	Trichloroethane	0.68	Phthalate	13,733
Styrene	0.68				

Source: Chang *et al*. 2002.
[a] As benzo(a)pyrene.

3.2 Environmental risks and benefits

3.2.1 Environmental risks

Soil and groundwater pollution is clearly a potential disadvantage of using wastewater in agriculture. Under most conditions, wastewater irrigation does not present a microbiological threat to groundwater since it is a process similar to slow sand filtration: most of the pathogens are retained in the top few meters of the soil, and horizontal-travel distances in uniform soil conditions are normally less than 20 meters. However, in certain hydrogeological situations (for example in limestone formations) microbial pollutants can be transported for much greater distances, and careful investigation is required in such cases (BGS, 2001). Chemical pollutants, among which nitrates are of principal concern in the case of domestic wastes, can travel for greater distances, and there is the potential risk that drinking-water supplies in the vicinity of wastewater irrigation projects may be affected. In general, therefore, and unless a rigorous hydrogelogical appraisal indicates otherwise, water supplies should not be located within, or close to, wastewater-irrigated fields; conversely, wastewater irrigation should not take place in areas where the groundwater is used for drinking-water supplies.

As a result of increased rates of salinization and waterlogging, soil pollution can occur through wastewater irrigation if adequate attention is not paid to leaching and draining requirements. Saline drainage waters should be used to irrigate salt-tolerant crops where possible, and crop and field rotation will generally be necessary to avoid long-term damage to the soil structure. Adherence to good irrigation practice is essential to avoid adverse environmental effects (Ayers and Westcot, 1985; Rhoades *et al*., 1992; Hillel, 2000; Tanji and Kielen, 2002). Often a trade-off has to be made between agricultural production and environmental protection, and this must be carefully evaluated at the project planning stage. Many of these potential disadvantages of wastewater irrigation, together with such hazards as odor, vector development, and the effects of accidental discharges of toxic substances, can be avoided by the use of properly treated wastewater. This includes adequate control of non-biodegradable and toxic industrial wastewaters, which generally require separate treatment or at least pretreatment prior to discharge to public sewers (Chapter 5).

Chemical risks to plant health

Crop yields may be reduced if the physicochemical quality of the wastewater used for irrigation is unsuitable—for example by being too saline or having concentrations of boron, heavy metals and other industrial toxicants, nitrogen, and/or sodium which inhibit plant growth either directly in the case of toxicants or indirectly by reducing the plant's ability to absorb nutrients. The principal (and still current) reference document on the physicochemical quality of water, including wastewater, used for crop irrigation is FAO's *Water Quality for Agriculture* (Ayers and Westcot, 1985). This may be supplemented by two later FAO publications *The Use of Saline Waters for Crop Production* (Rhoades *et al*., 1992) and *Quality Control of Wastewater for Irrigated Crop Production* (Westcot, 1997), and the World Bank publication *Salinity Management for Sustainable Irrigation: Integrating Science, Environment, and Economics* (Hillel, 2000).

In general treated domestic wastewaters, or treated municipal wastewaters that contain little industrial effluent, present no problem; care has to be exercised as the proportion of industrial effluent in the wastewater increases. However, even for treated domestic wastewaters, there are five parameters that should be monitored during the irrigation season: 1) electrical conductivity (as a measure of total dissolved solids or "salinity hazard"), 2) the sodium adsorption ratio (as a measure of the 'sodium hazard'),[14] 3) the concentrations of boron, 4) the concentrations of total nitrogen, and 5) pH.[15] These measurements are relatively easy to do in the case of large wastewater-use schemes, but at the smaller scale of urban/peri-urban agriculture they would not generally be possible. The environmental health departments of city and town councils should nonetheless be encouraged to conduct these five analyses reasonably regularly (for example, at least monthly) throughout the irrigation season.

3.2.2 Environmental benefits

If wastewater use schemes are managed well, they can have several environmental benefits (Mara and Cairncross, 1989):

- Avoidance of surface water pollution, which would occur if the wastewater were not used but discharged into rivers or lakes. Major environmental pollution problems, such as dissolved oxygen depletion, eutrophication, foaming, and fish kills, can thereby be avoided.
- Conservation or more rational use of freshwater resources, especially in arid and semi-arid areas—i.e. fresh water for urban demand, wastewater for agricultural use.
- Reduced requirements for artificial fertilizers, with a concomitant reduction in energy expenditure and industrial pollution elsewhere.
- Soil conservation through humus build-up and through the prevention of land erosion.
- Desertification control and desert reclamation, through irrigation and fertilization of tree belts.

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[14] The sodium absorption ratio is $[\mathrm{Na}] \div \{0.5([\mathrm{Mg}] + [\mathrm{Ca}])\}^{1/2}$ where [Na], [Mg] and [Ca] are the concentrations of sodium, magnesium and calcium, respectively, in milli-equivalents per liter.

[15] The FAO Guidelines (Ayers and Westcot, 1985) should be consulted for details of these parameters, crop sensitivities to boron, total nitrogen and pH, and how electrical conductivity and the sodium absorption ratio interact.

3.3 Agricultural and water resources management benefits

In addition to potential environmental benefits, there is a range of other benefits from reusing wastewater in agriculture. The most important benefits accrue to the agricultural and water management sectors. For agriculture these include:

- Reliable, and possibly less costly irrigation water supply;
- Increased crop yields, often with larger increases than with freshwater due to the wastewater's nutrient content;
- More secure and higher urban agricultural production, and contribution to food security
- Income and employment generation in urban areas; and
- Improved livelihoods for urban agriculturalists, many of whom are poor subsistence farmers, including a large share of women.

In terms of water resources management, the benefits include:

- Additional drought-proof water supply, often with lower cost than expanding supplies through storage, transfers, or desalinization;
- More local sourcing of water;
- Inclusion of wastewater in the broader water resources management context; and
- More integrated urban water resources management.

3.4 Objectives for improving wastewater irrigation

Faced with these risks and benefits, countries seeking to improve wastewater use in agriculture should pursue the following key objectives:

Objective 1: Minimize risk to public health;

Objective 2: Minimize risk to the environment;

Objective 3: Improve livelihoods for urban agriculturalists;

Objective 4: Integrate wastewater into the broader water resources management context.

Depending on the level of economic development, a country may seek to achieve one or a combination of objectives. Given the strong association between a country's income and the way it handles wastewater as presented in Chapter 2, low-income countries are likely to put the highest priority on minimizing the risk to public health while improving the livelihoods of urban agriculturalists. High-income countries, on the other hand, are more likely to emphasize environmental risk reduction and, especially when they are water-stressed or water scarce, a fuller integration of wastewater into their water resources management system.

Chapter 4. Assessing and Managing Microbial Risk to Public Health

4.1 Risk assessment and management framework of the 2006 WHO Guidelines

The assessment and management of the microbial risks to human health caused by wastewater use in agriculture is essential to avoid any excessive additional burden of disease for those who work in wastewater-irrigated fields or consume wastewater-irrigated foods.

The excreta-related pathogens and related diseases most commonly associated with wastewater are detailed in Box 3.1 and Table 3.1. However, a list of these pathogens and diseases says nothing about the risks they may pose to human health. Epidemiological studies of the types reviewed by Shuval *et al*. (1986) and Blumenthal and Peasey (2002) (section 3.1.1) provide good information on "actual" rather than "potential" risks (Box 3.2), but they are complicated and expensive to perform and are unlikely to be done, especially in low- and middle-income countries, on the scale required to provide information on local risks. Moreover, results from areas where diseases are endemic are not comparable to those where they are not endemic. In many high-income countries, health concerns are mainly with regard to enteric viruses associated with treated wastewater. The concentrations of enteric viruses are normally so small that it is difficult to establish an epidemiological endpoint; thus, the respective guidelines are largely based on the estimation of potential risk.

The 2006 WHO *Guidelines for the Safe Use of Wastewater, Excreta and Greywater* (WHO, 2006) have taken a radically different approach to the ones used in the 1973 and 1989 WHO Guidelines (WHO 1973, 1989). The 2006 WHO Guidelines are based on a risk assessment and management approach that follows the Stockholm Framework (Fewtrell and Bartram, 2001)—the same risk management framework that is now applied to all decisions about drinking-water and sanitation interventions—rather than specifying the required quality of treated wastewater, as was done in the 1973 and 1989 guidelines.

The 2006 WHO approach for microbial risks is (i) to define a tolerable maximum additional burden of disease, from which it is possible (ii) to derive tolerable risks of disease and infection, (iii) to determine the required pathogen reduction(s) to ensure that the tolerable disease and infection risks, and hence a tolerable maximum additional burden of disease, are not exceeded, (iv) to determine how the required pathogen reductions can be achieved, and (v) to put in place a system for verification monitoring (Table 4.1). This approach became possible only after the DALY (disability-adjusted life years) metric was developed and introduced by WHO and the World Bank in 1993 (World Bank, 1993a; see also Murray and Lopez 1996), allowing for the definition of a tolerable additional burden of disease and for the comparison of disease burdens resulting from different health risks (Box 4.1).[16] Using these concepts and approaches, the Australian *National Guidelines for Water Recycling: Managing Health and Environmental Risks* (EPCH/NRMMC/AHMC, 2006) and the quantitative microbial risk analysis (QMRA) procedures used by Mara *et al*. (2007) were developed.

The required degree of pathogen reduction (step iii above) can only be determined by QMRA (see Box 4.2)[17] which was first applied to wastewater use in agriculture by Asano *et al*. (1992), Shuval *et al*. (1997) and Tanaka *et al*. (1998). QMRA is the keystone of a rational management framework for microbial risk assessment and control in wastewater irrigation based on a 'multiple-barrier' approach to risk management (Figure 4.1).

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[16] A fuller explanation of DALYs is given in WHO (2010).

[17] A more detailed description is given in WHO (2006) and in Annex A.

Table 4.1 A framework for the management of microbial risks from wastewater use in agriculture

Step objective	Step activities and comments
Step 1 Define tolerable maximum additional burden of disease	The metric for disease burden is the 'disability-adjusted life year' (DALY) (see Box 4.1). The 2006 WHO Guidelines used a default value of $\leq 10^{-6}$ DALY loss per person per year (pppy) as consistent with accepted risks from drinking fully treated drinking water. A more appropriate value, at least initially in low- and middle-income countries, is $\leq 10^{-4}$ DALY loss pppy (see section A.1 of Annex A).
Step 2 Derive tolerable disease and infection risks	The tolerable risk of a disease per person per year is obtained from the equation: "tolerable DALY loss pppy ÷ DALY loss per case of the disease", and the tolerable risk of infection pppy from the equation: "tolerable disease risk ÷ disease/infection ratio" (see section 4.2.1).
Step 3 Conduct quantitative microbial risk analyses to determine required minimum total pathogen reductions	QMRA-Monte Carlo simulations (Box 4.2) are used to estimate the required minimum total pathogen reductions—for example, from raw wastewater to ingestion—such that the tolerable risk of infection determined in Step 2, and hence the tolerable additional burden of disease selected in Step 1, are not exceeded. The exposure scenario of involuntary ingestion of wastewater-contaminated soil particles is used for restricted irrigation, and that of the consumption of wastewater-irrigated foods eaten uncooked (salad crops, some vegetables) for unrestricted irrigation. The ranges of parameter values used in the QMRA-Monte Carlo simulations must be chosen to reflect local circumstances (see Table A.7 in Annex A).
Step 4 Determine how the required pathogen reductions are to be achieved	The pathogen reduction to be achieved by wastewater treatment is that required to protect the health of those who work in wastewater-irrigated fields (i.e., restricted irrigation)—but see section 4.3.2 for non-treatment options. If unrestricted irrigation is practiced additional post-treatment health-protection control measures must be selected to protect the health of those who consume wastewater-irrigated foods (Table 4.2); alternatively, but entailing additional costs, the degree of wastewater treatment may be increased.
Step 5 Verification monitoring	Verification monitoring must be carried out to confirm that the required pathogen reduction is being achieved by wastewater treatment (details are given in Annex B). Unrestricted irrigation: a Hazard Analysis Critical Control Point (HACCP) system should be put in place to monitor the efficacy of the health protection control measures listed in Table 4.2 (details are given in section B.2 of Annex B).

Sources: Adapted from WHO, (2006; and Godfree and Godfrey, 2008.

This approach includes both wastewater treatment and post-treatment health-protection control measures (Table 4.2 and section 4.3.1) and non-treatment options to be used in circumstances where, for one reason or another, wastewater treatment does not exist and is unlikely to exist for the immediate future (Table 4.2 and section 4.3.2).

QMRA determines numerical values for the health risks that result from particular sets of conditions relating to local practices in using wastewater in agriculture. As illustrated in Annex A, it is relatively straightforward to use the results from QMRA to select the most cost-effective set of conditions—i.e., the combination of health protection control measures detailed in Table 4.2, including wastewater treatment where it exists or is feasible— that does not cause any excessive additional burden of disease in those who work in wastewater-irrigated fields or consume wastewater-irrigated foods. In a few cases the risks determined by epidemiological studies and those estimated by QMRA have been compared and the agreement between them was found to be good (Mara *et al*. 2007).

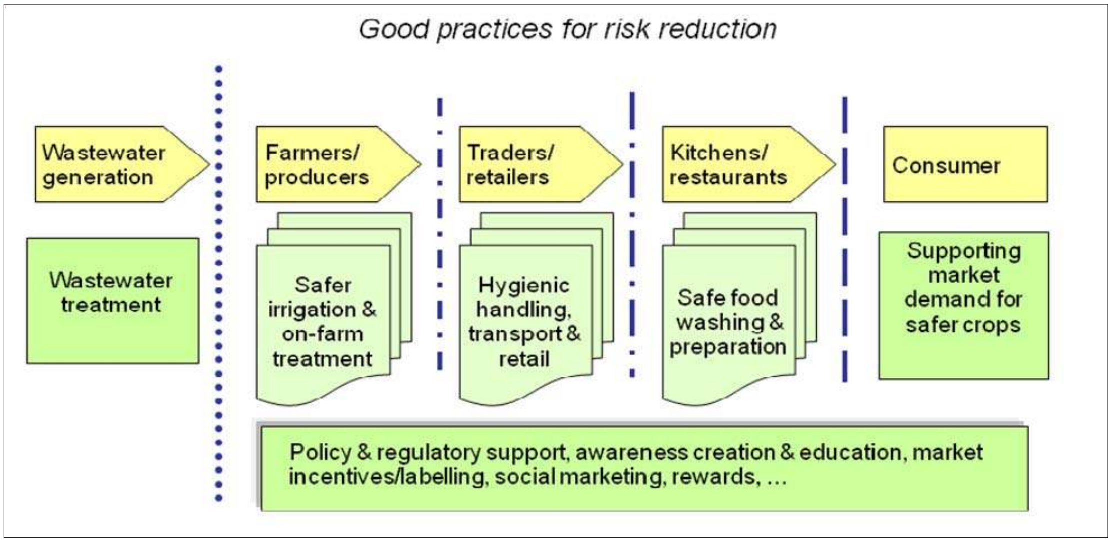
Box 4.1 Disability-adjusted Life Years (DALYs)

DALYs are a measure of the health of a population or burden of disease due to a specific disease or risk factor. DALYs attempt to measure the time lost because of disability or death from the disease compared with a long life free of disability in the absence of the disease. DALYs are calculated by adding the years of life lost due to premature death (YLL) to the years lived with a disability (YLD). Years of life lost are calculated from age-specific mortality rates and the standard life expectancies of a given population. YLD are calculated from the number of cases of the disease multiplied by its average duration and a severity factor ranging from 1 (death) to 0 (perfect health) based on the disease—for example, watery diarrhea has a severity factor from 0.09 to 0.12, depending on the age group.

DALYs are an important tool for comparing health outcomes because they account for not only acute health effects but also for delayed and chronic effects—i.e., they include both morbidity and mortality. When risk is described in DALYs, different health outcomes (e.g., fatal cancers and non-fatal diarrheal diseases) can be compared and risk management decisions prioritized.

Source: WHO, 2006.

Figure 4.1 The multiple barrier approach to microbial risk management



Source: Ilic *et al*., 2010.

Box 4.2 Quantitative microbial risk analysis

Quantitative microbial risk analysis (QMRA) determines a numerical value of the risk (i.e., probability) of disease and/or infection as a result of a person or a community being exposed to a specified number of a specified pathogen as a result of some activity—in this case the relevant activities are consuming wastewater-irrigated foods and working in wastewater-irrigated fields. QMRA can be used to estimate disease and infection risks for any pathogen as long as there are dose-response data available for it. The disease and/or infection risks can then be estimated by a dose-response equation (as shown in section A.3 of Annex A).

Interpreting values of risk: values of risk (probability) are in the range 0−1 and are expressed per person per exposure event or, more commonly in relation to wastewater use in agriculture, per person per year (pppy). For example, an infection risk of 0.01 (i.e., 1×10^{-2}) pppy means that each year an exposed individual has a 1% chance of becoming infected as a result of a given number of exposure events per year. Alternative ways of interpreting this infection risk of 0.01 pppy are (a) that the exposed individual will become infected once every 100 years (i.e., essentially once in his or her lifetime), or (b) that, for a community, an infection risk of 0.01 pppy means that every year 1% of the community will become infected.

Note that there is no such thing as a 'zero risk'. A risk can be very small—for example, 1×10^{-x} pppy, where x is very large—but it is <u>not</u> zero.

Monte Carlo risk simulations: many of the parameters used in QMRA risk determinations have 'uncertain' values—for example, it might be assumed that 10 mL of wastewater remains on 100 g of lettuce after irrigation, but this 'fixed' value of *exactly* 10 mL may not always occur: the value could be anywhere in the range of 5−15 mL, for example. To overcome, at least partially, the uncertainty of many of the parameters used in QMRA risk determinations, Monte Carlo risk simulations are used in which a *range of values* is assigned to each parameter used in the calculations, rather than a *single fixed value*, although a fixed value can be assigned to any given parameter if so desired. A computer program then selects at random a value for each parameter from the range of values specified for it and then determines the resulting annual risk.[a] The program repeats this process a large number of times (generally for a total of 1000 or 10,000 times) and determines the median and 95-percentile risks. This large number of repetitions removes some of the uncertainty associated with the parameter values and makes the results generated by multi-simulation QMRA-Monte Carlo risk analyses much more robust than those determined by simple QMRA calculations which use only 'fixed' parameter values, although of course they are still only as good as the assumptions made. Sections A.2−A.6 of Annex A illustrate the use of this 'QMRA-MC' approach to risk determination.

[a] See the Note at the end of Annex A concerning the availability of QMRA-MC computer programs.

Table 4.2 Health-protection control measures and associated pathogen reductions

Control measure	Pathogen reduction (log units)	Notes
A. Wastewater treatment	1−7	Pathogen reduction depends on type and degree of treatment selected.
B. On-farm options		
Crop restriction (i.e., no food crops eaten uncooked)	6−7	Depends on (a) effectiveness of local enforcement of crop restriction, and (b) comparative profit margin of the alternative crop(s).
On-farm treatment:		
(a) Three-tank system	1−2	System described in section 4.3.1.
(b) Simple sedimentation	0.5−1	Sedimentation for ~18 hours (section 4.3.1).
(c) Simple filtration	1−3	Value depends on filtration system used (section 4.3.2).
Method of wastewater application:		
(a) Furrow irrigation	1−2	Crop density and yield may be reduced.
(b) Low-cost drip irrigation	2−4	2-log unit reduction for low-growing crops, and 4-log unit reduction for high-growing crops.
(c) Reduction of splashing	1−2	Farmers trained to reduce splashing when watering cans used (splashing adds contaminated soil particles on to crop surfaces which can be minimized).
Pathogen die-off	0.5−2 per day	Die-off between last irrigation and harvest (value depends on climate, crop type, etc.).
C. Post-harvest options at local markets		
Overnight storage in baskets	0.5−1	Selling produce after overnight storage in baskets (rather than overnight storage in sacks or selling fresh produce without overnight storage).
Produce preparation prior to sale	1−2	(a) Rinsing salad crops, vegetables and fruit with clean water.
	2−3	(b) Washing salad crops, vegetables and fruit with running tap water.
	1−3	(c) Removing the outer leaves on cabbages, lettuces, etc.
D. In-kitchen produce-preparation options		
Produce disinfection	2−3	Washing salad crops, vegetables and fruit with an appropriate disinfectant solution and rinsing with clean water.
Produce peeling	2	Fruits, root crops.
Produce cooking	5−6	Option depends on local diet and preference for cooked food.

Sources: EPHC/NRMMC/AHMC, 2006; WHO, 2006; Amoah *et al*., 2007b; Abaidoo *et al*., 2010; and Keraita *et al*., 2010.

4.2 Currently recommended microbial risks assessment and management framework

4.2.1 *Viral, bacterial and protozoan risks*

The currently recommended management framework for the control of the viral, bacterial and protozoan risks resulting from wastewater use in agriculture includes five steps (Table 4.1):

Step 1: Define the tolerable maximum additional burden of disease

A tolerable maximum additional burden of disease resulting either from working in wastewater-irrigated fields or from consuming wastewater-irrigated food must be selected. Burdens of disease are now expressed as 'DALY losses' per person per year (pppy). The DALY loss associated with a case of a disease can be considered as the 'health cost' of one episode of that disease. Tolerable DALY losses are small—for example, 1×10^{-n} pppy, where n is in the range 1−10 (in order of magnitude terms).

The Australian National Guidelines and the 2006 WHO Guidelines both adopt a tolerable maximum additional burden of disease of 10^{-6} DALY loss pppy. However, the 2006 WHO Guidelines state:[18]

> Wastewater treatment may be considered to be of a low priority if the local incidence of diarrheal disease is high and other water-supply, sanitation and hygiene-promotion interventions are more cost-effective in controlling transmission. In such circumstances, it is recommended that, initially, a national standard is established for a locally appropriate level of tolerable additional burden of disease based on the local incidence of diarrheal disease—for example, $\leq 10^{-5}$ or **$\leq 10^{-4}$ DALY [loss] per person per year** (emphasis added) (WHO 2006, volume 2, section 4.5).

Given the high global incidence of diarrheal disease, which in order-of-magnitude terms is 0.1−1 pppy (Mathers *et al*., 2002; Kosek *et al*., 2003; *cf.* Table A.1 in Annex A), a tolerable maximum additional burden of disease of 10^{-4} DALY loss pppy is a more appropriate choice, or at least a more appropriate initial choice in low- and middle-income countries. As detailed in section A3.1 of Annex A, this results in an increase in diarrheal-disease incidence of only 1 percent.

Step 2: Derive tolerable disease and infection risks

The tolerable maximum additional burden of disease established in Step 1 must be 'translated' into tolerable disease and infection risks pppy, for one or more 'reference' pathogens, as follows:

$$\text{Tolerable disease risk pppy} = \frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of disease}}$$

$$\text{Tolerable infection risk pppy} = \frac{\text{Tolerable disease risk pppy}}{\text{Disease/infection ratio}}$$

Choice of 'reference' pathogen. Both the Australian National Guidelines and the 2006 WHO Guidelines applied QMRA to determine infection risks for three 'reference' pathogens:

- rotavirus (a viral pathogen),
- *Campylobacter* (a bacterial pathogen), and
- *Cryptosporidium* (a protozoan pathogen).

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[18] This is also stated in WHO, 2007, 2008a, and 2010; see also Haas, 1996.

These pathogens were chosen as 'reference' pathogens because (a) their DALY loss per case of disease was known, and (b) the dose-response data needed for QMRA were available for them. The 2006 WHO Guidelines showed that, for both restricted and unrestricted, irrigation the risk of rotavirus infection was higher than those of *Campylobacter* and *Cryptosporidium* infection, and thus rotavirus infection risks could be used on their own to assess the safety of wastewater-irrigation practices.

However, dose-response data for norovirus (formerly called Norwalk virus or Norwalk-like virus) are now available (Teunis *et al*., 2008). Norovirus is a better reference viral pathogen than rotavirus as it has a very high infectivity and causes diarrheal disease in both adults and children (whereas rotavirus causes diarrhea mainly in very young children). Thus norovirus is now considered the reference viral pathogen of choice for wastewater-use QMRA.

As shown in section A.3 of Annex A, the tolerable maximum norovirus infection risk, corresponding to a tolerable maximum additional burden of disease of 10^{-4} DALY loss pppy, is 0.14 pppy, which means that an individual will become infected with norovirus once every seven years.

Step 3: Conduct QMRA-MC risk simulations to determine required minimum total norovirus reductions for both restricted and unrestricted irrigation

The current state-of-the-art for conducting QMRA risk simulations comprises:

1. Use of norovirus as the reference viral pathogen.
2. Use of an improved method for calculating annual infection risks by QMRA-MC (Karavarsamis and Hamilton, 2010), which is explained in section A.2 of Annex A.
3. Exposure scenarios:
    - *Unrestricted irrigation:* consumption of wastewater-irrigated salad crops (typically lettuce as a non-root crop and onions as a root crop).
    - *Restricted irrigation:* involuntary ingestion of wastewater-saturated soil particles. This is a likely scenario as wastewater-saturated soil would contaminate the fieldworkers' fingers and some pathogens could be transmitted to their mouths and hence ingested. Two sub-scenarios are used: labor-intensive agriculture (typical of low-income countries) and highly mechanized agriculture (middle- and high-income countries).
4. Selection of a locally appropriate range of values for each parameter in the QMRA risk simulation—see Table A.7 of Annex A.
5. The QMRA-MC norovirus program for restricted irrigation is now run with the locally appropriate parameter ranges,[19] and then the QMRA-MC norovirus program for unrestricted irrigation is run.[20] The QMRA-MC results show the required log unit norovirus reductions which ensure that the tolerable maximum norovirus infection risk of 0.14 pppy is not exceeded.[21]

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[19] See the Note at the end of Annex A concerning the availability of these QMRA-MC computer programs.

[20] See Mara and Sleigh (2010d) for practical details on running QMRA-MC programs. Tables A.5, A.6 and A.9 in Annex A show typical simulated norovirus infection risks.

[21] Log unit reductions are $\log_{10}$ unit reductions. Thus a 1-log unit reduction = a 90% reduction, a 2-log unit reduction = a 99% reduction, a 3-log unit reduction = a reduction of 99.9%, and so on.

Step 4: Determine how the required pathogen reductions are to be achieved

The log-unit pathogen reductions for restricted and unrestricted irrigation determined in Step 3 are used as follows:

- *Restricted irrigation:* the required pathogen reduction has to be achieved solely by wastewater treatment (section 4.3.1) in order to protect the health of the fieldworkers —but see section 4.3.2 for non-treatment options.
- *Unrestricted irrigation:* using the same wastewater treatment as for restricted irrigation (since even with unrestricted irrigation there are fieldworkers whose health needs protection), the balance of the required pathogen reduction has to be achieved by a locally appropriate selection of the post-treatment health-protection control measures shown in Table 4.2—i.e., if wastewater treatment has to achieve an x-log unit reduction to protect the fieldworkers and if a total reduction of y log units is required to protect the consumers, then $(y - x)$ log units have to be achieved by a selection of post-treatment health-protection control measures. For example, if norovirus reductions of 1 log unit and 3 log units are required for restricted and unrestricted irrigation, respectively (see sections A.3 and A.5 of Annex A), then for unrestricted irrigation there is a 2-log unit reduction that has to be achieved by post-treatment health-protection control measures—for example, 1 log unit by die-off and 1 log unit by produce washing in clean water, or 2 log units by drip-irrigating low-growing crops such as lettuce.

Step 5: Verification monitoring

Wastewater treatment plants (WWTP) need to perform at or above their design performance —i.e., they must achieve at least their design pathogen removals. However, due to the difficulty and expense of monitoring WWTP effluents for pathogens (here, noroviruses), especially in low- and middle-income countries, recourse must be made to assessing WWTP performance by the removal of fecal coliforms (see section B.1 of Annex B).

In the case of unrestricted irrigation, in order to ensure continuous protection of consumer health, a Hazard Analysis Critical Control Point (HACCP) system should be put in place to monitor the efficacy of post-treatment or non-treatment health-protection control measures (section B.2 of Annex B).

4.2.2 Helminthic risks

The 2006 WHO Guidelines treat helminthic risks differently from viral, bacterial and protozoan risks. They make the same recommendation for human intestinal nematode eggs as was made in the 1989 WHO Guidelines ($\leq$1 egg per liter of treated wastewater), with the proviso that, if children under the age of 15 are exposed, additional protective measures (e.g., regular deworming at home or at school) be put into place. The only difference between the 1989 and 2006 Guidelines was that the recommendation for $\leq$1 egg per liter of treated wastewater was based on expert opinion in the 1989 Guidelines, but on epidemiological evidence in the 2006 Guidelines.

However, dose-response data for *Ascaris lumbricoides* have recently become available (Navarro *et al*. 2009) and thus it is now possible to conduct QMRA-MC risk simulations for *Ascaris*, which can therefore be considered as the ‘reference’ helminthic pathogen. It is very suitable for this role as it is generally the commonest helminth and its eggs are able to survive for very long periods of time (months−years) in the environment. Log unit reductions of *Ascaris* can now be determined by QMRA and these can be split between wastewater treatment and post-treatment health-protection control measures, as is done for viral, bacterial and protozoan pathogens since this allows for a lower level of wastewater treatment.

The 5-step management framework for the control of *Ascaris* risks is as follows:

Step 1: Define the tolerable maximum additional burden of disease

This is taken as 10^{-4} DALY loss pppy, as for viral, bacterial and protozoan pathogens. The current global DALY loss due to ascariasis is 1.8×10^{-3} pppy, so accepting a tolerable additional burden of ascariasis from wastewater use in agriculture of 10^{-4} DALY loss pppy means that the burden of ascariasis would increase from 0.0018 to 0.0019 DALY loss pppy, which is not epidemiologically significant (Mara and Sleigh 2010c).

Step 2: Derive tolerable disease and infection risks

As determined in section A.4 of Annex A, and using an *Ascaris* disease/infection ratio of 1 (i.e., all those infected with *Ascaris* develop ascariasis), the tolerable *Ascaris* infection risk is 1.2×10^{-2} pppy.

Step 3: Conduct QMRA-MC risk simulations to determine required minimum total Ascaris *reductions for both restricted and unrestricted irrigation*

This step is broadly the same as Step 3 for viral, bacterial and protozoan pathogens (section 4.2.1), but the QMRA-MC *Ascaris* programs for restricted and unrestricted irrigation are now run, with locally appropriate parameter ranges, for ranges of *Ascaris* egg numbers (rather than assuming pathogen numbers per 10^5 *E. coli*) —for example, 100−1000 eggs per liter of wastewater (unrestricted irrigation) or per kg of soil (restricted irrigation), 10−100 eggs per liter or kg, and 1−10 eggs per liter or kg. Then the QMRA-MC *Ascaris* program for un- restricted irrigation is run.[22] These QMRA-MC results then show the log unit *Ascaris* reductions which ensure that the tolerable maximum *Ascaris* infection risk of 1.2×10^{-2} pppy is not exceeded.

Step 4: Determine how the required pathogen reduction is to be achieved

Step 5: Verification monitoring

Steps 4 and 5 are the same as Steps 4 and 5 for viral, bacterial and protozoan pathogens (section 4.2.1).

4.3 Options for reducing microbial risks

4.3.1 *Wastewater treatment*

As detailed in sections A.3 and A.4 of Annex A, norovirus and *Ascaris* reductions of 3−4 log units are required to not exceed a maximum additional burden of disease of 10^{-4} DALY loss pppy. Thus wastewater treatment could be required to achieve only a 1−2 log-unit reduction, with the remaining 1−3 log units being achieved by post-treatment health-protection control measures.

Viruses, bacteria, protozoa

2-log unit reduction: wastewater treatment to produce a 2-log unit reduction can be achieved by simple treatment processes, such as an anaerobic pond (or equivalent anaerobic reactor) followed by either a facultative pond or a subsurface horizontal-flow constructed wetland.[23]

1-log unit reduction: wastewater treatment to produce a 1-log unit reduction can be readily achieved by very simple treatment processes, such as an anaerobic pond, a three-tank or three-pond system, or overnight settling. The three-tank (or three-pond) system is operated as a sequential batch-fed

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[22] See Mara and Sleigh (2010d) for practical details on running QMRA-MC programs; Tables A.8 and A.10 in Annex A show typical simulated *Ascaris* infection risks.

[23] See Mara (2004) for design details.

process: on any one day one tank (or pond) is filled with wastewater, the contents of another are settling, and the contents of the third are used for irrigation; this is a very reliable, almost foolproof, system. In small-scale urban agriculture, as opposed to large-farm agriculture, a single tank is generally sufficient (and more affordable): on any day in the morning the tank contents are used for crop watering, and the tank is then refilled and its contents allowed to settle until the following morning.

Helminth eggs

If it is assumed that in areas where ascariasis is hyperendemic untreated wastewater contains 1000 *Ascaris* eggs per liter (see Table A.8 in Annex A), a 3-log unit egg reduction is required to achieve ≤1 egg per liter. For root vegetables eaten raw, and assuming that a 2-log unit reduction occurs through produce peeling prior to consumption (Table 4.2), wastewater treatment is required to effect a reduction of only 1 log unit from 1000 to 100 eggs per liter. This reduction is also achieved by an anaerobic pond, a three-tank or three-pond system, or overnight settling.

4.3.2 *Non-treatment options*

Most wastewater used for crop irrigation is untreated and this causes disease in both fieldworkers and consumers (Shuval *et al*., 1986; WHO, 2006; Scott *et al*., 2010). However, in many parts of the world it would be counter-productive, as well as unenforceable in practice, for governments to ban the use of untreated wastewater for irrigation, given the often informal character of this sector. However, the current situation in many low-income countries in which wastewater irrigation is unrecognized, or where the authorities choose in practice to ignore it, is not sustainable (Drechsel *et al*. 2002, Ensink and van der Hoek 2009).

Clear policies are needed to balance the agricultural benefits and the associated risks to human health of wastewater use. Ensink and van der Hoek (2009) recommend a set of practical and easily enforceable measures to minimize the health risks associated with the use of untreated domestic wastewater:

- only produce that is cooked before being eaten can be grown with untreated wastewater
- root crops, such as potatoes, onions, and carrots, cannot be grown with untreated wastewater
- vegetables should be cultivated and irrigated using the ridge-and-furrow method
- biannual treatment of fieldworkers and their families with antihelminthic drugs
- general improvements in water supply and sanitation, including in local produce markets, in order to improve post-harvest practices and thus produce quality.

Improving hygiene in local markets can be very important: Ensink *et al*. (2007) found that vegetable contamination due to poor hygiene in local markets in Pakistan was more important than the quality of irrigation water. Nguyen *et al*. (2007) came to the same conclusion for fish grown in peri-urban wastewater-fed fishponds in Hanoi. However, in urban Ghana, where the irrigation water is more severely polluted, Amoah *et al*. (2007a, p. 455) concluded the opposite:

> Despite poor sanitary conditions in markets, post-harvest handling and marketing did not further increase the farm-gate contamination levels. To reduce the health risk associated with the consumption of contaminated lettuce safer farming and irrigation practices are required, while the remaining risk could best be addressed where lettuce is prepared for consumption.

The variability found in these studies confirms the need to evaluate contamination levels and practices at the local level.

Many health-protection control measures can be applied on-farm, at local produce markets, in street-food/fast-food outlets and restaurants, as well as domestic kitchens or food preparation areas (Table 4.2).[24]

Simple on-farm filtration practices suitable for use in urban agriculture include sand filters made from oil drums or buckets filled with fine-grained sand, soil filtration by digging an infiltration well adjacent to a wastewater canal, and covering the outlet of watering cans with mosquito netting to reduce pathogen-containing debris being applied to the crop. Debris can also be avoided by training urban farmers to collect their irrigation wastewater from well above the sludge layer in shallow sedimentation ponds.

Urban farmers often use watering cans to apply wastewater to their crops. This can be highly contaminating, but the farmers can be trained to use their watering cans in a less contaminating way by slightly changing their customary practice: capping the can outlet with a perforated shower rose, and irrigating from a height of less than 0.5 m, showed a combined average reduction of 2.5 log units of faecal coliforms and more than 2 helminth eggs per 100 g lettuce compared to the practice of uncapped spouts lifted more than 1 m high for irrigating (Drechsel *et al*. 2008). The pathogen reductions achieved were ascribed to reduced wastewater splashing which minimizes crop contamination by soil-based pathogens which are present from manure application and previous applications of wastewater.

4.4 Applying quantitative microbial risk analysis

4.4.1 *Recommendations for current practice*

QMRA combined with Monte Carlo risk simulations (QMRA-MC) is a powerful tool to use when assessing the safety of local practices for wastewater use in both large-farm agriculture and small-scale urban agriculture. It is also very easy and fast to use (Mara and Sleigh, 2010d).

If governments wish to regulate wastewater use in agriculture, it would be sensible for them to undertake QMRA risk simulations so that they have an estimate of the health risks associated with the agricultural and food-preparation practices in their locality. Unless they undertake rigorous and expensive epidemiological studies, it is only through QMRA-MC that policymakers can make rational decisions about how these practices can be best improved to reduce to an acceptable level the health risks to those who work in wastewater-irrigated fields and to those who consume wastewater-irrigated foods. Box 4.3 presents two examples of the usefulness of QMRA in making socio-economic decisions regarding wastewater use for unrestricted irrigation.

The examples in Box 4.3 raise two questions: (1) whether the risks from consuming wastewater-irrigated foods should be so much lower than those from drinking fully-treated drinking water, and (2) whether very large expenditures on wastewater treatment to achieve such very low risks are justified. If the answer to the first question is ‘No’ (and there does not appear to be any valid reason why the answer should not be ‘No’), then it follows that the answer to the second question is also ‘No’. This demonstrates the need to base decisions on *actual* risks, rather than on merely *potential* risks (Box 3.2). It also amply demonstrates the power of QMRA to assist in cost-effective decision making.

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[24] Further details are given in Ilic et al. (2010) and Keraita et al. (2010).

Box 4.3 Examples of the usefulness of QMRA

Shuval *et al*. (1997) used QMRA to estimate that the risk of hepatitis A from eating 100 g of lettuce irrigated with treated wastewater containing 1000 fecal coliforms per 100 mL (the 1989 WHO Guideline) on alternate days was ~10^{-7} per person per year (pppy). They also determined that the extra expenditure required to treat wastewater from ≤1000 fecal coliforms per 100 mL to the 1992 USEPA/USAID guideline value of zero fecal coliforms per 100 mL, which would reduce the risk to ~10^{-10} pppy, was US$35 million per case of hepatitis A averted. This is a clearly unjustifiable expenditure—a 300-bed hospital would cost about the same as 3−5 cases of hepatitis A averted.

Tanaka *et al*. (1998) used a dataset of viral concentrations in the effluents of advanced wastewater treatment plants in California, designed to achieve the Californian standard of ≤2.2 total coliforms per 100 mL for unrestricted irrigation to show by QMRA that the <u>infection</u> risks to consumers of wastewater-irrigated salad crops irrigated with 'fully' treated wastewater ('fully' here means a 5.2-log unit virus reduction after primary, secondary and tertiary treatment and chlorination) were in the range 10^{-8}−10^{-10} pppy—i.e., 4−6 orders of magnitude lower than the value of 10^{-4} pppy accepted by US EPA as the tolerable waterborne <u>disease</u> risk from drinking fully-treated drinking water (Macler and Regli, 1992).

QMRA-MC risk simulations can also be used to investigate "what if" scenarios: a question such as "What would the health risks be if people started to eat more lettuce?" can be answered simply by using the appropriate ranges of lettuce consumption in the QMRA-MC computer programs to reflect the anticipated increases in lettuce consumption.[25]

Moreover Table 4.2 can be used to answer questions such as "If a campaign to improve the food-hygiene practices of street-food vendors were successful, what effect would this have on the required level of wastewater treatment?"

Box 4.4 details the successful QMRA investigations in urban Ghana where there was concern about the adverse health effects resulting from the consumption of wastewater-irrigated lettuce.

4.4.2 Current challenges

QMRA combined with Monte Carlo risk simulations (QMRA-MC) is a powerful tool for assessing the safety of local practices for wastewater use in agriculture. However, there are several challenges that will need to be met if QMRA is to be adopted in countries where wastewater is used in agriculture. These challenges will be particularly acute in low- and middle-income countries.

1. Regional training courses in QMRA need to be established so that local sanitary/environmental and agricultural engineers and water-resource planners become competent in its use and application to local conditions.
2. Local regulators need to be trained in QMRA so that they can establish locally appropriate regulations for wastewater use in agriculture that reflect the local epidemiology of excreta-related diseases and that are both cost-effective and effective in protecting the health of those who work in wastewater-irrigated fields and consume wastewater-irrigated foods.
3. Government officials and extension workers need to understand the rationale of QMRA-based approaches to controlling the health risks posed by wastewater use in agriculture, in

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[25] Lettuce consumption might well increase if the Ministry of Health were to encourage people to eat more fresh fruit and vegetables (see the 'Five a Day' campaign by the UK government at http://www.5aday.nhs.uk).

order for them to: (a) endorse the approach, (b) work with local farmers, including local urban farmers, to introduce or improve on-farm practices to minimize the health risks, and (c) to communicate the safety of wastewater-irrigated foods to those who consume them. In addition local environmental health officials need to be trained in the basics of HACCP so that they can establish locally appropriate HACCP procedures to ensure the safety of wastewater-irrigated foods.

This will enable QMRA to be implemented and used correctly so that the most appropriate cost-effective and health-protective practices for the agricultural use of wastewater can be selected, implemented, and monitored.

Box 4.4 QMRA investigations in urban Ghana

In urban Ghana many people eat lettuce as part of street-vended fast food (sandwiches, etc.) typically at a rate of around 10−12 g on four occasions a week. Most of the lettuce is produced by urban farmers who use wastewater, graywater, drainage water or other contaminated waters for irrigation. Almost all the fast-food/street-food vendors say that they wash the lettuce with tap water and use disinfectants such as lemon, household bleach and vinegar during the preparation of lettuce salads, although it was believed that this washing/disinfection process was less than perfect. QMRA-MC investigations were done to determine the associated health risks as there was concern that the consumption of wastewater-irrigated lettuce and other salad crops was having an adverse effect on consumer health.

QMRA-MC risk simulations found that the annual infection risk associated with the consumption of lettuce irrigated under the current wastewater-irrigation and post-harvest practices common across the country showed a high median viral infection risk of ~0.1 pppy, whereas bacterial and protozoan infection risks were only $\sim 10^{-5}$ pppy. These infection risks resulted in about 477,000 mainly self-limiting cases of diarrheal disease, representing 0.68 episode per consumer per year; however, about 14 % and 0.1 % of these diarrheal-disease cases were severe and fatal, respectively. The resulting burden of disease was an annual DALY loss of 12,000, equivalent to a 0.017 DALY loss per consumer per year, with this figure representing nearly 10 % of the WHO-reported DALY losses occurring in Ghana due to various types of water-, sanitation- and hygiene-related diarrhea (Prüss-Üstün *et al.* 2008). The study also used QMRA-MC risk simulations to investigate *Ascaris* infection risks to both the urban farmers and consumers. It was found that the risk was ~1 pppy and that, for the farmers, this was due to the involuntary ingestion of wastewater-contaminated soil.

The study identified that poor on-farm and at-market practices were responsible for much of the contamination of the lettuce and hence the infection risks, and that simple on-farm and at-market measures, of the types identified in Table 4.2 and discussed in sections 4.3.1 and 4.3.2, could reduce crop contamination and infection risks to more acceptable levels.

Source: Seidu *et al*., 2008.

Chapter 5. Toward an Agenda for Improving Wastewater Use in Agriculture

5.1 Implementing measures for reducing public health risks

5.1.1 Progressing from unplanned to planned wastewater irrigation

In order to reduce public health risks associated with wastewater irrigation described in Chapters 3 and 4, countries tries will need to implement progressive measures for while responding to their health priorities. This response will be different for each country and will depend on what path it takes to ultimately reach the desired goal of planned wastewater irrigation that meets internationally-accepted health-based targets—such as those established by the 2006 WHO Guidelines for wastewater use in agriculture described in Chapter 4.

Much will depend upon the starting point of a particular country (see Table 2.4). For *low-income countries* facing water scarcity and seeking food security, there is not enough money or capacity to immediately build and operate the needed wastewater treatment systems that would ensure minimal health risks from wastewater irrigation. It is necessary to determine what steps countries can take today in order to reach the health-based targets of the 2006 WHO guidelines in the future, and to commit to working toward the targets within a realistic timeframe through stepwise implementation of a plan that leads to steady improvement in the quality of water and wastewater (von Sperling and Fattal, 2001). In the first stage, when environmental conditions are poor and local capacities limited, countries will have to rely on non-treatment options as outlined Chapter 4. Subsequently, a large benefit can usually be achieved at a comparatively low cost by focusing on rudimentary engineering solutions coupled with policy reforms and non-structural interventions. The experience gained in the first stage should lay the foundation for subsequent stages. Ideally, a timetable for progressive implementation should be defined, and adequate lead time should be allowed for achieving strategic goals.

Middle-income countries will normally have a different starting point, having already established some of the policies, legislation, institutions, and regulations needed for a more comprehensive water resources planning framework, and introduced some degree of wastewater management. But they may not have adequately addressed wastewater use in agriculture, or considered wastewater as part of local water resources. Experience gained in setting up the required infrastructure and institutional capacity for regulation and enforcement of wastewater management will improve progressively, assuming appropriate monitoring is in place, and should provide a solid foundation for moving on to subsequent stages. Affordability is still a critical issue, and attention should be focused on improved financial management and identification of opportunities for mobilizing needed investments for maintaining the systems in place, and then on step-wise upgrading of treatment systems and improving overall operations.

High-income countries generally have undergone an implicit stepwise implementation of standards as regulations for water and wastewater quality and use for irrigation have become progressively more stringent. But some of these countries have not yet fully addressed wastewater use in agriculture.

Many developing and high-income countries are now faced with trying to achieve more stringent standards, but are far from meeting them. For this reason, the concepts of strategic planning and stepwise implementation should be taken up and adapted to their specific needs. The challenge is not to copy the more than hundred years experience of the industrialized countries, but to learn from it and jumpstart a process to develop a multi-phased strategic plan that can be achieved in time intervals of 15 to 20 years.

At each stage of the process, countries should seek to implement those measures that provide the maximum net benefits, or, in the absence of sufficient information for a cost-benefit analysis, choose the most cost-effective measures for achieving a desired level of risk reduction (WHO, 2006). Examples of a low-income country, an upper-middle-income country, and a high-income country are provided below.

Phased improvements in wastewater treatment

To progress from unplanned to planned wastewater use for agriculture, the introduction of wastewater treatment is an essential strategic goal. Low-income countries should seek to introduce non-treatment options and simpler low-cost treatment options as a first step, and progressively move toward expanded sewerage systems and costlier treatment technologies as financial and operational capacity grows. An important part of this first step is to clearly define responsibilities for household, community, and public sanitation service provision, and to put in place the capabilities to monitor operations and verify that treatment targets are met (for example, by implementing the HACCP system described in Chapter 4 and Annex B). A progressive array of treatment options is shown in Table 5.1, along with possible pathways to expand sewerage and treatment as development occurs.

When planning for appropriate treatment systems, particularly those that can positively impact food safety, scale is an important factor (Table 5.1). Taking into account the common characteristics of cities in developing countries, four levels of scale are of interest:

- *On-site wastewater treatment and use,* i.e.wastewater management systems used at the site of wastewater generation. On-site systems may handle greywater and blackwater separately or combined. Typical non-sewered sanitation options can range from simple pit latrines, VIP latrines, and dry (composting) toilets, to septic tanks with gravity-fed leachfield, horizontal flow filter or natural treatment system. Ideally, only greywater from household storage tanks will be used for household gardens, or wastewater that has been processed by soil infiltration, and only composted human waste for adding nutrients.
- *Communal wastewater treatment and use,* i.e. systems where wastewater from a cluster of homes is collected and diverted for treatment close to the point of use on small agricultural plots. Communal systems might include unconventional collections systems like small-bore sewers or condominial sewers, and the recovered wastewater used for irrigation of communal plots. Appropriate treatment options can include septic tanks, Imhoff tanks, anaerobic ponds, storage ponds, or three tank systems.
- *Decentralized wastewater treatment and use*, i.e. the collection, treatment and use of wastewater from isolated medium-size communities, as well as from portions of larger urban areas contained within a minor watershed, at or near the point of wastewater generation, generally to irrigate larger urban or peri-urban plots. Appropriate low-cost decentralized treatment options can include waste stabilization pond systems (e.g., Lima's San Augustín project described in Box 2.6), upflow anaerobic sludge blanket reactors (UASB), wastewater treatment storage reservoirs (WTSR), or chemically enhanced primary treatment (CEPT).
- *Centralized wastewater treatment and use,* i.e. the collection and drainage of wastewater, and sometimes stormwater, from a large urban area using an extensive network of pumps and piping for transport to a central location for treatment and reclamation, usually near the point for convenient irrigation use. While waste stabilization pond or WTSR systems may be feasible for larger cities, due to land constraints large city systems will often be based on conventional treatment options, or appropriate technology options such as CEPT followed by sand filtration and disinfection (Libhaber, 2007). Membrane technologies are emerging as preferred technologies in high-income countries (Bixio *et al*, 2006). Within a large river basin encompassing multiple urban areas, many centralized facilities may be required.

Table 5.1 Progressive wastewater treatment options by level of economic development

Characteristics by level of economic development	**Low-income countries (43 countries) <$975 GNI/cap**	**Lower-middle-income countries (55 countries) $976-3,855 GNI/cap**	**Upper-middle-income countries (46 countries) $3,586-11,905 GNI/cap**	**High-income countries (66 countries, 27 OECD) >$11,906 GNI/cap**
Scale of interventions	Household gardens; Small-scale communal plots; Large urban or peri-urban plots with decentralized simplified sewerage systems; Large peri-urban plots with city-wide sewerage systems	Small-scale communal plots; Large urban or peri-urban plots with decentralized treatment systems; Large peri-urban plots with city-wide treatment systems	Large urban or peri-urban plots with decentralized treatment systems; Large peri-urban plots with city-wide treatment systems; Watershed level water management systems	Municipal reclamation and reuse projects for crop and landscape irrigation; Basin-wide water management systems
Evolution of typical treatment technology options (see WHO, 2006 for description of basic treatment options)	Household gardens: On-site latrine alternatives Septic tank Greywater collection *Communal plots:*[26] Imhoff tank Storage ponds Three tank system *Large plots or medium-size city:*[27] Waste stabilization ponds (WSP) Upflow Anaerobic Sludge Blanket Reactors (UASB)	Large plots or medium-size city: WSP systems[28] UASB Wastewater Treatment and Storage Reservoirs (WSTR) Chemically enhanced primary treatment (CEPT) Large city centralized system: Conventional treatment[29] + polishing ponds	Large plots or medium-size city: WSP systems UASB WSTR CEPT Large city centralized system: WSTR CEPT + sand filtration + disinfection Conventional treatment + polishing ponds Soil aquifer treatment (SAT) systems	Conventional treatment + tertiary treatment Membrane technologies (MBR, MF, UF, RO)[30] SAT systems

Sources: WHO (2006); Bixio *et al.* (2006); Libhaber (2007); Income data from World Bank (2010).
WSP = waste stabilization ponds; UASB = upflow anaerobic sludge blanket reactors; WSTR = wastewater treatment and storage reservoirs; CEPT = chemically enhanced primary treatment; SAT = soil aquifer treatment system; MBR = membrane bio-reactors; MF = microfiltration; UF = ultrafiltration; NF = nanofiltration; RO = reverse osmosis

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[26] Assumes communal drains or sewerage system available (e.g., small-bore sewers, condominial sewers, conventional sewers) with localized treatment plant.

[27] Assumes sewerage networks, interceptors, and decentralized treatment plants.

[28] Waste stabilization pond (WSP) systems typically include anaerobic + facultative + maturation ponds.

[29] Conventional treatment, for the purposes of this report, normally includes primary treatment (e.g., primary sedimentation) followed by secondary treatment process such as activated sludge and its variants (e.g., aerated lagoons and oxidation ditches, and trickling filters). Note that conventional systems do not meet microbiological quality requirements for unrestricted irrigation use without additional tertiary treatment processes (e.g., filtration, disinfection, or a polishing pond).

[30] Membrane technologies applicable to wastewater treatment and use include membrane bio-reactors (MBR), microfiltration (MF), ultrafiltration (UF), and reverse osmosis (RO).

Planning for control of industrial wastewater

In 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 facilities.

Quality standards are usually set up for industrial wastewater discharged into municipal sewerage systems, in order to ensure that heavy metals or other 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. Industrial discharges that cannot meet quality standards should be prohibited from discharging into municipal sewers. The establishment of industrial discharge standards is important in order to promote industrial pretreatment programs and control certain industrial discharges that may be critical to the operation of wastewater treatment plants and the quality of treated effluents and sludge byproducts.

The main elements of a successful industrial pretreatment program are the following (Idelovitch and Ringskog, 1997):

- 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 between the wastewater authority and the environmental regulator to ensure that industrial wastes are not improperly discharged into sewers, as well as for the correct disposal of effluent and sludge.

5.1.2 *Developing a strategic plan*

A strategic plan (comprising a long-term strategy and a phased action plan to meet the strategic goals, along with needed policy reforms) should be developed that will help to move from unplanned to planned wastewater irrigation and that meets internationally-accepted health-based targets. Recognizing that this goal cannot be achieved overnight or even in one phase, the action plan should be multi-phased and aim at steady and measurable progress toward the ultimate goal within an agreed and realistic timeframe (such as 15–20 years). The experience of country regulators in adapting to new WHO Guidelines also shows that it often takes a decade before the new regulatory framework is fully implemented (J. Bartram, personal communication).

Development of a strategic plan for wastewater use in agriculture should take place within a broader multisectoral planning framework for integrated water resources management, seeking the maximum economic yield from the use of an increasingly scarce resource. The incorporation of protocols for safe wastewater use into national water plans is important, especially when water and financial resources are scarce, not only to protect water quality but also to minimize wastewater treatment costs, to safeguard public health, and to obtain the maximum possible agricultural benefit from nutrients and organic matter contained in wastewater (Mara and Cairncross, 1989).

Possible steps to help develop a strategic plan for implementing health risk reduction measures are (adapted from Carr *et al.*, 2004):

1. Design and conduct a survey of wastewater and excreta use practices throughout the country or in specific districts. The survey could contain questions concerning:
   - The availability, types and status of wastewater treatment available
   - The types of crops grown in the area (whether they are eaten cooked or raw)
   - Techniques for wastewater and excreta application, e.g. bucket, furrow, sprinkler, drip, other
   - Options for protecting or controlling quality along the food supply chain from farm to fork
   - An assessment of human exposure to wastewater and excreta during agricultural practices, e.g. Do fieldworkers wear protective clothing? Do they practice good hygiene?
2. Evaluate and prioritize health risks, in the context of the national burden of disease, associated with the use of wastewater and excreta in agriculture.
   - Conduct interviews with health staff (doctors, nurses, pharmacists), farmers, families, community workers, teachers, consumer advocate groups, etc.
   - Review scientific studies of disease, clinical data, outbreak information, prevalence data, etc.
   - Conduct, if possible, a QMRA-MC risk simulation (see Chapter 4 and Annex A) to assess the safety of local practices for wastewater use in irrigation, and recommend appropriate pathogen reduction targets. If a QMRA is not possible then semi-quantitative risk ranking can be done, or if crops irrigated with severely polluted water are eaten raw the maximum risk reduction level can be targeted, as in the Ghana case (Box 5.2).
3. Based on steps 1 and 2, conduct national or district-level workshops to formulate appropriate (realistic) strategies for mitigating health impacts that include relevant stakeholders, e.g. farmers, traders, and consumer advocate groups
4. Develop national or other action plan and policies for the safe use of wastewater and excreta in agriculture considering cost-effectiveness of possible interventions that include both treatment and multiple barrier options. The plan should include time-bound interim health targets for the steady improvement in health outcomes over the medium and long term.
5. Strengthen institutional capacities – designate a responsible authority (or authorities) to monitor and enforce safe wastewater and excreta use practices.
6. Review and revise national strategy, action plan, and policies as needed.

A sample strategy and an action plan for the incremental application of the 2006 WHO Guidelines is presented in Box 5.1.

When developing a strategic plan it is important always to consider the alternative to this step-wise approach, which may be inaction if standards are set too high and cannot be achieved in a reasonable period of time. In Ouagadougou, for example, crop restrictions for using treated wastewater on a demarcated farming site near the treatment plant are so severe that food crop farmers returned to their informal sites using untreated wastewater (Drechsel, personal communication)**.** The step-wise approach includes the acceptance of wastewater irrigation at a standard much lower than required in developed countries given that post-treatment options for reducing risk can be added through a multi-barrier approach.

Box 5.1 Sample strategy and action plan for incremental application of WHO guidelines

Pathogen reduction targets: Phase in pathogen reduction targets over suitable period of time (e.g., 15−20 years) according to treatment capabilities and other feasible barriers. For example, for a large irrigation scheme in a low-income country, and assuming that the 2006 WHO risk assessment and management framework has been applied as shown in Annex A, interim log unit pathogen reduction targets could be set as follows for the reference pathogens norovirus and *Ascaris*:

	Implementation Phase: **DALY loss pppy:**	**Phase I** **1×10^{-4}**	**Phase II** **1×10^{-5}**	**Phase III** **1×10^{-6}**
Norovirus:	Restricted irrigation	1 log unit	2 log units	3 log units
	Unrestricted irrigation	4 log units	5 log units	6 log units
Ascaris eggs:	Restricted irrigation	1 log unit	2 log units	3 log units
	Unrestricted irrigation	3 log units	3 log units	4 log units

Treatment: Introduce or upgrade treatment at strategic locations where wastewater irrigation is taking place or could be encouraged, phased in over the plan time period. For example, treatment options to be considered could include:

> *First stage of treatment:* natural purification processes (e.g., abstraction suitable distance downstream from discharge); irrigation storage ponds or reservoirs designed for pathogen removal, waste stabilization ponds, upflow anaerobic sludge blanket reactors, primary treatment plus additional treatment (e.g., storage reservoir, chemically enhanced coagulation, coagulation + rapid sand filtration).
>
> *Second stage of treatment:* waste stabilization ponds, wastewater treatment and storage reservoirs, conventional secondary treatment (e.g. activated sludge, trickling filter, etc.), aeration ponds, etc.
>
> *Third stage of treatment:* waste stabilization ponds, conventional secondary treatment + storage reservoirs or disinfection, advanced tertiary processes (e.g., membrane filtration, disinfection), soil aquifer treatment system.

Strengthen local capacity: Assemble a team of health and agricultural outreach workers who can work with farmers and villagers to improve health and agricultural practices and develop feasible crop restriction strategies and other interventions as necessary.

Health and hygiene education: Expand existing hygiene and sanitation outreach programs to include information on potential health effects of wastewater use; educate farmers, produce vendors and consumers about food safety and hygiene.

Crop restriction: Work with farmers to develop feasible and health protective crop restrictions, especially in the areas of highest risk (e.g., where undiluted raw wastewater is used).

Wastewater application*:* Determine the safety level of current practices. As resources/technologies permit, shift over time to safer wastewater/excreta application practices where there is less human contact (e.g., drip and bubbler irrigation).

Human exposure control: Expand hygiene and health education programs in affected communities. Require protective clothing at larger wastewater/excreta use projects and where feasible. Provide clean water at markets for ‘freshening produce.’ Inspect general hygiene at food markets.

Other health interventions: Initiate or expand vaccination campaigns in affected areas (e.g. typhoid, hepatitis A). Complement hygiene and sanitation programs with periodic antihelminthic drug campaigns; this works well where antihelminthic drugs are widely available at low cost and where wastewater and excreta use is limited to distinct areas in a country as, for example, in Pakistan (Feenstra *et al*. 2000). Mass antihelminthic drug campaigns against intestinal nematode infection may need to be considered at least once per year in areas where 50−70% of the school-aged children have soil-transmitted helminthic infections. Where the prevalence of these infections exceeds 70% in school-aged children and more than 10% of the individuals are moderately or heavily infected, then the children should be treated 2−3 times a year (Montresor *et al*. 2002).

Industrial effluents: Initial efforts should be made to identify sources of industrial discharges. Phase in an approach that first requires the largest polluters to clean up their waste or divert them from the municipal sewers, and eventually requires all industrial discharges to be pretreated up to defined standards or diverted. Establish a charging mechanism for the remaining industrial effluent loads that can safely be treated at the municipal WWTP—for example, organic wastes (BOD or COD), suspended solids, nutrients.

Source: Adapted from Carr *et al*., 2004; WHO 2006; Mara, 2009; Mara and Sleigh, 2010c.

5.1.3 *Examples of phased implementation plans*

Three examples of how a phased strategic plan can be developed are shown below. In the case of a low-income country, Ghana, it required several steps before a cost-effectiveness analysis could be utilized to choose among possible multiple barriers to disease transmission (Box 5.2). In Chile, an upper-middle-income country, an emergency control program based on multiple barriers forestalled a cholera outbreak and the subsequent implementation of a sanitation plan allowed the country to go from virtually no treatment up to full wastewater treatment in the span of two decades (Box 5.3). Finally, the example of Israel, a high-income country facing extreme water scarcity, illustrates a mature wastewater irrigation program developed over more than four decades, that today reclaims 75 percent of all municipal sewage for agriculture and provides half of all irrigation water in the country, thus liberating significant freshwater sources for other higher-valued urban and industrial uses (Box 5.4).[31]

The examples demonstrate that countries at different levels of development, in very different circumstances, and following different implementation pathways, have been able to confront the health hazards associated with untreated wastewater use for agriculture and, in the incipient case of Ghana, have the possibility of continuing to work steadily toward the needed health risk reductions.

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[31] Two other examples for water-scarce lower-middle-income countries include Jordan (Box 2.7) and Tunisia (Box 2.8), both of which have also made impressive progress over a few decades.

Box 5.2 Ghana: From scratch, through the application of QMRA, to a national strategy

Food safety is an important topic in Ghana which is addressed by various national and district entities under the leadership of the Food and Drug Board of the Ministry of Health. As is common in similar countries in Sub-Saharan Africa, there are multiple hazards affecting food safety in Ghana, from the sale of date-expired food items to non-compliance with the most basic rules of hygiene in markets and restaurants. The reasons for this range from poor educational levels and low risk awareness to the inability to invest in electricity (for cool storage) or access to water to maintain an appropriate level of hygiene.

Urban farmers who specialize in exotic 'salad' vegetables for the urban market have received significant negative media attention over the past few years due to the use of highly polluted water from drains and wastewater streams. As a result, the public authorities are well aware of this risk factor and are under pressure to address it. Although cholera outbreaks are a common feature in Ghanaian cities, there have been no means to analyse transmission pathways and the contribution of any particular hazard (see Box 5.3). The authorities did not know where to invest their limited resources and, as usual in such situations, the better known risk factors, such as personal hygiene and safe drinking water, usually have received priority. However, in an attempt to address the 'obvious' risks from wastewater use, the Ministry of Local Government asked the Environmental Protection Agency in 2002 to arrest farmers using polluted irrigation water. This later proved unrealistic since in Accra alone there are some 1,000 farmers whose livelihoods depend on the practice. Then the Ministry of Food and Agriculture (MoFA) asked the International Water Management Institute (IWMI) for research assistance. With directorates in every city, MoFA was concerned by the arrests of 'its' farmers, while it lacked the capacity to address the problem.

To apply the 1989 WHO guidelines—i.e., to treat the wastewaters the urban farmers were using to an acceptable level—or to ask them to change the cash crops they were growing appeared unrealistic, and the focus shifted to safety options that could be realized on the urban farms, in markets and in kitchens (Drechsel *et al.*, 2002). Given the extremely high fecal coliform counts in the irrigation water (10^6–10^8 per 100 mL) and the fact that the crops grown are usually eaten raw, the target was to minimize as far as possible the fecal coliform count at the point of consumption. This has been the target of a number of projects since 2004 which can be considered as an early local adaptation of the 2006 WHO Guidelines.

The projects analyzed the pathways of vegetable contamination from farm to fork and determined the number of farmers and consumers in all major cities. This allowed QMRA to be run and DALYs lost to be calculated. The projects then tested with farmers, traders and food caterers various non-treatment options as described in section 4.3.2. The most promising with the highest adoption potentials were selected to be part of a national strategy for health-risk reduction targeting two main entry points: various safer irrigation practices depending on the site, and improved vegetable washing in the street-food sector. The implementation of the strategy, which is not yet funded but at the proposal stage, would be based on four pillars—significant awareness creation, social marketing, incentives, and regulations—to achieve the best possible adoption of recommended practices (Karg *et al.*, 2010). Based on the related implementation costs and the QMRA results, it was possible to calculate the cost-effectiveness of various combinations of safety practices— i.e., how much it would cost to avert a DALY. This analysis was carried out to understand in particular (i) how non-treatment options compare with wastewater treatment, and (ii)) how different adoption rates of non-treatment options affect their cost-effectiveness (Seidu and Drechsel, 2010).

The cost-effectiveness analysis also showed that it would increase the implementation costs of the health strategy only marginally if other principles of basic hygiene would be included (e.g., vegetable washing and hand washing) while the number of averted DALYs could significantly increase.

Even though the recommendations focus on non-treatment options, the studies also concluded that wastewater treatment would be cost-effective in combination with non-treatment options, if some partially broken down treatment plants with farm sites in the vicinity would be rehabilitated and farmers agreed to move to those areas. The value addition through farming (including aquaculture) could support the cost of maintaining the plants (Murray and Buckley, 2010). Such a system has been earmarked by the African Water Facility for testing in Accra and Kumasi. In general, however, planned reuse and intersectoral collaboration are likely to be the exception as local institutions are overstretched by more basic problems.

Box 5.3 Santiago, Chile—From fear of cholera to full wastewater treatment in two decades

In 1991, after suffering endemic typhoid over several decades, and facing the beginning of a cholera outbreak, both diseases being linked to indirect wastewater irrigation (see Box 2.7), the Government of Chile (GoC) took decisive action aimed at eliminating the hazard of using untreated wastewater and bringing these diseases under control. As a first step, the government created a National Commission to Avoid Cholera, which involved several ministries (Agriculture, Health, and Public Affairs), and put in place an emergency control program of public health interventions and sanitary education. The emergency program comprised interventions on three broad fronts:

- Improving irrigation and drinking water quality
- Changing the irrigation practices of farmers
- Changing the consumption behavior of the population

Measures to improve irrigation included the immediate construction of interceptors along some of the most polluted reaches of rivers serving as irrigation channels, and chlorination of others. Loans were offered farmers to encourage them to drill wells and provide clean water for irrigating their fields. Also, to induce famers to change their irrigation practices, the GoC banned the sale of wastewater-irrigated produce, removed this produce from the markets, and banned transportation of the produce outside Santiago metropolitan area. Banned crops included all vegetables normally consumed raw. This ban was accompanied by intensified sanitary inspection of irrigated areas, and the destruction of any banned crops that were encountered.

The most significant intervention was a Ministry of Health campaign to educate the public about the health risks of eating raw vegetables, augmented by growing press coverage about cholera and typhoid. Finally, the sale and consumption of raw vegetables and salads in restaurants was banned throughout the metropolitan area—a ban that continued for several years. For the first time, the government, the public, and the farmers worked together on a broad front to raise awareness of and resolve the problems and risks associated with using polluted rivers as a source of irrigation water.

The emergency control program was successful not only in preventing the spread of cholera into Chile, but also in controlling and reducing the rate of typhoid in the Santiago metropolitan area to unprecedented levels. Typhoid cases dropped from 3,558 average cases per year in the pre-intervention period from 1985-90 to 454 cases post-intervention in 1992. Since then, the incidence rate of typhoid in all of Chile has steadily declined from high annual rates in excess of 50 cases per 100,000 population from 1950 to 1990, to 12 cases per 100,000 population in 1993, and down to 2.2 cases per 100,000 population in 2006.

However, because the emergency program was not targeted at structural measures to control pollution from urban wastewater—but rather was aimed primarily at behavior—the sustainability and longer-term effect of these interventions was difficult to predict. Accordingly, the GoC also embarked on investing in engineering solutions. The first step was the completion of the construction of two major wastewater interceptors being financed by an existing World Bank project for Santiago Water Supply and Sewerage II. In addition, the project financed the construction of a pilot wastewater treatment plant —the first for Santiago—along with the preparation of a definitive feasibility study of wastewater treatment options for the greater Santiago metropolitan area. Early estimates of the full cost of treatment were on the order of US$78 per year, or about US$0.14 per m^3, to be added to the water and sewerage tariff.

As part of an economic study of environmental issues in Chile, a policy cost-benefit analysis was carried out of the cholera emergency program implemented in 1991, and of the proposed option of full wastewater treatment. The study confirmed that compared to the risk of inaction, the emergency program yielded health benefits in excess of corresponding costs, and avoided potentially costly export losses due to inaction. Regarding wastewater treatment and indirect irrigation use, the study found that combined annual benefits of reduced or avoided mortality and morbidity due to typhoid and cholera, avoided export losses, expanded farm output, and reduced consumer costs, when added together, amounted to between $23.7 to $76.6 million annually. These benefits alone would significantly offset the annual cost of full treatment ($78 million) without considering additional benefits such as reduced mortality and morbidity due to hepatitis and diarrheal diseases beyond typhoid and cholera (estimated at between $33.4 to $166.9 million annually), amenity and other environmental values, or the value of the water use rights of treated effluent. Thus, after decades of inaction, policymakers came to view wastewater treatment as a necessary and viable environmental infrastructure investment.

During and following the completion of the World Bank-supported project, the Chilean water and sanitation sector was phasing in major reforms so that the private sector could finance the huge investments needed to achieve universal water and sewerage services including wastewater treatment. The reforms were completed in 1998 and a 30-year concession was awarded to the private consortium AguasAndinas in 1999 to provide water and sewage services to the Santiago metropolitan area, which has now resulted in universal treatment for the city (see Box 2.7).

The completion of the Sanitation Plan guarantees that 130,000 hectares of agricultural land will be irrigated with clean water, so that the authorities can lift restrictions on growing vegetables. Also, health risks to farm workers who currently are in direct contact with polluted water will be fully controlled.

Sources: Bartone, 1994; Ferreccio, 1995; Laval and Ferreccio, 2007; Bitrán and Arellano, 2005; Larrain, 2009; Yayur, 2009.

Box 5.4: Israel's experience with wastewater reclamation and use for irrigation as part of integrated water resources management

Since the early 1970s, Israel has carried out significant efforts to achieve massive use of wastewater for agricultural purposes, and is presently using almost 72% of all the sewage produced in the country for irrigation – amounting to half of all irrigation water (Mekorot, 2007). As a result, in 2000 agriculture used less than 40% of the freshwater resources, down from almost 70% in 1985. During drought years, freshwater supply to agriculture is severely cut off, while farmers connected to reclaimed wastewater systems continue to receive a full quota (Juanicó, 2008).

Wastewater irrigation emerged as an unavoidable response to severe water scarcity, a concentrated population with high levels of water consumption and sewage production, and the pollution of limited water resources. In 1959, parliament passed a Water Law which defined sewage as a "water resource." However, wastewater irrigation was only practiced in isolated uncontrolled projects, and it was not until the 1970 cholera outbreak in Jerusalem that strict wastewater irrigation regulations were introduced, and the Ministry of Health was assigned regulatory responsibility.

An early stimulus for wastewater treatment and use was the World Bank Israel Sewerage Project, the first sewerage loan to be financed by the Bank. Approved in 1972, the Sewerage Project provided support to Israel's National Sewerage Program designed to improve and modernize the country's sewerage facilities, in order to protect and preserve water resources and to improve public health (Streit, 1986; Bartone, 1991). An ex post evaluation concluded that it was a successful project incorporating appropriate least-cost technology, and that the provision of sewage treatment and reuse facilities constituted a major environmental improvement and a significant supplementary source of water for irrigation. The project also pioneered the use of long-detention storage reservoirs for treatment. Other important features of this project were the provisions for cost-sharing and division of responsibility between municipalities wanting to dispose of wastewater and farmers wanting to use it.

Over the intervening decades, a regulatory structure evolved to protect public health and promote sustainable agriculture (Juanicó, 2008). In 1977, the Shelef Commission set different water quality standards for the irrigation of different crops, including unrestricted irrigation (Shelef, 1991). The Public Health Law of 1981 restricted wastewater irrigation to a list of allowed crops, and all reuse projects required a permit; and the Public Health Law of 1995 imposed treatment requirements for all towns with population greater than 10,000 (BOD < 20 mg/l and SS < 30 mg/l). The Halprin Commission in 1999 set public health requirements for wastewater irrigation following the California school. Finally, the Inbar Commission recommendations of 2003, approved in April 2010, set stricter environmental requirements for wastewater irrigation including nutrients, salts, metals and other pollutants.

While the initial effluent quality requirements were aimed at the protection of public health, the Inbar Commission requirements address the protection of the environment through sustainable reuse. A particular threat to sustainability linked to effluent irrigation is the salination of soils and aquifers, since salts are added during domestic and industrial use and are recycled together with the wastewater. There has been a steady decrease in salts and boron in sewage over the past two decades, as a result of the prohibition of brine discharges to sewers, modifications to domestic and industrial detergents, water softening and neutralization systems, and disinfection processes (Juanicó, 2008). In some instances, the desalination of reclaimed wastewater is also practiced.

Today, the use of treated effluent is an integral part of the national water demand management strategy in Israel (Arlosoroff, 2006). Regulations are in place to maximize wastewater use potential, minimize health and environmental risks, and enhance the potential to exchange reclaimed effluents for freshwater allocations. Since the 1990s irrigation allocation policy has concentrated on reducing freshwater use, replacing it with treated wastewater effluents. The cities pay for the sewerage treatment costs, while the water sector (i.e., Mekorot) pays for the extra treatment costs that may be needed for irrigation purposes and for the conveyance to irrigation sites. These additional costs were estimated at $0.21/m^3. Farmers, however, only pay between $0.13/m^3 and $0.19/m^3 for reclaimed water based on water quality – the balance is covered by the government as a subsidy (Zhou *et al*., 2006).

Of some 470 Mm^3 per year of urban and industrial wastewater generated in Israel, about 90% is treated and 72% is used in agriculture. About 110 Mm^3 per year of non-used effluent is disposed to the environment (Mekorot, 2006). One of the main goals for the coming decade is the treatment and reuse of all the wastewater in Israel for agriculture, thereby eliminating all environmental discharges. The new policy calls for secondary and tertiary treatment, and the delivery of the reclaimed effluent to farmers in exchange for their existing freshwater allocations (Arlosoroff, 2006; Bucknall, 2007). In addition, regulations, which came into effect at the beginning of 2005, require wastewater treatment plants to stabilize and treat the sludge they generate to make it suitable for agricultural use and avoid soil deterioration. (Zhou *et al*., 2006).

Effluent irrigation in Israel is based on a general concept of pre-treatment followed by seasonal storage followed by irrigation (M. Libhaber, personal communication). This is accomplished through a range of projects of different size and characteristics (Juanicó, 2008). At one extreme are the large-scale projects managed by Mekorot, Israel's national water company. An example is the Dan Region project that utilizes activated sludge treatment followed by soil aquifer treatment (SAT) and storage; the reclaimed wastewater is then pumped from the storage aquifer and utilized for unrestricted irrigation. At the other extreme are hundreds of small projects involving pre-treatment and surface storage in stabilization reservoirs that produce effluents of lower quality only suitable for restricted irrigation, but which have an overall effect on the economy and development comparable to that of the large projects (Juanicó, 2008). The national policy is to promote all sizes.

Farmers in Israel are organized in farming communities and cooperatives and decisions to irrigate with treated effluents, as well as for the assignation of land for stabilization reservoirs, are made by the farmer organizations so that there is no need for authorities to negotiate with individual farmers. This has facilitated the acceptance of the effluent irrigation concept.

Drip irrigation was introduced in the country on a massive scale in the 1980s (Juanicó, 2008). Today irrigation is carried out utilizing only efficient pressure irrigation methods – mostly drip irrigation and some micro-sprayer and sprinkler irrigation. Where effluents from storage reservoirs are used, clogging of the drippers is a problem. This problem is often solved by gravel filtration of the effluents (M. Libhaber, personal communication).

5.2 Promoting an integrated approach to planned wastewater use for irrigation

Previous sections have presented the risk assessment and management framework that allows for setting achievable public health targets for reducing risks associated with wastewater irrigation, and have discussed how to choose the needed combination of treatment and multi-barrier options to achieve the pathogen reduction targets. However, there are still a number of other common issues that require attention if planned wastewater irrigation is to be implemented successfully on a broader scale. These issues revolve around the need to embed wastewater use in the broader water resources management context. Before identifying these issues and examining them in detail, it is useful to consider how wastewater use for agriculture can be integrated in the broader context of water resources management.

5.2.1 Integrated water resources management and wastewater use for agriculture

Integrated water resources management (IWRM) has been the accepted international paradigm for efficient, equitable, and sustainable management of water resources since the early 1990s when the Dublin Conference on Water and the Environment and the Earth Summit at Rio de Janeiro set out the foundations of IWRM. The World Bank Group adopted IWRM as its policy in the 1993 Water Resources Management Policy Paper, and also emphasized that as water scarcity and wastewater disposal problems become more acute, it will become increasingly important to adopt and improve water conservation practices, desalinization and wastewater use systems, and overall pollution-reduction approaches (World Bank, 1993b).

There is no unambiguous definition of IWRM (Global Water Partnership, 2000). Instead, it consists of a number of principles that have been agreed, and can be expanded, extended, and adopted to local circumstances (Hirji and Davis, 2008), namely:

- Adopting a multisectoral approach to water management in association with river basin management;
- Encouraging stakeholder participation and devolution of responsibility;
- Promoting private sector involvement; and
- Employing economic instruments.

How each of these principles applies in the case of wastewater use for agriculture is discussed below. An example of the application of these principles in the European Union is given in Box 5.5. The EU example illustrates a growing recognition of the importance of wastewater use in confronting problems of water scarcity, public safety, and environmental protection. It also shows that in spite of being an emerging priority in the water-scarce EU countries, wastewater use policies and practice – and its contribution to IWRM – are still underdeveloped (Brissaud, 2008).

5.2.2 Adopting an integrated multisectoral approach to wastewater management

Wastewater use for agriculture requires coordinated decision-making across multiple sectors as it involves consideration of urban sanitation and land use policies, public health and environmental impacts, agricultural productivity, economic feasibility, and sociocultural aspects – all linked through a broader water resources management framework. This multisectoral nature of wastewater use requires the proper identification of the many interested stakeholders and institutions that are typically involved (Khouri *et al*., 1994).

Safe wastewater disposal is a major concern of public and semipublic sewerage and disposal authorities: national, state, and municipal water and sanitation agencies; organizations charged with safeguarding public health and the environment, such as national ministries of health and of the environment; and state or local health authorities responsible for monitoring effluent contaminant levels.

Irrigation is the responsibility of still other organizations, such as authorities, cooperatives and communes operating under the jurisdiction of agriculture or water resources ministries. These organizations are interested in the use of water and its timely provision and quality.

Urban agriculture introduces further local considerations of land use policies that fall under the aegis of urban and/or agriculture ministries, as well as regional or local planning bodies.

Box 5.5 EU Water Framework Directive and wastewater use

The Water Framework Directive (WFD), adopted by the European Parliament in 2000. It contains many of the principles of IWRM, including managing water quantity and quality for surface and groundwater, treating water as having an economic value, and enhancing consultation and participation. Its key requirement is the production of river basin management plans by all EU countries.

With regard to the WFD and wastewater treatment and use, a number of activities have been and are being carried out. First of all, the 1991 Urban Wastewater Treatment Directive (UWWTD) establishes the principle "Treated wastewater shall be reused whenever appropriate." In 2004, the third UWWTD implementation report concluded by stating that the challenges to implementing the WFD include: "… wastewater treatment, as well as wastewater reuse in order to ensure human health and protect the environment will receive further importance due to increased floods and droughts as a consequence of climate change."

The European Commission (EC) launched the AQUAREC project Integrated Concepts for Reuse of Upgraded Wastewater to investigate strategies, technologies and management practices for local, safe, publicly acceptable, economically feasible and sustainable use of treated wastewater for urban, peri-urban and agricultural use. The project found a growing acceptance of wastewater use practices, with more than 200 municipal wastewater use projects in Europe. However, the project found that only a limited fraction of the wastewater use potential is actually exploited. The results of the AQUAREC project provide a comprehensive overview of wastewater use concepts together with valuable knowledge and guidance to a whole range of stakeholders on their practical implementation, based on European, Israeli and Australian full-scale experiences.

The AQUAREC project found that EU financial institutions play a key role in favoring wastewater use schemes through existing subsidy programs that cover a number of areas, including planning, technical assistance and research, construction costs, actions contributing to regional objectives that are not locally cost-effective, and pay-for-performance incentives. Subsidies do not cover operation and maintenance costs.

In 2007, the European Commission (EC) carried out an in-depth assessment of water scarcity and droughts in the European Union. Following this assessment, in 2008 the EC launched a study "Assessment of alternative water supply options" to assess four alternative water supply options in Europe, namely desalination, wastewater use, ground water recharge, and rainwater harvesting. The study found that alternative water supply options can be successfully used to solve water management problems, both related to droughts, storm water management and water quality issues. For some of the regions studied, alternative water supplies are becoming the largest contributors to meeting water demand.

According to the EU Water Scarcity and Drought working group, the overall economic impact of drought events in the last 30 years at the EU level was around €100 billion. If the EU had achieved a 20% wastewater use target to reduce water scarcity in Europe this could have reduced the economic impact of drought in the EU by €20 billion in the last 30 years.

Finally, the EC also provides grants for research on wastewater use for agriculture. One example includes the AQUATEC project for southern Italy that evaluated the effectiveness of membrane filtration, simplified treatments (skipping nutrient removal processes), storage reservoirs, and constructed wetlands technologies to produce safe treated effluent for irrigation.

Sources: EU, 2000; EC, 2004; AQUAREC, 2006; Lopez *et al.*, 2006; Bixio and Witgens, 2006; MED-EUWI, 2007; Campling *et al.*, 2008.

Finally, there may be an organization such as a national or regional planning body or river basin authority concerned with water resource allocation and the enforcement of water laws specifying water use rights and/or water quality standards.

These varying sectoral interests and responsibilities must be considered and reconciled if a wastewater use is to succeed. As an ideal, wastewater use for irrigation and strategies for its implementation should be part of national water resources planning, and there should be a better integration of wastewater use issues into sectoral policies. At the local level, individual wastewater use projects should be part of the overall river basin planning effort – at the very least at the level of local urban watersheds. Multisectoral planning with due consideration of wastewater use for agricultural remains a major challenge, however, not only at national level but also in donor agencies – many of whom do not have clearly stated policies regarding wastewater reclamation and use or how to involve other sectors in such sanitation projects.

For the developing countries engaged in effluent irrigation for urban agriculture, the following cross-sectoral issues often arise, among others: wastewater use is undervalued due to the failure to quantify economic benefits accruing across sectors; water and land use policies are poorly coordinated across sectors; and wastewater treatment decision are too often made based on limited water quality criteria for disposal (such as removal of organic matter and nutrients) rather than integrated agricultural, public health, and ecosystem criteria that view wastewater as an asset.

Economic costs and benefits of wastewater irrigation

The decision to promote wastewater use should depend on a full accounting of the economic costs and benefits of projects. Most economic assessments, however, rarely encompass all relevant aspects of reuse and rarely go beyond financial feasibility analysis (Kfouri *et al.,* 2009).

Wastewater use projects are often undervalued when compared to other water projects because benefits such as watershed protection, local economic development, and improvement of public health are not properly quantified (Miller, 2006). Externalities are seldom included in the economic analysis for new wastewater irrigation projects. For example, the scarcity of water and the marginal cost of new sources (where existing sources are at or beyond their sustainable limit) are often ignored when considering the new wastewater treatment and use projects (Bixio *et al.*, 2006).

Similarly, the financial, social, and pollution burdens of effluent disposal to the environment are rarely considered in the economic analysis. Nor are the public health consequences of unplanned irrigation with wastewater that often takes place out of necessity in developing countries. Also, urban agriculture may have important economic impacts on employment, nutrition and poverty alleviation. Faruqui (2000) has argued that if the real and significant benefits of environmental and public health protection were correctly factored into economic analyses, wastewater collection, treatment and use should be among the top priorities for scarce public and development funds. However, the reality is that proponents usually only present vague economic estimates on the benefits and costs of wastewater use for urban and peri-urban agriculture, leaving donors and policy-makers unaware of the significance of effluent irrigation to the economy (Faruqui *et al.*, 2004b).

A few examples can be found to partially illustrate the economic importance of wastewater irrigation. For instance, in Pakistan, 26% of the vegetables produced nationally are grown using urban wastewater (Ensink *et al.*, 2004a). The value of wastewater in Pakistan is reflected in the land rents. In Haroonabad, land rents were on average 3.5 times higher for wastewater fields than for canal-water fields (Hussain *et al.*, 2001). In Quetta, land rents were double and in some cases up to six times higher for land with access to wastewater compared to land without access, and farmers paid 2.5 times more for the right to use wastewater than for regular irrigation water (Ensink *et al.*, 2004b). Higher land rents for wastewater farms on average result in higher income for the landowners but relatively less net profit for lessees. A proper economic analysis would have included all benefits and costs accruing to all stakeholders, including, for example, the opportunity costs of family labor, and environmental, health, and social impacts (Hussain *et al.*, 2001).

In another example from the public health sector, an economic analysis of cholera and typhoid prevention in Chile (Box 5.3) showed that the observed health benefits significantly offset the cost of providing wastewater treatment (Bartone, 1994).

An environmental valuation example from China (Xie *et al*, 2009) found that the indirect irrigation of 4.05 million ha of agricultural land with polluted water lead to reduced harvests, poor quality crops, and degraded soils. The economic loss attributed to these impacts was estimated at 61.3 billion yuan, equivalent to about 0.46 percent of GDP in 2003.

Many studies have pointed out the potential economic value of the nutrients contained in wastewater. The economic value of nitrogen contributions by reclaimed water in the City of Castell Platja d'Aro in Spain has been evaluated as €350 per hectare per year (MED-UEWI, 2007). Clearly, the nutrients in wastewater are beneficial and may reduce the amount of commercial fertilizers used by farmers. Whether the benefits justify the cost depends not only on agricultural productivity, but also on the costs that would be incurred for wastewater disposal without irrigation. These normally beneficial nutrients could, however, reach levels that are toxic to plants, cause lodging (excess leaf growth) in plants, or pollute underlying groundwater resources if applied excessively. Again, a proper economic analysis should account for all of the positive and negative factors.

Without focusing specifically on wastewater irrigation, a review was conducted on the economic dimensions of urban agriculture and its contribution to urban poverty reduction strategies (ODI, 2009), and found that urban agriculture contributes significantly to sustainable livelihood and development, mainly through income-generation from sale of produce and employment. The same study, however, points out that the economic dimension of urban agriculture has rarely been rigorously or comprehensively assessed, making it difficult to estimate how and the extent to which urban agriculture contributes to reducing urban poverty, and an international research agenda is proposed to address this shortcoming.

Water and land use policies and planning

Access to wastewater and land is a prerequisite for wastewater irrigation projects, yet in many cases of existing wastewater use neither resource is guaranteed.

Many poor farmers use wastewater without formal water rights, and if wastewater is withheld they will lose their livelihoods. In some cases, as in Mexico, customary water rights may be recognized and these rights can conflict with future planned wastewater use projects. For example, the city of Guanajuato began operating a wastewater treatment plant in 2002 – providing an option of selling treated effluent for industrial use (Silva-Ochoa and Scott, 2004). Only about 30% of traditional wastewater farmers have a water concession title (linked to the land) issued by federal authorities. The rest of the farmers are faced with uncertainty about their future share of irrigation water, although no commercial transaction with industrial users had as yet taken place at the time of reporting. In another example in Pakistan, local water and sanitation utilities brought suit against local farmers, challenging their rights to use wastewater (Ensink *et al.*, 2004a). The outcome was that farmers were forced to either pay for wastewater or abandon its use. However, in Faisalabad, farmers successfully appealed the outcome once they proved that they did not have access to another suitable water source.

Legislation may be required to define the rights of wastewater users to access, and the powers of those responsible for allocating those rights. To ensure safe effluent irrigation, access to wastewater can be made contingent on farmer compliance with health guidelines. In Mexico, for example, authorities have the power to withhold wastewater from farmers who do not comply with crop restrictions, and this has been a major factor in the success of the restrictions (Bahri, 2009).

Access to land and secure land rights are important for preserving the livelihoods of urban farmers. Maldonado (2009) and Arce *et al.* (2009) describe the land tenure situation of farmers in the peri-urban community of Carapongo on the outskirts of Lima, Peru (Box 5.6), and illustrates the precariousness of their situation – typical of many such communities in developing countries. Land rights are also important for commercial farming, which involves substantial investments in fertilizer, pesticides and water. Without secure tenure, farmers have difficulty accessing needed credit.

Box 5.6 Land issues and urban agriculture in the peri-urban community of Carapongo

Carapongo is a community of 3,200 inhabitants in the periphery of Lima, Peru where urban agriculture is commonplace. It covers some 464 ha, of which 46 per cent is cultivated land mainly under vegetable production, with indirect irrigation using polluted water from the Rimac River. About 60% of the population is involved in agriculture.

A recent study found that 37 percent of the producers in Carapongo occupy land that they own, although less than half held legal title. About 19 percent occupy rented land. Seven percent of farmers access land through informal squatting (*posecionarios*) on land located on the bank of the Rimac River. Seventeen percent of producers occupy land with a combination of ownership and rental. The rest have some other form of occupancy such as guardianship or share-cropping.

Even though farmers who were interviewed during the study generally declared that urban agriculture is not profitable, the majority obtain some income from the sale of crops or animals which makes it possible for them to make a subsistence living. Those farmers who have secure access to the land (either owned or rented) generally have more opportunities to earn a higher income and attain a better quality of life.

In recent years some 30 per cent of the agricultural land in Carapongo has been lost to urban sprawl. Agricultural lands are being converted into small residential plots, while in other places individual farm plots are being used wholly or partially for extraction of earth for brick-making or as construction material. The local government does not recognize urban agriculture as an important activity within the city development plan, and has designated the land use as urban residential, a classification which naturally conflicts with the perspective of the farmers.

To maintain the livelihoods of urban farmers, the study recommends the redesign of municipal land-use policies, encouraging co-operation between the Housing and Agricultural Associations, individual landowners and cultivators of the plots, and participation of all stakeholders in urban land-use planning, in order to increase security of land tenure for producers.

Source: Arce *et al*., 2009; Maldonado, 2009.

Any agricultural activity that uses treated wastewater should have sufficient land area to take full advantage of the available effluent (Egocheaga and Moscoso, 2004). Moreover, future increases in wastewater flows should be considered so at to ensure both treatment capacity and land resources will remain sufficient. When planning for wastewater use, wastewater treatment plants should be located near to existing or potential irrigation sites where effluent irrigation can be carried out on an economically appropriate scale. Conversely, land areas suitable for effluent irrigation should be identified and/or preserved in the vicinity of existing or planned treatment plants. The model provided by the Mendoza ACRE project (Box 5.7) illustrates how this can be done in a practical and productive way for a centralized treatment plant.

Even within urban areas it may be possible to find sufficient land areas that can be irrigated with effluent from decentralized wastewater treatment plants. An example is the Agricultural Zone of San Augustín (ZASA) in the periphery of Lima, Peru where a waste stabilization pond system was planned to service the farmers with safe irrigation water (see Box 2.6).

Box 5.7 Mendoza, Argentina—creating a special area for direct wastewater irrigation

The greater Mendoza metropolitan area has one million inhabitants, with 75% of the population connected to sewers in 1997, and coverage projected to increase 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 traditionally been used indirectly for irrigation. The Campo Espejo treatment plant was built in 1976 and upgraded in 1993 (see Box 5.9) and provides 1.7 m^3/s of effluent for direct irrigation.

The treated effluent from the *Campo Espejo* treatment plant is conveyed to a special 1,900 ha restricted irrigation area, *Area de Cultivos Restringidos Especiales* (ACRE). Farmers with properties within the special area receive treated effluent free of charge and are obliged to follow the irrigation regulations established for ACRE. 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 quality of the agricultural produce and the health of the agricultural workers are monitored by a special office of the *Departamento General de Irrigación*. An agreement of cooperation was recently signed between OSM and the ACRE farmers to study concerns of mutual interest, including the possibility of building effluent storage reservoirs that would optimize wastewater use during the dry season without requiring changes in the treatment plant operations, as well as the possibility of charging farmers part of the cost of treatment.

Sources: Idelovitch and Ringskog, 1997; Kotlis, 1998; Barbeito, 2001; Egocheaga and Moscoso, 2004.

A new paradigm for wastewater treatment decision-making

Technical standards for the design of municipal wastewater treatment systems often derive from environmental legislation that calls for the removal of organic matter and nutrients, and is focused primarily on pollution control and protecting the receiving water body (river, lake, wetland, groundwater, coastal zone). The resulting plants are built and operated for the downstream control of physical (temperature, pH, total solids, suspended solids), chemical (metals, oils, polymers, anions, and cations), and biological (biochemical oxygen demand (BOD_5) and in-stream dissolved oxygen) parameters (Egocheaga and Moscoso, 2004). In developing countries, these sanitation solutions are often viewed as costly means of preparing wastewater for unproductive disposal, and as a result resource-constrained governments seldom rank wastewater treatment high on their agendas (Murray and Buckley, 2010).

There is a need to shift the paradigm so as to see wastewater as an asset, and to manage water, wastewater, pollution control, and effluent irrigation in an integrated way while ensuring public health protection (Bahri, 2009). In this paradigm shift, treatment facilities are not designed for waste disposal but to conserve resources in wastewater and reduce pathogen risks (Murray and Buckley, 2010). Such solutions, based on appropriate technologies, are cheaper than conventional WWTPs designed purely for disposal.[32]

To minimize wastewater treatment costs, to safeguard public health, and to obtain the maximum possible agricultural benefit from nutrients and organic matter contained in wastewater, treatment plant design for irrigation use should focus primarily on reducing priority pathogens – particularly helminth eggs that threaten farmers' health – while preserving nutrients. Conventional secondary

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[32] Appropriate technologies for wastewater treatment are defined by Libhaber (2007) as simple treatment processes of proven technology, of low investment costs and especially of low operation and maintenance costs, simple to operate and with the capacity of yielding any required effluent quality. The author describes a gamut of such processes that exist and are especially suitable for developing countries with warm climates, since biological processes perform better at higher temperatures.

treatment systems are generally ineffective in removing helminth eggs and the bacteria or viruses of concern in developing countries, and are beyond the financial and operational capacity of most low-income countries (Bahri, 2009). In these countries, the focus should be on designing and building simple, low-cost treatment systems that guarantee significant removal of helminth eggs, which in combination with the application of multiple barriers can help achieve an acceptable level of risk reduction (as defined by the application of the risk assessment and management framework). As countries develop and progress up the treatment ladder (Table 5.1), and improve capacity for monitoring and enforcement of water and food safety standards, barriers addressing post-harvest contamination are still recommended (Keraita *et al.*, 2010).

This paradigm shift will require the development of new technical standards for wastewater treatment, including the proper management of health risks through the removal of microbial pathogens. For example, most Latin American countries have no technical standards for the determination and removal of helminth eggs (Egocheaga and Moscoso, 2004). Also, technical standards for the use of wastewater in agriculture are needed that take into account the characteristics of wastewater. Such standards should consider, for example, public health criteria (to protect farmers), suspended particulates (to prevent clogging of irrigation systems), nutrients (to rationalize the application of agrochemicals), and pathogens (for irrigation management).

Wastewater stabilization pond systems have long been recognized as an appropriate treatment technology for effluent irrigation and aquaculture schemes (Arthur, 1983; Bartone and Arlosoroff, 1987; Mara and Cairncross, 1989), especially for small and medium-size cities and for decentralized treatment around larger cities if land is available. Pond systems require less investment and have lower operation costs than many other conventional treatment systems (Arthur, 1983). More importantly, effluents from well-designed and operated pond systems achieve high levels of pathogen removal – typically 99.99% removal of fecal coliforms and complete removal of helminth eggs (Bartone and Arlosoroff, 1987; Mara and Cairncross, 1989). Waste stabilization ponds also transform organic wastes into algal biomass that, when applied to land, acts as a slow-release fertilizer.

While wastewater stabilization ponds are an attractive option from an economic, environmental, and effluent irrigation perspective, for centralized systems that treat the sewage flows from large cities the land requirements can be prohibitive unless inexpensive land can be found (Arthur, 1983). In such circumstances, conventional treatment systems may be needed. This is the case in China, where activated sludge systems are becoming the norm for medium- to large-scale centralized treatment plants (Murray and Buckley, 2010). The same authors point out, however, that for conventional systems treating wastewater for irrigation, designs are modified to minimize nutrient removal, thus lowering the cost when compared to plants designed for disposal. Furthermore, adding anaerobic sludge digestion and capturing biogas for on-site use can lead to long-term cost savings and reductions in carbon emissions. For more information of emerging wastewater treatment and irrigation use in China refer to Box 5.8.

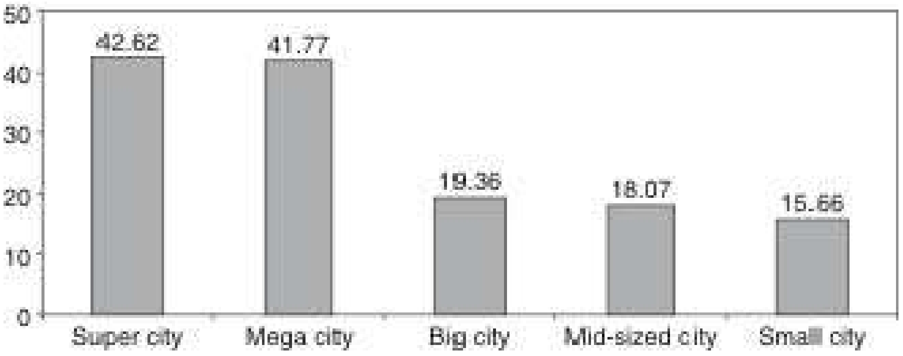
Biogas can also be recovered from low-cost anaerobic processes like covered anaerobic ponds, UASBs, and anaerobic filters, and the recovered gas used to produce energy for on-site use or for sale, thus contributing to financial viability (Libhaber, 2007). This is a further example of the new paradigm for managing wastewater as an asset.

Box 5.8 Emergence of wastewater treatment for irrigation use in China

In 2003, about 4.05 million ha of agricultural land was irrigated with polluted water in China, almost triple the area found in 1982. About two-thirds of this land is in northern China, which is already a water-scarce region. The impacts of this indirect wastewater irrigation are significant, leading to reduced harvests, poor quality crops, and degraded soils. The economic loss attributed to these impacts has been estimated at 61.3 billion yaun (US$7.4 billion*), equivalent to about 0.46 percent of GDP in 2003.

The government has acknowledged the seriousness of water pollution and since the mid-1990s and embarked on a major program to install wastewater treatment in cities. Progress, however, has been uneven and large differences exist in installed sewage treatment capacity by province and city. Of some 660 cities in China, wastewater treatment rates in mid- and small-sized cities are badly lagging (by half or more) behind those of cities with populations exceeding 1 million. It is reported officially that 56 percent of municipal sewage is treated in some form, although the treatment rate may reflect the installed wastewater treatment capacity rather than actual treatment, which is likely lower due to the lack of sewerage networks and funds for operation and maintenance in many cities.

Centralized Sewage Treatment Rates in China by City Size in 2003 (%)



Source: China Urban Development Statistics Yearbook, 2004.
Note: Super city = more than 2 million population; mega city = 1 to 2 million population; big city = 0.5 to 1 million population; mid-sized city = 0.2 to 0.5 million population; small city = less than 0.2 million population.

Activated sludge systems are becoming the norm for medium- to large-scale centralized treatment plants. However, for conventional systems treating wastewater for irrigation, designs are modified to minimize nutrient removal, thus lowering the cost when compared to plants designed for disposal. Furthermore, adding anaerobic sludge digestion and capturing biogas for on-site use can lead to long-term cost savings and reductions in carbon emissions.

Attention is shifting to the rising water pollution from 19,000 small towns and rural areas that have been developing rapidly in recent years, but most of which have no wastewater treatment plant. Untreated water pollution from these small towns has particularly severe impacts because it more directly affects ecological systems and agricultural production. Sewage treatment in small towns can be promoted through the introduction of cost recovery policies, selection of low-cost appropriate technologies, and the promotion of treated wastewater use for agriculture.

Sources: Xie *et al.,* 2009; Murray and Buckley, 2010.

*Exchange rate in 2003: 8.2770 yuan per US$.

5.2.3 Promoting stakeholder participation and social acceptance

Given the multi-sectoral nature of wastewater irrigation projects, the varying interests and responsibilities of stakeholders must be considered and reconciled if a project is to succeed. Khouri *et al*. (1994) suggest that practical steps to encourage and ensure stakeholder involvement would include the following:

- Identify all agencies and user organizations that would have an interest in the project, and list their responsibilities.
- Identify, after appropriate consultation, the lead agency for project planning and implementation.
- Develop and install consultative mechanisms giving all interested parties an opportunity to participate in the planning process and define their roles/responsibilities in project implementation.
- Ensure opportunities for irrigation water users to participate in project development so they are aware of the benefits and requirements of wastewater irrigation.
- Evaluate the organization and management of implementing agencies and propose changes as necessary.
- Identify and develop monitoring programs and legal measures for their implementation to ensure adherence to public health regulations.

Numerous benefits of stakeholder participation in integrated water management projects such as wastewater irrigation include improving public acceptance of decision, improving the quality of alternatives because to the wider range of expertise available, reduce the risk that opposition from disaffected groups will delay implementation of decisions, and increasing the likelihood of compliance with agreements reached during negotiations (Hirji and Davis, 2008).

Three key issues need attention when considering stakeholder participation: first, roles and responsibilities need to be clearly set; second, in order to promote wastewater use in agriculture it is essential to build trust, credibility and confidence among public officials and the general population; and third, when implementing multiple-barrier approaches, farmers and consumers must become active participants.

Clarifying stakeholder roles and responsibilities

An important lesson from the long and successful Israeli experience with wastewater irrigation is that there should be a clear separation of responsibilities between the urban and the rural sector regarding the treatment and application of wastewater (Juanicó, 2008). The evolution of the wastewater treatment and storage reservoirs is a case in point. During the eighties and early nineties the roles and responsibilities were not clearly defined and the regulators found enforcement difficult because the municipalities and farmers accused each other of being at fault for pollution. Open wastewater reservoirs can be excellent treatment units if operated correctly. However, if the reservoirs belong to farmers, they operate the reservoirs to meet irrigation needs and not treatment needs. The reservoirs should be under the control of whoever is responsible for sewage treatment and operated as treatment units (Juanicó, 2008). This situation was resolved in 1995 when the public health regulations assigned municipalities (as the producer of polluting wastewater) the whole responsibility of treatment and disposal, and this responsibility cannot be transferred to the rural sector or other parties. Now, where farmers run wastewater treatment, storage and use facilities, it acts as a subcontractor of the municipality (as any other private operator) while final responsibility before the regulatory agency remains with the municipality. At the national level, the costs of any additional treatment that may be needed for agricultural applications, storage, and conveyance to irrigation sites is borne by the state water agency, Mekorot, and part of the cost is recovered from farmers (Arlosoroff, 2006). While there are many different wastewater irrigation schemes in Israel, and all seem to work properly when responsibilities are clearly set (Juanicó, 2008).

Involving farmers and consumers in health protection measures

Without the general acceptance and involvement of the stakeholders – including regulatory authorities, water and sanitation companies, farmers, and consumers alike – wastewater treatment and irrigation projects are unlikely to succeed. The active participation of farmers and consumers is of particular importance. Farmers need to be educated on safe irrigation and post-harvest practices. Consumers need to be informed about the safe handling and preparation of food crops irrigated with wastewater.

In countries lower on the treatment ladder where a multi-barrier approach is essential, simple incentives to farmers and produce-sellers could accelerate risk reduction significantly, such as training in safer production and food handling practices (Keraita *et al.*, 2010). Also, recent work in Bangladesh shows the importance of multi-stakeholder processes in planning and implementing multi-barrier approaches (Robinson *et al.*, 2010). A learning alliance approach was adopted whereby local stakeholders were brought together to analyze the issues, and implement a participatory action plan to deal effectively with the raw wastewater irrigation problem. The process resulted in negotiation between parties that rarely communicated previously and led to demand-driven actions including engineering solutions, policy review and community awareness programs.

A higher willingness to pay for safer produce could be one of the best incentives for behavior change where regulations alone are not sufficient to support the adoption of safer food production and marketing (Keraita *et al.*, 2010). This was demonstrated during the cholera emergency in Chile (Box 5.3), where farmers moved to safer irrigation water supplies and consumers paid more for vegetables certified to irrigated with safe water (Bartone, 1994). Yet in low-income countries risk awareness is often not high enough to result in a higher willingness to pay. In such situations, social marketing strategies may be a way to increase consumers' risk awareness (Karg *et al*., 2010).

Building trust, credibility and confidence

The perception of some public officials and of the population is that treated wastewater still remains basically sewage. Nor is it widely known that in urbanized catchments the water cycle actually includes indirect, unplanned and uncontrolled use of – sometimes untreated – wastewater. This can be a major impediment to advancing effluent irrigation projects, and there are few more pressing and critical goals than to produce a change in the underlying stakeholders' perception of the water cycle (Bixio *et al.*, 2006).

An example of the need for strong farmer and public support comes from Tunisia where, despite strong institutional support, including the 2002 consolidation of the Ministry of Agriculture, Environment, and Water Resources to oversee integrated water management and water reuse, only 18 percent of reclaimed water is currently used. A major constraint has been social acceptance (Scott, 2005). The distrust of farmers is evidenced by their reluctance to irrigate with treated wastewater although it is priced below conventional irrigation water sources, and well below the cost of treatment (Kfouri *et al*., 2009).

The professional water community should strive to convey the value and safety of planned wastewater through whatever means available including education of the public and elected officials. Sustained, long-term public awareness campaigns aimed at target groups such as farmers and consumers are needed to foster acceptance of wastewater use (Miller, 2006). Public outreach and education programs, including school curricula, are essential for general public support of wastewater use programs.

Transparency, information sharing and involvement of users and local communities in the decision making process will also ensure greater acceptance of projects (Bahri, 2009). Involvement of local NGOs and environmental groups can help build up credibility, trust and confidence. As a basis for building trust between stakeholders, there is a need to convey simple, clear and reliable information. The establishment of a best management practice framework, as described earlier in this paper, and transparency in the management and decision process is very much needed (Bixio *et al.*, 2006). Water quality data must be widely available and freely shared with users and the general public. Communities need to be able to express their needs and suggestions in open multi-stakeholder platforms.

Cultural values may also play an important part in the acceptability of wastewater use, particularly where religious views on ritual purity are highly articulated, for example in Islam and Hinduism (World Bank, 2005). In order to address concerns in Islamic countries, *Fatwas* (i.e., legal statements issued by religious scholars) have been issued in Saudi Arabia and the United Arab Emirates stating that wastewater may be used for irrigation provided that the impurities present in raw wastewater are removed. This has succeeded in overcoming the religious concerns of authorities, farmers and the public (Bahri, 2008a).

5.2.4 Involving the private sector in financing and managing wastewater treatment

Given the very low initial levels of wastewater treatment in developing countries, and the vital importance of reducing health risks in wastewater irrigation projects, an approach is needed that simultaneously makes the best use of available investment resources to upgrade existing treatment plants and to build new facilities, and generates sufficient additional financial flows to ensure the sustainable operation of treatment facilities and provide for future expansions.

Wastewater treatment is capital intensive. Until recently, major treatment works in developing countries were financed by governments or public utilities, often with the help of loans from international or bilateral agencies accompanied by central government guarantees against commercial and political risk. Given the general lack of experience in wastewater treatment plant design and operation, major projects were typically contacted out piecemeal – preliminary studies and design with a specialized engineering firm, construction with a private contractor, equipment with one or more suppliers, and supervision with an engineering firm. As a result of government guarantees against commercial risk and public project management, many of the treatment plants built in developing countries were plagued by cost overruns, implementation delays, and operations and maintenance difficulties. In such cases WWTPs were on the road to failure as soon as they were commissioned (Murray and Drechsel, 2010).

In order to overcome these difficulties, some middle- and high-income countries have turned to the private sector to help operate and even finance treatment investments in large cities. Two models have been successful for wastewater treatment in general and wastewater irrigation in particular. The first model is the Design-Build-Operate (DBO) contract in which a firm or consortium of firms is responsible for building and subsequently operating the plant for a specified period of time. Payment is usually on a price per m^3 basis, and is tied to the successful operation of the plant and meeting effluent quality standards. In this case, the government or public utility owns the plant and still undertakes to finance the investment, but the commercial risk for operation is assigned to the private partner.

An improvement is to allocate the commercial risk for both investment and operation to a private consortium through a Build-Own-Operate-Transfer (BOOT) agreement. This model requires that the private partner builds, owns and operates the treatment plant for a defined period of time – usually 20 to 30 years – and transfers ownership to the public partner at the end of that time frame free of charge and in good operating condition. A variant of this model is the Build-Own-Operate (BOO) agreement in which private ownership is retained indefinitely. The private partner normally recovers its investment and operating costs through a price per m^3 payment over the life of the agreement.

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. A detailed description of the BOOT model is given by Idelovitch and Ringskog (1997), along with ways of sharing risks between the public and private partners. In general, 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 private sector is better able to assume the commercial risk, and also the technical risk deriving from design shortcomings.

Many examples now exist of DBO and BOOT/BOO agreements for wastewater treatment and use for irrigation. Table 5.2 provides information on seven such examples, including investment costs, form of private sector participation, and sources of financing. Specific details of how the wastewater treatment DBO and BOOT schemes were structured in Mendoza (Argentina), Santiago (Chile), Monterrey (Mexico), Amman and Zarqua (Jordan), and Tehran (Iran) are described in Box 5.9, along with descriptions of how treated wastewater is utilized for irrigation in Monterrey and Tehran. This experience with private sector participation cuts across lower-middle-income countries (Iran and Jordan), upper-middle-income countries (Argentina, Chile, and Mexico), and high-income countries (Kuwait and Qatar). While most of the plants described include conventional technologies such as activated sludge, and tertiary treatment options, waste stabilization ponds have also been utilized (Mendoza).

These examples show that it is possible through private sector participation to introduce wastewater treatment in countries with little prior experience (such as Argentina, Iran, and Jordan), to mobilize private sector investment, and to design and operate the treatment plants so as to meet water quality standards for wastewater irrigation.

The importance of the private sector participation in wastewater treatment has also been confirmed in a low-income country. A recent survey of about 70 mostly decentralized wastewater treatment plants in Ghana highlighted the relative success of plants built and operated by the private sector, while plants operated by or handed over to the public sector failed (Murray and Drechsel, 2010).

Table 5.2 Private sector participation in wastewater treatment for irrigation use and sources of financing

Wastewater treatment plant (capacity)	Cost (US$ millions)	Form of private sector involvement	Sources of financing
Mendoza, Argentina 1996 -Campo Espejo (1.7 m^3/s)	15	20 yr concession (BOOT); Union Transitoria de Empresas	Private investment
Santiago, Chile 2009 -El Trebal (4.4 m^3/s) -La Farfana (8.8 m^3/s) -Mapocho (1.8 m^3/s) in 2012	115 240 140	30 yr concession (BOO); AguasAndinas ; 50% AGBAR (Spain), 50% Suez (France)	Private bond market (AA+)
Monterrey, Mexico 1995 -Noroeste (0.5 m^3/s) -Norte (2.5 m^3/s) -Dulces Nombres (5.0 m^3/s)	325 (Total Investment)	Design, build, 3 yr operation (DBO); Separate consortia for each plant	OECF Loan ($110 M) Federal grant ($110 M) Self-financing ($115 M)
Qatar 2010 -Doha West (1.6 m^3/s)	260	10 yr DBO; Joint venture of Degrémont (France) and Marubeni Corp. (Japan)	Public Works Authority (Ashgal) of Qatar
Kuwait 2005 -Sulaibiya I (4.3 m^3/s) -Sulaubiya II (2.6 m^3/s planned)	430 N/A	30 yr concession (BOOT); UDC joint venture: 75% Kharafi Group (Kuwait), 25% Ionics (USA)	Private investment (loans from National Bank of Kuwait, Gulf Bank, and The Bank of Kuwait)
Jordan 2008 -As Samra (3.1 m^3/s)	169	25 yr BOOT As Samra Consortium: Suez Environnement (France), Infilco Degremont (USA) ,and Morganti Group (USA)	USAID ($78 M) Bank consortium lead by Arab Bank ($60 M) Gov't grant ($14 M) As Samra Consortium ($17 M) MIGA guarantee ($4.1 M)
Tehran, Iran 2009 - Southern WWPT (5.2 m^3/s)	121	Design, build, 2 yr operation (DBO); Joint venture of iLF (Austria), KEO (Kuwait), Parsconsult (Iran)	World Bank Loan ($54.4 M) Self-financing ($36.6 M) Government Grant ($30 M)

Sources: Mendoza (Idelovitch and Ringskog, 1997); Santiago (Larrain, 2009); Monterrey (Bartone, 2000); Qatar (http://www.degremont.com/en/nos-realisations/municipal-wastewater-and-reuse/doha-west--qatar/doha-west--qatar/); Kuwait (http://www.water-technology.net/projects/sulaibiya/); Jordan (http://www.miga.org/projects/index_sv.cfm?pid=656&pv=$); Tehran (World Bank, 2009; http://www.ilf.com/index.php?id=111&type=98&L=1&L=1)

Box 5.9 Private sector financing of wastewater treatment plants for irrigation use in Argentina, Chile, Mexico, Jordan and Iran

Mendoza, Argentina – planned direct wastewater irrigation: The *Campo Espejo* primary treatment plant was built in 1976 to treat an average flow of 1.7 m^3/s. It was operated by the public water company, *Obras Sanitarias de Mendoza* (OSM), and the effluent was discharged to irrigation canals and used for indirect irrigation. To upgrade the quality of the effluent, in 1993 OSM awarded a 20-year BOOT contract to build and operate a waste stabilization pond system required to meet the 1989 WHO guidelines for unrestricted irrigation The winning consortium, *Unión Transitoria de Empresas* (UTE), inaugurated the new *Campo Espejo* plant in 1996, consisting of 12 series of three ponds each (facultative + aerobic + polishing). The waste stabilization pond system occupies 320 ha and it is one of the largest such lagoon systems in Latin America.

The bidding process was straightforward. The bidding documents specified criteria for the quality of effluent, such as a meeting the 1989 WHO microbial guidelines (<1,000 FC/100ml and <1 helminth egg/liter), plus removal of at least 30% of BOD and 70% of suspended solids. The bidding documents also defined a certain level of fines for failure to produce an effluent of the standard specified. OSM guaranteed a minimum wastewater flow of 3 Mm^3/month. The selection criterion used was the wastewater treatment charge per m^3 proposed by the BOOT bidders. Five contractors submitted bids with proposed treatment charges varying from a 5¢/m^3 (UTE's winning bid) to 11¢/m^3 plus value added tax. Based on the winning bid price and the average treated effluent flow, UTE's initial investment of $15 million had an expected payback period of 7 years. (See also Box 5.7.)

Sources: Idelovitch and Ringskog, 1997; Kotlis, 1998; Barbeito, 2001.

Santiago, Chile – planned indirect wastewater irrigation: In 1999, following a decade of water sector reform, a 30-year concession was awarded to the private consortium AguasAndinas to provide water and sewage services to the Santiago metropolitan area. The new company immediately began implementing a Sanitation Plan for wastewater treatment plant construction, inaugurating the El Trebal plant (4.4 m^3/s) in 2001 and the La Farfana plant (8.8 m^3/s) in 2003. Currently 82% of the Santiago's wastewater is treated, and with the scheduled startup of the Mapocho plant (1.8 m^3/s) in 2012 the treatment level will reach 100%.

Upon completion of the Sanitation Plan in 2012, AguasAndinas will have invested a projected total of 654 Euro (US$896) in wastewater treatment – an achievement far beyond the resources of the GoC. This addition of wastewater treatment as a new service has led to a significant increase in the water tariff to recover this investment, but corresponds to applying the "polluter pays" principle to households and businesses that discharge wastewater. To protect poor households and ensure their access to water and sanitation services, the GoC provides a means-tested subsidy. The magnitude of these investments and the corresponding tariffs increases would be unlikely to survive politically if not accompanied by vigorous and sustained economic growth, which has helped make it possible for households to pay their share of the cost. (See also box 5.3.)

Sources: Larrain, 2009; Yayur, 2009.

Monterrey, Mexico – planned indirect wastewater irrigation: Monterrey, a city of 3.5 million people with over 10,500 industries, is located in a region of severe water scarcity. To secure needed additional water supply in the early 1990s, Monterrey petitioned the Federal Government for the right to construct a reservoir and divert flow from the San Juan River to reach a total of 10 m^3/s. The water rights belonged to farmers in the downstream State of Tamaulipas. In return, Monterrey committed to treating all of its municipal and industrial wastewater (8 m^3/s) before discharging it back to the San Juan River for protection of irrigation use in Tamaulipas.

To meet this commitment, three wastewater treatment plants were inaugurated in 1995 – Dulces Nombres (5.0 m^3/s), Norte (2.5 m^3/s), and Noroeste (0.5 m^3/s). All three WWTPs have sludge conditioning and dewatering, and a permit was being sought for land application in agriculture.

Each WWTP was built under a DBO arrangement with a three year operating requirement, by a separate consortia made up of design firm, a supplier firm, and a construction firm. The total cost of the project was $325 million. Financing came from an OECF loan ($110 million), a Federal grant ($110.), and self-financing by the Monterrey water and sewerage utility ($115 million). In 2000, the average cost of treatment was 13¢/ m^3 including debt repayment.

Cost recovery for sewerage and treatment is achieved through a 25% surcharge on metered domestic and industrial water consumption. Industry pays an additional 'decontamination charge' when effluent BOD_5 exceeds 450 mg/l, at a rate of 13¢/kg of BOD_5. With these tariffs, the Monterrey Water and Sewerage Service (SADM) covers costs and generates reserve funds for future expansions. By the year 2000, through a combination of 50% self-financing and 50% federal subsidy, and with the experience gained by managing the DBO contracts and taking over the operations of the three existing WWTPs after three years, SADM was able to build a 250 lps WWTP and was preparing to double the capacity of the Norte WWTP.

As a result of this project, in 1995 Monterrey became the first major city in Latin America to achieve universal sewerage and wastewater treatment, and safeguarded the downstream utilization of its wastewater for irrigation.

Source: Bartone, 2000.

Jordan – planned indirect wastewater irrigation: The original As Samra plant was built in 1985 and consisted of 32 ponds occupying 200 ha. It was designed to treat 0.8 m^3/s of wastewater, but almost from the beginning of operations it was severely overloaded, eventually handling almost 2.2 m^3/s, leading to concerns about the quality of treated effluents and raising concerns about the safety of wastewater use. In response, the As Samra plant was replaced in 2008 by a new conventional treatment plant with capacity to treat 3 m^3/s of wastewater from Amman and Zarqa (with a combined population of approximately 2.3 million people) with eventual expansion in 2015 to 6 m^3/s. This has been accomplished under a 25-year Build-Own-Operate-Transfer (BOOT) agreement signed in 2000 with a private consortium, and a total investment of $169 million. (See Box 2.8 for a broader description of the Jordan wastewater irrigation project.)

Source: http://www.miga.org/projects/index_sv.cfm?pid=656

Greater Tehran Southern WWTP – planned indirect wastewater irrigation: The Southern Wastewater Treatment Plant, inaugurated in 2009, reclaims 5.2 m^3/s of Tehran's wastewater for use in irrigation. It is an activated sludge plant with tertiary nitrification, chlorine disinfection, sludge digestion, energy recovery and utilization, and sufficient area to store sludge for one year. The plant was financed by the World Bank and tendered by the Tehran Sewerage Company as a DBO project with a two-year operating requirement, and built at a cost of US$121million. The plant – designed to meet the 1989 WHO guidelines – produces an effluent suitable for unrestricted irrigation and digested sludge suitable for land application.

The effluent is discharged to a nearby irrigation channel where it is mixed with other water sources, and goes to irrigate an additional 15,000 ha in the Varamin Plains irrigation scheme bringing the total to 50,000 ha and increasing the size of the irrigation project by 43%, making it one of the largest in the world. Digested sludge, after one year of storage, is applied to agricultural parcels at a rate of once every four years. Crops grown include wheat, cotton, cantaloupes, sunflowers and alfalfa. During the non-irrigation season the effluent is used for groundwater recharge.

Source: World Bank, 2000; 2009.

5.2.5 Using economic instruments

Since the international acceptance of the 1992 Dublin Principles, water has been viewed as an economic good (Principle 4). The commonly accepted application of this principle for financing wastewater collection, treatment and disposal is that the "polluter pays." This is analogous to the "user pays principle" for water abstraction, and assumes that wastewater fees should be used to recover the full costs or full values of wastewater treatment and disposal.[33] This means that, in principle, the fees paid by producers and dischargers of wastewater should achieve "full cost recovery," reflecting the operation and maintenance costs and the capital costs for renewing and expanding sewerage and treatment systems, and ultimately the opportunity costs (water scarcity) and externality costs (economic and environmental) of wastewater use.

In addition to cost recovery, other economic instruments may also be effective in mobilizing financing for wastewater treatment and use projects and reducing pollution loads. These may include pricing of treated wastewater, the use of subsidies for wastewater investments, implementing effluent taxes and creating environmental funds to encourage treatment, use of abstraction taxes, and designing wastewater fees for industry based on a combination of wastewater volume charges and waste loading charges.

Sustainable cost recovery

The principle of full cost recovery has been invoked in a number of country water policy frameworks and, for example, in the EU Water Framework Directive (Box 5.5). In practice, however, the reality is that few countries practice full cost recovery through wastewater charges. Recognizing the difficulties of achieving full cost recovery, the Camdessus Panel (Winpenny, 2003) formulated the concept of "sustainable cost recovery," which has subsequently been endorsed by the OECD (2009).

The Camdessus Panel's report identified three main characteristics of sustainable cost recovery:

- An appropriate mix of tariffs, taxes and transfers (the 3Ts) to finance recurrent and capital costs, and to leverage other forms of financing;
- Predictability of public subsidies to facilitate investment (planning); and
- Tariff policies that are affordable to all, including the poorest, while ensuring the financial sustainability of service providers.

Each country must find its own balance among the three basic sources of finance (the 3Ts) for renewing and expanding wastewater management systems, but should seek to rely on wastewater fees to cover operation and maintenance costs for sewerage, treatment and disposal services and increasingly to recover a portion of capital costs. However, public budgets based on taxes often continue to play a role in covering at least part of the capital costs of wastewater infrastructure through subsidies.

In the developing countries, the path to improved cost recovery should involve a phased approach, with wastewater charges increasing in stages to cover operation and maintenance costs, and eventually depreciation of assets and some new investments. In high-income countries, it may be possible to recover some of the opportunity and externality costs. Where a phased approach is adopted, the process for setting wastewater charges should be part of general water tariff reform, and a realistic balance of central-local obligations and responsibilities should be set out.

Pricing treated wastewater

Setting appropriate fees for treated wastewater provides an important incentive mechanism to encourage wastewater use (MED-EUWI, 2007). This may include:

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[33] For a more complete discussion of the full cost and full value of water, see Rogers *et al* (1998) and OECD (2009).

- *No charging:* Treated wastewater price is set to zero so as to increase its demand and thus reduce or avoid wastewater discharge into sensitive aquatic environments;
- *Defined percentage of freshwater price:* Treated wastewater use is often offered at a lower price than freshwater, thus stimulating wastewater use by farmers and increasing its acceptance. Table 5.3 gives examples of pricing wastewater irrigation schemes in several countries.
- *Price set at willingness to pay of users:* The price of treated wastewater is based on what the market will bear, without taking into account the costs required. Farmers' willingness to pay varies depending on the expected economic returns.

Of course, if the price to farmers is less than treatment, storage, and conveyance costs, they become the beneficiaries of transfers (subsidies) from the operators or taxpayers in general. In view of the actual low cost recovery from farmers for freshwater irrigation, the price of treated wastewater will have to be kept low to remain competitive and subsidies will persist.

Table 5.3 Examples of pricing for treated wastewater for irrigation as a percentage of freshwater price

Scheme	Freshwater price per m^3	Treated wastewater price per m^3	Percentage	Reference
Noirmoutier, FR	€1.54	€0.23-0.30	15-20%	MED-EUWI, 2007
Cyprus	€0.10	€0.10	100%	MED-EUWI, 2007
Israel	$0.31	$0.12	39%	MED-EUWI, 2007
11 projects in California, USA	n/a	n/a	Ave. 77%	APWA, 2005
Tunisia	$0.08	$0.02	25%	Kfouri *et al*., 2009
Syria	n/a	Free	0%	Kfouri *et al*., 2009
Yemen	n/a	Free	0%	Kfouri *et al*., 2009

Use of subsidies for investment

Public budgets have historically played a major role in financing initial investments in wastewater treatment through capital grants. This was the case in the USA, Europe, and Japan (Bartone, 1997) where grants were provided for wastewater treatment in general. Some developing countries are following this policy. Mexico, for example, provides a Federal grant of 50 percent of the WWTP investments.

Specifically for wastewater reclamation and use projects, the EU provides up to 50% grants for capital costs (AQUAREC, 2006), and other incentives (see Box 5.5). Similarly in the US, California provides up to 50% grants for water recycling facility planning and up to 25% capital grants for water recycling facility construction (SWRCB, 2008), and Florida is expanding grants and low-interest loans for municipal wastewater reclamation and use projects through the Regional Water Management Boards – analogous to water basin agencies (FDEP, 2003).

While there is a role for national grants (subsidies) and incentives for wastewater treatment investments in response to national environmental and agricultural priorities, care must be taken, however, to ensure that the mere existence of such grants does not distort investment decisions and promote the use of overly capital-intensive technologies when simpler, lower-cost technologies may be adequate to meet water quality objectives. In the positive examples presented in Table 5.2, a blend of private, international, and public financing was utilized in the case of Jordan, and a blend of local utility self-financing, international loan, and national grant was utilized in the cases of Monterrey and Tehran.

Effluent taxes and abstraction taxes

Several countries have introduced effluent taxes to encourage wastewater treatment and discourage discharge into natural waterways. This is an implementation of the "polluter pays principle," whereby users of water are charged for the pollution load they discharge. This tax can be utilized to create an environmental fund to encourage investment in wastewater treatment, as has been done on a river basin basis in countries like Germany, France, Brazil, China, Colombia, and Mexico (Bernstein, 1997). In addition, certain investments for the improvements in wastewater treatment and use can be offset against the effluent charge.

Abstraction taxes can be applied to pumped groundwater or diverted surface water so that farmers or other uses do not perceive freshwater as free, and may be more disposed to pay for treated wastewater.

Cost recovery from industry

To operate efficiently, wastewater treatment plants require competent operators and a steady flow of 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 high quality effluent and sludge are produced can the wastewater plant be considered successful and the capital used for its construction well invested.

The key to achieving sustainable operations and debt repayment is to charge for the wastewater volume and load discharged to municipal sewers for treatment (again, the 'polluter pays principle"). Households normally pay only a volumetric tariff for the wastewater they discharge, as the per capita pollution load varies only slightly,[34] and the volume is easily estimated as proportional to metered water consumption. Industrial discharges to municipal sewers, however, vary greatly both in volume and pollution load that they exert on a wastewater treatment plant (Bartone, 1995). Thus, large industrial dischargers will generally be charged for metered wastewater volumes, and for pollution loads in terms of the mass of organic waste (BOD_5 or COD), suspended solids (SS), nutrients (N, P) and/or other specific contaminants such as heavy metals, depending on the established treated effluent standards. This reflects the fact that the design of wastewater treatment plants is dictated in part by discharge volume (e.g., piping and hydraulic retention times for tanks), organic loading (e.g., energy requirements to supply oxygen for stabilization of organic pollutants), and SS loading (design of primary and secondary sedimentation units and digestors). If nutrient removal is required (not always the case for wastewater irrigation projects), advanced treatment processes may also have to be added and repaid by the principal contributors of nutrients. Finally, if metals or other contaminants are present in industrial wastewater, special conditioning of sludge may be required and should be charged to the source industries. Any pretreatment requirements should be met at industry expense prior to discharge into municipal sewers.

The coordination of national effluent taxes with municipal sewer use fees is essential so that a consistent message is sent to industrial dischargers. Also, it is essential to implement industrial discharge pretreatment and control programs as described in section 5.1.1, paid for by industry, so as to protect the operation of the wastewater treatment plant and guarantee the quality of effluent and sludge for subsequent agricultural use.

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[34] Per capita contributions to pollution loads have so little variance that concept of "Population Equivalent" (PE) is used in many European countries. A Population Equivalent (in waste-water monitoring and treatment) refers to the amount of oxygen-demanding substances whose oxygen consumption during biodegradation equals the average oxygen demand of the waste water produced by one person. For practical calculations, it is assumed that one unit equals 54 grams of BOD_5 per 24 hours.

Chapter 6. Concluding Remarks

Particularly in water-stressed countries, and in low-income countries, wastewater use for urban and peri-urban agriculture is an emerging priority. The limited data available in the literature indicate that wastewater irrigation is growing, and is likely to continue to grow. Four powerful drivers are responsible for this: increasing demands for limited water supplies in many parts of the world; increasing urbanization in developing countries; ever growing wastewater flows associated with the expansion of water supply and sewerage; and more urban households engaging in agricultural activities, especially if food prices continue to rise. Wastewater use for irrigation can provide a reliable source of water, improve agricultural productivity, reduce pollution, and create livelihood opportunities for urban households and contribute to their food security. However, there are tradeoffs that need to be managed, including risks to human health, plant health, and the environment.

Facing these risks and benefits, countries seeking to improve wastewater use in agriculture may pursue the following key objectives: (i) minimize risk to public health; (ii) minimize risk to the environment; (iii) improve livelihoods for urban agriculturists; and (iv) integrate wastewater into the broader water resources management context (section 3.4). Depending on the level of economic development, a combination of these objectives may be pursued (Table 6.1). For example, low-income countries are likely to put highest priority on minimizing the microbial risks to health while improving the livelihoods of urban farmers; but middle- and high-income countries may give higher priority to reducing chemical and environmental risks and, especially when they are water stressed, a fuller integration of wastewater into their water resources management system.

Table 6.1 Typical wastewater irrigation objectives of countries by level of development

Level of economic development	**Objective 1: Minimize risk to public health (priorities)**		**Objective 2: Minimize risk to environment (priority)**	**Objective 3: Improve livelihoods in Urban Agriculture (priority)**	**Objective 4: Integrate wastewater into water resources management (status)**
	Microbial Risks	**Chemical risks**			
Low-income countries	Urgent	Low	Low	Urgent	Low
Lower-middle-income countries	High	Emerging	Emerging	High	Incipient
Upper-middle-income countries	High	Urgent	Urgent	High	Evolving
High-income non-OECD countries	High	High	High	Low	Advanced
High-income OECD countries	Low	High	High, with focus on anthropogenic compounds	Nil	Advanced

Source: Authors.

Many countries have begun to address the respective objectives and progressed toward some degree of planned wastewater use in agriculture, including planning approaches, policy instruments, and investments. The most successful countries have labored for decades to achieve safe wastewater use. While each country is unique, the experiences of other countries can provide some lessons as to how to improve wastewater irrigation practices. This paper has sought to analyze a number of national experiences and understand how a country's level of development may influence pragmatic and practicable solutions for managing risks. Table 6.2 suggests types of interventions (planning approaches, policies, and investment) that may be most useful for developing countries, grouped by level of development.

Table 6.2 Typical interventions for planned wastewater use for agriculture, by level of development

Level of economic development	**Low-income countries**	**Lower-middle-income countries**	**Upper-middle-income countries**
• Typical planning approaches	• Strategic sanitation plans • Slum upgrading plans • Urban agriculture plans • Multi-barrier wastewater irrigation plans	• Sewerage master plans • Municipal wastewater treatment plans • Urban catchment plans • Urban agriculture plans • Multisectoral wastewater irrigation plan	• Wastewater reclamation and use plans • Water pollution control plans (municipal and industrial) • River basin plans • Emergency control plans
• Key policy instruments	• Water rights and land tenure security • Farmer and consumer training in safe food production and preparation practices • Sanitation subsidies for the poor	• Sustainable cost recovery • Sewer use charges for industry • Pricing irrigation water • Creation of dedicated wastewater irrigation areas • Clarification of stakeholder roles and responsibilities • Public outreach and education	• Sustainable cost recovery • Pricing treated wastewater • Effluent and abstraction taxes • Private sector involvement • Subsidies for WWTP planning and construction
• Potential areas for investments	• Urban sanitation projects • Urban agriculture projects • Urban livelihood projects • Microcredit programs • Slum-upgrading projects • Municipal management projects	• Water supply and sanitation projects • Wastewater treatment and reuse projects • Urban management and slum-upgrading projects • Irrigation projects • Industrial pollution control projects • Integrated water resources management projects	• Wastewater treatment and reuse projects; • Irrigation projects • Industrial pollution control projects • Integrated water resources management projects

Source: Authors

For those countries wishing to make it part of their water resources management strategies, the paper has the following key recommendations:

- The characteristics and key issues related to wastewater irrigation evolve as development occurs. Countries can gain considerable insight into how they might develop wastewater irrigation policies and projects by analyzing their position on the treatment ladder, and the global experience summarized in this paper.
- As unplanned wastewater irrigation with untreated wastewater around the world appears to be an order of magnitude greater than planned wastewater use, more attention should be paid to addressing and reducing the risks to the environment and especially to public health. The microbial health risks are especially severe in low- and lower-middle-income countries and disproportionately affect urban farmers and consumers, and should be given priority attention.
- The 2006 WHO Guidelines on wastewater use in agriculture present a new and radically different concept for reducing microbial health risks based on a risk assessment and management framework. For the first time, they provide countries at any level of development with the means to rationally take targeted steps to reduce health risks, even when wastewater treatment is not (yet) an option. The paper highlights the basic principles of the framework in an effort to ensure wider dissemination and application.
- The increasing industrialization of urban areas requires that chemical risks of wastewater irrigation be addressed, primarily through the introduction, progressive implementation, and enforcement of industrial wastewater pretreatment and control programs.
- As water scarcity grows, investment in wastewater treatment and irrigation systems will become more viable. To encourage such investments, governments should determine enabling wastewater use policy, establish a clear regulatory framework (based on the 2006 WHO Guidelines), and develop a strategy and action plan for moving from unplanned to planned wastewater use for irrigation.
- The wastewater use policy, the regulatory framework, and the strategy and action plan should all be set within an integrated water resource management context that addresses the institutional/planning, economic/financial, technological, and social issues that have been identified in this paper.

The experience of relatively successful countries, such as Israel and Chile, suggests that achieving safe wastewater irrigation requires steady progress on all of these fronts for several decades. Governments should be prepared to make a long-term commitment to action, and should be supported in this endeavor by the international donor community.

Annex A: Quantitative Microbial Risk Analysis: Developments since the 2006 WHO Guidelines

A.1 Selection of a More Appropriate Value for the Maximum Tolerable Additional Burden of Disease

The first task in any health-risk assessment is to establish the maximum tolerable additional burden of disease – i.e., the maximum DALY loss per person per year (pppy). The 2006 WHO Guidelines use a value of 10^{-6} pppy for this (section A2.3), but is this the most appropriate value to use, especially in low-income countries?

The Guidelines [volume 2, section 4.5] state that:

> *Wastewater treatment may be considered to be of a low priority if the local incidence of diarrheal disease is high and other water-supply, sanitation and hygiene-promotion interventions are more cost-effective in controlling transmission. In such circumstances, it is recommended that, initially, a national standard is established for a locally appropriate level of tolerable additional burden of disease based on the local incidence of diarrheal disease – for example,* $\leq 10^{-5}$ *or* ***$\leq 10^{-4}$ DALY [loss] per person per year*** [emphasis added].

This position was re-affirmed by WHO (2007) for drinking water in *Levels of Protection*, which was originally published as part of its 'Rolling Revision' of the drinking-water quality guidelines, and by WHO (2010). *Levels of Protection*, which is now formally incorporated into the WHO Drinking-water Quality Guidelines (WHO 2008a), reads in full as follows:

> *Although these Guidelines employ a* 10^{-6} *DALY [loss] per person per year reference level of risk, it is important to recognize that this level of risk may not be achievable or realistic in some locations and circumstances. This is because the magnitude of microbial, chemical or radio-logical contamination sources, the levels of exposure to these sources from all exposure routes (water, food, air, direct personal contact, etc.) and* ***the overall disease burden from these sources may be such that setting a 10^{-6} DALY [loss] per person per year level of risk from waterborne exposure is neither realistically attainable nor consistent with the overall levels of risk from all sources of exposure****. That is, in locations or situations where the overall burden of disease from microbial, chemical or radiological exposures by all exposure routes is very high, setting a* 10^{-6} *DALY [loss] per person per year annual risk from waterborne exposure will have little impact on the overall disease burden.* ***Therefore, setting a less stringent level of acceptable risk, such as 10^{-5} or 10^{-4} DALY [loss] per person per year, from waterborne exposure may be more realistic, yet still consistent with the goal of providing high-quality, safer water and encouraging incremental improvement of water quality*** [emphasis added].

In accordance with the Stockholm Framework (Fewtrell and Bartram 2001), this should also be applied to wastewater use in agriculture. The 'harmony' of the Stockholm Framework is that the acceptable disease risk from all water-related exposures should be the same − i.e., the tolerable additional burdens of disease from, for example, drinking fully-treated drinking water, from working in wastewater-irrigated fields, and from consuming wastewater-irrigated crops. Therefore, if a DALY loss of $\leq 10^{-x}$ pppy is acceptable for drinking fully-treated drinking water, then it is also acceptable for working in wastewater-irrigated fields and consuming wastewater-irrigated foods eaten uncooked.

This is really the key to the adoption of the 2006 Guidelines in developing countries since setting a tolerable maximum additional burden of disease of 10^{-4} DALY loss pppy, for example, means that the design disease risk and the design infection risk are both 2-log units higher, and the required pathogen reductions 2 log units lower, than for the 10^{-6} DALY loss pppy adopted as the 'default' value in the 2006

WHO Guidelines. However, it has to be decided whether a maximum tolerable additional DALY loss of 10^{-4} pppy acceptable or not.

Reasons in favor of a maximum tolerable additional DALY loss of 10^{-4} pppy

1. The reason why the 2006 Guidelines use this value of 10^{-6} DALY loss pppy is because, as noted in section A2.3, it is used in the third edition of the WHO *Drinking-water Quality Guidelines* (WHO, 2004, 2008a) since it corresponds very closely to the fatal waterborne 70-year lifetime cancer risk of 10^{-5} per person accepted by US EPA (Munro and Travis 1986). This 70-year risk of 10^{-5} per person is equivalent to an annual risk of 1.4×10^{-7} per person. Whether this is a reasonable level of acceptable risk can only be judged by knowing how many Americans die each year from cancer. Horner *et al*. (2009, Table 2.5) give the 2006 age−adjusted mortality rate from all causes of cancer for both sexes and all races as 181.07 per 100,000 population – i.e., an incidence of 1.8×10^{-3} pppy. Thus the fatal waterborne-cancer risk of 1.4×10^{-7} pppy is four orders of magnitude lower than the actual fatal all−cancer incidence of 1.8×10^{-3} pppy.

A DALY loss of 10^{-4} pppy would be equivalent to a fatal waterborne lifetime cancer risk of 10^{-3} per person and thus to an annual risk of $\sim 10^{-5}$ per person. This is two orders of magnitude lower than the actual fatal all−cancer incidence of $\sim 10^{-3}$ pppy – i.e., an additional DALY loss of 10^{-4} pppy would increase this by only ~1%.

2. The current global incidence of diarrheal disease is extremely high: in order-of-magnitude terms it is 0.1−1 pppy (Table A3.1; see also Kosek *et al*. 2003). A tolerable diarrheal disease risk of 10^{-2} pppy, equivalent to a 10^{-4} DALY loss pppy, is 1−2 orders of magnitude lower than the current diarrheal-disease incidence. For an individual it is equivalent to an additional episode of diarrheal disease once every 100 years (essentially once per lifetime), which is hardly a matter of significant public health concern − see also Haas (1996, 8) who comments on US EPA's use of a waterborne-disease risk of 10^{-4} pppy as follows:

> *It is becoming apparent that some key factors used for computing the 1:10,000 level of acceptable risk may not be correct. ... the total burden of waterborne illness associated with current water treatment practice in the United States may be as high as several million cases per year. This would translate to an annual illness rate of perhaps 1:100, suggesting that the current benchmark* [of 1:10,000] *may be far too stringent.*

3. Low- and middle-income countries diarrheal diseases caused a total DALY loss of 59 million in 2001 (Lopez *et al*., 2006; Ezzati *et al*., 2006). Thus in 2001, for the then total developing-country population of 5,615 millions (UNFPA 2002), the DALY loss due to diarrheal diseases was:

$$\frac{\text{59 million DALY lost per year}}{\text{5,615 million people}} = \sim 0.0105 \text{ pppy}$$

An additional DALY loss of 10^{-4} pppy would increase this to 0.0106 pppy – i.e., an increase of just under 1%. Such an increase is not epidemiologically significant (and, in any case, would be extremely difficult to detect).

Table A.1. Diarrheal disease (DD) incidence per person per year in 2000

World region	DD incidence in all ages	DD incidence in 0−4 year olds	DD incidence in 5−80+ year olds
Industrialized countries[a]	0.2	0.2–1.7	0.1–0.2
Developing countries	0.8–1.3	2.4–5.2	0.4–0.6
Global average	0.7	3.7	0.4

[a] In some industrialized countries diarrheal disease incidence is much higher − for example, 0.92 pppy for ‘infectious gastroenteritis’ in Australians of all ages (Hall *et al*., 2005) and 0.79 pppy for ‘acute gastroenteritis’ in Americans of all ages (Mead *et al*., 1999) − i.e., in the developing-country range shown in the table.
Source: Mathers *et al*. 2002.

Thus it seems perfectly reasonable to accept a maximum additional DALY loss of 10^{-4} pppy for wastewater use in agriculture. The required pathogen reductions would then be:

- To protect fieldworkers’ health (restricted irrigation, labor-intensive agriculture): 2 log units, and
- To protect crop consumers’ health (unrestricted irrigation): 4−5 log units.

The implications of these required pathogen reductions are:

- Wastewater treatment processes to achieve a pathogen reduction of only 2 log units are very simple and very low-cost, and
- Reliable post-treatment health-protection control measures (Table 4.2) can easily achieve the remaining 2−3-log unit reduction required for unrestricted irrigation − for example, pathogen die-off (which can be expected to achieve a reduction of at least 2 log units in warm climates) and produce washing in clean water (1 log unit).

A.2 Improved Method for Estimating Annual Infection Risks

Since the publication of the 2006 WHO Guidelines, an improved method of estimating annual infection risks from QMRA-MC simulations has been developed by Karavarsamis and Hamilton (2010), as follows:

1. Using the appropriate dose-response equation in an appropriate QMRA-Monte Carlo computer program, an estimate of median annual infection risk is determined by a Monte Carlo simulation in which the number of iterations is set equal to the number of days of exposure per year.
2. This is repeated 9,999 times, so that there are 10,000 estimates of median annual infection risk.

The median and 95-percentile values of these 10,000 estimates are then calculated in order to provide a much more robust estimate of median and 95-percentile annual infection risks.

Thus the program determines 10,000 estimates of median annual risk based on what happens in any one year of exposure (i.e., *n* exposures to a pathogen dose *d*), rather than (as in the procedure used in the Guidelines) a much less robust estimate of median annual risk determined from 10,000 estimates of annual risk based on what happens on any one day of exposure. This approach results in similar values for estimates of median annual risks, but much lower estimates for 95-percentile annual risks, and there is less ‘spread’ of results (Table A.2).

Table A.2. Unrestricted irrigation: comparison of the Karavarsamis-Hamilton method and the method used in the WHO Guidelines for estimating annual rotavirus infection risks from the consumption of wastewater-irrigated lettuce by 10,000 Monte Carlo simulations [a]

Wastewater quality (*E. coli* numbers per 100 mL)		Rotavirus infection risk pppy estimated by the method of Karavarsamis and Hamilton (2010)	Rotavirus infection risk pppy estimated by the method used in the 2006 WHO Guidelines
10^3–10^4	Median risk:	0.36	0.30
	95%-ile risk:	0.39	0.71
	Minimum:[b]	0.30	1.1×10^{-2}
	Maximum:[b]	0.44	0.97
100–1000	Median risk:	4.5×10^{-2}	3.5×10^{-2}
	95%-ile risk:	4.9×10^{-2}	0.11
	Minimum:	3.5×10^{-2}	1.0×10^{-3}
	Maximum:	5.5×10^{-2}	0.27
10–100	Median risk:	4.6×10^{-3}	3.5×10^{-3}
	95%-ile risk:	5.0×10^{-3}	1.2×10^{-2}
	Minimum:	3.5×10^{-3}	9.5×10^{-5}
	Maximum:	5.7×10^{-3}	3.0×10^{-2}

[a] Assumptions: 100 g lettuce eaten per person per 2 days; 10–15 mL wastewater remaining on 100 g lettuce after irrigation; 0.1–1 rotavirus per 10^5 *E. coli*; no pathogen die-off; $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$.
[b] The lowest and highest values of the 10,000 risk simulations.

Tables A.3 and A.4 detail the QMRA-MC estimates of infection risk for restricted and unrestricted irrigation, respectively, in the same way as determined in the 2006 WHO Guidelines, but with two important differences: (a) use of the Karavarsamis-Harrison method, and (b) without any pathogen die-off. The implications are:

- ***Restricted irrigation:*** if a maximum tolerable DALY loss of 10^{-4} pppy is adopted for fieldworkers (rather than the 10^{-6} DALY loss pppy used in the Guidelines), the tolerable rotavirus infection risk is ~10^{-1} and a pathogen reduction of 2 log units is required, which has to be achieved by wastewater treatment.
- ***Unrestricted irrigation:*** if a maximum tolerable DALY loss of 10^{-4} pppy is also adopted for consumers, and thus a tolerable rotavirus infection risk of ~10^{-1}, then a pathogen reduction of 4 log units is required (from 10^7–10^8 per 100 ml to 10^3–10^4 per 100 ml), which could be achieved by wastewater treatment (2 log units, as for restricted irrigation) and, for example, die-off (2 log units).

Table A.3. Restricted irrigation: labor-intensive agriculture with exposure for 300 days per year − median infection risks from involuntary ingestion of wastewater-contaminated soil estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations[a]

Soil quality (*E. coli* per 100 g)[b]	Infection risk per person per year		
	Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7−10^8	1	0.70	2.1×10^{-2}
10^6−10^7	0.96	0.12	2.1×10^{-3}
10^5−10^6	0.28	1.3×10^{-2}	2.1×10^{-4}
10^4−10^5	3.3×10^{-2}	1.3×10^{-3}	2.1×10^{-5}
10^3−10^4	3.3×10^{-3}	1.3×10^{-4}	2.1×10^{-6}

[a] Assumptions: 10−100 mg soil ingested per person per day for 300 days per year; 0.1−1 rotavirus and *Campylobacter*, and 0.01−0.1 *Cryptosporidium* oocyst, per 10^5 *E. coli*; $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$ for rotavirus; $N_{50} = 896 \pm 25\%$ and $\alpha = 0.145 \pm 25\%$ for *Campylobacter*; $r = 0.0042 \pm 25\%$ for *Cryptosporidium*. No pathogen die-off.

[b] Soil quality taken, as a worst-case scenario, as the wastewater quality.

Table A.4. Unrestricted irrigation: median infection risks from the consumption of wastewater-irrigated lettuce estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations[a]

Wastewater quality (*E. coli* per 100 mL)	Infection risk per person per year		
	Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7−10^8	1	1	0.94
…			
10^3−10^4	0.37	1.7×10^{-2}	2.9×10^{-4}
100−1000	4.4×10^{-2}	1.7×10^{-3}	2.9×10^{-5}
10−100	4.6×10^{-3}	1.8×10^{-4}	2.9×10^{-6}
1−10	4.6×10^{-4}	1.7×10^{-5}	2.9×10^{-7}

[a] Assumptions: 100 g lettuce eaten per person per 2 days; 10−15 mL wastewater remaining on 100 g lettuce after irrigation; 0.1−1 rotavirus and *Campylobacter*, and 0.01−0.1 *Cryptosporidium* oocyst, per 10^5 *E. coli*; no pathogen die-off; $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$ for rotavirus; $N_{50} = 896 \pm 25\%$ and $\alpha = 0.145 \pm 25\%$ for *Campylobacter*; $r = 0.0042 \pm 25\%$ for *Cryptosporidium*.

A.3. Unrestricted Irrigation: Norovirus Infection Risks

Recently it has become possible to use QMRA-Monte Carlo techniques to estimate norovirus infection risks (Mara and Sleigh 2010a,c). The dose-response data needed to do this were only published in 2008 (Teunis *et al*. 2008), so it was not possible for norovirus to have been considered in the 2006 WHO Guidelines.

Norovirus (NV, formerly called Norwalk or Norwalk-like virus) is the major viral pathogen causing diarrheal disease in adults − in contrast rotavirus mainly affects children under 5, and commonly under 2, years of age, although NV does cause diarrhea in children (Patel *et al*., 2008). It is therefore a better reference viral pathogen than rotavirus for wastewater-use studies as young children are less exposed than adults, either as field-workers (although they may play in wastewater-irrigated fields while their mothers work in them) or as consumers (children under 2, especially, eat little wastewater-irrigated foods). That norovirus is a more suitable reference viral pathogen than rotavirus is illustrated by the fact that in the USA during 1998−2007 there were 1,773 confirmed foodborne norovirus outbreaks, but only 4 confirmed foodborne rotavirus outbreaks (CDC 2009).

Using a DALY loss per case of 9×10^{-4} per case of NV disease (Kemmeren *et al*., 2006) and an NV disease/infection ratio of 0.8 (Moe 2009), the tolerable NV disease and infection risks corresponding to a tolerable DALY loss of 10^{-4} pppy are:

$$\text{Tolerable NV disease risk} = \frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of NV disease}} = \frac{10^{-4}}{9 \times 10^{-4}} = 0.11 \text{ pppy}$$

$$\text{Tolerable NV infection risk} = \frac{\text{Tolerable NV disease risk pppy}}{\text{NV disease/infection ratio}} = \frac{0.11}{0.8} = 0.14 \text{ pppy}$$

The NV dose-response dataset of Teunis *et al.* (2008) was used in place of the beta-Poisson equation in the QMRA-MC computer program developed to determine median NV infection risks pppy. The resulting estimates of median risk obtained, using the same assumptions as for the index pathogens in Table A.4, are given in Table A.5, which shows that a reduction of 4 log units results in an NV infection risk of 0.25 pppy, which is only marginally higher than the tolerable NV infection risk of 0.14 pppy determined above. Table A.5 also includes, for comparison, rotavirus infection risks – these are broadly similar to the norovirus infection risks.

Lettuce consumption in urban Ghana: norovirus infection risks

Exposure to wastewater pathogens present in wastewater-irrigated foods varies with differences in consumption patterns which need to be accounted for in the risk calculations. For example, Seidu *et al.* (2008) reported that people in urban Ghana commonly consume ~10−12 g of lettuce in ready-to-eat street-vended food on each of four days per week.[35] NV infection risks for a DALY loss of 10^{-4} pppy and for this Ghanaian consumption of lettuce were determined by 10,000 Karavarsamis-Hamilton Monte Carlo simulations for various wastewater qualities (Table A.6). A 3-log unit NV reduction achieves an NV infection risk of 0.3 pppy, which is a little higher than the tolerable NV infection risk of 0.13 pppy. However, a 4-log unit reduction is feasible as it could be simply achieved by treatment (1 log unit) and produce disinfection (3 log unit) (*cf*. Table 4.2).

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[35] This refers to a specific situation in one developing country and may or may not be representative of what happens elsewhere; however, it is much less than the 100 g of lettuce consumed on alternate days used by Shuval et al. (1997) to reflect the situation in Israel (this value of 100 g per 2 days was also used in the 2006 WHO Guidelines).

Table A.5. Unrestricted irrigation: median norovirus and rotavirus infection risks per person per year from the consumption of 100 g of wastewater-irrigated lettuce every two days estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations[a]

Wastewater quality (*E. coli* per 100 mL)	Median norovirus infection risk pppy	Median rotavirus infection risk pppy
10^7−10^8	1	1
…		
10^3−10^4	0.25	0.36
100−1000	2.9×10^{-2}	4.5×10^{-2}
10−100	2.9×10^{-3}	4.6×10^{-3}

[a] Assumptions: 10−15 mL wastewater remaining on 100 g lettuce after irrigation; 0.1−1 norovirus per 10^5 *E. coli*; no pathogen die-off; $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$ for rotavirus; and dose-response data (Teunis *et al*., 2008) ± 25% for norovirus.
Source: Mara and Sleigh, 2010a.

Table A.6. Unrestricted irrigation: median norovirus infection risks per person per year from the consumption of 10−12 g of wastewater-irrigated lettuce on four occasions per week estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations[a]

Wastewater quality (*E. coli* per 100 mL)	Median norovirus infection risk pppy
10^7−10^8	1
…	
10^4−10^5	0.31
10^3−10^4	3.6×10^{-2}

[a] Assumptions: 10−15 mL wastewater remaining on 100 g lettuce after irrigation; 0.1−1 norovirus per 10^5 *E. coli*; no pathogen die-off; dose-response data (Teunis *et al*., 2008) ± 25%.
Source: Mara and Sleigh, 2010a.

Parameters used in QMRA risk simulations

Table A.7 lists the parameters used in QMRA risk simulations and gives recommendations for the ranges to be used for each.

Table A.7. Parameters used in QMRA-MC risk simulations

Parameter	Units	Notes
E. coli (or fecal coliform) count in wastewater (unrestricted irrigation) or in soil (restricted irrigation)	per 100 mL or per 100 g	Run the QMRA-MC program for single-log ranges (10^x−10^{x+1})—e.g., for unrestricted irrigation, from 10^7−10^8 (raw wastewater) to 1−10 ("Californian" treated wastewater)
Number of noroviruses per 10^5 *E. coli*	n.a.	Typical range: 0.1−1.
Wastewater remaining on 100 g crop after irrigation (unrestricted irrigation)	mL	Value depends on crop – e.g., 10−15 mL for lettuce, 1−5 mL for onions[a]
Quantity of crop consumed per person (unrestricted irrigation)	g per exposure event	Use local values[b]
Quantity of soil ingested per person (restricted irrigation)	mg per day	Use, for example, 10−100 mg per day for labor-intensive agriculture, and 1−10 mg per day for highly mechanized agriculture
Exposure (every *n* days for unrestricted irrigation, or *n* days per year for restricted irrigation)	n.a.	For unrestricted irrigation this could be a fixed value—e.g., 2 days, as used by Shuval *et al*. (1997), or a range—e.g., 3−5 days for someone who eats a sandwich on 3−5 days per week.
Pathogen reduction factor [die-off]	log units	Set range to 0–0 for die-off to be excluded from QMRA-MC risk simulations.
Disease/infection ratio	n.a	Set range to 1−1 for infection risk to equal disease risk (i.e., to determine norovirus infection risks).
Variation of dose-response data from value in dataset	±%	Commonly ±25%. This allows for some uncertainty in the dose-response dataset.
Number of simulations in each QMRA-MC run	n.a.	Usually 10,000 or 1000.

[a] Shuval *et al*. (1997) found mean values of 10.8 mL per 100 g lettuce and 0.4 mL per 100 g cucumbers. Hamilton (2005) (quoted in EPHC/NRMMC/AHMC 2006) reported mean values of 3.3–8.9 mL per 100 g cabbages (three types) and 1.9 mL per 100 g broccoli.

[b] Shuval *et al*. (1997) used a fixed value of 100 g in Israel; Seidu *et al*. (2008) used a range of 10−12 g in Ghana.

A.4. Unrestricted Irrigation: *Ascaris* Infection Risks

Ascaris lumbricoides parasitizes ~1.2 billion people in developing countries (de Silva *et al*. 2003). Female *Ascaris* worms produce ~200,000 eggs per day and, although most *Ascaris* eggs only survive for a few weeks on crop surfaces, some remain viable for several months and so represent a risk to health when they are ingested with wastewater-irrigated foods eaten uncooked (Strauss 1985). It would be very useful to be able to quantify *Ascaris* risks as its properties (pathogenicity, development and survival in the environment) are very different from those of viral and bacterial pathogens, despite it having an overall feco-oral environmental transmission route.

Ascaris dose-response data were published only in 2009 (Navarro *et al*. 2009), so it was not possible to have used *Ascaris* as a reference helminthic pathogen in the 2006 WHO Guidelines. Even though the 2006 WHO guideline value for helminth eggs of ≤1 egg per liter of treated wastewater is based on epidemiological data, it is nevertheless very useful to be able to determine required log unit reductions of *Ascaris* (which is generally the commonest helminth and the eggs of which are able to survive for very long periods of time in the environment) by QMRA and thus to split these between wastewater treatment and post-treatment health-protection control measures (Table A.2), as is done for viral, bacterial and protozoan pathogens, since this allows a lower level of wastewater treatment.

For a tolerable DALY loss of 10^{-4} pppy, a DALY loss per case of ascariasis of 8.25×10^{-3} (Chan 1997) and, as a worst-case scenario, an *Ascaris* disease/infection ratio of 1 (i.e., all those infected with *Ascaris* develop ascariasis), the tolerable *Ascaris* infection risk is given by:

$$\frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of ascariasis}} = \frac{10^{-4}}{8.25 \times 10^{-3}} = 1.2 \times 10^{-2} \text{ pppy}$$

Median *Ascaris* infection risks pppy from the consumption by children under 15 of raw carrots irrigated with wastewaters containing specified numbers of *Ascaris* eggs were determined by a QMRA-Monte Carlo computer program based on the Karavarsamis-Hamilton method and using the values of N_{50} and α determined by Navarro *et al*. (2009) for the beta-Poisson equation (these authors found that the beta-Poisson equation was better for *Ascaris* than the exponential equation). The resulting estimates of median *Ascaris* infection risk are given in Table A.8, which shows that 1 egg per liter results in an *Ascaris* infection risk of ~6×10^{-3} pppy, which is just below the tolerable *Ascaris* infection risk of ~10^{-2} pppy determined above. Thus, in ascariasis-hyperendemic areas (~1000 eggs per liter of raw wastewater) a 3-log unit reduction of *Ascaris* eggs is required. This could be achieved, for example, by a 1-log unit reduction by treatment and a 2-log unit reduction by produce peeling (*cf*. Table 4.2).

Table A.8. Unrestricted irrigation: median *Ascaris* infection risks for children under 15 from the consumption of raw wastewater-irrigated carrots estimated by 10,000 Karavarsamis−Hamilton Monte Carlo simulations[a]

Number of *Ascaris* eggs per litre of wastewater	Median *Ascaris* infection risk pppy	Notes
100–1000	0.86	Raw wastewaters in hyperendemic areas.
10–100	0.24	Raw wastewaters in endemic areas.
1–10	2.9×10^{-2}	Treated wastewaters.
1	5.5×10^{-3}	Wastewater quality required to comply with the 1989 and 2006 WHO Guidelines.
0.1–1	3.0×10^{-3}	Highly treated wastewaters.
0.1	5.5×10^{-4}	Wastewater quality recommended by Blumenthal *et al.* (2000) to protect children under 15.
0.01–0.1	3.0×10^{-4}	Treated wastewaters in non-endemic areas.

[a] Assumptions: 30–50 g raw carrots consumed per child per week; 3–5 mL wastewater remaining on 100 g carrots after irrigation; N_{50} = 859 ± 25% and α = 0.104 ± 25%; no *Ascaris* die-off .

Source: Mara and Sleigh, 2010b.

A.5. Restricted Irrigation: Norovirus Infection Risks

In the 2006 Guidelines health risks for restricted irrigation were estimated by assuming the fieldworkers involuntarily ingested wastewater-contaminated soil. An ingestion of 10−100 mg of soil per day for 300 days per year was used to represent labor-intensive agriculture in developing countries. With hygiene education it is not infeasible to postulate that the quantity of soil ingested can be substantially reduced, perhaps to 1−10 mg per day. Table A.9, which gives norovirus infection risks for this quantity of soil ingestion for 300 days per year, shows that a norovirus reduction of 1 log unit results in a norovirus infection risk of 0·32 pppy (i.e., one episode of norovirus diarrhoea every three years), which is higher than the tolerable norovirus infection risk of 0·13 pppy determined in section A.3 (one episode of norovirus diarrhoea every seven years), but acceptable if combined with sustained hygiene education and the provision of (a) hand-washing facilities on or adjacent to the site being irrigated, and (b) oral rehydration salts/solutions whenever required.

A.6 Restricted Irrigation: *Ascaris* Infection Risks

Table A.10 gives the equivalent calculations for *Ascaris* as given in Table A.9 for norovirus. It shows that, in areas where ascariasis is hyperendemic, a 1-log unit reduction results in an ascariasis risk of $1{\cdot}5 \times 10^{-2}$ pppy, which is close to the tolerable ascariasis risk of $1{\cdot}2 \times 10^{-2}$ pppy determined in section 3.4.

Table A.9. Restricted irrigation: median norovirus infection risks from the ingestion of 1−10 mg of wastewater-saturated soil per day for 300 days per year estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations[a]

Noroviruses per 100 g soil	Median norovirus infection risk pppy
100−1000	0.98
10−100	0·32
1−10	$3{\cdot}7 \times 10^{-2}$

[a]Assumptions: soil quality per 100 g taken, as a worst-case scenario, as the wastewater quality per 100 mL; 10^5 noroviruses per 10^5 *E. coli*; no pathogen die-off; dose-response data (Teunis *et al.*, 2008) ± 25%.

Source: Mara and Sleigh, 2010c.

Table A.10. Restricted irrigation: median *Ascaris* infection risks from the ingestion of 1−10 mg of wastewater-saturated soil per day for 300 days per year estimated by 10,000 Karavarsamis-Hamilton Monte Carlo simulations[a]

Ascaris eggs per kg soil	Median *Ascaris* infection risk pppy
100−1000	0·14
10−100	1.5×10^{-2}
1−10	$1{\cdot}5 \times 10^{-3}$

[a]Assumptions: soil quality (eggs per kg) taken, as a worst-case scenario, as the wastewater quality (eggs per liter); $N_{50} = 859 \pm 25\%$ and $\alpha = 0{\cdot}104 \pm 25\%$; no pathogen die-off.

Source: Mara and Sleigh, 2009c.

Availability of QMRA-MC computer programs

The QMRA-Monte Carlo computer programs referred to in this Annex are freely available, together with User Guides, at:

http://www.personal.leeds.ac.uk/~cen6ddm/QMRA.html

All these programs, with the exception of the one for *Ascaris*, use a range of pathogen-to-*E. coli* numbers − for example, 0.1−1 pathogen per 10^5 *E. coli*. This approach was taken by Shuval *et al*. (1997) and adopted in the 2006 WHO Guidelines, as there are very few, and in many situations no, data on pathogen numbers in developing-country wastewaters, whereas *E. coli* (or fecal coliform) numbers are available or, if not available, are easy to obtain. However, setting the range of pathogen numbers to 10^5−10^5 per 10^5 *E. coli* in the QMRA-MC programs (i.e., equating pathogen and *E. coli* numbers) means that the programs would determine pathogen risks directly (as done, in Table A.9 for norovirus), rather than as a range of *E. coli* numbers per 100 mL.

A "QMRA Beginner's Guide" is available at:

http://www.personal.leeds.ac.uk/~cen6ddm/QMRAbeginners.html

Annex B: Verification Monitoring of Pathogen Reductions Achieved by Wastewater Treatment and Health-protection Control Measures

B.1 Wastewater Treatment

It is not generally possible in developing countries, nor in most non-research situations in industrialized countries, to undertake routine monitoring of viral, bacterial and protozoan pathogens in treatment-plant effluents. Recourse has to be made to the use of indicator bacteria, typically fecal coliforms (section B.1.2).

Helminth eggs can be counted in raw and treated wastewaters, although the enumeration technique is not straightforward. If waste stabilization ponds are used for wastewater treatment, then the mean hydraulic retention time in the ponds can be used to calculate egg removal efficiencies (section B.1.2).

B.1.1 Indicator bacteria

Fecal coliforms are the most commonly used indicator bacteria, and they are very easy to count using a very simple 5-tube most-probable-number (MPN) technique – full details of how to conduct this test are given in Ayres and Mara (1996).

If the QMRA-MC risk simulations show that wastewater treatment should achieve a 2-log unit pathogen reduction (see section A3.2), then the fecal coliform count has to be reduced from 10^7−10^8 per 100 mL to 10^5−10^6 per 100 mL, although a prudent designer might design the treatment plant to achieve a 3-log unit reduction of fecal coliforms (i.e., from 10^7−10^8 per 100 mL to 10^4−10^5 per 100 mL), given the uncertainty of the relationship between pathogen and fecal coliform numbers and how this might change through the treatment plant. Regular (perhaps weekly or fortnightly, but certainly monthly) monitoring would be required to show whether or not the effluent from the treatment plant contained $\leq 10^5$ (or $\leq 10^4$) fecal coliforms per 100 mL.

B.1.2 Helminth egg removal in waste stabilization ponds

Waste stabilization ponds (WSP) (Mara 2004, Shilton 2006) are currently the only wastewater treatment process that can be reliably designed for helminth egg removal (Ayres *et al*., 1992). The design equation is:

$$R = 100[1 - 0.41\exp(-0.49\theta + 0.0085\theta^2)] \qquad \text{(B.1)}$$

where R is the percentage egg removal in a WSP which has a mean hydraulic retention time of θ days. Thus, if the number of eggs in the raw wastewater (E_i eggs per liter) and θ are known, the number of eggs in the pond effluent (E_e eggs per liter) can be determined.

For a series of WSP comprising an anaerobic pond, a facultative pond and n equally-sized maturation ponds E_e is given by:

$$E_e = E_i(1 - r_a)(1 - r_f)(1 - r_m)^n \qquad \text{(B.2)}$$

where $r = R/100$ and the subscripts a, f and m refer to the anaerobic, facultative and maturation ponds, respectively – see 'Worked Example A' below.

Equation B.2 can be rearranged as follows:

$$E_i = \frac{E_e}{(1 - r_a)(1 - r_f)(1 - r_m)^n} \qquad \text{(B.3)}$$

Equation B.3 is useful because it permits the WSP operator to determine the maximum number of eggs in the raw wastewater that the ponds can remove down to any required level of E_e eggs per liter − see 'Worked Example B' below.

Worked Example A: Known number of eggs per liter of raw wastewater

Suppose (a) the raw wastewater to be used for unrestricted irrigation contains 1000 eggs per liter; (b) QMRA-MC risk simulations have shown that a total *Ascaris* egg reduction of 3 log units is required for unrestricted irrigation (*cf*. Table A.8); and (c) it has been decided that this is to be achieved by (i) wastewater treatment in a WSP system comprising a 1-day anaerobic pond and a 5-day facultative pond, and (ii) produce washing in clean water, which achieves a 1-log unit *Ascaris* reduction. Thus wastewater treatment in the WSP has to achieve a 2-log unit *Ascaris* reduction and therefore the effluent from the facultative pond has to contain ≤10 eggs per liter. From equation B.1 r_a ($=R_a/100$) = 0.75 and $r_f = 0.96$ [$r_m = 0$ as there are no maturation ponds], and therefore from equation B.2:

$$E_e = E_i(1 - r_a)(1 - r_f) = 1000(1 - 0.75)(1 - 0.96) = 10 - \textit{satisfactory}.$$

Verification monitoring can thus simply be based on measurements of helminth eggs in the raw wastewater (see Ayres and Mara, 1996) and the values of the WSP retention times in the irrigation season (these are given by V/Q, where V is the pond volume in m^3 and Q is the wastewater flow in m^3/day). This is very advantageous as counting the number of eggs per liter of raw wastewater is much easier than counting egg numbers of ~10 per liter and below.

Worked Example B: Unknown number of eggs per liter of raw wastewater

Suppose that the exact number (or range of numbers) of eggs per liter of the raw wastewater is unknown, but that it is known that local raw wastewaters 'never' contain more than around 200−500 eggs per liter. Then, from equation B.3, for the 1-day anaerobic pond and the 5-day facultative pond to produce an effluent with ≤10 eggs per liter:

$$E_i = \frac{E_e}{(1 - r_a)(1 - r_f)} = \frac{10}{(1 - 0.75)(1 - 0.96)} = 1000 \text{ eggs per liter}$$

Thus there would be little need for verification monitoring – perhaps only once or twice during the irrigation season – as the number of eggs in the raw wastewater that the WSP system can cope with (i.e., without exceeding the required effluent quality) is much higher than the numbers of eggs commonly encountered in the raw wastewater.

B.2 Health-protection Control Measures

To assess the efficacy of the health-protection control measures listed in Table 4.2, a Hazard Analysis Critical Control Point (HACCP) system should be established. HACCP systems consist of the following seven principles (FAO, 2003):

1. Conduct a hazard analysis.
2. Determine the Critical Control Points (CCPs).
3. Establish critical limit(s).
4. Establish a system to monitor control of the CCP.
5. Establish the corrective action to be taken when monitoring indicates that a particular CCP is not under control.
6. Establish procedures for verification to confirm that the HACCP system is working effectively.

7. Establish documentation concerning all procedures and records appropriate to these principles and their application.

Principles 1−4 for unrestricted irrigation:

Principle 1: HACCP is applied to both the wastewater treatment plant and each of the post-treatment health-protection control measures in operation since if one of them performs sub-optimally or fails completely, it becomes a health hazard.

Principle 2: The number of CCPs corresponds to the wastewater treatment plant effluent and each post-treatment health-protection control measures in operation.

Principle 3: The critical limit of each CCP is the number of *E. coli* (or fecal coliforms) which shows unequivocally that the design removal for the CCP is being achieved. In the case of pathogen die-off (*x* log units per day) it is not possible to determine the time interval between the last irrigation and consumption (as the food may be kept refrigerated at home for a few days before it is consumed), but it is possible to monitor the time interval between the last irrigation and the appearance of the food in local shops and supermarkets.[36]

Principle 4: The system to monitor control of the CCP comprises sampling and microbiological analysis at an established frequency (e.g., weekly or fortnightly, certainly not less than monthly).

Since HACCP for unrestricted irrigation is solely concerned with the safety of wastewater-irrigated foods, principally those eaten uncooked, it is worth noting that ready-to-eat foods (such as prepared sandwiches and salads on sale in local shops and supermarkets) are deemed to be of 'acceptable' quality in the United Kingdom if they contain $<10^4$ *E. coli* per 100 g (Gilbert *et al*., 2000).[37] Thus if lettuce, which is a common constituent of many ready-to-eat foods, can contain up to 10^4 *E. coli* per 100 g, then it is clearly not necessary to irrigate it with a treated wastewater containing $<10^4$ *E. coli* per 100 mL, especially as post-treatment die-off always occurs. This illustrates the inherent problem with the 1989 WHO Guidelines which require ≤1000 fecal coliforms per 100 mL for unrestricted irrigation, and the inherent advantage of the Australian National and the 2006 WHO Guidelines which permit the inclusion of pathogen reductions that occur post-treatment.

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[36] This is routinely done, for example, in Australia (EPHC/NRMMC/AHMC 2006).

[37] This guideline value is used in many other countries, including Australia, Canada and New Zealand (Institute of Medicine, 2003).

Annex C: Projects on Wastewater Irrigation Approved in Fiscal Year 1999-2009

Country	Region	Project Title	Total Project Amount ($m)	Bank Commitment ($m)	Bank Commitment to Wastewater Reuse* ($m)	Wastewater Reuse as a Share of Bank Commitment (%)	FY of Approval	Status as of Sept 09	Product Line
Cape Verde	Africa	Energy and Water Project	50	17.5	1.20	7%	1999	Closed	IBRD/IDA
Mauritania	Africa	Urban Development Program	100	70	0.00	0%	2002	Active	IBRD/IDA
China	East Asia and Pacific	Second Beijing Environment Project	1255	367.9	0.00	0%	2000	Closed	IBRD/IDA and GEF[#]
China	East Asia and Pacific	Hebei Urban Environment Project	293	150	0.00	0%	2000	Closed	IBRD/IDA
China	East Asia and Pacific	Second Tianjin Urban Development Project	336	150	10.40	7%	2003	Active	IBRD/IDA
China	East Asia and Pacific	Hai Basin Integrated Water and Environmental Management Project	33	17	0.29	2%	2004	Active	GEF
China	East Asia and Pacific	Ningbo Water and Environment Project	292	130	0.00	0%	2005	Active	IBRD/IDA
Indonesia	East Asia and Pacific	Municipal Innovations Project	7.2	5	0.10	2%	1999	Closed	IBRD/IDA
Thailand	East Asia and Pacific	Sapthip Wastewater Biogas and Renewable Energy Project	5	6.5	1.36	33%	2009	Active	Carbon Offset
Brazil	Latin America and Caribbean	Rio Grande Do Norte Integrated Water Resources Management Project	59.8	35.9	0.30**	1%	2008	Active	IBRD/IDA
Egypt	Middle East and North Africa	Alexandria Development Project	110	100	0.00	0%	2008	Closed	IBRD/IDA
Iran	Middle East and North Africa	Tehran Sewerage Project	340	145	0.47	0.32%	2000	Closed	IBRD/IDA
Iran	Middle East and North Africa	Ahwaz and Shiraz Water Supply and Sanitation Project	470	279	2.28	1%	2004	Closed	IBRD/IDA
Iran	Middle East and North Africa	Northern Cities Water Supply and Sanitation Project	344	224	0.00	0%	2005	Active	IBRD/IDA
Jordan	Middle East and North Africa	Amman Water and Sanitation Management Project	136	55	0.00	0%	1999	Closed	IBRD/IDA
Jordan	Middle East and North Africa	Conservation of Medicinal and Herbal Plants Project	14	5	0.20**	4%	2003	Active	GEF
Lebanon	Middle East and North Africa	Ba'Albeck Water and Wastewater Project	50	43.53	0.39	1%	2002	Active	IBRD/IDA
Morocco	Middle East and North Africa	First Water Sector Development Policy Loan	100	100	0.00	0%	2007	Closed	IBRD/IDA
Tunisia	Middle East and North Africa	Water Sector Investment Project	258	103	3.62	4%	2000	Closed	IBRD/IDA
Tunisia	Middle East and North Africa	Tunis West Sewerage Project	72	66.8	9.10	14%	2007	Active	IBRD/IDA
Tunisia	Middle East and North Africa	Second Water Sector Investment Project	163	30.6	6.96	23%	2009	Active	IBRD/IDA
Yemen	Middle East and North Africa	Sana'a Water Supply and Sanitation Project	28	25	0.00	0%	1999	Closed	IBRD/IDA
Yemen	Middle East and North Africa	Rural Water Supply and Sanitation Project	29	20	0.20**	1%	2001	Active	IBRD/IDA
Yemen	Middle East and North Africa	Urban Water Supply and Sanitation Project	150	130	0.10**	0.08%	2003	Active	IBRD/IDA
Yemen	Middle East and North Africa	Sana'a Basin Water Management Project	30	24	0.00	0%	2003	Active	IBRD/IDA
India	South Asia	Rajasthan Water Sector Reconstructing Project	180	140	0.10**	0.07%	2002	Active	IBRD/IDA

* Estimations based on data provided in the project appraisal documents

**Estimations were not available in the project appraisal documents. Costs of studies and strategy preparation were assumed to be $ 0.1 million and costs of pilot sites were assumed to be $ 0.2 million.

GEF grant accounts for $18.6m

Source: Authors

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