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Non-Pathogenic Trade-Offs of Wastewater Irrigation

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Abstract

The volume and extent of urban wastewater generated by domestic, industrial and commercial water use has increased with population, urbanization, industrialization, improved living conditions and economic development. Most developing-country governments do not have sufficient resources to treat wastewater. Therefore, despite official restrictions and potential health implications, farmers in many developing countries use wastewater in diluted, untreated or partly treated forms with a large range of associated benefits. Aside from microbiological hazards, the practice can pose a variety of other potential risks: excessive and often imbalanced addition of nutrients to the soil; build-up of salts in the soils (depending on the source water, especially sodium salts); increased concentrations of metals and metalloids (particularly where industries are present) reaching phytotoxic levels over the long term; and accumulation of emerging contaminants, like residual pharmaceuticals. As these possible trade-offs of wastewater use vary significantly between sites and regions, it is necessary to carefully monitor wastewater quality, its sources and use for location-specific risk assessment and risk reduction.

Introduction

Increased population, urbanization, improved living conditions and economic development have driven the generation of increased volumes of wastewater by the domestic, industrial and commercial sectors (Asano et al., 2007; Lazarova and

Bahri, 2005; Qadir et al., 2009). In most developing countries, urban drainage and disposal systems are such that domestic wastewater is mixed with industrial wastewater. Although water-quality management is reported to be a high priority and a major concern of developing-country governments, most do not have sufficient resources to treat wastewater. In India, only 24 per cent of wastewater generated by households and industry is treated before its use in agriculture or disposal to rivers (Minhas and Samra, 2003). In Pakistan, only 2 per cent of wastewater is treated (IWMI, 2003). Similar challenges are found in other parts of Asia, Africa and Latin America (Scott et al., 2004). Wastewater treatment plants in most cities in developing countries are non-existent or function inadequately (Qadir et al., 2007). Therefore, wastewater in partially treated, diluted or untreated form is diverted and used by urban and peri-urban farmers to grow a range of crops (Ensink et al., 2002; Murtaza et al., 2009).

Contrary to the situation of wastewater management in most developing countries, the use of recycled (treated) wastewater has been on the increase in recent years in several countries in the Middle East and North Africa, the Mediterranean, and parts of the USA, Latin America and Australia (Qadir et al., 2007; USEPA, 2004).

Despite official restrictions and potential health implications, farmers in many developing countries use diluted, untreated or partly treated wastewater because:

- Wastewater is a reliable or often the only water source available for irrigation throughout the year.
- Wastewater irrigation often reduces the need for fertilizer application as it is a source of nutrients.
- Wastewater use involves less energy even when pumping, if the alternative clean water source is from deep groundwater, which reduces costs.
- Wastewater generates additional benefits including greater income from cultivation and marketing of high-value crops such as vegetables, which create year-round employment opportunities (Buechler and Mekala, 2005; IWMI, 2003; Keraita and Drechsel, 2004; Keraita et al., 2008; Lazarova and Bahri, 2005).

Research and decision-making on wastewater irrigation have tended to focus on the impacts on the health of food consumers and producers, economic implications for producers' livelihoods, and food diversity, quality and prices. However, the biophysical implications (both positive and negative) of wastewater use and management in agricultural ecosystems have received relatively little attention (Asano et al., 2007; Lazarova and Bahri, 2005; Pescod, 1992; Pettygrove and Asano, 1985; Qadir et al., 2009).

This chapter addresses environmental quality in wastewater source and use areas, including natural water bodies that receive wastewater, through conceptual and empirical case-study consideration of the following constituents and processes: macro- and micronutrient levels; concentrations of total salts and specific ion species; levels of heavy metals; and presence and intensity of organic constituents. Environmental quality, and the positive and negative trade-offs of these constituents and processes (Table 6.1) are the focus of this chapter. Pathogenic risks (viruses, bacteria, protozoa, helminth eggs and faecal coliforms) are addressed in Chapters 3, 4 and 5.

Wastewater sources and their possible implications

Wastewater is a generic term used for any water that has been adversely affected in quality by anthropogenic activities. Urban wastewater may be a combination of some or all domestic effluent, water from commercial establishments, industrial effluent and stormwater that does not infiltrate into soil and other urban run-off. Wastewater contains a broad spectrum of contaminants resulting from different sources, warranting suitable treatment to remove such substances before it should be used in agriculture to grow a range of crops.

Greywater comprises 50–80 per cent of residential wastewater. It is a specific term that refers to water generated from domestic processes such as dishwashing, laundry and bathing, but does not include wastewater from toilets, which is termed blackwater. Greywater is distinct from blackwater in the amount and composition of its chemical and biological contaminants. It gets its name from its cloudy appearance and from its status as being neither freshwater nor heavily polluted.

Wastewater contains different types and levels of undesirable constituents, depending on the source from which it is generated and the level of its treatment. In general, industrial wastewater contains higher levels of contaminants – metals and metalloids, and volatiles and semi-volatiles – than domestic wastewater and needs greater treatment before disposal or use. In contrast, domestic wastewater contains higher levels of pathogens. Because of the presence of residues of detergents and soaps, domestic wastewater is usually alkaline (pH > 7) unless it gets mixed with some acidic industrial constituents. In the case of mixed domestic-industrial wastewater, a common situation in developing countries, the composition of raw wastewater depends on the types and numbers of industrial units and the characteristics of the residual constituents. Table 6.1 provides an overview of different constituents of wastewater and their possible implications for agriculture, ecosystems and human health, as well as importance regionally.

Positive trade-offs

Reliable irrigation supply

In general, a reliable supply of water for irrigation and essential nutrients are critical inputs to crop-production systems; to a large extent, wastewater irrigation fulfils

Table 6.1 *Constituents of wastewater and their possible implications*

Constituent	Implications: Positive	Implications: Negative	Geographical occurrence
Macronutrients: Nitrogen (N), phosphorous (P) and potassium (K)	• No or minimal need for chemical N, P and K fertilizers • N supplied through wastewater helps in crop establishment in early growth stages by mitigating the negative effects of excess salts if added through wastewater irrigation or present in pre-irrigation soil • P added to the wastewater-irrigated soil helps in crop establishment throughout the growth period • Optimal level of K helps in crop maturity and quality, and in mitigating the negative effects of excess salts (particularly sodium) applied through wastewater irrigation or present in pre-irrigation soil	• Excess N applied through wastewater may lead to excessive vegetative growth (green biomass), delay in crop maturity, lodging and low economic yield • Excess N and P in wastewater can cause eutrophication of natural water bodies and in irrigation systems, undesirable growth of algae, periphyton attached algae and weeds • Leaching of N can cause groundwater pollution and methaemoglobinemia (generally in infants) in case of drinking N-rich groundwater (particularly high levels of nitrates, NO_3) • P can accumulate in the soil where it is immobile	• Particularly in developing countries where wastewater has high organic content (from domestic, residential, food-processing sources) and is used in untreated, partly treated and diluted forms
Total dissolved solids (TDS) and major ionic elements: sodium (Na), calcium (Ca), magnesium (Mg), chloride (Cl) and boron (B)	• Ca supplied through wastewater improves soil structure and counterbalances the negative effects of accompanying high concentrations of Na and Mg • High electrolyte concentration, particularly resulting from Ca salts, improves hydraulic properties of low-permeability soils	• Excess Na and Mg can cause deterioration of soil structure and undesirable effects on hydraulic properties such as infiltration rate and hydraulic conductivity • Excess salts impact plant growth through osmotic effects • Specific ion effects from Cl, B and Na possible, including phytotoxicity • Deterioration of water quality of natural surface-water bodies receiving wastewater or drainage from wastewater-irrigated land • Salt leaching into groundwater	• Particularly in arid and semi-arid areas with high primary salinity where large-scale wastewater irrigation is practised and agricultural drainage is either non-existent or non-functional, or where saline drainage water is reused in irrigation

Table 6.1 *(Continued)*

Constituent	Implications: Positive	Negative	Geographical occurrence
Metals and metalloids: cadmium (Cd), chromium (Cr), nickel (Ni), zinc (Zn), lead (Pb), arsenic (As), selenium (Se), mercury (Hg), copper (Cu), manganese (Mn)	• No or minimal need for micronutrient fertilizers supplying essential metals ions such as Cu, Zn, Fe, and Mn	• Excess levels in irrigated soils and the environment may reach phytotoxic levels • Systemic uptake by crops, particularly those consumed by humans and animals • Possible toxicity in humans and animals • Possible contamination of groundwater under highly permeable and shallow water table conditions	• Particularly in rapidly industrializing regions, like south and southeast Asia, where industrial waste is often mixed with domestic wastewater. • In Africa more localized e.g. near mining areas or tanneries
High organic matter content, suspended solids and algal particles	• Organic matter added through wastewater improves soil structure; can enhance cation exchange capacity and bind, and gradually releases essential nutrients for crop growth • Organic matter may also hold some undesirable metal ions rendering them in less available form for plants • Can contain nutrients	• Plugging of micro irrigation systems such as drippers and sprinklers • Hypoxic conditions due to depletion of dissolved oxygen in water • Possible occurrence of septic conditions • Possibility of increased mortality in fish and other aquatic species	• Particularly in developing countries where wastewater that is high in food, industrial and/or organic content is used in untreated or partly treated forms
Emerging contaminants (residual pharmaceuticals, endocrine disruptor compounds, active residues of personal care products)	• Only limited evidence of possible uptake by crops and the food chain, especially in developing countries where use of pharmaceuticals and personal care products is lower than in developed countries	• Possible contamination of groundwater with emerging contaminants and other contaminants, particularly under highly permeable and shallow water table conditions	• Particularly in developed countries or where industries release residual pharmaceuticals, endocrine disrupting compounds and active residues of personal care products into wastewater without treatment
Pathogens: viruses, bacteria, protozoa, helminth eggs, faecal coliforms	• None	• Can cause a range of communicable diseases for farmers, traders and food consumers, such as diarrhoea, typhoid, dysentery, cholera, gastroenteritis, ascariasis, hepatitis, ulcer, food-poisoning	• Particularly in low-income countries in tropical regions where sanitation is poor and endemic disease burden is high, like in sub-Saharan Africa

both. This is particularly important in situations where wastewater is the only source of irrigation water available throughout the year. Estimates show that at least 20 million hectares are irrigated globally with different forms of wastewater – treated, untreated, partly treated and diluted (Jiménez and Asano, 2008; Raschid-Sally and Jayakody, 2008). In terms of irrigation potential in countries producing large volumes of wastewater, Minhas and Samra (2004) estimated that wastewater generated from large urban settings in India alone can irrigate 1.5 million ha. The supply of this water is continuous and independent of the rainfall, although it is still subject to scarcity resulting from drought, canal irrigation systems and availability of electricity. Although the land holdings in wastewater-irrigated areas are often small, irrigation allows for year-round farming, which may help smallholders escape from poverty.

Nutrient availability

The nutrient potential of wastewater stems from its composition, which in turn depends on the source of generation, dilution and treatment aspects. This is illustrated in Table 6.2, which shows concentrations of macronutrients (nitrogen, N; phosphorous, P; and potassium, K) in wastewater generated from some cities in India. The concentrations of these nutrient elements are highly variable: N (11–98mg per litre), P (1–30mg per litre) and K (16–500mg per litre).

The concentrations of nutrients vary widely in wastewater. Although the nutrient-supplying capacity is considered to be a major driver for untreated wastewater use in agriculture, managing the nutrient availability in wastewater is a challenge. Treatment is generally considered to remove most nutrients, implying that farmers favour untreated over treated wastewater as an irrigation source. Comparative evaluation of macronutrient concentrations in untreated and treated wastewater from Haryana, India (Figure 6.1) suggests otherwise, revealing that treated wastewater contained sufficient levels of these nutrients (Yadav et al., 2002). The concentration of N in untreated wastewater (40.1mg per litre) decreased to 29.7mg per litre in treated wastewater, indicating 74 per cent of N was retained. The percentages of P and K retained in treated wastewater were 79 per cent and 57 per cent, respectively.

Table 6.2 *Concentrations of macronutrients (N, P and K) in wastewater generated from some cities in India*

Location	N (mg l^{-1})	P (mg l^{-1})	K (mg l^{-1})	Reference
Nagpur	55–68	9–11	31–37	Kaul et al. (2002)
Calcutta	14–17	1–2	16	Mitra and Gupta (1999)
Haryana	32–70	15–30	250–500	Gupta et al. (1998)
Haryana	25–98	4–13	28–152	Baddesha et al. (1986)
Indore	11–64	1	20–54	CSSRI (2004)

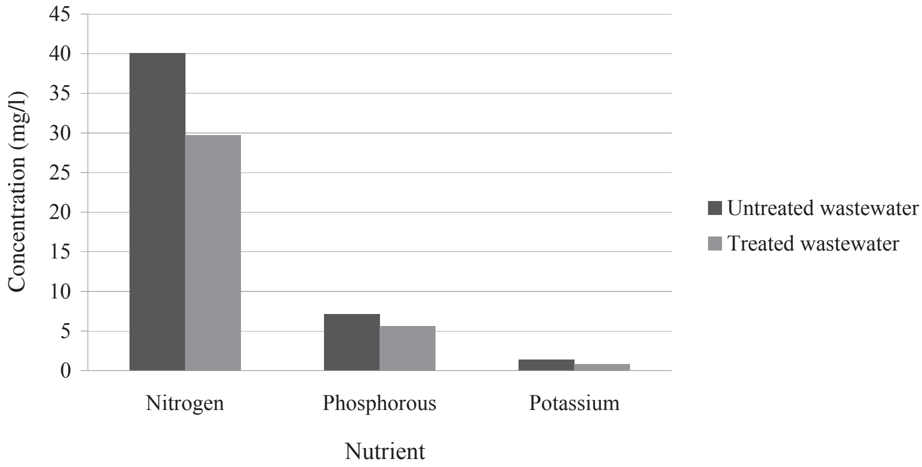

Figure 6.1 *Comparative evaluation of macronutrient concentrations in untreated and treated wastewater from Haryana, India*

Source: Based on the data from Yadav et al. (2002)

Table 6.3 *Concentrations of micronutrients (Fe, Zn and Mn) in wastewater generated from some cities in India*

Location	Fe (mg l^{-1})	Zn (mg l^{-1})	Mn (mg l^{-1})	Reference
Nagpur	1.41–1.57	0.9–1.2	0.14–0.20	Kaul et al. (2002)
Calcutta	449–656	0.3–0.4	0.65–0.66	Mitra and Gupta (1999)
Haryana	6–25	1.6–28.0	0.8–2.8	Gupta et al. (1998)
Haryana	0.6–21.8	0.13–0.90	0.25–0.60	Baddesha et al. (1986)
Indore	0.14–0.21	0.01–0.11	0.19–2.14	CSSRI (2004)

In addition to macronutrients, wastewater irrigation also adds a range of micronutrients such as iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu). Table 6.3 provides information on the concentrations of micronutrients in wastewater generated from some cities in India.

Although the fertilizer value of wastewater is of great importance, periodic monitoring is required to estimate the nutrient loads in wastewater and adjust fertilizer applications (Lazarova and Bahri, 2005). Excessive nutrients can cause nutrient imbalances, undesirable vegetative growth and delayed or uneven maturity, and can also reduce crop quality and pollute groundwater and surface water. However, an optimal supply of macro- and micronutrients through treated wastewater eliminates or minimizes the need for the application of costly chemical fertilizers.

Organic matter and organic carbon

Like the supply of nutrients through wastewater irrigation, the presence of organic matter in wastewater may have positive or negative implications depending on the nature of the organic materials. In terms of positive effects, organic matter added through wastewater improves soil structure, acts as a storehouse of essential nutrients for crop growth and enhances charge characteristics of irrigated soils, such as cation exchange capacity (CEC), which may hold undesirable metal ions on the cation exchange sites rendering them in less available form for plants. Since heavy metals in ionic form are positively charged cations, an increase in CEC results in greater chances of cations being adsorbed on the soil's exchange sites.

Studies undertaken in India on the long-term effects of wastewater irrigation on the physical properties of soil reveal an increase in aggregate stability, water-holding capacity, hydraulic conductivity and total porosity (Jayaraman et al., 1983; Minhas and Samra, 2004). There was almost a consistent increase in these soil parameters with wastewater-irrigation duration. For example, the hydraulic conductivity of the freshwater-irrigated soil was 19.1cm h^{-1}, which increased to 23.6cm h^{-1} after 15 years of wastewater irrigation; a 24 per cent increase in soil hydraulic conductivity. It further increased to 26.6cm h^{-1} after 25 years of wastewater irrigation; a 39 per cent increase over freshwater-irrigated soil (Table 6.4). The data on gradual increase in soil hydraulic conductivity in wastewater-irrigated soils suggest an increase of about 1.5 per cent per year. Soil hydraulic conductivity is a crucial soil physical parameter that indicates the ease of water movement through the soil profile. The increase in other soil physical parameters, such as aggregate stability, water-holding capacity and total porosity, contributes to water storage in the soil, thereby increasing water-use efficiency and productivity. This is particularly important under conditions in which water resources for agriculture are scarce.

In addition to the beneficial effects of soil organic matter on soil physical parameters, the organic carbon status of wastewater-irrigated soils increases irrespective of soil and agro-climatic conditions. Baddesha et al. (1997) observed an increase in the organic carbon level of the upper 0.3m soil depth with the application of wastewater for irrigation in India. Minhas and Samra (2004) reported that sandy loam soils irrigated with wastewater had higher organic carbon levels than those irrigated with groundwater. Studies on the long-term effects of wastewater irrigation reveal an increase in soil organic carbon of 80 per cent after 15 years of wastewater irrigation (Jayaraman et al., 1983; Minhas and Samra, 2004). The soil organic carbon level in freshwater-irrigated soil was 1.42 per cent, which increased to 2.56 per cent (Figure 6.2). As depicted by the organic carbon status

Table 6.4 *Effects of 15 and 25 years of wastewater irrigation on selected soil physical properties*

Soil physical parameter	Freshwater	Wastewater (15 years)	Wastewater (25 years)
Aggregate stability (%)	72.4	84.4 (17)[a]	83.5 (15)
Water-holding capacity (%)	33.2	49.7 (50)	59.8 (79)
Hydraulic conductivity (cm h^{-1})	19.1	23.6 (24)	26.6 (39)
Total porosity (%)	36.2	49.7 (37)	59.8 (65)

[a]Figures in parenthesis in the last two columns indicate percentage increase in the selected parameters in wastewater-irrigated soil over the soil irrigated with freshwater.
Source: Modified from Jayaraman et al. (1983); Minhas and Samra (2004)

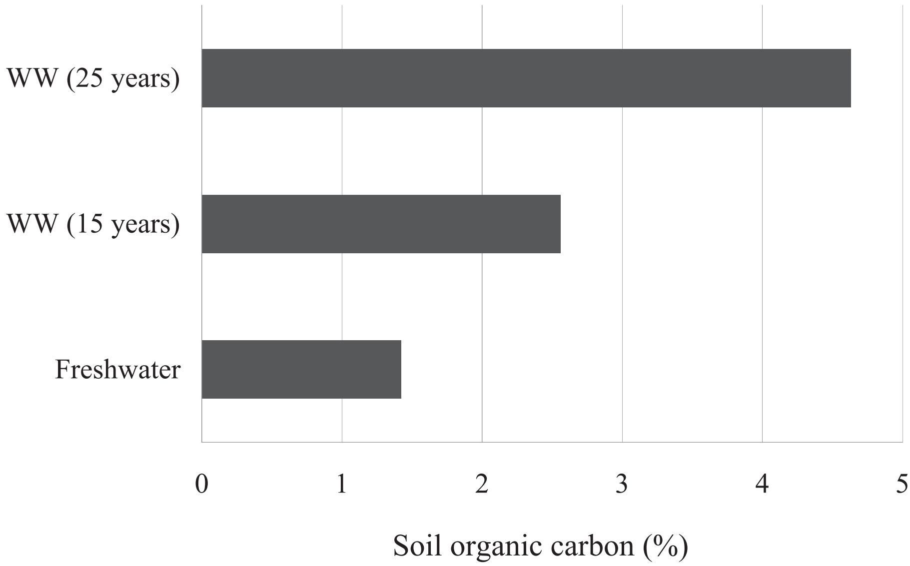

Figure 6.2 *Organic carbon dynamics in soil as affected by freshwater irrigation and wastewater (WW) irrigation for 15 and 25 years in India*

Source: Based on the data from Jayaraman et al. (1983)

of soil irrigated with wastewater for 25 years, this trend continued as the organic carbon percentage increased to 4.63 per cent, indicating a 226 per cent increase over the freshwater-irrigated soil and an 81 per cent increase over the soil irrigated with wastewater for 15 years.

Although soils of arid and semi-arid regions have low levels of organic carbon (Lal, 2001), this soil carbon pool is not only important for the soil to perform its productivity and environmental functions, but also plays a vital role in the global carbon cycle (Lal, 2004). In addition to providing essential nutrients and improving soil physical properties, wastewater irrigation contributes to mitigating the accelerated greenhouse effects by increasing soil organic carbon, which is a crucial soil quality parameter.

Soluble salts and calcium

The high dissolved solids concentrations of most wastewater may in general have negative consequences for its use in irrigation as indicated in Table 6.1. However, for some sodic and saline-sodic soils with low permeability (low infiltration rate and low hydraulic conductivity), the presence of inorganic electrolytes in wastewater, particularly resulting from Ca salts, improves hydraulic properties. These soils are characterized by the occurrence of excess sodium (Na^+) at levels that can adversely affect soil structure. Structural problems in these soils created by certain physical processes (slaking, swelling and dispersion of clay minerals) and specific conditions (surface crusting and hard-setting) may affect water and air movement, run-off and erosion, sowing operations, seedling emergence, root penetration and crop development (Qadir and Schubert, 2002). Therefore, high-electrolyte wastewater containing an adequate proportion of divalent cations such as Ca^{2+} can be used for sodic and saline-sodic soil amelioration without the need to apply a calcium-supplying amendment (see Chapter 11).

Negative trade-offs

Excessive levels of nutrients

Maintaining adequate levels of nutrients in wastewater is a challenging task because of the possible negative impacts of their excessive addition to the wastewater-irrigated soils. In the case of macronutrients such as N and P, there are three possible impact pathways:

- Excess N applied through wastewater may lead to excessive vegetative growth (green biomass), delay in maturity, lodging and low economic yield.
- Excess N and P in wastewater can cause eutrophication of natural water bodies and in irrigation systems, undesirable growth of algae, periphyton attached algae and weeds.
- Leaching of N can cause groundwater pollution and methaemoglobinemia (decreased ability of blood to carry vital oxygen around the body, generally in infants) in case of drinking N-rich groundwater (particularly high levels of nitrates, NO_3).

Nitrates are highly soluble and can easily be moved through wastewater-irrigated soils. The implication of the retention of nutrients and other wastewater

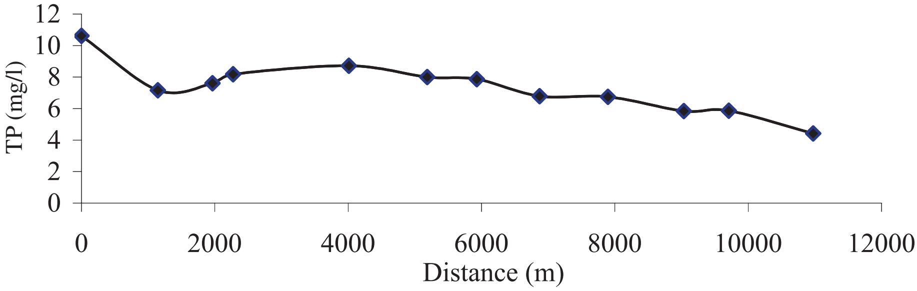

Figure 6.3 *Total phosphorous (TP) with distance downstream of discharge point, Rio Guanajuato, Mexico, 1998*

Source: Scott et al. (2000)

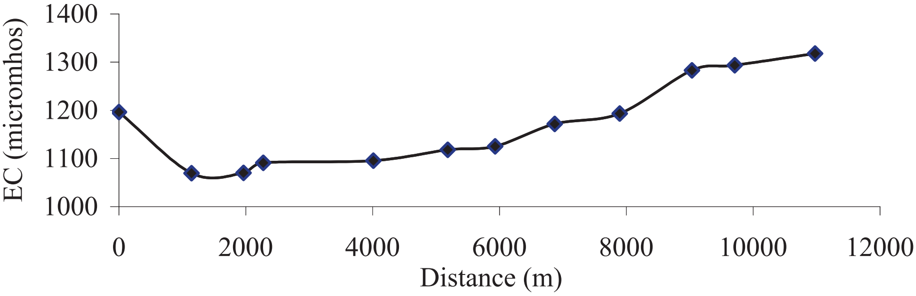

Figure 6.4 *Electrical conductivity (EC) with distance downstream of discharge point, Rio Guanajuato, Mexico, 1998*

Source: Scott et al. (2000)

contaminants in soil is that they do not reach water bodies into which wastewater would otherwise be disposed.

Nevertheless, the impact of wastewater discharge on receiving waters poses a significant challenge. Particularly in arid and semi-arid regions, irrigation withdrawal of wastewater-dominated river flows and the return flow of drainage result in two biophysical processes that have been observed in different contexts worldwide. First, high nutrient concentrations tend to be ameliorated through land application of wastewater and the retention of both P and N in agricultural produce. Fodder grass is especially well suited to wastewater irrigation (with relatively continuous year-round flow) and acts to retain N and P applied in wastewater. Figure 6.3 presents illustrative results of total phosphorous (TP) concentration in river flow in Mexico with the distance downstream of the wastewater discharge point (Scott et al., 2000).

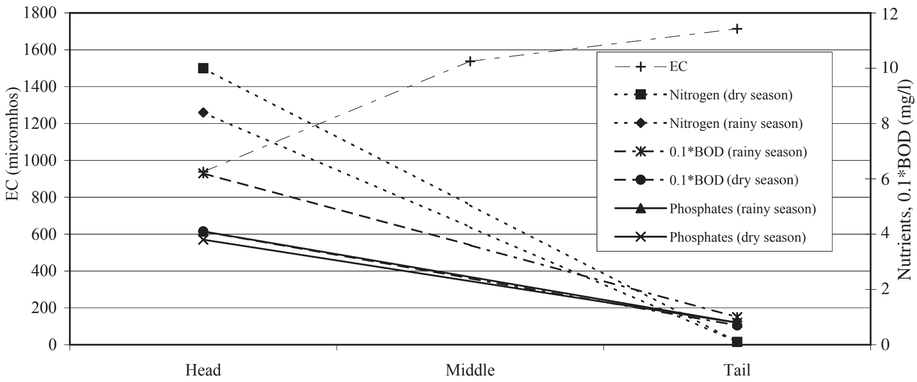

Figure 6.5 *Head–tail water quality, Tula Irrigation District, Mexico, 1997–98*

The second process is salt concentration in receiving waters both as a result of high total dissolved solids (TDS) in wastewater and due to the high irrigation applications of wastewater, whether for leaching requirements or available supplies. Successive reuse of wastewater along the river course builds up TDS, while the biochemical oxygen demand (BOD) and nutrient levels decrease, as shown in Figures 6.4 and 6.5 for wastewater-dominated rivers in two separate locations in Mexico. Similar results have been reported for Hyderabad, India, by McCartney et al. (2008).

Excessive levels of salts and sodium

As noted above, wastewater is more saline than freshwater because salts are added to it from different sources (Qadir and Minhas, 2008). There are no economically viable means to remove the salts once they enter wastewater because the techniques are prohibitively expensive, such as cation exchange resins or reverse osmosis membranes, which are only used to produce high-quality recycled water (Toze, 2006a). Saline wastewater contains excess levels of soluble salts while sodic water is characterized by excess levels of Na^+. In many cases, both salts and Na^+ are present in excess concentrations, resulting in saline-sodic wastewater (Qadir et al., 2007).

Salts and other inorganic contaminants in wastewater originate from two broad categories of industries. The first category includes those industries that generate wastes with high salt concentrations. Examples are rayon plants and the chemical manufacturing industry (caustic soda, soap and detergents), among others. The second category consists of industries that generate varying levels of toxic wastes; for example, pesticides, fertilizers, pharmaceuticals and chromium-rich waste (Minhas and Samra, 2004). The amount and type of salts used in an industry and the relevant treatment affect its wastewater quality. In addition, the implications are complex when industrial or commercial brine waste streams are not discharged into separate waste sewers, but into main urban sewers that convey wastewater to the treatment plants or to disposal channels leading to farmers' fields. There are no restrictions on salt concentrations in industrial wastewater to be discharged into urban sewers (Lazarova and Bahri, 2005). Therefore, salinity and sodicity levels in mixed domestic-industrial wastewater largely depend on salt concentrations and the relative volume of industrial wastewater to domestic wastewater.

Salinity and sodicity related characteristics in wastewater generated in different areas of the Indian subcontinent are given in Table 6.5. Salinity (EC) levels ranged from 1.9 to 4.0 dS m^{-1} while sodicity (SAR) levels were between 3.2 and 20.8. In terms of salt accumulation in irrigated soils in Faisalabad, Pakistan, Simmons et al. (2009) found salinity (EC) and sodicity (SAR) levels in wastewater-irrigated soils to be 51 per cent and 63 per cent higher than freshwater-irrigated fields. In addition, soil alkalinity increased marginally under wastewater irrigation (pH 8.92) compared to canal-water irrigation (pH 8.75).

Excess salts added via wastewater irrigation result in negative effects on crops, soils and groundwater. Plant growth is affected by the osmotic and ion-specific effects, and by ionic imbalance. Osmotic effects depress the external water potential, making water less available to the plants. Excess levels of certain ions, such as Na^+ and chloride (Cl^-), cause ion-specific effects leading to toxicity or deficiency of certain nutrients in plants (Grattan and Grieve, 1999). In the case of sodic wastewater irrigation, the excess levels of Na^+ and bicarbonate (HCO_3^-) result in the gradual development of sodicity problem in soils, thereby exhibiting structural problems created by certain physical processes (Qadir and Minhas, 2008). Irrigation with saline and/or sodic wastewater may impact groundwater quality. In well-drained soils, there is the possibility of movement of salts and other contaminants through the soil profile into unconfined aquifers (Bond, 1998). The quality of wastewater, soil characteristics and the initial quality of the receiving groundwater are the important factors that determine the extent to which salts in wastewater impact groundwater quality.

Table 6.5 *Average salinity and sodicity related characteristics in wastewater generated in the Indian subcontinent*

Location	EC (dS m^{-1})[a]	SAR	RSC ($mmol_c\ l^{-1}$)	Reference
Faisalabad	3.1	16.0	4.2	Qadir and Minhas (2008)
Karnailwala	2.3	12.6	2.3	Hussain (2000)
Judgewala	4.0	20.8	6.2	Hussain (2000)
Marzipura	3.0	16.7	5.2	Hussain (2000)
Haryana	1.9	3.2	4.5	Qadir and Minhas (2008)

[a]As a salinity parameter, EC refers to electrical conductivity; sodicity parameters consist of Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC).

METAL AND METALLOIDS

Some metals and metalloids are essentially required for adequate plant growth, but are toxic at elevated concentrations; for example, copper (Cu), molybdenum (Mo), nickel (Ni), selenium (Se) and zinc (Zn). Most of the industries in developing countries discharge untreated effluent containing variable concentrations of metals and metalloids. Since there is no separation of industrial and domestic wastewater, the wastewater channels carry a blend of industrial and domestic wastewater. The exact metals discharged and their concentrations vary with the type of industry. Several studies in Pakistan reveal that industrial effluents discharged in major cities of Pakistan have had higher concentrations of chromium (Cr), lead (Pb) and cadmium (Cd) than their permissible limits in irrigation water (Hussain, 2000; Khan et al., 2007; Murtaza et al., 2008). The United Nations Industrial Development Organization (UNIDO, 2000) reported that the textile, tanning, paint and cement industries in Karachi (Pakistan) discharge raw effluent with lead (Pb) concentrations above the threshold limit at the industry outlet. Also in Africa, where larger industries are most often only along the coast, streams polluted with chromium were found close to tanneries (Binns et al., 2003). Threshold levels of metals and metalloids are given in Table 6.6. For threshold levels in soils see Chang et al. (2002).

Several studies have been carried out to evaluate the implications of wastewater irrigation on the concentrations of metals and metalloids in soils and crops (Bahri, 2009; Hamilton et al., 2007; Lazarova and Bahri, 2005; Minhas and Samra, 2004; Qadir et al., 2000; Simmons et al., 2009). In a comprehensive sampling programme undertaken in two peri-urban areas of Faisalabad, Pakistan, Simmons et al. (2009) quantified the impacts of long-term untreated wastewater irrigation on soil quality and the yield and quality of grain and straw of three wheat varieties. Wheat straw is used as a fodder in the area. In terms of heavy metal contamination and potential risks through the fodder–milk–human food chain, they did not find significant differences in aqua regia-digested soil's Cd and Zn concentrations between freshwater- and wastewater-irrigated plots. The metal ion concentrations in soils remained below the European Commission Maximum Permissible Levels for Cd, Pb, and Zn in sludge-amended soils. In all wheat varieties subject to wastewater irrigation, Cd and Pb concentrations remained below the European Commission Maximum Permissible Levels for these metals in feed materials (Table 6.7).

Based on a survey study carried out along the Musi River in India, Minhas and Samra (2004) detected transfer of metal ions from wastewater to cows' milk via grass grown on wastewater-irrigated soil and fed to the animals. The proportion of samples showing excessive amounts of pollutants in grass ranged from 4 per cent for Cd to 100 per cent for Pb. Milk samples were highly contaminated with both metal ions ranging from 1.2 to 40 times higher than the permissible limits. Qadir et al. (2000) found that in the case of irrigation with untreated wastewater, leafy vegetables accumulated certain metals such as Cd in greater

Table 6.6 *Recommended maximum concentrations (RMC)[a] of selected metals and metalloids in irrigation water*

Element	RMC mg l^{-1}	Remarks
Aluminium	5.00	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
Arsenic	0.10	Toxicity to plants varies widely, ranging from 12mg per litre for Sudan grass to less than 0.05mg per litre for rice.
Beryllium	0.10	Toxicity to plants varies widely, ranging from 5mg per litre for kale to 0.5mg per litre for bush beans.
Cadmium	0.01	Toxic at concentrations as low as 0.1mg per litre in nutrient solution for beans, beets and turnips. Conservative limits recommended.
Chromium	0.10	Not generally recognized as an essential plant growth element. Conservative limits recommended.
Cobalt	0.05	Toxic to tomato plants at 0.1mg per litre in nutrient solution. It tends to be inactivated by neutral and alkaline soils.
Copper	0.20	Toxic to a number of plants at 0.1 to 1.0mg per litre in nutrient solution.
Iron	5.00	Non-toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of phosphorus and molybdenum.
Lithium	2.50	Tolerated by most crops up to 5mg per litre. Mobile in soil. Toxic to citrus at low concentrations with recommended limit of < 0.075mg per litre.
Manganese	0.20	Toxic to a number of crops at a few-tenths to a few mg per litre in acidic soils.
Molybdenum	0.01	Non-toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Nickel	0.20	Toxic to a number of plants at 0.5 to 1.0mg per litre; reduced toxicity at neutral or alkaline pH.
Lead	5.00	Can inhibit plant cell growth at very high concentrations.
Selenium	0.02	Toxic to plants at low concentrations and toxic to livestock if forage is grown in soils with relatively high levels of selenium.
Zinc	2.00	Toxic to many plants at widely varying concentrations; reduced toxicity at pH ≥ 6.0 and in fine textured or organic soils.

[a]The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10,000 m^3 ha^{-1} yr^{-1}). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates less than 10,000 m^3 ha^{-1} yr^{-1}. The values given are for water used on a long-term basis at one site.
Source: Ayers and Westcot (1985); Pescod (1992)

amounts than non-leafy species. Sharma et al. (2007) concluded that wastewater irrigation increased contamination of edible parts of vegetables with Cd, Pb and Ni, resulting in potential health risks in the long term. Similar findings have been documented from a study conducted in Harare, Zimbabwe where farmers used wastewater for irrigating leafy vegetables (Mapanda et al., 2005). Generally, metal ion concentrations in plant tissue increase with concentrations in irrigation water. Concentrations in the roots are usually higher than in the leaves.

Table 6.7 *Differences in average metal ion (Zn, Cd and Pb) concentrations in straw of three wheat varieties and aqua regia-digested concentrations in soil samples under canal-water and wastewater-irrigated areas*

Irrigation	Metal ion concentration in wheat straw (mg kg^{-1})			Metal ion concentration in soil (mg kg^{-1})		
	Zn	Cd	Pb	Zn	Cd	Pb
Canal water	8.66 (±1.33)[a]	0.064 (±0.036)	0.353 (±0.204)	55.8 (±2.69)	1.56 (±0.147)	9.79 (±0.204)
Wastewater	10.5 (±1.89)	0.173 (± 0.133)	1.280 (±0.628)	58.7 (±6.79)	1.66 (±0.160)	8.62 (±1.33)
MPL[b]	–[c]	< 1.0	< 10.0	< 300	< 3.0	< 300

[a]Values in parentheses indicate ± standard deviation.
[b]Maximum permissible levels (MPL) based on the European Commission Directive 2002/32/EC for Pb and Cd in feed materials and Directive 2002/32/EC for sludge-amended soils.
[c]Not available.
Source: Based on Simmons et al. (2009)

While reviewing the use of reclaimed water in the Australian horticultural production industry, Hamilton et al. (2005) classified potentially phytotoxic metals in wastewater (reclaimed water) into four groups based on their retention in soil, translocation in plants, phytotoxicity and potential risk to the food chain. They classified Cd, Co, Mo and Se in Group 4, posing the greatest risk to human and animal health even though they may appear in wastewater-irrigated crops at concentrations that are not generally phytotoxic. This is supported by the WHO, which lists boron and cadmium to be of particular concern because of their high level of toxicity and bioaccumulation in crops (WHO, 2006a).

Uncontrolled metal and metalloid inputs to soils via wastewater irrigation are undesirable because, once accumulated, it is extremely difficult to remove them. This situation may subsequently lead to toxicity to plants grown on contaminated soils; absorption by crops, resulting in metal and metalloid levels in plant tissues which may be harmful to the health of humans or animals consuming the crops; and transport from soils to groundwater or surface water, thereby rendering the water hazardous for other uses (Murtaza et al., 2009).

The potential hazard of metals and metalloids can be determined by estimating their cumulative total loading in the soils. Table 6.8 provides information on the length of time for wastewater-irrigated soils (cation exchange capacity, CEC 5–15 $cmol_c\ kg^{-1}$) to reach loading limits of some metals and metalloids. The data used represent calcareous, alluvial soils from three locations in Pakistan: Faisalabad, Peshawar and Haroonabad. The time required for Cd to reach its loading limit varied between 13 years for the heavily industrialized city of Faisalabad to 67 years for the less industrialized, small city of Haroonabad. The estimates of metal and metalloid loading suggest that their accumulation is a slow process even in cases of untreated wastewater irrigation. However, it would be extremely difficult to

Table 6.8 *Estimated length of time for wastewater-irrigated agricultural soils to reach metal limits in three locations in Pakistan*[a]

Location	Metal	Concentration (mg L^{-1})	Annual input (kg ha^{-1})[b]	Loading limit (kg ha^{-1})[c]	Estimated time (years)
Faisalabad	Cd	0.05	0.75	10	13
Peshawar	Cd	0.04	0.60	10	17
Haroonabad	Cd	0.01	0.15	10	67
Faisalabad	Cu	0.17	2.54	250	99
Peshawar	Cu	0.26	3.88	250	65
Haroonabad	Cu	0.35	5.22	250	48
Faisalabad	Ni	0.38	5.67	250	44
Peshawar	Ni	1.25	18.64	250	13
Haroonabad	Ni	0.14	2.09	250	120
Faisalabad	Pb	0.21	3.13	1000	319
Peshawar	Pb	0.70	10.44	1000	96
Haroonabad	Pb	0.04	0.60	1000	1676

[a]Calcareous, alluvial soils.
[b]Based on wastewater irrigation application at 1.5m depth per year (15,000m^3 ha^{-1}).
[c]Considering cation exchange capacity (CEC) of the soils: 5-15 $cmol_c$ kg^{-1}.

ameliorate soils once they reach the loading limits of certain metals and metalloids. The amounts of metals removed by crops are small (<10 per cent of the added metal) compared with the amounts applied to the soils (Page and Chang, 1985).

Emerging contaminants of concern

With changes in lifestyle and increase in living standards, more and more contaminants are being added to wastewater, including endocrine disruptor compounds, hormones, residual pharmaceuticals and active residues of personal care products (PCPs), among others. Endocrine disruptors (sometimes also referred to as hormonally active agents) include the estradiol compounds commonly found in the contraceptive pill, phytoestrogens, pesticides and industrial chemicals such as phenols (Table 6.9). They are exogenous substances that can act like hormones in the human endocrine system and disrupt the functions of endogenous hormones. These substances tend to be present at very low concentrations even in treated wastewater and may have adverse physiological effects in animals and humans. At least 45 chemicals have been identified as potential endocrine disrupting contaminants, including industrial contaminants such as dioxins and polychlorinated biphenyls (PCBs), insecticides like dichlorodiphenyltrichloroethane (DDT) and carbaryl, and herbicides (2,4-D and atrazine).

In addition to containing endocrine disruptor compounds, wastewater may convey hormones. Irrigation with hormone-rich wastewater can increase the

Table 6.9 *Maximum tolerable concentrations of selected pesticides, emerging contaminants and other pollutants in wastewater-irrigated soils*

Pollutant	Soil concentration mg kg^{-1}	Pollutant	Soil concentration mg kg^{-1}
Aldrin	0.48	Methoxychlor	4.27
Benzene	0.14	PAHs (as benzo[*a*]pyrene)	16.0
Chlordane	3.00	PCBs	0.89
Chloroform	0.47	Pentacholorophenol	14.0
2,4-D	0.25	Pyrene	41.0
DDT	1.54	Styrene	0.68
Dicholorobenzene	15.0	2,4,5-T	3.82
Dieldrin	0.17	Tetrachloroethane	1.25
Dioxins	0.00012	Tetrachloroethylene	0.54
Heptachlor	0.18	Toluene	12.0
Hexacholorobenzene	1.40	Toxaphene	0.0013
Lindane	12.0	Trichloroethane	0.68

Source: Based on Human Health Protection (Chang et al., 2002; WHO, 2006a)

endogenous production of hormones (phytohormones) in legume crops such as alfalfa. Ingestion of the forage crop by sheep and cattle might cause infertility problems in the animals (Shore et al., 1995). For many substances, such as steroid oestrogens, biodegradation and sorption are the main fate processes. However, there remains a paucity of information on the persistence of many of these substances in soil (Young et al., 2004).

A related group of concern is residual pharmaceuticals (e.g. analgesics, caffeine, cholesterol-reducing drugs and antibiotics). Some tend to survive even advanced wastewater treatment. There are concerns that soils irrigated with wastewater containing such contaminants may not retain them, resulting in their percolation through the soil to the groundwater. Although many residual pharmaceuticals may not be toxic, they can have health implications through their effects on the immune and hormonal systems of animals and humans.

The levels of active residues of PCPs are also increasing in wastewater. Percolation of PCPs through wastewater-irrigated soils has implications for groundwater quality deterioration with possible subsequent effects on human health. There may also be some unspecified toxic effects in the form of antibiotic-resistant bacteria development by repeated exposure of the pathogens to antibiotic levels in wastewater and contaminated streams (Bouwer, 2005).

While the presence of these chemicals in the environment and the potential ecological consequences are generally alarming, the concentrations found in surface-water bodies and other environmental compartments so far are very low. Possible health effects have been related mainly to aquatic life (Young et al., 2004) but not positively in humans, although there are many indications of possible adverse effects (Bouwer, 2005; Colborn et al., 1993). There is, however, still little data concerning the occurrence and fate of organic micro-pollutants: during and after irrigation; in view of crop uptake; and possible human health impacts through the food-crop chain.

Many of the chemicals might face rapid microbial degradation or adsorption by the soil organic matter and are unlikely to enter the plant tissue through the root (Chang et al., 2002). But even if this might happen, the comparison of common concentration in raw wastewater with other sources of these chemicals so far points to very low risk for human health (Toze, 2006b). More studies are needed; especially in view of quantitative simulation models for risk assessment.

Risk assessment

Chemicals can affect the health of soils, crops and humans. For some heavy metals the 'soil–plant barrier' protects the food chain from these elements, in other cases bioaccumulation occurs (see Chapter 11). Acceptable levels of chemical parameters therefore depend on their behaviour, the proposed reuse applications of the water (e.g. food vs. fodder vs. fuel production) and site-specific factors, such as the degree of dilution with water from other sources.

To develop numerical limits of pollutant loading rates in the land application of wastes in general, essentially the same informational elements are needed (Chang et al., 2002):

- Hazard identification – the toxic chemicals to be considered are identified.
- Dose-response evaluation and risk characterization – the maximum permissible exposure level in the exposed subjects is determined for each chemical, based on the dose-response characteristics associated with a predetermined acceptable risk level.
- Exposure analysis – realistic exposure scenarios depicting the routes of pollutant transport are formulated to identify the subjects of exposures.

Analysing wastewater quality as a risk indicator is appropriate where dose-response relationships between water quality, soil quality, plant growth and human health have been well established. This is, for example, the case for salinity indicators and most macro- and micronutrients as they are affecting soil and crop health, but remains an increasingly difficult challenge where human health is concerned.

In this case, dose-response relationships may be derived from data obtained in epidemiological investigations, extrapolations from animal studies, or toxicity assays on mammalian or bacterial cells. Epidemiological data can provide the most realistic cause–effect relationships, but are only available for a very limited number of chemicals. Another challenge, especially in developing countries, is the required investment in analytical laboratory capacity. The long latency period of disorders caused by many environmental toxicants, such as cancer, reduces the quality of

Box 6.1 Quantitative chemical risk assessment

Quantitative chemical risk assessment (QCRA) is a tool increasingly used in risk-management decision-making, following the success of its microbiological equivalent (QMRA, see Chapters 3, 4, and 5). In QCRA, available data and information regarding toxicity is combined with estimates of exposure to calculate the likelihood and severity of human health effects. In some circumstances, limitations in evaluating chemical toxicity and exposure potential introduce significant uncertainties into such a risk assessment. Like in QMRA, probabilistic approaches, such as Monte Carlo techniques, can be used to quantify the uncertainty in the human health risk-assessment process (Washburn et al., 1998). Based on the assumption that food-chain transfer is the primary route of exposure to potentially hazardous pollutants in wastewater and sewage sludge, numerical limits defining the maximum permissible pollutant concentrations in soils were presented for a set of organic and inorganic pollutants by Chang et al. (2002), while Weber et al. (2006) showed a modelling example of how to predict environmental (no-effect) concentrations in the absence of comprehensive quantitative analytical data.

the data by hindering the determination of the effects (Weber et al., 2006). Risk-assessment models are required (see Box 6.1).

Once established, dose-response relationships will allow proposition of an acceptable daily intake (ADI) for each specific chemical. To derive the numerical limits for pollutant input in land application, the process quantitatively backtracks the pollutant transport through the food chain (and/or other exposure routes) to arrive at an acceptable pollutant concentration for the receiving soil to determine the 'predicted no-effect concentration'. In order to demonstrate an acceptable risk to health or the environment, its value should be larger than the analysed or 'predicted environmental concentration' (Weber et al., 2006).

Among nutrients and heavy metals, excess or deficiency in crops does not only depend on absolute individual concentrations but on the balance of the elements, on the kind of organic matter available which might bind them and on the soil conditions (like acidity and the redox status) which can determine their solubility and uptake by roots. In these cases, wastewater analysis can only give a first indication; soil analysis might be more appropriate. This also applies to organic contaminates which are in the soil and subject to a range of biotic and abiotic processes. An often neglected option for metals and metalloids is the analysis of the crops on the respective farms especially when transmission through the food chain is of interest. Plant analysis usually provides a much more accurate assessment of possible uptake than soil or water analysis. However, it also reflects uptake from all locally available sources of nutrients or contaminants in the soil, which might be irrigation water, chemical farm inputs or, particularly in urban farming, also traffic exhaust (Bakare et al., 2004). Such a situation would require a comparative analysis before conclusions about a particular source can be drawn.

In all cases, sampling and analysis will have to consider spatial and temporal variations in water quality and accumulation of contaminants in the soil or plants over time. This requires ideally long-term monitoring or a set-up which allows comparing sites with different exposures.

While the assessment of soil and water salinity can be carried out in the field with an electrode, the analysis of nutrients usually requires laboratory equipment. Depending on the concentration of the elements in the sample in general the equipment gets more complex and expensive moving from macronutrients to micronutrients or heavy metals. Although many research institutions and universities in developing countries will have laboratories to analyse most of the macro- and some micronutrients, external support is often required in view of heavy metals or organic contaminants. A low-cost alternative is to predict the risk based on environmental factors and application practices using, for example, the Pesticide Impact Rating Index (PIRI), a free software package developed by CSIRO in Australia (www.clw.csiro.au/research/biogeochemistry/organics/projects/piri.html).

When the concentrations of constituents such as heavy metals or organic contaminants are known in the plant tissue, or in food in general, which is eventually consumed by a particular consumer group, it is possible to calculate human exposure (intake). The exposure of the consumer is then compared to the 'acceptable daily intake' (ADI, see above), for example, where the intake of a component such as pesticides might be unavoidable, or to the 'tolerable daily intake' (TDI), such as for heavy metals. The exposure can be obtained using the basic equation: Exposure (mg/kg body weight/day) = Consumption (mg/kg body weight/day) × Residue (mg/kg). As TDIs are regarded as representing a tolerable intake for a lifetime, they are not so precise that they cannot be exceeded for short periods of time. Short-term exposure to levels exceeding the TDI is not a cause for concern, provided the individual's intake averaged over longer periods of time does not appreciably exceed the level set (WHO, 2006b).

Detailed information on sampling and analysis of common contaminants can be found in standard text books for soil, water and plant analysis, or the WHO website of the Water, Sanitation, Hygiene and Health Unit at www.who.int/water_sanitation_health/en.

CONCLUSIONS

While from the microbiological perspective wastewater is perceived more as a biophysical hazard, its chemical content presents a more complex situation with both positive and negative impacts on soils, crops and water bodies, which are important considerations not only for the farmer but also for managing wastewater treatment and discharge.

The concentrations of nutrients vary widely in wastewater. Although reliable availability for irrigation and nutrient-supplying capacity are considered to be major drivers for untreated wastewater use in agriculture, maintaining adequate levels of nutrients in wastewater is a challenging task because of the possible negative impacts of their excessive addition to soils. In terms of salt content, there are no economically viable means to remove the salts once they enter wastewater because the techniques are prohibitively expensive, and are only used to produce high-quality recycled water. However, wastewater containing an adequate proportion of divalent cations such as calcium can be used as an amendment for calcium-deficient soils such as sodic and saline-sodic soils.

Some metals and metalloids supplied through wastewater irrigation are essentially required for adequate plant growth, but are toxic at elevated concentrations. Most of the industries in developing countries discharge untreated effluent containing variable concentrations of metals and metalloids. Since there is often no separation of industrial and domestic wastewater, the wastewater channels can carry a blend of industrial and domestic wastewater. Depending on the level of industrialization and type of industries, the exact metals and metalloids discharged and their concentrations vary widely. In many developing countries, impacts might remain localized but the situation requires careful monitoring, especially in transitional economies.

However, the quality of chemical risk assessments varies considerably between different hazards. While the effects of excess nutrient or heavy metal levels on soil productivity or crop health have been studied for some time, there is only limited information on other factors such as the fate and impact of organic contaminants in irrigation water with regard to human health. There is a significant need for computer-based models similar to those developed for microbiological risk assessments (see Chapter 5).

Like the supply of nutrients through wastewater irrigation, the presence of organic matter in wastewater may have positive or negative implications depending on the nature of the organic materials added through wastewater irrigation. In terms of positive effects, organic matter added through wastewater improves soil structure, acts as a storehouse of essential nutrients for crop growth and enhances charge characteristics of irrigated soils. In addition, the organic carbon status of wastewater-irrigated soils increases irrespective of soil and agro-climatic conditions.

The search for win–win solutions would entail preserving the positive outcomes of wastewater irrigation while monitoring, assessing and, if required, minimizing possible negative effects (see Chapter 11). However, this often requires management interventions beyond the farm level. In other words, the agricultural and sanitation sector will have to work together.

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