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Irrigation in Developing Countries Using Wastewater

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Wastewater is an important source of water and nutrients for irrigation in developing countries, particularly but not restricted to those located in arid and semi-arid areas. The use of wastewater is widespread and represents around 10 percent of the total irrigated surface worldwide, although varying widely at local levels. While the use of wastewater has positive effects for farmers, mainly related to their income level, it also has negative effects on human health and the environment. The negative effects impact not only farmers but also a wide range of people. Because wastewater reuse is currently necessary, it is important for governments to put in place wise but feasible management practices, such as the ones discussed in this paper, to improve the benefits while reducing and controlling the drawbacks. In order to implement sustainable reuse of wastewater and to contribute to food security, reuse projects need to be planned and constructed for the long term and based on local needs.

Keywords: Agriculture, Effects, Management practices, Non-intentional reuse, Wastewater.

1. Introduction

Irrigation is a key factor in securing food supplies in many developing countries. Of the world's total arable land, 17 percent is irrigated and produces 34 percent of the crops (Pescod 1992). Three-quarters of the irrigated area (192 million hectares) is located in developing countries (United Nations 2003), and as a consequence there is a high dependence on water for food production (figure 1). Frequently in these countries, wastewater is used to irrigate land because of high demand for water (70 percent of total use), the availability of wastewater, the productivity boost that the added nutrients and organic matter provide, and the possibility to sow all year round. Wastewater irrigation can be very important locally.

Wastewater is used to irrigate in many forms. It can be used as treated (reclaimed water) or non-treated (raw wastewater) and it can be applied directly to crops or indirectly after discharge and dilution with water from rivers or reservoirs. Sometimes reuse is part of a planned project, but most of the time—and particularly in developing countries—it just happens. In industrialized countries water reuse is part of a strategy to protect water bodies and to reduce wastewater treatment costs. It is usually performed only after high ecological standards of wastewater treatment have been achieved, and as a consequence reclaimed water has a low organic matter and nutrient content. In contrast, in developing countries reuse is frequently a spontaneous response to a shortage of water and job opportunities. It is generally practiced with "poor quality" water (even raw wastewater), which farmers like for its

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fertilizing properties but mostly because it is the only way to earn a living (Jiménez and Garduño 2001; IWMI 2003).

Figure 1. Freshwater withdrawals for agricultural use in 2000

Source: World Resources Institute 2000.

Wastewater can even be used for agricultural irrigation in cities. This "urban agriculture" is practiced in urban and peri-urban areas of arid or wet countries, depending on wastewater availability, local demand for fresh food products, and people living on the verge of poverty who have no job opportunities. Wastewater flowing in open channels is used to irrigate very small plots of land where trees, fodder, or any other product that can be introduced to the market in small quantities (flowers and vegetables) or be used as part of the family diet are grown (Cockram and Feldman 1996; Ensink et al. 2004b).

Like any activity, the use of wastewater to irrigate has both advantages and drawbacks. This paper discusses these aspects, and based on scientific work and practical experiences it proposes ways to obtain maximum benefits while reducing the risks.

1.1. Advantages of using wastewater for agricultural irrigation

- It permits higher crop yields, year-round production, and enlarges the range of crops that can be irrigated, particularly in (but not limited to) arid and semi-arid areas.
- Recycles organic matter and other nutrients to soils.
- It therefore reduces the cost of fertilizers (or simply makes them more accessible to poor farmers).
- Reduces the use of synthetic fertilizer.

- Acts as a low-cost wastewater disposal method that can also be hygienic (under controlled conditions).
- Avoids discharging pollutants to surface water bodies (which have a considerably lower treatment capability than soils).
- Increases the economic efficiency of investments in wastewater disposal and irrigation.
- Conserves freshwater sources and reduces negative impacts on surface water bodies.
- Can recharge aquifers through infiltration.
- Improves soil properties (soil fertility and texture).
- The cost of pumping wastewater from nearby channels is lower than the cost of pumping groundwater.
- It offers additional benefits such as greater income generation from cultivation and marketing of high-value crops, which contribute to improved nutrition and better education opportunities for children.

1.2. Risks and drawbacks of using wastewater for agricultural irrigation

- To maximize the benefits and minimize drawbacks, wastewater reuse must be carefully planned.
- Because the impact of pollution is generally less and takes longer in soils (and aquifers) than in surface water, some governments may delay the construction of necessary wastewater treatment facilities.
- Water salinity and metal content in soils is increased in the long term.
- Storage capacity is needed to adapt/reconcile continuous wastewater production with crops' water demand and water supplied by precipitation.
- Under non-controlled conditions (a) pathogens contained in wastewater can cause health problems for humans and cattle; (b) some substances that may be present in wastewater can be toxic to plants, cattle, or humans consuming crops; (c) some substances that may be present in wastewater can reduce soil productivity; and (d) infiltration of wastewater to aquifers may cause aquifer pollution with pathogens and organic matter.

2. Extent of wastewater use

There is no complete global inventory on the extent to which wastewater is used to irrigate land, mostly due to a lack of heterogeneous data and the fear that countries have about disclosing information; economic penalties can be imposed if produce is found to have been irrigated with low-quality water.[1] Nonetheless, the global figure commonly cited is at least 20 million hectares in 50 countries (around 10 percent of irrigated land) are irrigated with raw or partially treated wastewater (United Nations 2003).

It is also estimated that one-tenth or more of the world's population consumes crops irrigated with wastewater (Smit and Nasr 1992). Of course, wastewater use varies considerably from one region to another. In Hanoi, Vietnam, for instance, up to 80 percent of vegetables produced are irrigated with wastewater (Ensink et al. 2004a). The regional situation certainly depends on the level of wastewater

1. For instance, Jordan's export market was seriously impacted in 1991 when countries from the Arabian Peninsula and the Persian Gulf restricted imports of fruit and vegetables irrigated with inadequately treated wastewater (McCornick et al. 2004).

treatment (35 percent on average in Asia, 14 percent in Latin America and the Caribbean, and levels approaching 0 percent in Africa [WHO and UNICEF 2000]). And because the cost of improving sanitation is considerable compared to other needs, it is estimated that, for the foreseeable future, untreated wastewater will continue to be used for irrigation. Figures 2 and 3 are a collection of non-homogeneous data from different countries that gives an idea of the number of hectares irrigated with treated and non-treated wastewater.

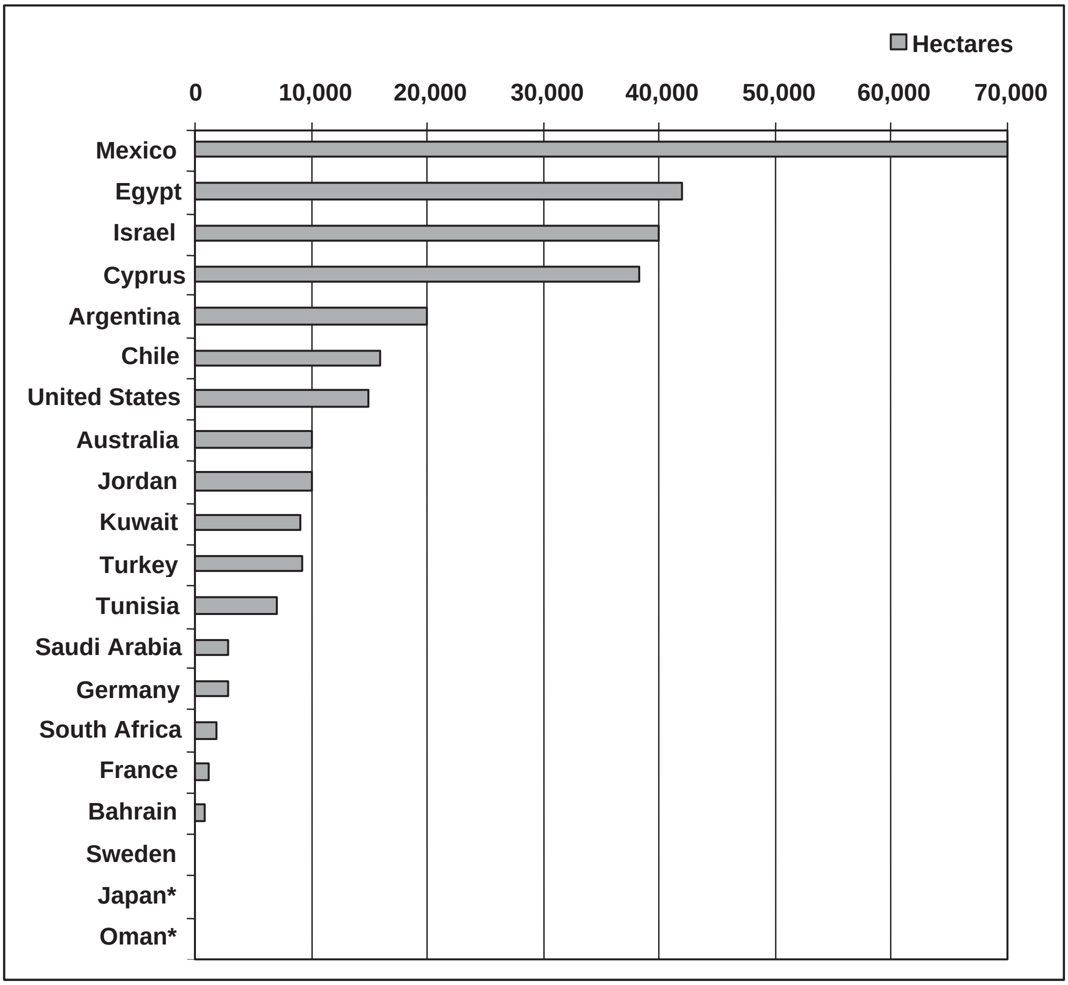

Figure 2. The number of hectares irrigated with reclaimed and treated wastewater

Note: Information may vary from source to source. Some countries report agricultural wastewater use without mentioning the amount of hectares involved.

*No data available.

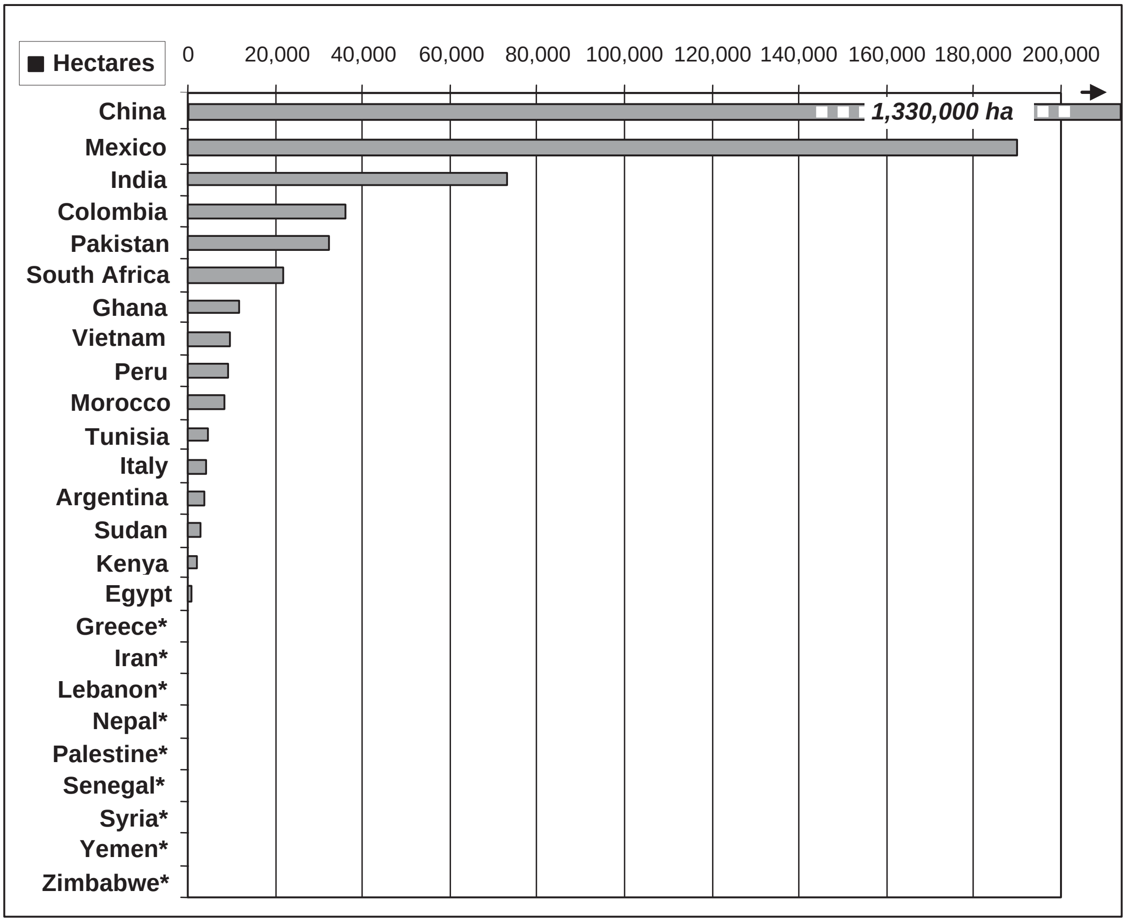

Figure 3. The number of hectares in selected countries irrigated directly and indirectly with wastewater

Note: Information may vary from source to source. Some countries report agricultural wastewater use without mentioning the amount of hectares involved.

*No data available.

3. Effects on human health

Surprisingly, the health effects of irrigating with wastewater can be both positive and negative. The positive effects have not been fully studied, but they have begun to be recognized in literature and are related to food security in poor areas. Thanks to wastewater, it is possible (and commonly the only way) to produce food and increase income in poor areas, thus also increasing nutrition and the quality of life. Malnutrition plays a significant role in the death of 50 percent of all children in developing countries (10.4 million children under the age of five die annually from it, according to Rice et al. [2000]). A study in Tanzania showed that a village where a rice irrigation scheme had been developed with wastewater had more malaria vectors than a nearby savannah village but a lower level of malaria transmission. The village with the irrigation scheme had more resources to buy food, children had a better nutritional status, and the villagers were more likely to buy and use mosquito nets (Ijumba 1997).

Negative effects are due to the presence in wastewater of pathogens and toxic chemical compounds. Four groups are at risk: (1) agricultural workers and their families; (2) crop handlers; (3) consumers of crops, meat, and milk; and (4) those living near the areas irrigated with wastewater, particularly children and the elderly. Wastewater contains a variety of excreted organisms, and the types and concentrations vary depending upon the background levels of disease in the population. Many pathogens can survive for long enough periods of time in soil or on crop surfaces and thus be transmitted to humans or animals. The most environmentally resistant pathogens are helminth (parasitic worm) eggs, and they are recognized as the main health risk in the use of wastewater for irrigation because of their resistance and persistence (WHO 1989), particularly for developing countries where levels found in wastewater are seven to 80 times greater than those found in developed countries' wastewater (Jiménez 2003).

Helminthiases (infestation with parasitic worms) are common diseases with an uneven distribution around the world. In developing countries, the affected population is 25–33 percent, whereas in developed ones it is less than 1.5 percent. The problem is more severe in regions where poverty and poor sanitary conditions prevail; under these conditions helminthiasis reaches 90 percent of the population (Bratton and Nesse 1993). There are several kinds of helminthiasis; ascariasis is the most common and is endemic in Africa, Latin America, and the Far East. There are 1.3 billion infections globally. Furthermore, even though it is a disease with a low mortality rate, most of the people affected are children under 15 years with problems of faltering growth and/or impaired fitness. Approximately 1.5 million of these children will probably never catch up, even if treated (Silva et al. 1997).

Besides helminthiasis, other diseases related to the use of wastewater are as follows: cholera, typhoid, shigellosis, gastric ulcers caused by *Helicobacter pylori*, giardiasis, amebiasis, and spoon-shaped nails (Blumenthal and Peasey 2002). There are gender implications of using wastewater, because crops such as vegetables need a high labor input, which is often supplemented by female households. Transfer of pathogens to other family members could occur if basic standards of hygiene are not maintained when women return to household activities and do evening cooking chores (Van der Hoek et al. 2002).

Regarding chemical compounds in wastewater, the major health concern is due to metals. Many of them are biologically beneficial in small quantities but become harmful at high levels of exposure. For some, no human toxicological threshold has yet been established for wastewater intended for irrigation (i.e., cobalt and copper) or the thresholds are rather high (i.e., boron, fluorine, and zinc). Cobalt, copper, and zinc are not considered here because plants are not likely to absorb them in sufficient quantities to prove harmful to consumers and are toxic to plants far before reaching a content that is toxic to humans (Chang et al. 2002). There is a limit for hexavalent chromium, however, because it is rapidly reduced to trivalent chromium, which forms a less soluble solid phase in wastewater or soils. Cadmium is the metal that causes the largest risk. Its uptake can increase with time, depending on soil concentration, and is toxic to humans and animals in doses much lower than those that visibly affect plants. Absorbed cadmium is stored in the kidney and liver, but meat and milk products are unaffected (Pescod 1992).

Cadmium is a particular concern when industrial wastewater alone or mixed with sewage is used to irrigate.

Wastewater contains a wide variety of organic compounds, some of them toxic or having cancer or embryo/fetal effects. The specific effect depends on the type of compound, its concentration, and the route and duration of exposure. Normally, the effects are long term. Of particular concern is a specific kind of organic compound, named endocrine disrupters,[2] that has been recently identified in municipal wastewater. Endocrine disruptors derive from many sources, including pesticides, persistent organic pollutants, nonionic detergents, and human pharmaceutical residues. Many of these substances are resistant to conventional wastewater treatment and may persist in the environment for some time. Human health effects potentially linked to exposure to these chemicals include breast, prostate, and testicular cancer; diminished semen quantity and quality; and impaired behavioral/mental, immune, and thyroid function in children. Although direct evidence of adverse health effects in humans is lacking, reproductive abnormalities, altered immune function, and population disruption potentially linked to exposure to these substances have been observed in amphibians, birds, fish, invertebrates, mammals, and reptiles (WHO 1999).

Organic compounds (including endocrine disrupters) have not been studied to a large extent, but in general it is known that even if recalcitrant in water they are reduced by several mechanisms in soils (British Geological Survey et al. 1998). And if wastewater is treated, they are at least partially removed. Nevertheless, these health risks associated with chemicals found in wastewater need to be given more attention, particularly in developing countries where the pace of industrialization is accelerating without proper treatment and disposal. In these countries, municipal and industrial wastewater are often not segregated—creating a potentially dangerous mixture of toxic substances that must be handled cautiously. And, in particular, care must be taken with phtalates isolated from aquifers that have formed with the infiltration of wastewater used to irrigate land (Jiménez 2004; British Geological Survey et al. 1998).

4. Effects on soils

Soil is a very complex mixture of mineral and organic substances in concentrations that vary widely in different regions and climates. For this reason, it is very difficult to say whether wastewater compounds and in what concentrations cause problems or provide benefits. Nonetheless, it is currently known that the most visible effect of using wastewater for irrigation is a productivity increase due to its content of nutrients and organic matter (Mara 2003; U.S. EPA 1992). Nutrients make wastewater an effective fertilizer, while organic matter improves soil texture.

Nitrogen is present in several chemical forms (nitrate, ammoniacal nitrogen, organic nitrogen, and nitrites). Most crops only absorb nitrates, but the other forms are transformed into them in soils (National Research Council et al. 1996). Nitrates are very soluble in water, and as a consequence they are washed out of soil by irrigation and polluting aquifers or surface water bodies. It is therefore

2. Chemicals that mimic hormones or have anti-hormone activity and interfere with the functioning of endocrine systems in various species.

important to adjust the amount of nitrogen added with the wastewater. This amount depends on the soil's original nitrogen content (0.05–2 percent) and crop demand (from 50 to 350 kilograms of nitrogen per hectare [kg/ha] [Girovich 1996]), values that are equivalent to irrigation rates of 125–875 millimeters for domestic wastewater with a medium nitrogen content and that indicate, for most crops, that wastewater has a greater nitrogen content than needed. With phosphorus, it is the opposite. Phosphorus is very scarce in soils and must almost always be added. Wastewater normally contains lower amounts of phosphorus than required by crops (6–12 milligrams of phosphorus per liter [mg/L]), and does not negatively impact the environment, even if applied for long periods through effluents, because it is stable and can be accumulated in soils (Girovich 1996). The third macronutrient, potassium, exists in high concentrations in soils (3 percent) but is not bio-available to plants. Approximately 185 kg/ha of potassium are required and sewage can supply part of this demand (Mikkelsen and Camberato 1995).

Besides adding nutrients, irrigating with wastewater enriches the humic content by supplying organic matter, which increases soil humidity, retains metals (through cationic exchange and the formation of organo-metallic compounds), and enhances microbial activity (Ortega-Larrocea et al. 2002). If organic matter content in wastewater is less than 350–500 mg/L, all these effects enhance soil productivity by avoiding soil clogging. Recycling nitrogen, phosphorus, potassium, and organic matter to soil is important because it closes their ecological cycles instead of interrupting them, as is traditionally done when these compounds are removed from wastewater, trapped into sludge, and dumped with it in confinement sites or landfills. But in the case of phosphorus, recycling is even more important because its reserves are limited and dwindling; recycling it is even being promoted by the phosphate industry (CEEP 2001).

Irrigating with wastewater also has negative effects on soils. The most common one reported is an increase in metal content that, depending on the level, may or may not be harmful. The use of domestic wastewater (treated or not) to irrigate results in the accumulation of metals in upper layers of soil with no negative effects on crops, even when applied over long periods of time (several decades). However, wastewaters containing industrial effluents with high metal contents not only accumulate metals but also cause damage to crops and eventually to consumers. Regardless of the wastewater metal content, for metal uptake by crops a certain level has to be reached in soils but also be present in the mobile fraction. Metals are fixed to soils with a pH of 6.5–8.5 and/or with high organic matter content. Fortunately, sewage pH is always slightly alkaline (7.2–7.6). This value, combined with an important soil and wastewater alkalinity maintains original soil pH. The elements of major concern are cadmium, copper, molybdenum, nickel, and zinc. In some cases, the presence or absence of other divalent metals in the soil can influence the uptake of heavy metals.

Wastewater containing solids may clog soils, depending on its concentration (100–350 mg/L), soil porosity, and chemical composition (mineral ones that are not biodegraded are the worst). This will require regular soil drying and periodic removal of soil by raking or scraping for infiltration recovery.

Long term, the main problem that water reuse causes is soil and groundwater salinization. This occurs even with freshwater if appropriate soil washing and land drainage are not furnished, and in that sense wastewater reuse will accelerate the processes due to a higher salt content. Salinity effects are of concern particularly in arid and semi-arid regions where accumulated salts are not flushed from the soil profile by natural precipitation and where wastewater reuse is a necessity. The salinization build-up rate also depends on the water quality, soil transmissivity, organic matter content, land drainage, irrigation rate, and depth to the groundwater level. Depending on the type of soils and the washing and drainage conditions, salinity problems can occur with conductivities greater than 3 deciSiemens per meter (dS/m) in dissolved solids greater than 500 mg/L (being severe if greater than 2,000 mg/L), chlorine less than 140 mg/L, and a sodium absorption ratio (SAR) greater than 3–9. Other problems related to salinity are toxic effects caused by sodium, bicarbonates, and boron.

Israel, as an example, uses 70 percent of its municipal effluents for agricultural irrigation and has experience with soil salinization. Because removing salts from wastewater is much more expensive than preventing their entry into it, an extensive salt control program has been adopted. This program includes saline discharge control to sewerage and regulation of the quantity of salts (sodium, boron, chlorides, and fluorides) used for ion exchanger regeneration and in detergents. As a result of this measure, chlorides in sewage have dropped from 120 mg/L in 1992 to 60 mg/L in 2002, and boron has dropped from 0.6 mg/L in 1999 to 0.3 mg/L in 2002 (expected to reach 0.2 mg/L by 2008) (Weber and Juanicó 2004). Certainly, countries reusing wastewater to irrigate will follow this example.

5. Effects on crops

There are two types of effects on crops: (1) those that affect yields and (2) those that modify crop quality (appearance, flavor, or pollutant presence). As already mentioned, yield is in general increased by the fertilizing compounds present in wastewater, but it can also be diminished if toxic compounds are present. For instance, nitrogen applied to plants when it is not needed may induce more vegetative than fruit growth and also delay ripening. This has been observed for beets, cane, and rice (Pescod 1992; Morishita 1988). Concerning phosphorus, high contents (above those commonly present in municipal wastewater) reduce copper, iron, and zinc availability in alkaline soils. Boron is toxic to several crops. Salinity, besides reducing soil productivity, increases salt content in crops. This can be a problem for some crops such as vineyards for wine production. And crops' appearance is affected by chlorides (less than 140 mg/L in sensitive ones or greater than 350 mg/L in resistant ones) and carbonates (greater than 500 mg/L of calcium carbonate). Both compounds burn leaves when sprinklers are used to irrigate (Pescod 1992).

Concerning pollution, crops can be contaminated with microbes, heavy metals, and organic toxic compounds (in that order of frequency and importance). Contamination can happen by direct contact of irrigation water with edible parts or, in the case of metals, through absorption from soils, depending on environmental conditions and the type of plants. Crop pollution depends not only on water quality but also on agricultural practice (quantity of water applied and irrigation method). Oron et al. (1992) and Najafi et al. (2003) found that microbial pollution is reduced if irrigation is performed by subsurface dripping rather than through sprinklers or furrows. Pollution depends also on the type of crops. For example, Armon et al. (2002) found that zucchini spray-irrigated with poor-quality wastewater accumulated higher levels of cryptosporidium oocysts (160–20,000 oocysts/kg) on the surface than other types of crops. Zucchini has hairy, sticky surfaces and grows close to the ground and therefore may concentrate certain types of pathogens on its surface. Trees are less likely to produce polluted fruits because they are located far from the irrigating sites and polluted soils. Crop contamination occurs not only as a result of wastewater irrigation but also during washing, packing, transportation, and marketing, which are frequently not addressed by water reuse criteria, giving the impression that irrigation is the only problem.

Generally speaking, toxic organic compounds have a large size and high molecular weight that do not allow them to be absorbed by plants (Pahren et al. 1979), but some toxic organic compounds present in wastewater can remain in fruits and leaves by direct contact. Pesticides are a great concern, but the main polluting pathway is their direct application to fields rather than their introduction through wastewater. Endocrine disruptors might also pose some concerns. Mansell et al. (2004) have demonstrated that hormones like 7-estradiol, estriol, and testosterone have very low sensitivity to photodegradation through ultraviolet light exposure over a 24-hour period (less than 10 percent).

6. Effects on cattle

Cattle can suffer health or growth problems if they consume forage polluted with wastewater. Nevertheless, in some areas of the developing word where water is scarce, cattle are not only fed with forage grown with wastewater but also allowed to drink it (Ensink et al. 2004a). Some protozoan can infect animals if they survive in irrigated crops, although this is not the main transmission pathway. There is only limited evidence indicating that beef tapeworm (*Taenia saginata*) can be transmitted to the population consuming the meat of cattle grazing on wastewater irrigated fields or fed crops from such fields. There is strong evidence, however, that cattle grazing on fields freshly irrigated with raw wastewater or drinking from raw wastewater canals or ponds can become heavily infected by Taenia, causing cysticerosis (Shuval et al. 1985).

Although no problems have been reported in relation to cattle that consume fodder irrigated with wastewater, fodder irrigated with high nitrogen content water can cause grass tetany, a disease related to an imbalance of nitrogen, potassium, and magnesium in pasture grasses. Cadmium in much lower doses that visibly affects plants may be harmful to animals. Absorbed cadmium is stored in the kidney and liver, leaving meat and milk products unaffected. Something similar happens with copper, which may be harmful to ruminants (cows and sheep but not to mono-gastric animals) at concentrations too low to visibly affect plants. Molybdenum causes adverse effects in animals consuming forage with 10–20 parts per million and low copper content. The consumption of crops with more than five milligrams of molybdenum per kilogram of feed is toxic to cattle, particularly ruminants. Toxicity is related to the ingestion of copper and sulphates.

7. Effects on water

Irrigating with wastewater modifies not only the quality of the wastewater itself but also affects surface and water bodies.

7.1. Irrigation wastewater

Wastewater improves in quality when it is used to irrigate for the same reasons that soils and crops become polluted. This positive effect has been widely documented in literature, and there is even a treatment process known as soil aquifer treatment, or SAT (Bouwer 1987, 1991). Its application to soils and crops reduces the content of microorganisms (6–7 log for bacteria and 100 percent of helminths and protozoan), organic matter (greater than 90 percent, including recalcitrant compounds), nutrients (phosphorus, 20–90 percent; nitrogen, 20–70 percent), and metals (70–95 percent), but salinity is increased.

Most microorganisms are retained in upper soil layers by filtration or absorption. Removal is more efficient as the size of the soil grains decreases and there are more active adsorption sites. The distance required to remove microorganisms increases if microorganisms are small in size or if soils are fractured or have macro pores such as occurs in coarse-grain materials, fractured or structured clays, fractured rocks, or limestone caverns (Foster et al. 2004). Microorganisms' adsorption in soils is favored by low pH, high salt concentration in the sewage, and high relative concentrations of calcium and magnesium over monovalent cations such as sodium and potassium on soil.[3]

Most organic compounds of human, animal, or plant origin contained in sewage are rapidly transformed in soils to stable, non-toxic organic compounds (humic and fulvic acids). Actually, soils can biodegrade a wider variety and a greater amount of organic compounds than water bodies can. Water application under controlled conditions (limited irrigation rate and intermittent flooding) permits the biodegradation of hundreds of kilograms of biological oxygen demand per hectare per day (kg BOD /ha/d) with no impact on the environment (Bouwer 1991). BOD levels are virtually reduced after a few meters of percolation through the soil, where total organic carbon (TOC) values of 1–5 mg/L can still be measured. Removal of several recalcitrant compounds such as organochlorides or endocrine disrupter compounds by adsorption and biodegradation has been reported in some soils and in several days (WHO 1999; Mansell et al. 2004).

The amount of nitrogen remaining in wastewater after irrigation depends on the nitrogen content and the amount of water applied to crops. Nitrogen removal is enhanced if flooding and drying periods are alternated, which promotes a nitrification/denitrification process on soil that can remove about 75 percent of the nitrogen in sewage (Bouwer 1987).

Phosphorus in sewage (5–50 mg/L) is biologically converted to phosphate. In calcareous soils and at an alkaline pH, phosphate precipitates with calcium to form calcium phosphate. In acid soils, phosphate reacts with iron and aluminum oxides in the soil to form insoluble compounds. Sometimes phosphate is initially immobilized by adsorption to the soil and then slowly reverts to insoluble forms, allowing more adsorption of mobile phosphate. In clean sands with about neutral pH, phosphate can be relatively mobile (Bouwer 1991).

As mentioned earlier, metals are retained in the upper soil layers, either remaining bound to the organic fraction or precipitated due to pH. Only a small fraction of metals infiltrates lower layers and a

3. Additional information on this subject can be found in Jiménez (2003).

much smaller one still enters crops. For instance, around 80–94 percent of cadmium, copper, nickel, and zinc are removed in the first five to 15 centimeters, 5–15 percent is lixiviated by runoff, and 1–8 percent is absorbed by grasses (Pescod 1992). A similar process occurs with fluorine and boron (Ayres and Wescot 1985).

To understand why irrigation water is salinized, one must know that during irrigation an extra amount of water always has to be applied to remove from soils the salts accumulated in the root zone due to water evaporation. This activity is known as leaching, and the water employed for it is called the leaching fraction, which must also be removed from the agricultural site by means of agricultural drainage. If the whole process is not carried out properly, soils tend to become saline and lose their productivity. This operation is critical in areas where evaporation is important (arid and semi-arid areas) and where the phreatic level is high and pushes salts to the soil surface.[4] Besides evaporation, the extent of water salinization depends on the type of soils and the hydraulic loading rate. In sandy soils, hydraulic loading rates are much higher than evaporation losses (e.g., 50 meters per year [m/yr] versus 1.5 m/yr) and the salt concentration in the renovated water from SAT systems will be about the same as that of the sewage effluent (or slightly higher). If clay or organic matter is present in the soil, there will be cation adsorption and ion exchange, which increases salinization (Pescod 1992).

7.2. Groundwater

An indirect consequence of irrigated agriculture is aquifer recharge, and it occurs in permeable soils whether it is performed with fresh, reclaimed, or reused wastewater (Foster et al. 2004). Recharge happens almost always non-intentionally and has the advantage of increasing the local availability of water. Water infiltration is due to the excess of water applied to irrigate as well as the infiltration of irrigating water during its storage and transportation. Foster et al. (2004) analyzed recharge from wastewater used to irrigate in a number of locations (Miraflores, the peri-urban area of Lima, Peru; Wagi Dhuleil, Jordan; Mezquital Valley, Mexico; Leon, Mexico; and Hat Yai, Thailand) and estimated that at least 1,000 millimeters per year of water is recharged, a value that in many cases exceeds the local pluvial precipitation. Rashed et al. (1995) estimate that infiltration is equivalent to 50–70 percent of the water used for agriculture. Consequently, it must be accepted that agricultural water reuse will recharge the aquifer and try to plan it in the best possible way.

The impact on groundwater quality depends on several factors, such as the irrigation rate, the irrigation wastewater quality, the vulnerability of the aquifer, the form in which irrigation is performed, the rate of artificial compared to natural recharge, the original quality of underground water and its potential use, the time under irrigation, and the type of crops (Foster et al. 2004). The impact from nitrogen is the effect most frequently cited in literature and with it the risk of causing methemoglobinemia in infants. In spite of this, a recent investigation prepared on behalf of the World Health Organization concludes that although in the past it has been accepted that consumption of drinking water high in nitrates causes methemoglobinemia in infants, it now appears that nitrate may be one of a number of co-factors that play a sometimes complex role in causing the disease (Fewtrell 2004).

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4. *Phreatic* refers to the underground water in the zone below the water table.

Furthermore, given the apparently low incidence of possible water-related methahemoglobinemia, the complex nature of the role of nitrates, and individual behavior, it is currently inappropriate to attempt to link illness rates with nitrate levels in drinking water. Notwithstanding this discussion, it is evident that aquifers beneath agricultural fields often display larger nitrate concentration, and its presence can be considered as an indication of pollution.

Concerning microorganisms, as mentioned above, the vadose zone removes them efficiently at a relatively short distance (some meters).[5] Nevertheless, some microorganisms, particularly viruses, can reach aquifers if they are present in high concentrations in reused water, wastewater is applied in very permeable or fractured soils, or the phreatic level is high (Foster et al. 2004).

Normally, metals have little impact on aquifers since domestic wastewater contains low levels. According to Leach et al. (1980) the most toxic metals to humans—cadmium, lead, and mercury—were absent in groundwater at five sites in the United States after 30–40 years of applying secondary and primary effluents at rates between 0.8 m/yr and 8.6 m/yr to different crops. The reason given was that the initial metal content and a soil pH greater than 6.5 precipitated metals.

Organic matter reaching aquifers from percolating reclaimed water varies between 1–5 mg/L of TOC. If wastewater is used to irrigate, the content can rise to 6–9 mg/L of TOC. Both ranges are higher than what is commonly accepted as safe for water reuse recharge for human consumption (1–2 mg/L of TOC), and even for low concentrations the concern would be what kind of compounds caused the TOC. Some of them lead to the formation of organochlorides if water is used for human consumption and disinfected with chlorine (the most common method). Foster et al. (2004) found that in aquifers recharged with wastewaters the potential of trihalomethanes (THM) formation oscillates between 20 and 45 micrograms per milligram of TOC and can produce disinfected water with a concentration of up to 100 micrograms per liter. Other compounds can be toxics of industrial origin or possibly endocrine disrupters. Luckily, absorption of these types of substances is very effective in soils, as already described.

Due to the infiltration of wastewater to aquifers, in the long term, salt content in aquifers will always increase. Based on the original quality, present and future use, as well as interconnections between the aquifer and other water bodies, this effect may or may not be relevant (Farid et al. 1993).

7.3. Surface water

Surface water bodies are affected because they receive water from irrigation drainage and runoff. Impacts depend on the extent that wastewater has been in contact with soil, on the type of water body (i.e., river, irrigation channel, lake, or dam), and their use, as well as the hydraulic retention time and the part played within the ecosystems. In any case, if water is being used for human consumption, viruses and bacteria are the major concern, since protozoan and helminths ova are almost always removed by soils (even through horizontal infiltration), with the exception of extreme rain events where protozoan transportation has been also demonstrated (Scott et al. 2004). Microorganisms are a concern even if drinking water treatment plants are available, since they are not normally designed to treat high

5. Vadose refers to the underground water in the zone above the water table.

microorganism contents and are inefficient in inactivating microbes resistant to conventional disinfection methods (such as protozoa or viruses). Something similar happens with toxic organic compounds, which can affect surface water bodies' quality because they can consume dissolved oxygen; this is not very common because such compounds are easily removed from soil. The main impact to surface water bodies is caused by the remaining nitrogen in wastewater that causes eutrophication of lakes, reservoirs, and rivers with low-speed flows. Eutrophication not only affects the water but also superior life, like birds and fish, with the consequent biodiversity, fishing, and recreational loss.

8. Effects on infrastructure

To reconcile wastewater production with water demand by crops, storage capacity is needed. Lagoons and dams built for this purpose contribute to improving wastewater quality, because they treat it, at least partially, through sedimentation, biological and physical degradation, photolysis, adsorption, desorption, and competition between species. According to Juanicó and Milstein (2004), lagoons and dams can remove the following: (a) suspended solids; (b) organic matter in an extent depending on the retention time; (c) heavy metals; (d) detergents; (e) organic pollutants (such as phthalates, alkyl phenols, alkyl benzenes, and hydrocarbons); and (f) most of the bacteria and helminths. In spite of these advantages, reservoirs have the drawback, for arid and semi-arid regions, of evaporating water. For instance, the large-scale pond system of Khirbet As Samra near Amman, Jordan, with a surface of 181 hectares, evaporates 13–18,000 cubic meters of water per day in summer, when the need for water is highest. This volume accounts for 20–25 percent of the water flow (Duqqah 2002). As a consequence of evaporation, the concentration of salts in the remaining effluent increases by at least 25 percent, which affects agriculture. In addition, because they are unlined, reservoirs and lakes can leak water to the subsoil. Both problems can, to a certain extent, be controlled by using small reservoirs in a series and placing compacted clay or synthetic membranes on the bottom. Whether this is affordable, however, will depend on local conditions.

Lagoons and dams, like any stagnant water body, can suffer eutrophication due to the nutrient content in wastewater. Aquatic plants in reservoirs can serve as habitats of vectors of diseases like malaria, filariasis, and West Nile fever. In Haroonabad and Faisalabad, India, mosquitoes (*Anopheles* and *Culex*) have even been reported in wastewater stabilization ponds (Ensink et al. 2004c).

Coupled with other uses, dams and lagoons are often employed for aquaculture, in some cases illegally when wastewater is involved. Fish production is used for family consumption or for sale, particularly in Asia (e.g., Kazakhstan, Cameroon, Bangladesh, China, Vietnam, Cambodia, and Indonesia). Health effects are frequently associated with pathogens, especially trematodes (a kind of helminth), but they can also arise due to metals. Finally, reservoirs if filled with wastewater can present odor problems.

Like reservoirs, irrigation channels can evaporate and infiltrate water (especially when unlined, which is the most common case in developing countries). Infiltration is proportional to the length of the channel. Open channels can also treat wastewater through aeration, desorption, degradation, or disinfection with UV sunlight. When nutrients are present and the flow is slow, however, aquatic plants like *Eichohornia crassipies* (lilies or water hyacinth), *Verticillata Hydrilla*, *Typhas* sp. (cattail), and *Lemna* sp. (duckweed) can grow. As an example, in Mexico, 12,000 kilometers of channels and 19,000 kilometers of irrigating drains were reported infested with aquatic weeds in 2000 (27 percent and 63 percent of the total, respectively). In addition, more than 50 percent of the water bodies related with agriculture also displayed eutrophication. Eutrophicated channels become the habitat of disease vectors and are sources of bad odors. Irrigation channels not only convey original wastewater but also agricultural water drainage, transporting remaining polluting agents to other water bodies.

Irrigation systems also affect the use of wastewater. Depending on their efficiency, they use more or less water and therefore reduce or increase water infiltration from irrigation to subsoil and water discharges to surface water bodies. Also, it has been observed that (depending on the irrigation system) pollution in soils and crops can increase or be reduced. Some irrigation systems promote erosion, favor waterlogging and soil compaction, and enhance or reduce health risks to farmers.

9. Effects on socioeconomic aspects

The social perception of agricultural wastewater reuse varies from one community to another. Societies with high income and no previous contact with water reuse frequently oppose it due to the potential impact on health and the environment, odor problems, its tendency to devalue property, and changes to water and soil uses. The situation is completely different in poor areas lacking in job opportunities, where water reuse represents the only possibility of improving living standards by increasing income and ensuring food supplies. In areas where wastewater is an important production factor, people use up to 50–80 percent of their income on food (Raschid-Sally et al. 2005); thus, even in small plots and with inappropriate water quality, agricultural production contributes to supporting families and complementing their diets (Ratta and Nasr 1996). For these reasons, between 15 percent (in Hanoi) and 68 percent (in several cities of India and Africa) of poor cities practice urban agriculture using raw wastewater. The mean annual net income per farmer using wastewater to irrigate varies from US$155 in Yaoundé, Cameroon, to $2,800 in Hyderabad, India (Raschid-Sally et al. 2005). In fact, the possibility of having wastewater to irrigate instead of freshwater made land rents in the El Mezquital Valley, Mexico, increase from $171 to between $351 and $940 per year, because, besides increasing yields, irrigating with wastewater enables three crops to be harvested per year instead of one (Jiménez 2005a). For most of these communities, food security and nutrition are more important than infectious disease transmission.

10. Effects on legal matters

Besides having social ramifications, the use of wastewater also has legal ones. The present use of wastewater for agriculture is creating rights, even if it is not a planned activity and does not fulfill environmental norms, because customary rights are recognized almost worldwide. These rights can conflict with future planned reuse projects, especially if treated wastewater is expected to be sold at a higher price than the one paid by the original user of the raw wastewater. In some countries, like Pakistan, wastewater rights for agriculture are even charged for, recognizing that, even though it is a product considered “unacceptable” in other parts of the world, it nevertheless has an economic value (Ensink et al. 2004b). In Quetta, Pakistan, farmers were paid $12,000 per year for wastewater, 2.5 times more than the price of freshwater. But also, and by contrast, public health concerns have led to several court cases in Pakistani cities (Ensink et al. 2004c). Following a trial, also in Quetta, farmers were forced by local residents to test the pathogen content of their products through a national certified laboratory. After demonstrating that their crops were not polluted even though irrigated with wastewater, the farmers were allowed to continue their practice. In Hyderabad, a large number of court cases have occurred over the last ten years initiated by local water utilities or sanitation agencies. The outcome of these court cases was that farmers were either forced to pay for wastewater or to abandon its use altogether. In the case of Faisalabad, a group of wastewater farmers successfully appealed against one of these court orders after proving they had no access to another suitable water source.

11. Critical water management practices

To maximize the benefits and reduce the drawbacks of wastewater irrigation, several management practices must be put in place, the combination of which should offer an optimum solution for a given set of local conditions. The use of an integral management approach has several advantages, because, besides being a more reliable multi-barrier system, it permits flexibility and the selection of lower and more socially and economically acceptable control measures to protect health and the environment while fostering food security. The management practices discussed below can be used in several combinations.

a. **Segregation, pretreatment, and reduction of noxious compounds in domestic wastewater.** Pollutants such as heavy metals, toxic organic compounds, and salts coming mainly from industrial discharges are difficult to remove from wastewater, and so it is cheaper, easier, and safer to prevent them from being discharged into the sewage system in the first place. Beside this, it is also important to promote cleaner industrial production processes in order to avoid the use and discharge of toxic compounds, as well as to educate society to reduce the use of toxic compounds at home and their unsafe disposal.

b. **Wastewater treatment.** Whenever possible, wastewater treatment is needed to reduce pollutants. In that respect, organic matter and nutrients are not targeted compounds for agricultural purposes, especially if soils are poor, while pathogens are of the most importance. This need implies different treatment technologies than those conventionally used to protect water bodies. Fortunately, in a number of cases, this option can be implemented at a reduced cost that is affordable to developing countries (Pescod 1992; Mara 2003; Jiménez and Garduno 2001). A particular need that has to be considered in developing countries for wastewater treatment selection is the efficiency and reliability of a process for removing helminth ova (Jiménez 2005b).

c. **Water management.** When there is the possibility of using additional sources of water, an option for partially controlling the negative impacts caused by wastewater is to blend it with freshwater, or to use them in an alternative way by preferring freshwater close to the harvesting period.

d. **Wastewater storage.** As mentioned above, storing wastewater as part of the irrigation system improves its quality by reducing the content of pathogens and pollutants associated with suspended solids. For this reason, maximizing storage time is important when designing wastewater irrigation systems.

e. **Aquifer protection.** To avoid negative effects stemming from the infiltration of wastewater, it is recommended to do the following: (a) recognize its occurrence and quantify the phenomenon; (b) before reusing water, establish cost-effective patterns of rational water use and management; (c) improve agricultural irrigation practices; (d) establish criteria to drill wells used to supply water for human consumption in the surroundings (i.e., distances to irrigation sites, depth of extraction, and appropriate construction); (e) promote water reuse for agriculture, preferably in zones where aquifers are less vulnerable; and (f) undertake constant and efficient monitoring of underground water (Foster et al. 2004).

f. **Agriculture management:**

- **Crop selection and restrictions.** Crops are enormously varied in nature and behavior; therefore, an appropriate selection can reduce the different risks generated by the use of wastewater. Crops can be selected to overcome salinity and toxicity due to chlorides, sodium, and boron, and reduce health hazards for consumers (FAO and UNESCO 1973). The crops that are of major health concern are those that are eaten raw by humans or animals. Irrigation of landscape plants, industrial crops, and afforestation for commercial purposes (fruit, timber, fuel, and charcoal) or environmental protection display a much lower risk, mainly due to limited human contact. In order to be effectively implemented by farmers, crop selection needs to consider economic benefits. For instance, flowers can be selected as crops because they carry a low health risk and a high economic value.
- **Site restrictions.** Wastewater's negative impact can also be controlled by limiting the sites where it is applied. Normally, water areas with restricted access to public, far from potable water sources, or where the aquifer is at a sufficient depth (less than 3 meters) should be preferred. Also, irrigation areas can be limited to fields where it is possible to have buffer areas around them or where soils have a significant depollution capacity. Wastewater irrigation of pasturing sites should be avoided.
- **Irrigation methods.** Besides the normal factors considered when selecting an irrigation method when using wastewater (i.e., water availability, climate, soil, crops to be grown, cost of irrigation method, and the ability of the farmer to manage the system), other considerations need to be taken into account, such as possible contamination of plants and harvested product, health threats to farm workers, environmental impacts, salinity, and toxicity hazards. Basin or flood irrigation involves complete coverage of the soil surface and will contaminate vegetables growing near to the ground as well as root crops. Besides not being an efficient method of irrigation, it also exposes farm workers to the effluent more than any other method. Furrow irrigation does not wet the entire soil surface, thus limiting crop contamination. If the effluent is transported through pipes and delivered into individual furrows by means of gated pipes, then risk to irrigation workers will be reduced. Sprinkler irrigation contaminates ground crops,

fruit trees, and farm workers, and it can provoke severe leaf damage if water contains chlorides or bicarbonates, resulting in significant yield losses. Trickle and dip irrigation, particularly when the soil surface is covered with plastic sheeting or other mulch, uses effluent more efficiently and can often produce higher crop yields; it certainly provides the greatest degree of health protection for farm workers and consumers (Pescod 1992).

- **Control of soil salinization.** Normally, wastewaters are not very saline (200–500 mg/L or 0.7–3.0 dS/m). On specific occasions (i.e., saline soils areas, saline discharges to sewers, or sea intrusion to water supplies that generates sewage), however, salinity concentration exceeds the 2,000 mg/L level. In these cases, appropriate water management practices need to be followed to prevent soil salinization through leaching and drainage. Several recommendations are documented but are beyond the scope of this paper.
- **Crop management practices valid under saline water use will be valid under wastewater use.** These practices are aimed at preventing damage to crops caused by salt accumulation surrounding the seeds. This is achieved by planting on the shoulder of the ridge, using sloping beds with seeds planted on the sloping side but above the water line, and irrigating alternate rows so that the salts can be moved beyond the single seed row.
- **Land soil management is important.** Done properly it makes irrigation with wastewater easier, reduces salinity problems, and increases irrigation efficiency. Typical activities include leveling of land to a given grade, establishing adequate drainage (both open and sub-surface systems), and deep plowing and leaching to reduce soil salinity.
- **Irrigation timing.** Proper timing of irrigation is important to ensure removal of nitrogen through nitrification/denitrification when there are eutrophication risks to lakes or reservoirs posed by the discharge of the drainage water. Also, to reduce transportation of pesticides, irrigation must not be performed just after their application to fields.
- **Irrigation rates.** Gauging of irrigation rates should be done in such a way that water demand by crops is satisfied but the infiltration of low-quality wastewater to the subsoil is avoided.

g. **Education and participation.** When using wastewater (even treated), it is important to inform the population of the associated risks, the water quality, and measures that can be used to reduce or control such risks. To that end, planned education and information campaigns need to be conducted on an ongoing basis. In particular, the proper agricultural practices, the use of protective clothing, and how to properly wash and disinfect vegetables and fruits grown in wastewater should be addressed. While using wastewater that has been treated to a high level will diminish the need for public participation and education, it is nevertheless very costly.

h. **Health campaigns.** The health sector should undertake ongoing campaigns to monitor the effects on public health and subsequently supply farmers and their families with anthelmintic drugs.

12. Policies

A coherent national policy on wastewater use in agriculture is essential to controlling present risk and avoiding future ones. The policy must define the division of responsibilities among the ministries and authorities involved and provide for their collaboration. Institutional mechanisms for implementing the national policy must be established and legal backing provided for the enforcement of regulations. Realistic standards must be adopted to safeguard public health as well as to provide protection from adverse environmental impacts.

To be successful, a multiple-barrier approach based on the measures discussed is required to strengthen regulations and institutions. Governments must be prepared to control the whole process within a broader framework of a national effluent-use policy that forms part of the national water resources plan. These policies need to involve local authorities, farmers, and regional/federal health and environmental protection authorities. Laws and norms need to clearly define water rights, water quality, and agricultural restrictions (e.g., on crops, sites, soils, farming practices). Economic tools may also be useful, but they need to take into account that, in most developing countries, the agricultural sector experiences economic difficulties and that food security is essential. Therefore, social and political considerations should be taken into account when economic tools are applied. Also in this regard, it must be considered that even though farmers wish to take advantage of the effluent, very often they are neither able nor willing to pay to subsidize the disposal cost of wastewater that is the responsibility of polluters.

13. Conclusions and recommendations

Given agriculture's high demand for water, as well as an increase in the urban population that demands food and produces wastewater, agricultural water reuse is bound to grow. In developing countries there are several examples of the use of wastewater to irrigate and, as long as wastewater production increases along with demand for food, the governments of such countries will increasingly have to adopt planned approaches rather than unplanned ones. Governments need to take control of the situation in order to progressively but constantly put in place management measures to protect health and the environment, while also giving a productive use to wastewater. Governments need to accept that the volume of wastewater used to irrigate is and will be the most important reuse of water in the world (Asano 1998).

The major challenge in using marginal-quality water for irrigation is to maximize the benefits for farmers and society while minimizing adverse environmental and health impacts. Several examples of positive and negative effects according to each situation were given in this paper. And since wastewater is a cheap source of water and nutrients, and in many places the only possible source of water, it will continue to be used to grow crops. Improving this practice is thus necessary to meeting the United Nations' Millennium Development Goals to enhance food security and environmental quality over the next 50 years.

Wastewater management needs to be approached in a novel way in order to include agricultural demands, socioeconomic and institutional realities, the importance of helping nature to close ecological cycles and, most of all, to include the idea that to improve the quality of life does not necessarily mean the same thing in different regions. This integral approach implies modifying some of the more traditional sanitation concepts in order to achieve a balance between long- and short-term ecological risks and society's pressing needs. To ban irrigation with wastewater would mean eliminating thousands of thriving micro-economies based on growing wastewater-irrigated crops and increasing surface water pollution, negatively impacting the health of downstream water users. Therefore, instead of promoting unrealistic policies, it would be best to learn lessons from the hundreds of unplanned agricultural reuse cases all over the world and try to gradually improve existing practices to reduce the risks.

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