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Control of pathogenic microorganisms in wastewater recycling and reuse in agriculture

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1 INTRODUCTION

As presented in detail, in Chapter 11, raw domestic wastewaters normally carry the full spectrum of pathogenic microorganisms – the causative agents of bacterial, virus and protozoan diseases endemic in the community and excreted by diseased and infected individuals. While recycling and reuse of wastewater for agriculture, industry and non-potable urban purposes can be a highly effective strategy for developing a sustainable water resource in water short areas, nutrient conservation and environmental protection, it is essential to understand the health risks involved and to develop appropriate strategies for the control of those risks. This chapter will concentrate on the control of pathogenic microorganisms from wastewater in agricultural reuse since this is the most widely practised form of reuse on a global basis. However, more and more water specialists, natural resource planners and economists see water as an economic good and, as time goes on, there will be an increased motivation to divert recycled wastewater from low income agriculture to areas where the added value of water is greater, such as industrial and non-potable urban uses including public parks, green belts, golf courses, football fields. As time goes on and water shortages in arid areas increase, there will undoubtedly be an expansion of the reuse of purified wastewater for industrial and a wide variety of urban/non-potable purposes. There are some specific heath guidelines and standards for such uses, but they will not be reviewed in this chapter.

The control measures for agricultural reuse include establishing and enforcing microbial guidelines for effluent quality, regulation of the types of crops to be irrigated, minimizing the potential for crop contamination by various irrigation techniques and the treatment of the wastewater to an *appropriate degree* so as to control potential health risks, both to the farmers and the consumers of crops, from pathogenic microorganisms in the wastewater stream. This chapter will deal with the above questions.

2 PATHOGENIC MICROORGANISMS CAN BE TRANSMITTED BY WASTEWATER IRRIGATION

Pathogenic microorganisms in the wastewater stream can be transmitted to healthy individuals and cause disease if improper regulation and control methods in wastewater irrigation are practised. In order for disease causing microorganisms or pathogens in the wastewater stream flowing from a community to infect a susceptible individual they must be

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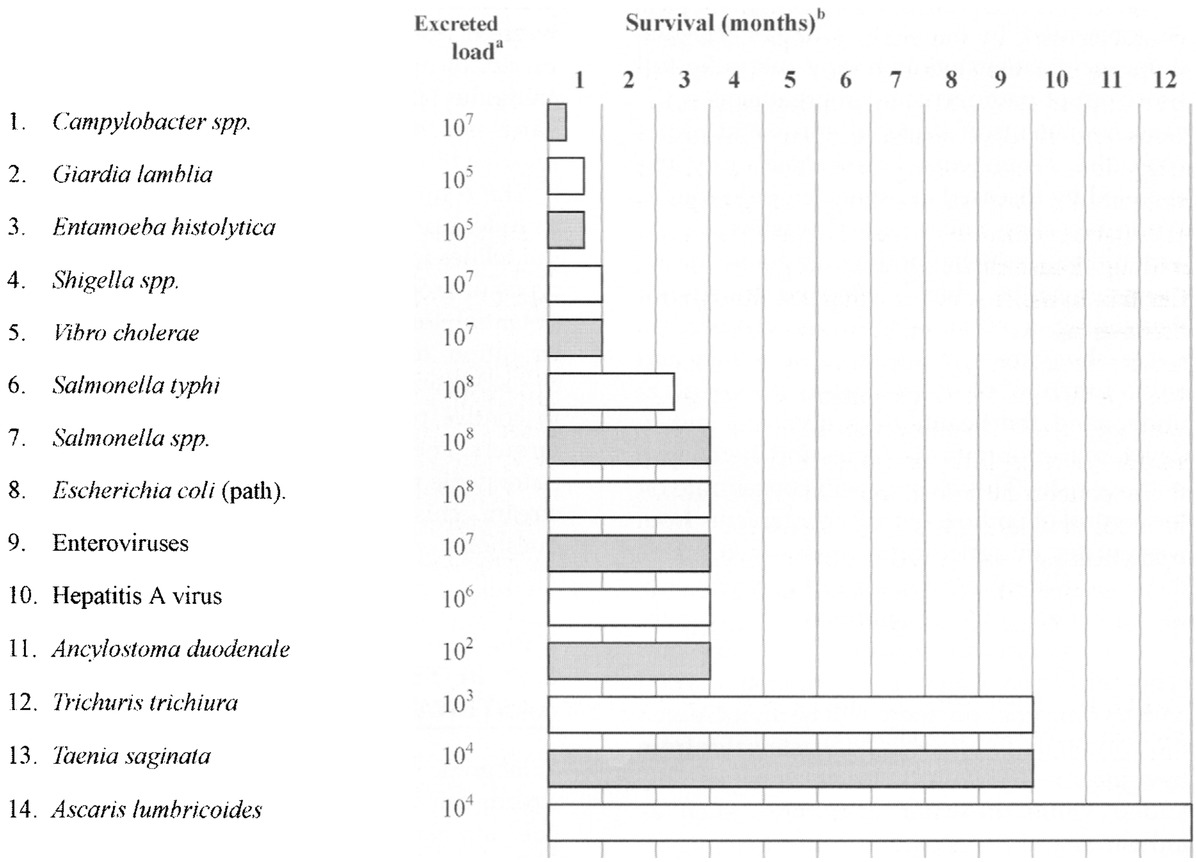
able to survive in the environment (i.e. in water, soil, or food) for a period of time and they must be ingested in a sufficiently high number. Factors that affect the survival of pathogens in soil include antagonism from soil bacteria, moisture content, organic matter, pH, sunlight and temperature. Excreted enteric pathogens such as bacteria, viruses, protozoa, and helminth eggs do not usually penetrate undamaged vegetables but can survive for long periods in the root zone, in protected leafy folds, in deep stem depressions, and in cracks or flaws in the skin.

Data from numerous field and laboratory studies have made it possible to estimate the persistence of certain enteric pathogens in water, wastewater, soil, and on crops. These survival periods in the environment are presented in summary graphic form in Fig. 15.1. For example, it appears that *Campylobacter* may survive in soil or on crops for only a few days, whereas most bacterial and viral pathogens can survive from weeks to months. The highly resistant eggs of helminths, such as *Trichuris*, *Taenia* and *Ascaris*, can survive for 9–12 months, but their numbers are greatly reduced during exposure to the environment.

Field studies in Israel have demonstrated that enteric bacteria and viruses can be dispersed for up to 730 m in aerosolized droplets generated by spray (sprinkler) irrigation, but their concentration is greatly reduced by detrimental environmental factors such as sunlight and drying (Teltsch *et al.*, 1980; Applebaum



[a] Typical average number of organism/g feces
[b] Estimated average life of infective stage at 20–30°C.

Fig. 15.1 Survival times of enteric pathogens in water, wastewater, soil and on crops (from Shuval *et al.*, 1986 - based partially on data from Feachem *et al.*, 1983).

et al., 1984; Shuval *et al.*, 1988, 1989a). Thus, most excreted pathogens can survive in the environment long enough to be transported by the wastewater to the fields and to the irrigated crops. The contaminated crops eventually reach the consumer, although by then the concentration of pathogens is greatly reduced. The rapid natural die-away of pathogens in the environment is discussed in a later section as it is an important factor in reducing the health risks associated with wastewater reuse.

Theoretical analysis suggests that a number of epidemiological factors determine whether various groups of pathogens will cause infections in humans through wastewater irrigation. We have developed a model to evaluate the empirical epidemiological data and to formulate control strategies (Shuval *et al.*, 1986).

Table 15.1 summarizes the epidemiological characteristics of the main groups of enteric pathogens as they relate to the five factors that influence the transmission and degree of infections and disease resulting from wastewater irrigation. This summary provides a simplified theoretical basis for ranking the groups of pathogens according to their potential for transmitting disease through wastewater irrigation. On this basis, it appears that the helminthic diseases are the ones most effectively transmitted by irrigation with raw wastewater because they persist in the environment for relatively long periods; their minimum infective dose is small; there is little or no immunity against them; concurrent infection in the home is often limited; and latency is long and a soil development stage is required for transmission.

In contrast, the enteric viral diseases should be least effectively transmitted by irrigation with raw wastewater in developing countries with low levels of sanitation in the home, despite their small minimum infective doses and ability to survive for long periods in the environment. Due to poor hygiene in the home, and the prevalence of concurrent routes of infection in some areas, most of the population has been exposed to, and acquired immunity to, most of the enteric viral diseases as infants. Most enteric viral diseases impart immunity for life, or at least for very long periods, so that they are not likely to re-infect individuals exposed to them again, e.g. through wastewater irrigation. The transmission of bacterial and protozoan diseases through wastewater irrigation lies between these two extremes. In developed countries with higher levels of home sanitation and little concurrent disease transmission due to poor hygiene practice, there will be lower levels of immunity to diseases which could be transmitted by wastewater irrigation or vegetables eaten uncooked.

3 REVIEW OF RESEARCH FINDINGS ON DISEASE TRANSMISSION BY WASTEWATER IRRIGATION

This section will provide an extensive review and evaluation of the research findings on disease transmission by wastewater irrigation based on available scientific papers published in recognized journals and in numerous unpublished government reports, university theses, and private papers obtained during an intensive world-wide search carried out with the help of international and national

TABLE 15.1 Epidemiological characteristics of enteric pathogens *vis-à-vis* their effectiveness in causing disease through wastewater irrigation

Pathogen	*Persistence in environment*	*Minimum infective dose*	*Immunity*	*Concurrent routes of infection*	*Latency/soil development stage*
Viruses	Medium	Low	Long	Mainly home contact, food and water	No
Bacteria	Short/medium	Medium/high	Short/medium	Mainly home contact, food and water	No
Protozoa	Short	Low/medium	None/little	Mainly home contact, food and water	No
Helminths	Long	Low	None/little	Mainly soil contact outside home and food	Yes

agencies and individuals. Over 1000 documents, some more than 100 years old, were examined in the course of this study, but few offered concrete or reliable epidemiological evidence of health effects. Most of them based their conclusions on inference and extrapolation. Nonetheless, about 50 of these reports provided enough credible evidence based on sound epidemiological procedures to make a detailed analysis useful. Those studies are reviewed in detail in the UNDP-World Bank report on which this chapter is partially based (Shuval *et al.*, 1986). Our general conclusions of some of the more pertinent studies are presented below.

One of the goals of our studies for the UNDP/World Bank study (Shuval *et al.*, 1986; Shuval, 1990), as described in this chapter, was to re-evaluate all the credible, scientifically valid and quantifiable epidemiological evidence of the real human health effects associated with wastewater irrigation. Such evidence is needed to determine the validity of current regulations and to develop appropriate technical solutions for existing problems.

3.1 Illness associated with wastewater irrigation of crops eaten raw

In areas of the world where the helminthic diseases caused by *Ascaris* and *Trichuris* are endemic in the population, and where raw, untreated wastewater is used to irrigate salad crops and/or other vegetables generally eaten uncooked, the consumption of such wastewater-irrigated salad and vegetable crops may lead to significant levels of infection. Khalil (1931) demonstrated the importance of this route of transmission in his pioneering studies in Egypt. Similarly, a study in Jerusalem (Shuval *et al.*, 1984) provided strong evidence that massive infections of both *Ascaris* and *Trichuris* may occur when salad and vegetable crops are irrigated with raw wastewater. These diseases almost totally disappeared from the community when raw wastewater irrigation was stopped (Fig. 15.2). Two studies from Darmstadt, Germany (Krey, 1949; Baumhogger, 1949) provided additional support for this conclusion.

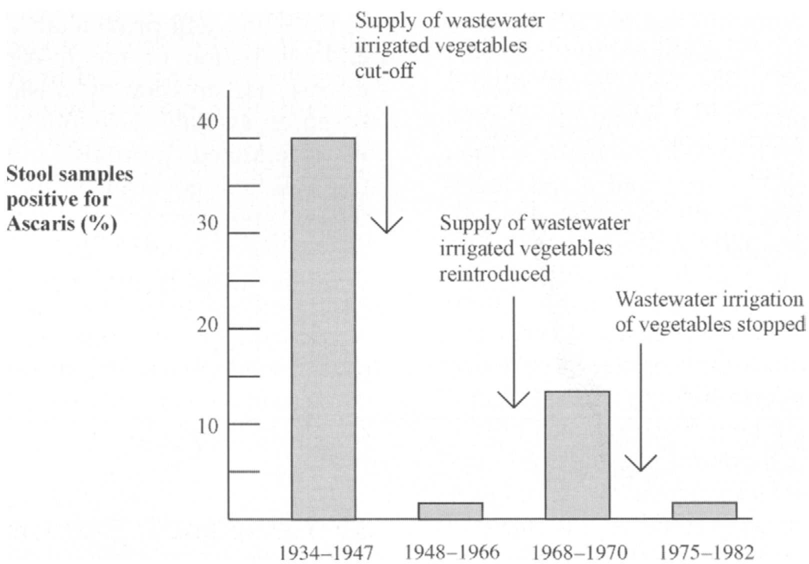


Fig. 15.2 Relationship between Ascaris-positive stool samples in population of western Jerusalem and supply of vegetables and salad crops irrigated with raw wastewater in Jerusalem, 1935–1982 (from Shuval *et al.*, 1986 – based on partially on data from Ben-Ari, 1962; Jjumba-Mukabu and Gunders, 1971; Shuval *et al.*, 1984).

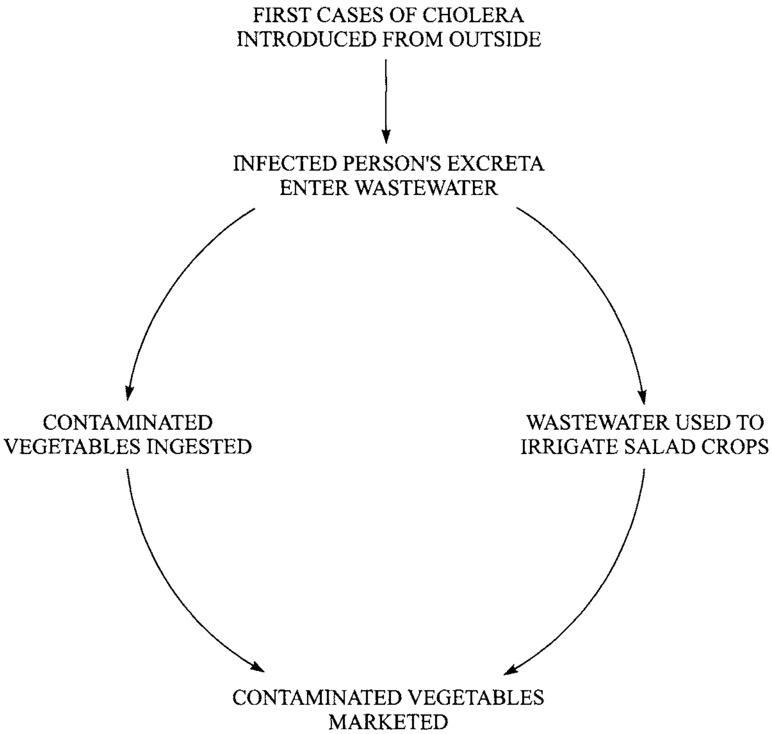


Fig. 15.3 Hypothesized cycle of transmission of Vibrio cholerae from first cholera carriers introduced from outside the city, through wastewater-irrigated vegetables, back to residents in the city (from Fattal *et al.*, 1986b).

These studies also indicate that regardless of the level of municipal sanitation and personal hygiene, irrigation of vegetables and salad crops with raw wastewater can serve as a major pathway for continuing and long-term exposure to *Ascaris* and *Trichuris* infections. Both of these infections are of a cumulative and chronic nature, so that repeated long-term re-infection may result in a higher worm load and increased negative health effects, particularly among children.

Cholera can also be disseminated by vegetable and salad crops irrigated with raw wastewater if it is carrying cholera vibrios. This possibility is of particular concern in non-endemic areas where sanitation levels are relatively high, and the common routes of cholera transmission, such as contaminated drinking water and poor personal hygiene, are closed. Under such conditions, the introduction of a few cholera carriers (or subclinical cases) into a community could lead to massive infection of the wastewater stream and subsequent transmission of the disease to the consumers of the vegetable crops irrigated with the raw wastewater, as occurred in Jerusalem in 1970. The hypothesized cycle of transmission from the first imported case from outside the city through wastewater irrigated vegetables back to the residents is shown in Fig. 15.3 (Fattal *et al.*, 1986b).

Similarly, our study from Santiago, Chile (Shuval, 1984), strongly suggests that typhoid fever can be transmitted by fresh salad crops irrigated with raw wastewater. The number of typhoid fever cases in Santiago rose rapidly *annually* at the beginning of the irrigation season, after 16 000 ha of vegetables and salad crops (usually eaten uncooked) had been irrigated with raw wastewater. The relatively high socioeconomic level, good water supply, and good general sanitation in the city supports the hypothesis that wastewater irrigation can become a major route for the transmission of such bacterial disease.

3.2 Cattle grazing on wastewater irrigated pastures

Wastewater is often used to irrigate pasture for cattle and sheep. What are the health risks associated with this practice? There is only limited epidemiological evidence to indicate that beef tapeworms (*Taenia saginata*) have been transmitted to populations consuming the meat of cattle grazing on wastewater-irrigated fields or fed crops from such fields. However, there is strong evidence from Melbourne, Australia (Penfold and Phillips, 1937), and from Denmark (Jepson and Roth, 1949) that cattle grazing on fields freshly irrigated with raw wastewater or drinking from raw wastewater canals or ponds can become heavily infected with the disease. This condition can become serious enough to require veterinary attention and may lead to economic loss. Irrigation of pastures with raw wastewater from communities infected with tapeworm disease may provide a major pathway for the continuing cycle of transmission of the disease to animals and humans.

3.3 Exposure of wastewater farmers to disease

Obviously the individuals most intensely exposed to the wastewater stream at the farms where wastewater irrigation is practised, are the farmers themselves. Some of the studies with the clearest epidemiological evidence relates to the health of such farm workers. Sewage farm workers exposed to raw wastewater in areas of India, where *Ancylostoma* (hookworm) and *Ascaris* infections are endemic, have much higher levels of infection than other agricultural workers (Krishnamoorthi *et al.*, 1973). The risk of hookworm infection is particularly great in areas where farmers customarily work barefoot, because the broken skin of their feet is readily penetrated by the motile hookworm larva. Sewage farm workers in this study also suffered more from anaemia (a symptom of severe hookworm infestation) than the controls. Thus, there is evidence that continuing occupational exposure to irrigation with raw wastewater can have a direct effect on human productivity and, thus, on the economy.

Sewage farm workers are also liable to become infected with cholera if the raw wastewater being used for irrigation is from an urban area experiencing a cholera epidemic. This situation is particularly likely to arise in an area where cholera is not normally endemic and where the level of immunity among the sewage farm workers is low or non-existent. This proved to be the case in the 1970 cholera outbreak in Jerusalem (Fattal *et al.*, 1986b). In a related study (Fattal *et al.*, 1985), we have shown that irrigation workers exposed to aerosols from spray irrigation of both fresh water and wastewater had significantly higher rates of serum positivity to antibodies of *Legionella pneumophila*, the causative agent of Legionnaires' disease, as compared to the non-exposed control group of farmers and their families. This study does show that virulent pathogens can be transmitted by aerosols from spray irrigation and can infect highly exposed workers. However, it does not suggest that Legionnaires' disease is transmitted by wastewater irrigation any more than by fresh water, where the organisms are very often found.

Studies from industrialized countries have thus far produced only limited, and often conflicting, evidence of the incidence of bacterial and viral diseases among wastewater irrigation workers exposed to partly or fully treated effluent, or among workers in wastewater treatment plants exposed directly to wastewater or wastewater aerosols. Most morbidity and serological studies have been unable to give a clear indication of the prevalence of viral diseases among such occupational exposed groups.

It is hypothesized that many sewage farmers or treatment plant workers have acquired relatively high levels of permanent immunity to most of the common enteric viruses endemic in their communities at a much younger age. Thus, by the time they are exposed occupationally, the number of susceptible workers is small and not statistically significant. Presumably this is also the case among infants and children in developing countries, because they are exposed to most endemic enteric viral diseases by the time they reach working age. Although this is not the case for some bacterial and protozoan pathogens, multiple routes of concurrent infection with these diseases may well mask any excess infection among wastewater irrigation workers in developing countries.

3.4 Exposure of residents in the vicinity of wastewater farms

A number of studies have evaluated the potential negative health effects that might result from living in the vicinity of farms where wastewater irrigation, particularly sprinkler irrigation is practised. There is little evidence linking disease and/or infection among population groups living near wastewater treatment plants or wastewater irrigation sites with pathogens contained in aerosolized wastewater. Most studies have shown no demonstrable disease resulting from such aerosolized wastewater, which is caused by sprinkler irrigation and aeration processes. Researchers agree, however, that most of the earlier studies have been inadequate.

Recent studies in Israel suggest that aerosols from sprinkler irrigation with poor microbial quality wastewater can, under certain circumstances, cause limited infections among infants living near wastewater-irrigated fields. The studies, however, also concluded that these were negligible and could be controlled by better treatment of the wastewater (Fattal *et al.*, 1986a, 1987; Shuval *et al.*, 1988, 1989b).

These findings support the conclusion that, in general, relatively high levels of immunity against most viruses endemic in the community block additional environmental transmission by wastewater irrigation. Therefore, the additional health burden is not measurable. The primary route of transmission of such enteroviruses, even under good hygienic conditions, is through contact infection in the home at a relatively young age. As already mentioned, such contact infection is even more common in developing countries, so that a town's wastewater would not normally be expected to transmit a viral disease to rural areas using it for irrigation.

3.5 Epidemiological evidence of beneficial effects from wastewater treatment

When raw wastewater is used for irrigation there is no doubt that the wastewater stream carries very high concentrations of pathogens. Conventional wastewater treatment plants were not normally designed to reduce the concentration of pathogenic microorganisms, however, such treatment can nonetheless provide a degree of removal up to about 85–95% reduction in coliform bacteria and pathogens. Some epidemiological studies have provided evidence that negative health effects can be reduced when wastewater is treated for the removal of pathogens. For example, Baumhogger (1949) reported that, in 1944, residents of Darmstadt who consumed salad crops and vegetables irrigated with raw wastewater experienced a massive infection of *Ascaris;* but the residents of Berlin, where biological treatment and sedimentation were applied to the wastewater prior to the irrigation of similar crops, did not.

Another study on intestinal parasites was conducted on school children near Mexico City (Sanchez Levya, 1976). The prevalence of intestinal parasites in children from villages that used wastewater irrigation did not differ significantly from that in children from the control villages, which did not irrigate with wastewater. The lack of significant difference between the two groups may have resulted from long-term storage of the wastewater in a large reservoir for weeks or months prior to its use for irrigation. It is assumed that sedimentation and pathogen die-away during long-term storage were effective in removing the large, easily settleable protozoa and helminths, which were the pathogens of interest in this study. This study provides the first strong epidemiological evidence of the health protection provided by microbial reductions achieved in wastewater storage reservoirs.

Furthermore, the absence of negative health effects in Lubbock, Texas (Camann *et al.*, 1983) and in Muskegon, Michigan (Clark *et al.*, 1981), appears to be associated with the fact that well-treated effluents from areas of low endemicity were used for irrigation.

Data from these field studies strongly suggest that pathogen reduction by wastewater treatment, including long-term storage in wastewater reservoirs, can have a positive effect on human health. In all the above studies, this positive effect was achieved despite the use of effluent which had not been disinfected and which contained a few thousand of fecal coliform bacteria per 100 ml. These data agree with water quality data on pathogen removal and suggest that appropriate wastewater treatment resulting in effective reduction of coliforms to the level of a few thousand/100 ml, but not total removal, can provide a high level of health protection.

3.6 Conclusions from the analysis of the epidemiological studies

It is possible to draw certain conclusions from the series of epidemiological studies on the health effects of wastewater reuse in agriculture. The studies from both developed and developing countries indicate that the following diseases are occasionally transmitted via raw or *very poorly* treated wastewater:

1. The general public may develop ascariasis, trichuriasis, typhoid fever or cholera by consuming salad or vegetable crops irrigated with *raw wastewater*, and probably tapeworm by eating the meat of cattle grazed on wastewater-irrigated pasture. There may also be limited transmission of other enteric bacteria, viruses and protozoa.
2. Wastewater irrigation workers may develop ancylostomiasis (hookworm), ascariasis, possibly cholera and, to a much lesser extent, infection caused by other enteric bacteria and viruses, if exposed to raw wastewater.
3. Although there is no demonstrated risk to the general public residing in areas where wastewater is used in sprinkler irrigation, there may be minor transmission of enteric viruses to infants and children living in these areas, especially when the viruses are not endemic to the area and raw wastewater or very poor quality effluent is used.

Thus, the empirical evidence on disease transmission associated with *raw wastewater* irrigation in developing countries strongly suggests that helminths are the principal problem, with some limited transmission of bacterial and viral disease. The above ranking, based on empirical data, agrees with that predicted in our model.

In interpreting the above conclusions, one must remember that the vast majority of developing countries are in areas where helminthic and protozoan diseases such as hookworm, ascariasis, trichuriasis, and tapeworm are endemic. In some of these areas, cholera is endemic as well. It can be assumed that in most developing countries, in populations with low levels of personal and domestic hygiene, the children will become immune to the endemic enteric viral diseases when very young through contact infection in the home.

In conclusion, epidemiological evidence of disease transmission associated with the use of *raw wastewater* in agriculture in developing countries indicates that the pathogenic agents may be ranked in the following order of declining importance:

1. *High risk*: helminths (*Ancylostoma*, *Ascaris*, *Trichuris* and *Taenia*)
2. *Lower risk*: enteric bacteria (cholera, typhoid, shigellosis and possibly others); protozoa (amebiasis and giardiasis)
3. *Least risk*: enteric viruses (viral gastroenteritis and infectious hepatitis).

As pointed out earlier, these negative health effects were all detected in association with the use of *raw or primarily treated* wastewater. Therefore, wastewater treatment processes that effectively remove all, or most, of these pathogens, according to their rank in the above list, could reduce the negative health effects caused by the utilization of raw wastewater. While helminths are very stable in the environment, bacteria and viruses rapidly decrease in numbers in the soil and on crops.

Thus, the ideal treatment process prior to wastewater recycling and reuse, should be particularly effective in removing helminths, even if it is somewhat less efficient in removing bacteria and viruses. Wastewater treatment technologies that can be used to achieve this goal are discussed later in this chapter. In general, the above ranking of pathogens will not apply to the more developed countries or other areas in which helminth diseases are not endemic. In those areas the negative health effects, if any, resulting from irrigation with raw or partly treated wastewater will probably be associated mainly with bacterial and protozoan diseases and, in a few cases, with viral diseases. Whatever the country or the conditions, however, the basic strategies for control are the same – the pathogen concentration in the wastewater stream must be reduced and/or the type of crops irrigated must be restricted.

Overall, our studies have demonstrated that the extent to which disease is transmitted by wastewater irrigation is much less than was widely believed to be the case by public health officials in the past. Moreover, this study does not provide epidemiological support for the use of the much-copied California standard requiring a coliform count of 2/100 ml for effluent to be used in the irrigation of edible crops and even less support for the more recent USEPA/USAID recommended guideline of zero fecal coliforms. No detrimental health effects were detected or reported when well-treated wastewater with much higher coliform counts was used.

4 THE DEVELOPMENT OF HEALTH STANDARDS AND GUIDELINES FOR WASTEWATER REUSE

4.1 The importance of health guidelines and standards for reuse

One of the most important and widely practised administrative methods for protecting the public health from the risks of uncontrolled wastewater irrigation, particularly of vegetables and salad crop consumed uncooked, is the establishment of guidelines or legally binding standards for the microbial quality of wastewater used for irrigation. This section will review the scientific basis and historical and social forces that influenced the evolution of microbial standards and guidelines for wastewater reuse for agricultural purposes. This analysis will draw extensively on World Bank and World Health Organization studies and reports whose goal was a cautious re-evaluation of the credible scientific evidence which could provide a sound basis for establishing safe and feasible health guidelines for wastewater reuse (Engelberg Report, 1985; Shuval *et al.*, 1986; WHO, 1989; Shuval, 1990).

The strict health regulations governing wastewater reuse that have been developed in the industrial countries over the past 60 years, such as those of the Department of Health of the State of California, which requires an effluent standard of 2 coliforms/100 ml for irrigation of crops eaten uncooked, and even the more recent USEPA/USAID (1992) recommended guidelines for unrestricted effluent use in agriculture of zero fecal coliforms, have been based to a great extent on early scientific data indicating that most enteric pathogens can be detected in wastewater and that they can survive for extended periods in wastewater-irrigated soil and crops (see Fig. 15.1). Many health authorities have erroneously concluded that, because pathogens can survive long enough to contaminate crops, even if their numbers are very low and below the minimum ineffective dose level, they still pose a serious risk to public health. However, these regulations were formulated at a time when sound epidemiological evidence was rather scanty. As a result, policy makers used the cautious 'zero risk' approach and introduced very strict regulations that they hoped would protect the public against the potential risks thought to be associated with wastewater reuse. Most industrial countries were not concerned that these regulations were overly restrictive because the economic and social benefits of wastewater reuse were of only marginal interest.

Many of the current standards restrict the types of crops to be irrigated with conventional wastewater effluent to those not eaten raw. Regulations like those in California, requiring the effluent used for the irrigation of edible crops to have a bacterial standard approaching that of drinking water (2 coliforms/100 ml), are usually not technically feasible or sustainable without very highly skilled operators and a high-tech service infrastructure. This is particularly true for developing countries, but even applies to many developed countries. In reality, a standard of 2 coliforms/100 ml for irrigation is superior to the quality of drinking water for the majority of urban and rural poor in developing countries (where fecal coliforms are generally in excess of 10/100 ml of drinking water).

In developed countries, where these crop restrictions can normally be enforced, vegetable and salad crops are not usually irrigated with wastewater. In the developing countries, many of which have adopted the same strict regulations, public health officials do not approve of the use of wastewater for irrigation of vegetable and salad crops eaten raw. However, when water is in short supply such crops are widely irrigated illegally with raw or poorly treated wastewater. This usually occurs in the vicinity of major cities, particularly in semi-arid regions.

Since the official effluent standards for vegetable irrigation are not within the obtainable range of common engineering practice and for economic considerations, new projects to improve the quality of effluent are not usually approved. With the authorities insisting on unattainable, expensive and unjustifiable standards, farmers are practising widespread uncontrolled and unsafe irrigation of salad crops with raw wastewater. The highly contaminated vegetables are supplied directly to the nearby urban markets, where such horticultural products can command high prices. This is a classic case in which official insistence on the 'best' prevents cities and farmers from achieving the 'good'.

Some inconsistency exists between the strict California standards, which require edible crops to be irrigated with wastewater of drinking water quality, and the actual agricultural irrigation with normal surface water as practised in the USA and other industrialized countries with high levels of hygiene and public health. There are few, if any, microbiological limits on irrigation with surface water from rivers or lakes, which may be polluted with raw or treated wastewater. For example, the US Environmental Protection Agency's water quality criteria for unrestricted irrigation with surface water is 1000 fecal coliforms/100 ml (USEPA, 1972). A WHO world survey of river water quality has indicated that most rivers in Europe have mean fecal coliform counts of 1000–10 000/100 ml. And yet none of these industrialized countries has restrictions on the use of such river water for irrigation.

A number of microbial guidelines have been developed for recreational waters considered acceptable for human contact and swimming. In the USA, for example, microbial guidelines for recreational water have, in the past, ranged from 200 to 1000 fecal coliforms/100 ml, although they currently are at about 10 fecal coliforms/100 ml. In Europe, guidelines vary from 100 coliforms/100 ml in Italy to 20 000 coliforms/100 ml in Yugoslavia. The European Community has recommended a guideline of 2000 fecal coliforms/100 ml for recreational waters (Shuval *et al.*, 1986).

It is difficult to explain the logic of a 2 coliforms/100 ml standard for effluent irrigation when farmers all over the USA and Europe can legally irrigate any crops they choose with surface water from free-flowing rivers and lakes, which often have fecal coliform levels of over 1000/100 ml. It is even more difficult to explain the epidemiological rationale of the 2 coliforms/100 ml standard for effluent irrigation, while in Europe recreational water for bathing is considered acceptable at 2000 fecal coliforms/100 ml.

4.2 The World Bank/World Health Organization initiative to re-evaluate wastewater reuse guidelines

Because of the questions raised in Section 4.1 above, and the fact that the strict coliform standards adopted by many countries were rarely enforced and often found to be unfeasible for economic reasons and due to the lack of adequate technical infrastructure, in 1981, the World Bank and the World Health Organization initiated an extensive multidisciplinary study on the health effects of wastewater irrigation. The primary goal was to obtain an up-to-date scientific evaluation of the public health justification and validity of existing standards and guidelines and to develop alternatives if this was deemed to be justified. These studies were carried out by teams of epidemiologists, engineers, agronomists and environmental specialists simultaneously and independently at three different environmental sciences and public health research centers – the London School of Hygiene and Tropical Medicine, the International Reference Centre on Wastes Disposal, Zurich and the Division of Environmental Sciences of the Hebrew University of Jerusalem, Israel. These groups, working independently, prepared reports summarizing their findings, analysis and recommendations (Feachem *et al.*, 1983; Shuval *et al.*, 1986; Blum and Feachem, 1985).

In July 1985, a group of environmental experts, including engineers and epidemiologists, meeting at Engelberg, Switzerland, under the auspices of UNDP, World Bank, WHO, UNEP and IRCWD, reviewed the preparatory scientific studies which provided new epidemiological data and insights and from them formulated new proposed microbiological guidelines for treated wastewater reuse in agricultural irrigation (Engelberg Report 1985). The group accepted the main findings and recommendations of the UNDP-World Bank study (Shuval *et al.*, 1986) and concluded that 'current guidelines and standards for human waste use are overly conservative and unduly restrict project development, thereby encouraging unregulated human waste use'. The new guidelines recommended in the Engelberg Report were later accepted and approved by a WHO Meeting of Experts (WHO, 1989). However, before the WHO Executive approved those recommendations for publication as an official WHO document, the report was sent out for review and approval by a panel of some 100 epidemiologists, public health officials and environmental engineers. Thus, these new recommended guidelines for the microbial quality of effluent used for wastewater irrigation of edible crops carry the stamp of approval of the highest international authority on public health and environmental matters. Other important international technical assistance agencies joined the WHO in supporting the new recommended guidelines for wastewater irrigation including the World Bank, The Food and Agricultural Organization (FAO), The United Nations Environment Program (UNEP) and the United Nations Development Program (UNDP). Meanwhile, a number of governments in developing and developed countries have adopted the new WHO recommended guidelines, including France.

There were a number of innovations in the new recommended guidelines. Since the possibility of transmitting helminth disease by wastewater irrigation of even non-edible crops was identified as the principal health problem, a new, stricter approach to the use of raw wastewater was developed. The new WHO guidelines recommend effective water treatment in all cases to remove helminths to a level of *one or fewer helminth eggs per liter.* The main innovation of the WHO guidelines is: for crops eaten uncooked, an effluent must contain one or fewer helminth eggs per liter, with a *geometric mean of fecal coliforms not exceeding 1000/100 ml.* This is a much more liberal coliform standard than the early California requirement of 2 total coliforms/100 ml.

An attractive feature of the new WHO (1989) effluent guidelines is that they can be readily achieved with low cost, robust waste stabilization pond systems and wastewater storage and treatment reservoirs that are particularly suited to developing countries. The high levels of pathogen removal that can be achieved by such low-cost stabilization pond systems are shown in Fig. 15.4. In conjunction with alternating wastewater storage reservoirs even higher degrees of treatment with an added safety factor can be achieved. Most studies indicate that the critical design parameter to achieve the WHO microbial guidelines in the effluent is a long detention period of up to 25–30 days in maturation ponds or long

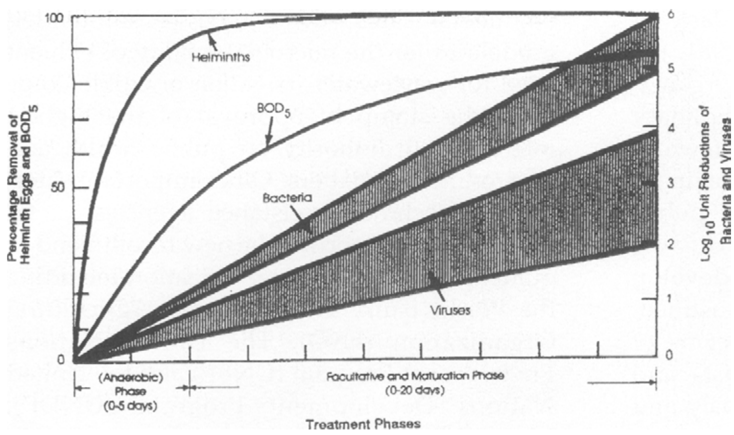


Fig. 15.4 Generalized removal curves for BOD, helminth eggs, excreted bacteria and viruses in wastewater stabilization ponds at temperatures above 20°C (from Shuval *et al.*, 1986).

detention times of several months in batch-operated storage reservoirs prior to the irrigation season (see Chapter 26).

4.3 The USEPA/USAID initiative for wastewater reuse guidelines

The US Environmental Protection Agency (USEPA), with the support of the US Agency for International Development (USAID), established their own rigorous recommended guidelines in 1992 of zero fecal coliforms/100 ml, a BOD of 10 mg/l, a turbidity of 2 NTU and a free chlorine residual of 1 mg/l. This quality of wastewater effluent can only be achieved in very costly high-tech wastewater treatment plants that require a high level of technological infrastructure for operation and maintenance, so that they can continuously meet such very rigorous standards. These guidelines were drafted by one of the leading American consulting engineering firms under contract to USAID. Such consulting engineering firms often tend to favor such high-tech treatment processes. Again, these new American guidelines are essentially as strict as those required for drinking water and reaffirm the 'no risk' or 'fail safe' approach that has been taken by the Americans in setting wastewater reuse guidelines and standards. The fact that little if any natural river water or water at approved bathing beaches in the USA or elsewhere could meet these recommended irrigation guidelines did not seem to bother those who drafted and approved the new American guidelines. No one has suggested that such river water should not be allowed for irrigation purposes, nor has any health risk from such irrigation been reported.

5 THE DEVELOPMENT OF A RISK ASSESSMENT/COST-EFFECTIVENESS METHOD FOR EVALUATION OF GUIDELINES

The WHO Guidelines are supported by numerous international technical assistance agencies and have been adopted by France and a number of other developed and developing countries. However, some groups have favored the stricter 'no risk' USEPA/USAID recommended guidelines and have questioned whether the WHO guidelines provide a sufficiently high level of safety and health protection. The debate over the appropriateness of the various guidelines has so far been on a qualitative level.

We have carried out a study aimed at developing a quantitative risk assessment and cost-effectiveness approach based on a mathematical model and experimental data, to arrive at a comparative risk analysis of the various recommended microbiological guidelines for unrestricted irrigation of vegetables normally eaten uncooked (Shuval and Fattal, 1996; Shuval *et al.*, 1997). The guidelines that were compared are those of the World Health Organization (<1000 fecal coliforms/100 ml) and those recommended by the USEPA/USAID (zero fecal coliforms/100 ml).

5.1 Risk assessment model

For the purposes of this study, the risk assessment model, estimating the risk of infection and disease from ingesting microorganisms in drinking water, developed by Haas *et al.* (1993) was selected. However, certain modifications were required since we are estimating the risk of infection associated with eating vegetables irrigated with wastewater of various microbial qualities. The basic model of Haas *et al.* (1993) for the probability of infection (P_I) from ingesting pathogenic microorganisms in water is:

$$P_I = 1 - [1 + N/N_{50}(2^{1/\alpha} - 1)]^{-\alpha} \qquad (1)$$

where

P_I = risk of infection by ingesting pathogens in drinking water
N = number of pathogens ingested
N_{50} = number of pathogens that will infect 50% of the exposed population
α = the ratio N/N_{50} and P_I

Various studies have shown a wide variation in the probability of infected persons becoming ill, with morbidity rates varying between 1 and 97%, depending on the virulence of the pathogen, and the age, nutritional and general health status of the subjects. Since not every person infected by the ingestion of pathogens becomes ill, an independent estimate is made of P_D, the probability of contracting a disease:

$$P_D = P_{D:I} \times P_I \qquad (2)$$

P_D = the risk of an infected person becoming diseased or ill
$P_{D:I}$ = the probability of an infected person developing clinical disease.

5.2 Determining the number of pathogens ingested

In order to make an estimate of the number of pathogens ingested from eating wastewater-irrigated vegetables, we first had to determine, through laboratory experiments, the amount of liquid that might cling to vegetables irrigated with wastewater. It was then possible to estimate the concentration of indicator organisms and pathogens that might remain on such wastewater irrigated vegetables and be ingested by subjects eating such vegetables. In doing this we assumed that any microorganisms contained in the residual wastewater remaining on the irrigated vegetables would cling to the vegetables even after the wastewater itself evaporated.

Based on laboratory determinations, we have estimated that the amount of wastewater of varying microbial qualities that would cling to the outside of wastewater irrigated cucumbers would be 0.36 ml/100 g (or one large cucumber) and 10.8 ml/100 g on long leaf lettuce (about three lettuce leaves).

Based on these measurements, we estimated the amount of indicator organisms that might remain on the vegetables if irrigated with raw wastewater and with wastewater meeting the WHO guidelines. In the case of irrigation with raw wastewater, we estimated that the fecal coliform (FC) concentration was 10^7/100 ml. In the case of irrigation with wastewater meeting the WHO guidelines the FC concentration would be 10^3/100 ml. We then estimated that the enteric virus:FC ratio in wastewater, based on various studies (Schwartzbrod, 1995), is $1{:}10^5$. For the purposes of this preliminary risk estimate we have assumed that all of the enteric viruses are a single pathogen, such as the virus of infectious hepatitis, so that it will be possible to make certain assumptions as to median infectious dose and infection to morbidity ratios. This errs on the conservative side.

We also assumed that under actual field conditions there would be a certain degree of indicator and pathogen die-away and/or removal from the wastewater source and irrigated vegetables until the final ingestion by the subject in the home. These factors include settling, adsorption, dessication, biological competition, UV irradiation from sunlight, and a degree of removal and/or inactivation by washing of the vegetables in the home. A number of studies have indicated that there is rapid die-off or removal of bacterial indicator organisms as well as pathogenic bacteria and viruses in wastewater irrigated soil and on crops by as much as 5 logs or 99.999% in 2 days under field conditions (Rudolfs *et al.*, 1951; Bergner-Rabinowitz, 1956; Sadovski *et al.*, 1978;

Armon *et al.*, 1995). Armon *et al.* also suggest that there is the possibility of the regrowth of bacteria on vegetables contaminated with wastewater, but presented no data to support this hypothesis. In any event, *human enteric viruses cannot ever multiply under environmental conditions*. Asano and Sakaji (1990) have determined virus die-off in the environment under field conditions of wastewater reuse, which indicate that in 2 weeks the total virus inactivation reaches some 99.99%, while in 3 days there is a 90% reduction of virus concentration. Even superficial washing of vegetables in the home can remove an additional 99–99.9% of the virus contamination. Schwartzbrod (1995) has estimated that there would be as much as a 6 log reduction (99.9999%) of virus concentration between irrigation with wastewater and consumption of the crops if the total time elapsed reached 3 weeks. To be on the conservative side, we have estimated that the total virus inactivation and/or removal from the wastewater source until ingestion results in a reduction in virus concentration by 3 logs, or 99.9%, although a 99.99% loss is not unreasonable and might occur in most cases.

5.3 Estimates of risk of infection and disease

Based on the above tests results and assumptions we now can estimate the number of pathogens ingested by a subject who eats a 100 g of cucumber or 100 g (three leaves) of long lettuces irrigated with wastewater of various qualities. In this preliminary risk estimate we have selected the enteric virus infectious hepatitis, which can result in serious disease sequelae and which has had a clear epidemiological record indicating the possibility of it being environmentally transmitted and waterborne (Schwartzbrod, 1995). We have assumed that the median infectious dose for 50% of the exposed subjects to become infected (N_{50}) could range between 30 and 1000 PFU. We have also assumed that while the ratio of infections to clinical disease is often as low a 100:1, we shall estimate, as a worst case, that 50% of those infected will succumb to clinical disease ($P_{D:I} = 5$). We also assumed, based on vegetable consumption patterns in Israel, that on an annual basis a subject would consume 100 g of lettuce or cucumbers/day for 150 days($P_{D:I} = 25$). We have assumed that $\alpha = 0.5$, however, even assuming $\alpha = 0.2$ does not lead to a significantly increased risk.

First, as a positive control test of the model, we have estimated the risk of infection and disease from consuming vegetables irrigated with raw wastewater with an estimated initial fecal coliform level of 10^7. Based on the above assumptions, including a 3 log die-away, we have estimated that under such conditions a 100 g cucumber or 100 g (three leaves) of lettuce irrigated with raw wastewater will have a final level of contamination of FC of $10-10^2$. Based on that level of FC contamination and a virus:FC ratio of $1:10^5$, it can be estimated that there is a probability, in the case of irrigation with raw wastewater, that one cucumber in 10 000 will carry a single enteric virus and that one leaf of lettuce in 1000 will carry a single enteric virus. Based on these estimates of ingesting enteric viruses, more specifically the infectious hepatitis virus, we have estimated the risk of infection and disease that might result. The rate of disease, from eating 100 g lettuce, among a population eating such vegetables irrigated with *raw wastewater* is between 10^{-3} to 10^{-4} or about one case per 1000 to one case per 10 000 individuals exposed to risk.

This rate of infection has been found to correlate well with the disease rates detected in our field studies of the cholera outbreak in Jerusalem (Fattal *et al.*, 1986b) and typhoid fever in Santiago, Chile (Shuval, 1984), which were clearly associated with the irrigation of vegetables normally eaten uncooked with raw wastewater. Thus our estimates based on the laboratory data, our assumptions and using the Haas mathematical model provided a reasonably close approximation of the degree of risk of disease that occurs in real world situations. This is a vital step in the validation of the reliability and usefulness of such a predictive simulation model and helped assure us that our predictions of risk under various conditions have a reasonably sound basis.

We then proceeded to evaluate the risk of disease if crops were irrigated with wastewater that meets the WHO guidelines. If the effluent is treated to meet the WHO guidelines for irrigation of vegetables to be eaten uncooked of 1000 FC/100 ml, the risk of hepatitis infection and disease estimates for lettuce is reduced to about 10^{-7}–10^{-8}, which means that the chances of becoming infected and diseased from such a low level of exposure is somewhere around one person per million people exposed per year or less. We have also calculated the annual risk of disease from the more infectious, but less severe, rotavirus as 10^{-5}–10^{-6}/year.

Are these a high level of risk or a low level of risk? In order to shed some light on what are considered reasonable levels of risk for communicable disease transmission from environmental exposure it should be noted that the USEPA has determined that microbiological quality guidelines for drinking water microbial standards should be designed to ensure that human populations are not subjected to *risks of infection by enteric disease greater than* 10^{-4} (*or 1 case per 10 000 persons per year*) (Regli *et al.*, 1991). Thus, compared with the USEPA estimates of reasonable acceptable risks for waterborne disease acquired from drinking treated drinking water, the WHO wastewater reuse guidelines appear to be safer by some one to two orders of magnitude.

5.4 Cost/effectiveness analysis

At this stage of our study we have made only some very preliminary estimates of the cost/-effectiveness associated with meeting the various wastewater effluent guidelines. As an example we shall present the hypothetical case of a Third World city of 1 million population about to build a wastewater treatment plant to assure safe utilization of the effluent for agricultural irrigation of vegetable crops, including those eaten uncooked, which would serve the population of the city. It is assumed that they have opted for a waste stabilization pond system that will meet the WHO guidelines. They want to compare the cost and risks at that level of treatment to the cost and risks if they had adopted the USEPA/USAID guidelines for treatment for vegetables eaten uncooked. We have assumed, for the purposes of this illustration only, that the unit cost of wastewater treatment to meet the various guidelines can roughly be estimated as follows:

WHO guidelines – 1000 FC/100 ml
(in stabilization ponds) $0.125/M^3
or the cost/person/year (assuming
100 M^3/person/year) $12.5/p/year
US-EPA/US-AID guidelines – 0 FC/100 ml
$0.40/M^3
or the cost/person/year (assuming 100 M^3/person/year) $40.00/p/year.

The estimate of treatment costs for meeting WHO guidelines does not necessarily apply to all situations but is generally illustrative of a situation that may apply in hot sunny climates in developing countries where low cost land is available for effective stabilization pond treatment. According to this estimate, the additional cost for that city to meet the US-EPA/US-AID guidelines would be $25 500 000/year.

We have assumed that half the population consumes wastewater irrigated vegetables on a regular basis and that the degree of annual risk of contracting a case of infectious hepatitis associated with the use of irrigated vegetables eaten uncooked with wastewater meeting the WHO guidelines is in the worst case some 2×10^{-6} (or about 1 case per year per 500 000 exposed persons) as estimated in this study. If we assume that the USEPA/ USAID guidelines, which require no detectable FC/100 ml, will achieve an essentially zero risk of disease, than we can estimate that the one case of infectious hepatitis per year would have been prevented. Thus the additional cost of treatment would result in a cost of about $25 000 000 for each case of disease prevented. In the case of rotavirus disease, the cost would be some $2 500 000 per case prevented. If, however, the true level of risk associated with the WHO guidelines is closer to the 10^{-7} level, estimated by the less conservative interpretation of the results of this study, then no detectable reduction of risk would be gained by the additional investment of $25 000 000 required to meet the strict and expensive USEPA/USAID guidelines.

It is questionable whether this level of additional treatment associated with major additional expenditures is justified to reduce further, the already negligibly low levels of risk of infection and disease that our estimates indicate are associated with the new WHO Guidelines.

Our conclusion is that the new WHO guidelines, which are based on extensive epidemiological evidence and can be achieved with low-cost wastewater treatment technology, provide a high degree of public health protection at a reasonable cost. There is little or no justification, in our opinion, for the unreasonably restrictive 'zero risk' USEPA/USAID guidelines, which are exceedingly expensive to achieve and require costly high-tech wastewater treatment technology, which provides little if any measurable increase in health protection.

Thus, after well over a century, health guidelines for wastewater reuse have gone through a complete cycle from no regulation or control in the 19th century to unreasonably strict standards in the earlier part of this century to what now appears to be a scientifically sound and rational basis with a less restrictive approach as recommended by the WHO guidelines. It is hoped that this new approach will encourage the development of controlled wastewater reuse for the benefit of mankind, while providing an appropriate level of health protection.

6 CONTROL OF CROPS AND IRRIGATION METHODS TO REDUCE HEALTH RISKS

Early in the development of wastewater irrigation for agriculture, methods of reducing health risks by controlling the type of crops grown or the methods of irrigation have been proposed and in some cases used effectively. The risk of transmission of communicable disease to the general public by irrigation with raw or settled wastewater can be reduced by a number of agronomic techniques. Some of these restrict the types of crops grown, and others, through modification and/or control of irrigation techniques, prevent or limit the exposure of health-related crops to pathogens in the wastewater.

6.1 Regulating the type of crops

One of the earliest and still most widely practised remedial measures is to restrict the type of crops irrigated with raw wastewater or with the effluent of primary sedimentation. Since there is ample evidence that salad crops and other vegetables normally eaten uncooked are the primary vehicles for the transmission of disease associated with raw wastewater irrigation, forbidding the use of raw effluent to irrigate such crops can be an effective remedial public health measure. Although such regulations have been effective in countries with a tradition of civic discipline and an effective means for inspection and enforcement of pollution control laws, they will likely be of less value in situations where those preconditions are absent.

In many arid and semi-arid areas near major urban centers, where subsistence farmers irrigate with raw wastewater, the market demand for salad crops and fresh vegetables is very high. Thus, governmental regulations forbidding farmers to grow such crops would be little more than a symbolic gesture. Even under the best of circumstances, it is difficult to enforce regulations that work counter to market pressures; to enforce regulations that prevent farmers from obtaining the maximum benefit from their efforts under conditions of limited land and water resources would be impossible.

6.2 Controlling irrigation methods

Basin irrigation of salad and vegetable crops usually results in direct contact of the crops with wastewater, thus introducing a high level of contamination. Sprinkler irrigation of salad crops also results in the deposit of wastewater spray on the crops and their contamination. The level of contamination may be somewhat less than basin irrigation. Many vegetables that grow on vines (i.e. tomatoes, cucumbers, squash, and the like) can be partially protected from wastewater contact if properly staked and/or grown hanging from wires that keep them off the ground, although some of these vegetables will inevitably touch the ground.

Well-controlled ridge-and-furrow irrigation reduces the amount of direct contact and contamination. These methods cannot completely eliminate direct contact of the wastewater with leafy salad crops and root crops.

Drip irrigation causes much less contamination of the crops than any other irrigation method. In fact, our studies indicate the use of drip irrigation tubes under polyethelene plastic surface sheeting used as a mulch can vastly reduce or totally eliminate crop contamination. In our studies, we determined that the level of enteroviruses and bacterial indicator organisms on cucumbers grown under such protective drip irrigation systems was negligible during the first 24 hours after the introduction of a massive seeding of microorganisms into the wastewater effluent stream used for irrigation. After 24 hours no contamination of irrigated crops was detectable (Sadovski *et al.*, 1976, 1978). Drip irrigation is the most costly form of irrigation, but its hygienic advantages make it attractive as a safe method of wastewater irrigation of sensitive vegetable and salad crops, even when the microbial quality of the effluent is not up to the strictest standards.

Fruit orchards do well with basin or ridge-and-furrow irrigation, but normal overhead sprinkler irrigation leads to direct contamination of the fruit. With low-level low-pressure sprinkler irrigation, however, the main spray is below the level of the branches, and the fruit is less likely to be contaminated. In all cases, windfalls picked from the ground will have been in contact with wastewater-contaminated soil. Another possible control measure is to discontinue irrigation with wastewater at a specified period, such as 2 weeks, before harvesting the crop. This option is feasible for some crops, but the timing of a vegetable harvest is difficult to control. In addition, some types of vegetables are harvested over long periods of time from the same plot.

Some of the above irrigation control techniques can help reduce the danger of crop contamination, but they are feasible only in fairly advanced and organized agricultural economies. Health regulations dependent upon any of the above procedures to protect certain high-risk crops from contamination must be enforced by legal sanctions and frequent inspections. If well-organized inspection and law enforcement systems are not present, as in some developing countries, the value of these options as a major remedial strategy may be limited. However, in the case of large centrally operated sewage farms, managed by the government or large well-organized companies, such procedures can be of value.

7 WASTEWATER TREATMENT

7.1 What are the goals of wastewater treatment for recycling and reuse?

Obviously, the degree of wastewater treatment, particularly as it relates to the effective removal and inactivation of pathogenic microorganisms, will have a critical effect in controlling any possible health risks associated with wastewater irrigation. The microbiology of wastewater treatment is reviewed in depth in Chapters 19–28. Thus it is beyond the scope of this chapter to review all possible wastewater treatment technologies suitable for wastewater recycling and reuse. However, we shall attempt to review some general principles and to emphasize low cost treatment technologies particularly suited to warm climates in developing countries.

In areas with plentiful rainfall, wastewater has traditionally been disposed of or diluted in large bodies of water, such as rivers and lakes. High priority has been given to maintaining the oxygen balance of these bodies of water to prevent serious detrimental effects, such as anaerobic conditions and odors from wastewater pollution. Most of the conventional processes used to treat wastewater in industrial countries have been designed primarily to remove the suspended and dissolved organic fractions, which decompose rapidly in natural bodies of water. The organic matter in wastewater, usually measured as biochemical oxygen demand (BOD), provides rich nutrients to the natural microorganisms of the stream, which multiply rapidly and consume the limited reserves of dissolved oxygen (DO) in the streams. If oxygen levels drop too far, anaerobic conditions may develop, serious odors may evolve and fish may die. However, for recycling and reuse of wastewater for agricultural irrigation, a high degree of BOD removal in the effluent is not directly relevant since, with land disposal, the soil is not harmed, but benefits from high level of organic matter and plant nutrients deposited on it. However, removal of organic matter, as represented by BOD, may be necessary when chemical disinfection processes are required, after the biological treatment stage, to achieve the microbial effluent standards.

A secondary goal of conventional wastewater treatment has been to reduce pathogenic microorganisms in order to protect the quality of the sources of drinking water used by downstream communities. However, conventional biological wastewater treatment systems, such as biological filtration and activated sludge, are not particularly efficient in removing pathogens. Thus, communities that draw their drinking water from surface sources cannot depend upon upstream wastewater treatment plant systems to reduce pathogens to a safe level. Therefore, they must remove the pathogens with their own drinking water treatment plants using a series of highly efficient, technical, and costly processes (i.e. coagulation, sedimentation, filtration and chemical disinfection). The most effective conventional wastewater treatment system is activated sludge, which removes 90–99% of the viruses, protozoa and helminths and 90–99.9% of the bacteria. Conventional processes cannot achieve higher levels of pathogen removal without additional expense for chemical disinfection, such as chlorination, and additional sand filtration. Further research and development are needed to improve the removal of helminths by conventional methods. However, the new micro/nanofiltration processes hold much promise in the effective removal of helminths and all other pathogenic microorganisms from wastewater.

7.2 Low cost wastewater stabilization ponds provide high quality effluent

In contrast to conventional treatment systems, studies have shown that well-designed multicell stabilization ponds allowing 20–30 days of retention can remove almost 100% of the helminth eggs (Yanez *et al.*, 1980; Feachem *et al.*, 1983; Mara and Silva, 1986; Fattal *et al.*, 1998). Bacteria, viruses and protozoa are often attached to larger fecal particles that settle out in pond systems. At best, however, only 90% can be removed by sedimentation.

The most effective process for removing bacteria and viruses in stabilization ponds is natural die-off, which increases with time, pH and temperature. Many developing countries have hot climates in which stabilization ponds are exposed to the direct rays of the sun and may reach temperatures up to 40°C. The pH at midday is commonly 9 or higher due to the photosynthetic activity of the algae. Predatory or competing microorganisms may also affect die-off by attacking or damaging pathogens directly or indirectly. Exposure to the ultraviolet rays of the sun may also play a role in killing pathogens in ponds. Long retention times, however, appear to be the most important factor in reducing bacterial concentrations in pond systems.

In warm climates with temperatures in excess of 20°C, a pond system with 4–5 cells and a 20- to 30-day retention time usually reduces the fecal coliform concentration by 4–6 log orders of magnitude – i.e. by 99.99–99.9999%. Thus, if the initial concentration of fecal coliform bacteria in the raw effluent is approximately 10^7/100 ml, the effluent will contain 10^3 or 1000/100 ml. The same pond system will reduce enteric viruses by 2–4 log orders of magnitude (i.e. from an initial concentration of about 1000/100 ml to 10 or fewer/100 ml). Helminth eggs will be removed almost completely, while the BOD will be reduced by about 80%. Fig. 15.4 shows the generalized removal curves for BOD, heiminth eggs, bacteria, and viruses in a multicell stabilization pond system in a warm climate.

Our cooperative studies with Egyptian colleagues in the city of Suez on waste stabilization pond treatment of wastewater for irrigation and aquaculture have demonstrated that with well-designed and well-operated multicell ponds with 30 days of detention, an effluent of 10–100 fecal coliforms/100 ml was consistently achieved (Mancy, 1996). In our studies at a waste stabilization pond pilot plant system, treating primary effluent from the Jerusalem Municipal treatment plant, an effluent of 1000 fecal coliforms/100 ml was achieved with 25–30 days of detention (Fattal *et al.*, 1997).

Waste stabilization ponds are therefore highly suitable for treating wastewater for irrigation. They are more efficient in removing pathogens, particularly helminths, than are conventional wastewater treatment systems. In addition, they produce a biologically stable, odorless, nuisance-free effluent without removing too many of the nutrients. Thus, ponds should be the system of choice for wastewater irrigation in warm climates, especially if land is available at a reasonable price. Ponds are particularly attractive for developing countries because they cost little to build and maintain and are robust and fail-safe. They should never be considered a cheap substitute. In reality they are superior to conventional methods of treatment in almost all respects. Although ponds require relatively large land areas, land costs are, in many cases, not a serious obstacle.

When wastewater will be used to irrigate crops for human consumption, the goals of treatment are the reverse of the goals of conventional treatment. The primary goal for treatment of wastewater to be used for irrigation must be removal of pathogenic microorganisms in order to protect the health of the farmers and consumers. Removal of the organic material, however, which contains valuable agricultural nutrients is neither necessary nor desirable, although aerobic conditions should be maintained because a black, highly odorous, anaerobic wastewater effluent would probably be an environmental nuisance to farmers and nearby residents.

7.3 Public health advantages of wastewater treatment and storage reservoirs

Since wastewater is generated by the community 365 days a year and the irrigation season in most areas is limited to a number of months per year, a means must be found to handle wastewater flows during non-irrigation periods. If allowed to flow unrestricted, the effluent will contaminate the region's natural bodies of water.

A suitable solution is the storage and treatment reservoirs pioneered in Israel (Juanico and Shelef, 1994; Pearson *et al.*, 1996). Such reservoirs are designed to upgrade the quality of the effluent during the long residence time in the reservoirs and to store up to 8–10 months of wastewater flow in the rainy winter months to be used for irrigation during the dry summer season. They are often preceded by settling ponds and/or by conventional stabilization ponds, and may also be designed to catch surface runoff. The operational regimes of such reservoirs vary. Some are operated to change between non-steady-state flow and batch while others are operated sequentially, receiving and storing influent for extended periods, after which the inflow is stopped for a period of stabilization and bacterial decay prior to the discharge for irrigation. Log mean concentration of microorganisms in often partially treated typical wastewater influent at the entrance of the reservoir per 100 ml are: hetrotrophic bacteria 10^7–10^8, fecal coliforms 10^6–10^7, enteroccoci 10^4–10^6 and F^+ bacteriophages 10^5–10^6.

The results at the outlet in such reservoirs show that, in general, the quality of the effluents is much improved and is best at the beginning of the irrigation season when the reservoir is full of old effluent (long detention time), but sharply deteriorates when the water level drops and new wastewater continues to be pumped into the reservoir

(Juanico and Shelef, 1994; Pearson *et al.*, 1996). The die-off rate of microorganisms in the summer is higher than in the winter. We have shown that there is a significant correlation between the mean hours of sunshine in the month and the rate of bacterial die-off. Thus with greater sunshine duration in the summer months the bacterial die-off is highest (Fattal *et al.*, 1996). However, in single reservoirs during the summer the relative volume of the influent, raw or partially treated is higher, leading to poorer bacterial quality of the effluent since the pond levels are at their lowest during the intensive irrigation season. Coliform removal is high in the epilimnion, where high pH values occur due to algal activity, and low in the hypolimnion where pH values are low (Liran *et al.*, 1994). The logs mean reduction of hetrotrophic bacteria, *E. coli*, enterococci and F^+ bacteriophages at the outlet of the reservoir are: 1, 3, 2.5 and almost 4 logs, respectively (Fattal *et al.*, 1993). The mean reduction of BOD is 76%, COD 72% and TSS 45% (Fattal *et al.*, 1993).

In order to improve the quality of the effluent, innovative changes were made in Israel in the design of such stabilization/storage reservoirs (Liran *et al.*, 1994; Juanico and Shelef, 1994; Juanico, 1996; Friedler and Juanico, 1996). The storage of the effluent was changed from seasonal to multiseasonal and/or from single reservoir to two or more reservoirs used sequentially as batch reservoirs, supplying effluents for irrigation only from reservoirs which no longer receive fresh influent. By doing so, the input of the effluent from treatment units into the reservoir is stopped before reservoir effluent is released for irrigation. Another improvement was made by implementing better treatment of the wastewater before entering into the reservoir. The performance of the improved batch stabilization reservoirs, when properly designed and operated, showed that they are able to remove fecal coliform bacteria by up to five orders of magnitude (i.e. 99.999%). Such improved alternating reservoirs systems can normally produce an effluent which can easily meet the WHO guidelines for unrestricted irrigation of 1000 fecal coliforms/100 ml or less.

7.4 Remedial environmental methods assures greater health protection

The history of public health progress has proven that the broadest and most effective public health benefits are obtained from remedial or preventive measures taken by a central authority and involving environmental interventions that lower the level of exposure of large populations to environmentally transmitted disease. Such measures as central plants for the purification of drinking water supplies, pasteurization of milk, and area-wide campaigns for reducing the breeding sites of malaria-carrying mosquitoes are well-known examples of success using this strategy. Any remedial action based on changing personal behavior and lifestyle through education, law enforcement, or both, is a much slower process and, in general, has succeeded only in areas with relatively high educational levels and living standards.

The wastewater storage and treatment/storage reservoir option reviewed above offers this type of centrally managed and engineered form of remedial environmental intervention. It is the only remedial measure that will simultaneously reduce the negative health effects for sewage farm workers and for the public that consumes wastewater-irrigated vegetables. It is also the only measure that can bring about health benefits in a short time without massive changes in personal behavior or restrictive regulations that depend on complex inspection and law enforcement procedures. However, it does require central organizational and management capacity, availability of major financial resources and availability of land.

Although it may be appropriate in some situations to restrict the type of crops grown or to control wastewater irrigation practices, such regulations are difficult to enforce where there is great demand for salad crops and garden vegetables. In arid and semi-arid zones (as well as some humid areas), where irrigation is highly desirable, many economists and agricultural authorities consider it economically prudent to allow unrestricted wastewater irrigation of cash crops in high demand. That goal can only be achieved with an effective high level of wastewater treatment as suggested in this chapter.

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