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Contaminant Management in Water Reuse Systems

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Preface

Although wastewater has been increasingly used to grow a range of crops for income generation and livelihood resilience in urban and peri-urban areas, irrigation with untreated or partially treated wastewater may result in negative impacts on irrigated crops, soils, and groundwater along with implications for human and environmental health through chemical and microbial risks. With the potential for environmental risks due to concentrations above the maximum allowable levels, the major chemical constituent groups that need to be addressed in wastewater-irrigated environments are metals and metalloids, essential nutrients, salts and specific ionic species, and persistent organic pollutants. To avoid potential negative impacts, conventional wastewater treatment options, which can control the release of these contaminants into the environment, remain the key to protecting water quality for beneficial uses in agriculture, aquaculture, and agroforestry systems. Effective legislation, monitoring, and enforcement are also essential and often neglected management strategies. At the farm level, some low-cost irrigation, soil, and crop management options, discussed in this chapter, are available to reduce the risk from contaminants added through wastewater irrigation.

43.1 Introduction

Wastewater generated by domestic, municipal, and industrial sectors has been increasingly used, particularly in dry areas, to provide water and nutrients to agriculture, aquaculture, and agroforestry systems. While such use helps in income generation and livelihood resilience amid water scarcity, use of wastewater in untreated or inadequately treated forms may result in negative impacts on human and environmental health through chemical and pathogenic risks [16,24,29].

Although farmers using untreated or partially treated wastewater provide a service by avoiding or decreasing effluent entering into polluted streams and applying it to soils, thus reducing the pollutant load in downstream locations, such irrigation also generates risk for farm communities and consumers of farm products. Polluted canals and ditches, and wastewater-irrigated fields create hazards in which children and other residents are exposed to harmful pathogens and chemicals [10]. Consumers of farm produce also are at risk when they handle and ingest contaminated vegetables, particularly when the food is eaten raw or prepared with inadequate care toward reducing contamination risk.

Although wastewater treatment is the best choice in managing wastewater in agriculture, wastewater treatment in developing countries is limited, as investments in treatment facilities have not kept pace with persistent increases in population and the consequent increases in wastewater volume in many countries. A key challenge in almost all cases relates to the fact that the price of treated water does not justify its treatment cost. Thus, most of the treatment plants are either abandoned in the short-run or are highly subsidized to ensure their sustenance. Even where wastewater treatment plants are externally funded, they usually only treat a small fraction of the produced wastewater and can face, depending on their type, significant maintenance problems.

The average estimated rates of wastewater treatment are just 8% in low-income countries and 28% in lower-middle-income countries [32]. Thus, much of the wastewater generated in developing countries is not treated, and much of the untreated wastewater is used for irrigation by small-scale farmers. Where irrigation with untreated or inadequately treated wastewater cannot be avoided or is otherwise common, negative impacts on irrigated crops, soils, and groundwater are likely to affect human and environmental health [1,21,24,38]. However, some farm-based measures and low-cost treatment options can reduce the risk for environmental and human health [38]. This chapter elaborates the contaminant risks resulting from the use of untreated or partially treated wastewater and provides insight into the contaminant risk management strategies leading to safe and productive use of wastewater in agriculture.

43.2 Contaminants in Wastewater and Risk Management Options

Wastewater contains different types and levels of undesirable constituents, depending on the source from which it is generated and the level of its treatment. The nonpathogenic components of wastewater aside from organic chemicals, debris, and solutes, can comprise a range of elements that can be essential plant nutrients, undesirable salts, metals and metalloids, and pesticides, residual pharmaceuticals, endocrine disruptor compounds, and active residues of personal care products in toxic concentrations [33,35]. The pathogenic components could be viruses, bacteria, protozoa, and multicellular parasites. The concentrations of these constituents above the permissible limits have bearing on human and environmental health [38].

With the potential for environmental risks due to concentrations above the maximum allowable levels, the chemical constituents that need to be addressed in wastewater-irrigated environments can be divided into: (1) metals and metalloids, such as cadmium, chromium, nickel, zinc, lead, arsenic, selenium, mercury, copper, and manganese, among others; (2) nutrients such as nitrogen, phosphorous, and magnesium, which in high concentrations might suppress other nutrients and/or affect plant growth otherwise negatively; (3) salts and specific ionic species such as sodium, boron, and chloride; and (4) persistent organic pollutants, such as pesticides as well as residual pharmaceuticals, endocrine disruptor compounds, and active residues of personal care products, among others. A generic framework for contaminant management while irrigating with wastewater is presented in Figure 43.1.

To avoid potential negative impacts, conventional wastewater treatment options, which can control the release of salts, metals and metalloids, nutrients, and emerging contaminants into the environment, remain the key to protect water quality for beneficial uses in agriculture, aquaculture, and agroforestry systems. In the case of metals, metalloids, nutrients, and emerging contaminants, pretreatment and/or segregation of industrial wastewater from the domestic and municipal wastewater stream is an important task [23]. Effective legislation, monitoring, and enforcement are also essential and often neglected management strategies. The sources of salts in wastewater can be reduced by using technologies in industrial sectors that reduce salt consumption vis-à-vis discharge into the sewage system. In addition, restrictions can be imposed on the use of certain products for domestic use that are major sources of salts in wastewater [17].

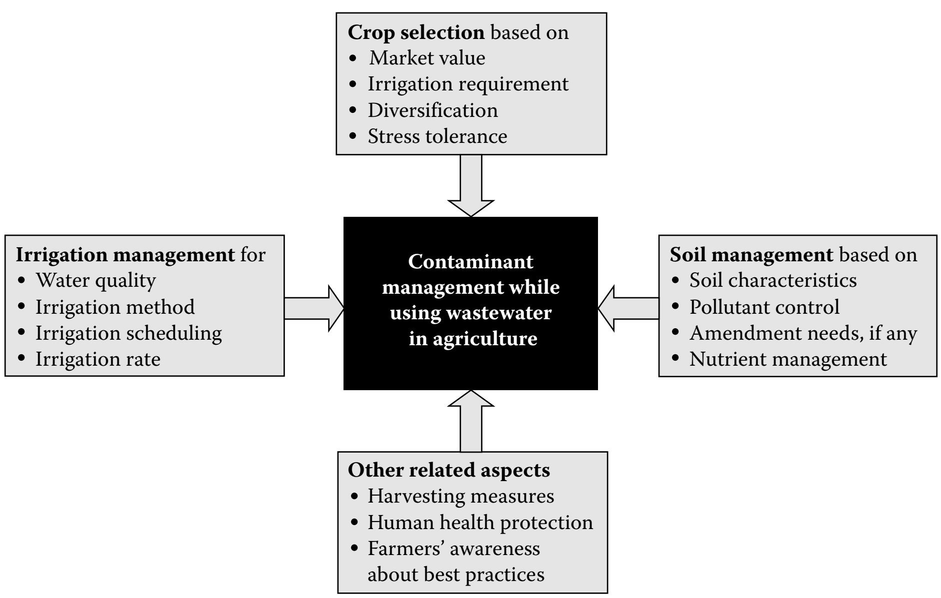

FIGURE 43.1 A framework for contaminant management while irrigating with wastewater, illustrated by four major categories, which are interrelated and implicate each other.

43.2.1 Metals and Metalloids

All of the potentially toxic metals are naturally present in the environment in trace amounts and are ingested with food, water, and air. Human bodies have the ability to deal with these background levels. The World Health Organization (WHO) has established guidelines on allowable consumption of various toxins and guidance values in irrigation water [38]. Several of these metals and metalloids are of particular concern due to their adverse effects on agricultural productivity as well as environmental and human health. In a review of using reclaimed water in the Australian horticultural production industry, Hamilton et al. [11] classified potentially phytotoxic metals in wastewater into four groups based on their retention in soil, translocation in plants, phytotoxicity, and potential risk to the food chain. They categorized cadmium, cobalt, selenium, and molybdenum as posing the greatest risk to human and animal health because they may appear in wastewater-irrigated crops at concentrations that are not generally phytotoxic, but posing risks to human and animal health. The WHO guidelines also consider cadmium with particular concern because of high levels of toxicity and bioaccumulation in crops [38].

Metals such as cadmium, mercury, and lead do not have any essential function but they are detrimental, even in small quantities, to plants, animals, and humans and accumulate because of their long biological half-life [9]. Other metals and metalloids, such as manganese, zinc, boron, or copper are, in small concentrations, essential micronutrients, but harmful to crops in higher concentrations. Some, like copper and zinc, become toxic to plants before they reach high enough concentrations to be toxic to humans; thus, plants function here as a barrier mitigating potential health risks [11,15].

In terms of risk management options with regard to metals and metalloids, the following are important for consideration: (1) soil-based treatment options; (2) crop-based management strategies; (3) crop restrictions; and (4) land retirement zones or other uses of land.

43.2.1.1 Soil-Based Management Options

Soil-based treatment options include the use of soil amendments such as gypsum, lime, phosphate materials, hydrous iron and manganese oxides, clay minerals, and organic matter. These soil amendments form insoluble complexes of metals and metalloids, thereby reducing their availability at low concentrations in the root zone and reducing their assimilation by plants. The amendments have been shown to immobilize metals and metalloids through the (1) formation of insoluble metal phosphate minerals; (2) sorption of contaminants on iron and manganese oxide surface exchange sites and coprecipitation; (3) sorption of contaminants on exchange sites of organic materials including manure, compost, and sewage sludge; and (4) sorption of contaminants on exchange sites at clay mineral surfaces or incorporation into the mineral structure of zeolites, natural aluminosilicate minerals, and aluminosilicate by-products.

Although soil-based management through the application of amendments offers an opportunity to immobilize or minimize bio-availability of metals and metalloids, there are practical limitations, which must be considered. These include the management of sites cocontaminated with several elements, cost and availability of amendments, cost of long-term monitoring programs, and suitability to particular soil and climatic conditions. In addition, there would be a need to follow up in the postmanagement phase, particularly in restricting the flush of acidic water, which may trigger the conversion of insoluble complexes of metals and metalloids into soluble and readily available forms at concentrations that may be phytotoxic and have implications for environmental, human, and livestock health.

43.2.1.2 Crop-Based Management Strategies

Soils contaminated with metals and metalloids can be improved through the use of certain plant species. This approach is broadly known as the phytoremediation of metal and metalloid contaminated soils [4,5,31]. As an important category of phytoremediation, phytoextraction involves the use of pollutant-scavenging plants to transport and concentrate metals and metalloids from the soil into above-ground biomass, which may be harvested to remove the elements from the field. The efficiency of phytoextraction for a given metal is the product of the dry matter yield of shoot and concentration of the metal in shoot.

The plants able to accumulate high concentrations of metals are known as hyperaccumulators. The concentrations of metals accumulated in such plants may be 100 times greater than those occurring in nonaccumulator plants growing on the same substrates [4]. More than 400 plant species have been categorized as hyper-accumulators of metals and metalloids. Following harvest of the metal-enriched plants, the weight and volume can be reduced by ashing. Metal-enriched plants can be disposed of as hazardous material or, if economically feasible, used for metal recovery.

Because the costs of growing a phytoremediation crop are minimal as compared to those of soil removal and replacement, the use of plants to remediate hazardous soils is seen as having great promise [4]. However, phytoremediation has certain limitations; the most crucial is the duration of its action, which may take years or even decades, thereby limiting its practical applicability under situations where more and more contaminants may be added to the soil than their removal through the phytoremediation process.

43.2.1.3 Crop Restrictions

Some crops are more prone than others to contamination with metals and metalloids and/or pose a greater risk to human health due to levels of dietary intake. For example, in the case of irrigation with untreated wastewater, leafy vegetables accumulate certain metals such as cadmium in greater amounts than nonleafy species (Figure 43.2). However, consideration must be given to the quantities of leafy vegetables actually consumed and hence their contribution to the dietary intake of heavy metals such as cadmium.

A shift in crop choice is only feasible and sustainable if there is a market and comparative market value for the alternative crop.

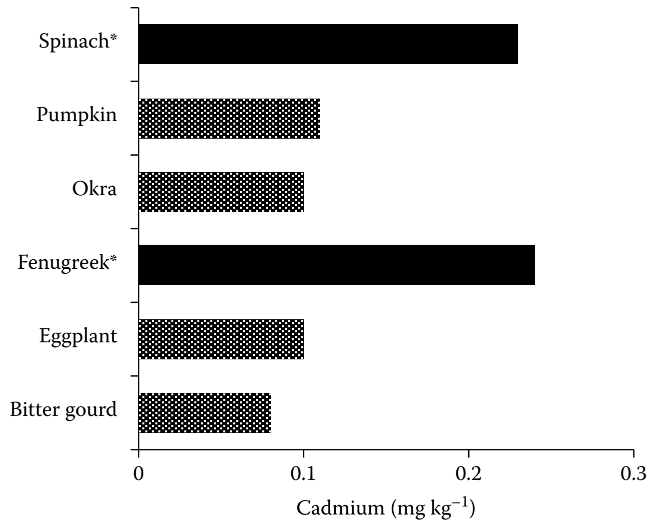

FIGURE 43.2 Cadmium concentration (mg kg^{-1}) in vegetables grown on urban agricultural soils irrigated with untreated wastewater. Spinach and fenugreek are leafy vegetables while others are nonleafy vegetables. (Based on data from Qadir, M., Ghafoor, A., and Murtaza, G. 2000. Cadmium concentration in vegetables grown on urban soils irrigated with untreated municipal sewage. *Environment, Development and Sustainability*, 2(1), 11–19.)

In addition, investing financial resources and time in acquiring the tools and skills to adopt alternative cropping patterns would be a challenge if farmers do not have secure land tenure to plant those plant species that take a long time to give financial returns, such as agroforestry systems. Therefore, crop restrictions can be hard to implement if necessary conditions such as market demand, land rights, and supporting extension services are not effectively in place. However, there are examples of successful or partly successful implementation of crop restriction in wastewater use schemes in several countries such India, Mexico, Peru, Chile, Jordan, and Syria [2,29].

43.2.1.4 Land Retirement Zones or Other Uses

Where there are no further options to maintain the farm, the affected areas might have to be mapped and taken out of production. Simmons et al. [34] developed a General Linear Regression Model to predict the spatial distribution of soil cadmium in a cadmium/zinc cocontaminated cascading irrigated rice-based system in Thailand. Preliminary validation indicated that the model can predict soil cadmium based on minimal soil sampling and the field's proximity to primary outlets from in-field irrigation channels and subsequent interfield irrigation flows. While cadmium is of high risk, soil sampling alone might not be a sufficient indicator of the actual health risk. However, zoning and taking contaminated areas out of food production for land retirement or other uses should be accompanied by adequate compensation for farmers or landowners or providing them income generating alternative livelihood opportunities, associated with training and assured markets.

43.2.2 Nutrient Elements

Although wastewater usually contains valuable nutrients essential for plant growth, the concentrations of the nutrients can vary significantly, and might reach levels that are in excess of crop needs or have antagonistic effect on certain nutrients when present at elevated levels. Therefore, maintaining appropriate levels of nutrients in wastewater is a challenging task and periodic monitoring is required to estimate the nutrient loads in wastewater and adjust fertilizer applications accordingly. Excessive nutrients can cause nutrient imbalances, undesirable vegetative growth, delayed or uneven maturity, and can also reduce crop quality while polluting groundwater and surface water supplies. The amount of nutrients applied via wastewater irrigation can vary considerably if it is raw, treated, or diluted with stream water.

To avoid excessive or unbalanced additions of particular nutrients to wastewater-irrigated soils and crops, farmers can select crops that are less sensitive to high nutrient levels or that can take advantage of high amounts of phosphorus and nitrogen. Land- and soil-based management options depend not only on the type of crop but also on the local soil and site characteristics. Medium- to fine-textured soils, for example, may hold more nutrients than sandy soils, thereby releasing fewer amounts of nutrients in the water percolating through the soil and adding to the groundwater. However, there is a need for groundwater quality monitoring when groundwater is shallow and used for drinking purposes.

Observations from larger urban settings in developed countries showed that effluent treatment by land application for cropping and forestry is often less economical than other treatment techniques. This might be due to the increasing economic land value near cities, but in particular the need in temperate climates to cater to the cold season when soils might be sealed by ice and plants not growing or in a dormant state [14]. In addition, where soils have only restricted internal drainage capacity, their degradation can occur through waterlogging and salinization [14,36]. Hence, most land disposal processes are dependent on freely draining soils and the existence of some diversion structure to store effluent during periods of low absorption capacity or crop water demand.

Riparian buffers can be used to remove sediments, nitrogen, and phosphorus, among other pollutants. Riparian buffers, both the grassed and forested portions, serve to slow water velocity, thus allowing sediment to settle out of the surface runoff water. The grassed portion of the buffer functions as a grass vegetated filter strip. In addition to acting as buffer zones, riparian buffers consisting of grasses, shrubs, trees, or mixed vegetation take up nutrients and thus reduce nutrient loads in water.

Based on data reported on the effects of different sizes of riparian buffers on the reduction of sediment and nutrient loads from field surface runoff [18], and economic valuation, based on shadow price of a pollutant, of the undesirable pollutant addition from wastewater to water bodies such as rivers [13], data reveal that forest-based riparian buffers are more efficient in reducing pollutant loads and increasing economic gains. The total benefits from the reduction in suspended solids, nitrogen, and phosphorus from field surface runoff into water bodies may range from €0.13 m^{-3} for grass-based systems to €0.49 m^{-3} for forest-based systems. These results suggest that options beyond the typical wastewater treatment plant could be used for water quality improvement for environmental and economic benefits.

43.2.3 Salts and Specific Ions

Wastewater contains more soluble salts than freshwater because salts are added to it from different sources. There are no economically viable means to remove the salts once they enter wastewater because of the prohibitively expensive techniques such as cation exchange resins or reverse osmosis membranes, which are only used to produce high-quality recycled water [25,37]. The amount and type of salts used in an industry and the relevant treatment affect the quality of wastewater it generates. For example, in the tannery industry, skins are usually salted with 50%–100% salt by weight and hides with 40%–50% salt [25]. These values suggest that each ton of salted skins contributes over a half ton of salt to the environment. In terms of salt concentration, wastewater from tanneries contains salt in the range of 10–50 g L^{-1}. For comparison, the domestic sector adds about 0.3–0.5 g of dissolved salt to each liter of its wastewater [25]. The situation is complicated when industrial or commercial brine waste streams are not discharged into separate waste sewers, but rather into main urban sewers that convey wastewater to the treatment plants or to disposal channels leading to farmers' fields.

Considering the presence of soluble salts in excessive concentrations, wastewater can be divided into: (1) saline wastewater containing excess levels of soluble salts; (2) sodic wastewater characterized by excess levels of sodium; and (3) saline-sodic wastewater having both salts and sodium in excess concentrations. For long-term irrigation with saline and/or sodic wastewater, there is a need for site-specific preventive measures and management strategies, which may include the following.

43.2.3.1 Crop Selection and Diversification

Considerable variation exists among crops in their ability to tolerate saline conditions [20]. Appropriate selection of crops or crop variety capable of producing profitable yield also with saline and/or sodic wastewater is vital at given levels of salt and sodium concentrations [25]. Such selection is generally based on the ability of the species to withstand elevated levels of salinity in irrigation water and soil [20] while also providing a saleable product or one that can be used on-farm [12]. The salt tolerance of a crop is not an exact value because it depends on several soil, crop, and climatic factors. This diversity can be exploited to identify local crops that are better adapted to saline and/or sodic soil conditions. Several field crops, forage grasses and shrubs, bio-fuel crops, and fruit-tree and agroforestry systems can suit a variety of salt-affected environments [28]. Such systems linked to secure markets should support farmers in finding the most suitable and sustainable crop diversifying systems to mitigate any perceived production risks, while ideally also enhancing the productivity per unit of saline wastewater and protecting the environment.

43.2.3.2 Irrigation Management Strategies

There could be different options to irrigate crops with saline wastewater, such as surface or flood irrigation, manual irrigation with watering cans, furrow irrigation, sprinkler irrigation, and micro-irrigation such as drip or trickle irrigation. Flood irrigation is the lowest cost method with low water use efficiency. With a medium level of health protection, furrow irrigation needs land leveling. It is suitable when there is a greater leaching need to remove high levels of salts. Without the need of land leveling, irrigation with sprinklers involves medium to high cost and medium water use efficiency. Sprinkler irrigation systems have the advantage of reducing the amounts of water and salts applied to soil and crop [28]. As sprinkler irrigation may cause leaf burn from salts absorbed directly through wetted leaf surfaces where climatic conditions favor fast evaporation [1], irrigation at night can help avoid this. Alfalfa leaves, for example, are known for margin leaf-burn when sprinkled with saline water of 3–5 dS m^{-1}. Sprinkler irrigation of cotton when practiced during daytime with saline water of 4 dS m^{-1} may cause about 15% reduction in lint yield. Several other factors affect salt deposition on leaf surfaces when sprinkler irrigation is practiced, including leaf age, shape, angle, and position on plant; type and concentration of salt; ambient temperature; air velocity; irrigation frequency; and length of time the leaf remains wet [19]. Since the problem is also related more to the number than the duration of sprinkler irrigation, infrequent and heavy irrigations should be preferred over frequent and light sprinkler irrigations [27]. Drip irrigation systems are costly, but highly efficient in water use along with the highest levels of health protection. The clogging of drippers, on the other hand, may limit the use of drip irrigation systems for wastewater. Therefore, filtration is needed to prevent clogging of emitters.

43.2.3.3 Drainage Management for Root Zone Salinity Control

While using saline wastewater, the volume of irrigation water applied should be in excess of crop water requirement (evapotranspiration) or predictable rainfall should be taken into consideration to leach excess salts from the root zone. Salinity control by effective leaching of the root zone becomes an important option for farmers who do not have limited water allocations. In order to calculate leaching requirement, farmers will need assistance to analyze the electrical conductivity of their soils and irrigation water. The leaching required to maintain salt balance in the root zone may be achieved either by applying sufficient water at each irrigation to meet the leaching requirement or by applying, less frequently, a leaching irrigation sufficient to remove the salts accumulated from previous irrigations. The leaching frequency depends on the salinity status in water or soil, salt tolerance of the crop, and climatic conditions [27]. The amount of rainfall should be taken into consideration while estimating the leaching requirement and selecting leaching method. Although leaching is essential to prevent root zone salinity, leaching under saline wastewater irrigation may result in the movement of nitrates, metals and metalloids, and salts to the groundwater. Therefore, monitoring of groundwater levels and quality is an essential indicator of environmental performance [17]. In addition, adequate soil drainage is considered an essential prerequisite to achieve leaching requirement vis-à-vis salinity control in the root zone. Natural internal drainage alone may be adequate if there is sufficient storage capacity in the soil profile or a permeable subsurface layer occurs that drains to a suitable outlet [8].

43.2.3.4 Conjunctive Use with Freshwater

Saline wastewater can be used for irrigation in conjunction with freshwater, if available, through cyclic and blending approaches. These approaches allow a good degree of flexibility to fit into different situations. Guidelines pertaining to water quality for irrigation in terms of salinity and sodicity related parameters are available [1,38]. The cyclic strategy involves the use of saline wastewater and nonsaline irrigation water in crop rotations that include both moderately salt-sensitive and salt-tolerant crops. Typically, the nonsaline water is also used before planting and during initial growth stages of the salt-tolerant crop, while saline water is usually used after seedling establishment [22,30]. The cyclic strategy requires a crop rotation plan that can make the best use of the available good-quality water and saline wastewater, and take into account the different salt sensitivities among the crops grown in the region, including the changes in salt sensitivities of crops at different stages of growth. The advantages of a cyclic strategy include: (1) steady-state salinity conditions in the soil profile are never reached because the quality of irrigation water changes over time, (2) soil salinity is kept lower over time, especially in the topsoil during seedling establishment, (3) a broad range of crops, including those with high economic value and moderate salt sensitivity, can be grown in rotation with salt-tolerant crops, and (4) conventional irrigation systems can be used. Blending consists of mixing good- and poor-quality water supplies before or during irrigation. Saline wastewater can be pumped directly into the nearest irrigation canal or water channel. The amount of saline wastewater pumped into the canal can be regulated so that target salinities in the blended water can be achieved [22,30].

43.2.3.5 Crop Planting Techniques

Since most crops are salt sensitive at the germination stage, their establishment is important to avoid the use of saline wastewater during this critical growth stage. Under field conditions, it is possible to apply modifications to planting practices in order to minimize salt accumulation around the seed and to improve the stand of crops that are sensitive to salts during germination; for example, sowing near the bottom of the furrows on both sides of the ridges, raising seedlings with freshwater and their transplanting, using mulches to carry over soil moisture for longer periods, and increasing seed or seedling rate per unit area, thereby increasing plant density to compensate for possible decrease in germination and growth rates.

43.2.3.6 Soil and Water Treatment

Irrigation with sodic wastewater needs provision of a source of calcium to mitigate sodium effects on soils and crops. Gypsum is the most commonly used source of calcium; its requirement for sodic water depends on the sodium concentration and can be estimated through simple analytical tests. Gypsum can be added to the soil, applied with irrigation water by using gypsum beds, or placing gypsum stones in water channels. In the case of calcareous soils, containing precipitated or native calcite, the dissolution of calcite can be enhanced through plant root action to increase calcium levels in the root zone. Therefore, a lower rate of gypsum application may work well on calcareous soils. Plant residues and other organic matter left in or added to the field can also improve chemical and physical conditions of the soils irrigated with sodic wastewater. In addition, biological treatment of salt-prone wastewater by standard activated-sludge culture can be triggered by the inclusion of salt-tolerant organisms to improve treatment efficiency.

43.2.4 Persistent Organic Pollutants

In developing countries, the exposure of crops and farmers to organic contaminants is probably higher through pesticide application than organic contaminants in irrigation water. The challenge of any related risk mitigation starts with its assessment, which is costly if based on actual analysis. Thus, it is mostly based on observations [38]. An alternative between both extremes may be risk assessment based on easy to measure environmental factors and application practices [35]. The analysis of emerging contaminants, like residual pharmaceuticals or endocrine disruptor compounds would be more difficult and costly [38].

For residual pharmaceuticals, the approach for environmental risk assessments is, for example, regulated by the European Medicines Agency in their Guidelines on the Environmental Risk Assessment of Medicinal Products for Human Use (EMEA/CHMP/SWP/4447/00 corr 1*, 2006) and Environmental Impact Assessment for Veterinary Medicinal Products (CVMP/VICH/592/1998–CVMP/VICH/790/2003). These risk assessments start with an estimation of the exposure by calculating a predicted environmental concentration (PEC), based on dosage of pharmaceuticals or consumption data. These PECs are then compared to predict no effect concentrations (PNEC) in order to assess potential risks. Although pharmaceuticals and other emerging pollutants can accumulate in soil as a result of long-term irrigation with wastewater [6, 7] and may transfer from soils to crops, their amounts taken up by plants seem too small to cause acute toxic effects to humans [3]. However, little is known regarding health risks arising from the long-term uptake of small concentrations of mixtures of micropollutants with food and with drinking water use in poor communities in downstream areas.

Chemical stability and slow natural attenuation of certain persistent organic pollutants makes remediation of these pollutants a particularly intractable environmental challenge. The degree to which wastewater containing persistent organic pollutants needs to be treated depends on (1) pollutant loads, that is, concentration in wastewater × wastewater volume over time; (2) behavior of these compounds in the soil, which could be assessed through specific bioavailability tests to be performed before costly remediation strategies undertaken, for example, in the case of some compounds, a short time after their addition to the soil, diffusion and specific sorption processes lead to "aging" of these pollutants, a process that sequesters these compounds and inactivates their toxic effects; (3) soil properties as soils with large buffer capacities (adequate pH, high soil organic matter content, loamy clay texture, high cation exchange capacity, medium to deep profile) have the capacity to receive and filter larger pollutant loads. For the sites already contaminated with these compounds, the approach usually taken is to isolate the affected sites, and either remove the contaminated soil or rely on phytoremediation. In general, however, it remains crucial to ensure that industrial wastewater is treated at the source and/or separated from other wastewater streams used for irrigation.

As pesticide contamination is more likely to reach significance through direct onsite application, farm-based measures like the use of alternative pesticides or integrated pest management remain the key for risk reduction. To avoid pesticides entry into streams used for irrigation or other purposes, buffer zones, run-off reduction, and use of wetlands for remediation could be considered [35]. Containment of contaminated water in dams or wetlands may provide time for pesticides to be removed by sedimentation or through degradation. Farming practices that reduce runoff such as the provision of vegetation cover or vegetation buffer strips can help reduce the environmental impacts. The key removal mechanisms for most organic substances are sorption and biodegradation [38]. Removal efficiencies are usually greater in soils rich in silt, clay, and organic matter.

43.3 Summary and Conclusions

To avoid or reduce the contaminant risks from irrigation with untreated or partially treated wastewater, the major chemical constituents that need to be addressed can be grouped into metals and metalloids, nutrients, salts and specific ionic species, and persistent organic pollutants. The strategies for contaminant risk management have been mainly focused on wastewater treatment options, which have been demonstrated to be beneficial when treated wastewater is used in agriculture. Some farm-based measures can also reduce contaminant risk for environmental and human health under situations where untreated or partially treated wastewater is used for irrigation. However, the number of strategies that have been economically assessed and proven to be cost-effective for contaminant risk management when irrigating with wastewater is rather limited, but all mention a positive impact.

The right combination of flexible policies, effective institutions, and wise financial planning can help in implementing contaminant risk management strategies as an interim measure to gradually reach a level when most wastewater in developing countries would be available in treated form for safe and productive reuse by all means.

References

1. Ayers, R.S. and Westcot, D.W. 1985. Water quality for agriculture, Food and Agriculture Organization of United Nations (FAO) Irrigation and Drainage paper 29 Rev 1., FAO, Rome, Italy.
2. Blumenthal, U.J., Peasey, A., Ruiz-Palacios, G., and Mara, D.D. 2000. Guidelines for wastewater reuse in agriculture and aquaculture: Recommended revisions based on new research evidence, WELL Study, Task No: 68 Part 1. http://www.lboro.ac.uk/well/resources/well-studies/full-reports-pdf/task0068i.pdf. Accessed on February 20, 2014.
3. Boxall, A.B., Johnson, P., Smith, E.J., Sinclair, C.J., Stutt, E., and Levy, L.S. 2006. Uptake of veterinary medicines from soils into plants. *Journal of Agricultural and Food Chemistry*, 54(6), 2288–2297.
4. Chaney, R.L., Angle, J.S., Broadhurst, C.L., Peters, C.A., Tappero, R.V., and Sparks, D.L. 2007. Improved understanding of hyperaccumulation yields commercial phytoextraction and phytomining technologies. *Journal of Environmental Quality*, 36(5), 1429–1443.
5. Cunningham, S.D., Berti, W.R., and Huang, J.W. 1995. Phytoremediation of contaminated soils. *Trends in Biotechnology*, 13(9), 393–397.
6. Dalkmann, P., Broszat, M., Siebe, C., Willaschek, E., Sakinc, T., Hübner, J., Amelung, W., Grohmann, E., and Siemens, J. 2012. Accumulation of pharmaceuticals, enterococcus, and resistance genes in soils irrigated with wastewater for zero to 100 years in central Mexico. *Plos One*, 7(12), e45397.
7. Durán-Alvárez, J.C., Prado-Pano, B., and Jiménez, B. 2012. Sorption and desorption of carbamazepine, naproxen and triclosan in soil irrigated with raw wastewater: Estimation of the sorption parameters by considering the initial mass of the compounds in the soil. *Chemosphere*, 88(1), 84–90.
8. Fisher, H. and Pearce, D. 2009. Salinity reduction in tannery effluents in India and Australia, ACIAR Project (AH/2001/005) Final Report, Australian Centre for International Agricultural Research, Canberra, Australia.
9. Göethberg, A., Greger, M., and Bengtsson, B.E. 2002. Accumulation of heavy metals in water spinach (*Ipomoea aquatica*) cultivated in the Bangkok region, Thailand. *Environmental Toxicology and Chemistry*, 21(9), 1934–1939.
10. Grangier, C., Qadir, M., and Singh, M. 2012. Health implications for children in wastewater-irrigated peri-urban Aleppo, Syria. *Water Quality, Exposure and Health*, 4(4), 187–195.
11. Hamilton, A.J., Boland, A.M., Stevens, D., Kelly, J., Radcliffe, J., Ziehrl, A., Dillon, P., and Paulin, B. 2005. Position of the Australian horticultural industry with respect to the use of reclaimed water. *Agricultural Water Management*, 71(3), 181–209.

12. Hamilton, A.J., Stagnitti, F., Xiong, X., Kreidl, S.L., Benke, K.K., and Maher, P. 2007. Wastewater irrigation: The state of play. *Vadose Zone Journal*, 6(4), 823–840.
13. Hernández-Sancho, F., Molinos-Senante, M., and Sala-Garrido, R. 2010. Economic valuation of environmental benefits from wastewater treatment processes: An empirical approach for Spain. *Science of the Total Environment*, 408(4), 953–957.
14. Jayawardane, N.S., Biswas, T.K., Blackwell, J., and Cook, F.J. 2001. Management of salinity and sodicity in a land FILTER system, for treating saline wastewater on a saline-sodic soil. *Australian Journal of Soil Research*, 39(6), 1247–1258.
15. Johnson, S. 2006. Are we at risk from metal contamination in rice? *Rice Today* (July-September), 12(3), Los Baños, Philippines.
16. Keraita, B., Drechsel, P., and Konradsen, F. 2010. Up and down the sanitation ladder: Harmonizing the treatment and multiple-barrier perspectives on risk reduction in wastewater irrigated agriculture. *Irrigation and Drainage Systems*, 24(1–2), 23–35.
17. Lazarova, V. and Bahri, A. 2005. *Water Reuse for Irrigation: Agriculture, Landscapes, and Turf Grass*. CRC Press, Boca Raton, FL.
18. Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correll, D.L. et al. 1995. *Water Quality Functions of Riparian Forest Buffer Systems in the Chesapeake Bay Watershed*, U.S. Environmental Protection Agency, EPA 903-R-95-004/CBP/TRS 134/95, Washington, DC.
19. Maas, E.V. and Grattan, S.R. 1999. Crop yields as affected by salinity. In: R.W. Skaggs and J. van Schilfgaarde (eds.), *Agricultural Drainage*, ASA-CSSA-SSSA, Madison, WI, USA, pp. 55-108.
20. Maas, E.V. and Hoffman, G.J. 1977. Crop salt tolerance – current assessment. *Journal of the Irrigation and Drainage Division*, 103(2), 115–134.
21. Murtaza, G., Ghafoor, A., Qadir, M., Owens, G., Aziz, M.A., Zia, M.H., and Saifullah. 2010. Disposal and use of sewage on agricultural lands in Pakistan: A review. *Pedosphere*, 20(1), 23–34.
22. Oster, J.D. 1994. Irrigation with poor quality water. *Agricultural Water Management*, 25(3), 271–297.
23. Patwardhan, A.D. 2008. *Industrial Waste Water Treatment*. Prentice Hall of India, New Delhi, India.
24. Pescod, M.B. 1992. *Wastewater Treatment and Use in Agriculture*. FAO Irrigation and Drainage Paper No. 47, FAO, Rome, Italy.
25. Qadir, M. and Drechsel, P. 2010. Managing salts while irrigating with wastewater. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, 5(016), 1–11.
26. Qadir, M., Ghafoor, A., and Murtaza, G. 2000. Cadmium concentration in vegetables grown on urban soils irrigated with untreated municipal sewage. *Environment, Development and Sustainability*, 2(1), 11–19.
27. Qadir, M. and Minhas, P.S. 2008. Wastewater use in agriculture: Saline and sodic waters. In: S.W. Trimble (ed.), *Encyclopedia of Water Science*, 2nd Edition. Taylor & Francis, Boca Raton, FL, pp. 1307–1310.
28. Qadir, M., Tubeileh, A., Akhtar, J., Larbi, A., Minhas, P.S., and Khan, M.A. 2008. Productivity enhancement of salt-affected environments through crop diversification. *Land Degradation and Development*, 19(4), 429–453.
29. Qadir, M., Wichelns, D., Raschid-Sally, L., Minhas, P.S., Drechsel, P., Bahri, A., and McCornick, P. 2007. Agricultural use of marginal-quality water—Opportunities and challenges. In: D. Molden (ed.), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK, pp. 425–457.
30. Rhoades, J.D. 1989. Intercepting, isolating and reusing drainage waters for irrigation to conserve water and protect water quality. *Agricultural Water Management*, 16(1–2), 37–52.
31. Salt, D.E., Blaylock, M., Kumar, P.B.A.N., Dushenkov, S., Ensley, B.D., Chet, I., and Raskin, I. 1996. Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. *Nature Biotechnology*, 13(5), 468–474.
32. Sato, T., Qadir, M., Yamamoto, S., Endo, T., and Zahoor, A. 2013. Global, regional, and country level need for data on wastewater generation, treatment, and use. *Agricultural Water Management*, 130, 1–13.
33. Siemens, J., Huschek, G., Siebe, C., and Kaupenjohann, M. 2008. Concentrations and mobility of human pharmaceuticals in the world's largest wastewater irrigation system, Mexico City-Mezquital Valley. *Water Research*, 42(8–9), 2124–2134.
34. Simmons, R.W., Noble, A.D., Pongsakul, P., Sukreeyapongse, O., and Chinabut, N. 2009. Cadmium-hazard mapping using a general linear regression model (Irr-Cad) for rapid risk assessment. *Environmental Geochemistry and Health*, 31(1), 71–79.
35. Simmons, R., Qadir, M., and Drechsel, P. 2010. Farm-based measures for reducing human and environmental health risks from chemical constituents in wastewater, In: P. Drechsel, C.A. Scott, L. Raschid-Sally, M. Redwood, and A. Bahri (eds.), *Wastewater Irrigation and Health: Assessing and Mitigating Risks in Low-income Countries*, Earthscan, London, International Development Research Centre (IDRC)-International Water Management Institute (IWMI), 209–238.
36. Su, N., Bethune, M., Mann, L., and Heuperman, A. 2005. Simulating water and salt movement in tile-drained fields irrigated with saline water under a serial biological concentration management scenario. *Agricultural Water Management*, 78(3), 165–180.
37. Toze, S. 2006. Reuse of effluent water—benefits and risks. *Agricultural Water Management*, 80(1–3), 147–159.
38. WHO (World Health Organization) 2006. *Guidelines for the Safe Use of Wastewater, Excreta and Grey Water: Volume 2. Wastewater Use in Agriculture*. WHO, Geneva, Switzerland.