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Wastewater Irrigation in Developing Countries

Health Effects and Technical Solutions

Summary of World Bank Technical Paper Number 5

by Hillel I. Shoval

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WASTEWATER IRRIGATION IN DEVELOPING COUNTRIES

Health Effects and Technical Solutions

Summary of World Bank Technical Paper Number 51

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**WASTEWATER IRRIGATION
IN DEVELOPING COUNTRIES**

Health Effects and Technical Solutions

Summary of World Bank Technical Paper Number 51

by Hillel I. Shuval

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This discussion paper is based on research carried out by the UNDP-World Bank Integrated Resource Recovery Project (GLO/84/007) as reported in World Bank Technical Paper Number 51, "Wastewater Irrigation in Developing Countries: Health Effects and Technical Solutions," by Hillel I. Shuval, Avner Adin, Badri Fattal, Eliyahu Rawitz, and Perez Yekutiel, Washington, D.C., 1986.

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ABSTRACT

This discussion paper on wastewater irrigation in developing countries is for administrators and planners as well as for professionals in the fields of agriculture, water resources, urban development, public health, and environmental protection. It provides a concise introduction to the policy and technological aspects of recycling wastewater from urban areas for agricultural irrigation. Such recycling endeavors help countries to conserve their resources, develop their economy, and protect the environment.

The paper consists of a nontechnical summary of a 324-page UNDP-World Bank report (World Bank Technical Paper Number 51), which was the culmination of a three-year interdisciplinary global study of the latest developments in the field. The technical recommendations and policy guidelines in this document have been reviewed by a group of environmental scientists and epidemiologists convened by the World Health Organization, the United Nations Environment Programme, the United Nations Development Programme, and the World Bank (Engelberg Report 1985), and in 1988 by a WHO group of experts. These groups have judged that the principles presented in this paper provide a sound scientific and public health basis for planning wastewater irrigation projects.

Although this report concentrates on the problems of developing countries and some of the solutions uniquely suitable to such areas, the general approach and the underlying scientific and technical principles are also applicable to industrialized countries.

More detailed technical information is available in the original report, which can be obtained from the World Bank, Washington, D.C.

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TERMS AND ABBREVIATIONS

Activated Sludge	A conventional biological wastewater treatment process.
Aerobic	With the presence of oxygen.
Anaerobic	Without the presence of oxygen.
BOD	Biochemical oxygen demand; a measure of the organic strength of wastewater.
CDC	Center for Disease Control (USA).
CEC	Cation exchange capacity; a characteristic of soil, related to the ability to retain dissolved salts.
COD	Chemical oxygen demand; a measure of the organic strength of wastewater.
Coliforms	Normal bacteria of the enteric tract of mammals used as an indicator of fecal pollution.
DO	Dissolved oxygen.
<u>E. coli</u> /Fecal coli	A more specific fecal indicator organism; see coliforms.
Endotoxin	Toxic compound formed by bacteria.
EPA	Environmental Protection Agency (USA).
Facultative	A system that functions both aerobically and anaerobically.
Geometric Mean	<u>See</u> Log Mean.
g	Gram.
ha	Hectare = 10,000 m ² = 2.5 acres.
HAV	Infectious hepatitis Type A; a viral disease.
ID ₅₀	Infective dose or the number of pathogens required to infect 50 percent of the persons who ingest them.
IRCWD	International Reference Center for Wastes Disposal, Dübendorf, Switzerland.
K ₂ O	A potassium salt used as a chemical fertilizer.
kg	Kilogram.

Kibbutz	Collective agricultural settlement in Israel; plural, kibbutzim.
km	Kilometer.
l/c/d	Liters per capita per day.
Log Mean	The mean value of a series of numbers based on calculation; the mean of the logarithms of the numbers.
Log ₁₀ Removal	Removal efficiency expressed in log ₁₀ units; i.e., $4=10^{-4} = 99.99$ percent removal.
m	Meter.
μm	Micron (1 micron = 10^{-6} meters)
m ²	Square meter.
m ³	Cubic meter.
Maturation Pond	<u>See</u> Polishing Pond.
MCM	Million cubic meters.
mg	Milligram.
MGD	Million gallons per day.
ml	Milliliter.
MOH	Medical Officer of Health--a senior public health official.
Morbidity Rate	The rate at which illness from a specified disease occurs in a community; usually expressed as cases/100,000 population.
N	Nitrogen.
NEERI	National Environmental Engineering Institute, at Nagpur, India.
NH ₃	Ammonia.
Night Soil	Human excreta--feces and urine.
N-K-P	Nitrogen-potassium-phosphorus used as a chemical fertilizer.
NPV	Net Present Value can be defined as the present worth of benefits less the present worth of costs. The present worth of an amount in any specific year can be calculated using $P = F/(1+i)^n$, where F = future value, i = discount rate (interest factor), n = period in the future. Therefore, the NPV of a stream would require calculating the present worth for each period and then summing them up.

Oxidation Pond	<u>See</u> Stabilization Pond.
P ₂ O ₅	A phosphorus salt used as a chemical fertilizer.
PAHO	Pan American Health Organization, the regional office of the WHO for the Americas.
pH	A measure of acidity.
Polishing Pond	Stabilization pond following a wastewater treatment system to provide additional treatment.
ppm	Parts per million.
Primary Treatment	Usually screening and sedimentation of wastewater.
Prospective Study	A method of studying the health effects of an environmental factor by making current observations for a given time period of the morbidity or mortality rates on exposed and control population groups (<u>see</u> Retrospective Study).
Retrospective Study	A method of studying the health effects of an environmental factor by observing the past morbidity or mortality rates of the exposed and control population group (<u>see</u> Prospective Study).
Seroepidemiology	A study of the rate of infection of a disease in a population group by analyzing blood samples for antibodies to the disease.
Secondary Treatment	Usually a biological wastewater treatment process following primary treatment.
S.S.	Suspended solids.
Stabilization Pond	An open pond system used to treat wastewater where algae, bacteria, and sunlight provide natural purification.
TDS	Total dissolved solids.
TSS	Total suspended solids.
UNDP	United Nations Development Programme.
UNEP	United Nations Environment Programme.
WHO	World Health Organization.

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ACKNOWLEDGMENTS

The continued support and sage guidance of Saul Arlosoroff, Carl Bartone, Charles Gunnerson, and John Kalbermatten of the UNDP-World Bank Water and Sanitation Program staff at various times made this study possible. The fine cooperation of the staff of The Environmental Health Division of The World Health Organization, Geneva, and The International Reference Center for Wastes Disposal, Dübendorf, Switzerland, is also sincerely appreciated. The hospitality provided the author by the Massachusetts Institute of Technology during the preparation of this manuscript is hereby acknowledged.

I. INTRODUCTION: WASTEWATER IRRIGATION FOR WATER CONSERVATION AND ENVIRONMENTAL PROTECTION

In developed and developing countries alike, the disposal of wastewater from urban areas can pose a serious threat to the environment. The surface and underground sources of drinking water may become contaminated by pathogenic microorganisms and toxic chemicals. Recreational and fishing areas in rivers and lakes and along coastal shores may become polluted, and odors and mosquito breeding may become a problem if wastewater is disposed of improperly. Thus, the proper treatment and sanitary disposal of wastewater should be a high priority in urban development programs if they are to protect the health of the public and preserve the amenities of the environment.

However, many developing countries perceive wastewater treatment and disposal as an unavoidable yet nonproductive expense. As a result, funds for investments in technical solutions have often been limited or not readily available. In areas where water is in short supply, recycling of wastewater for agricultural irrigation can provide a strong economic impetus because it helps to conserve resources (including water and soil nutrients) and protect the environment by preventing river pollution, protecting water quality, and preventing seawater intrusion in coastal areas. In addition, recycling may often be the least-cost solution for wastewater disposal.

This report describes the health problems associated with wastewater irrigation and the technical solutions that have been developed to make it an economically attractive option for developing countries.

The idea of recycling wastes to agriculture is not new. In China and other parts of Asia, night soil (human feces and urine) has been used to fertilize crops and replenish depleted soil nutrients since ancient times. The earliest sewage farms documented in the literature appear to be those of Bunzlau, Germany, which were in operation in the sixteenth century.

With the increased use of water carriage sewerage systems during the nineteenth century, more countries became interested in wastewater farming or land application, particularly in Europe. The First Royal Commission on Sewage Disposal in England gave its official blessing to the practice in 1865, stating "The right way to dispose of town sewage is to apply it continuously to the land and it is by such application that the pollution of rivers can be avoided." During this same period, the conservationist movement in Europe began advocating that land application should become part of a policy for resource recycling and returning nutrients to the soil. In 1868 Victor Hugo gave voice to this view in Les Miserables: "All the human and animal manure which the world loses...by discharge of sewage to rivers...if returned to the land, instead of being thrown into the sea, should suffice to nourish the world."

Thus, the use of wastewater in agriculture or in land application arose with the desire to prevent pollution in rivers and to conserve water and nutrients to improve

agriculture. These early reasons for wastewater reuse remain valid to this day, although the emphasis has changed as a result of experience, scientific advances, and economic considerations, as will be explained later in this discussion.

II. WASTEWATER IRRIGATION PRACTICES: PAST AND PRESENT

Early Major Wastewater Irrigation Projects

With the publication of a report of the First Royal Commission in England in 1865, land treatment became one of the principal means of sewage disposal. Sewage farms were established in Edinburgh, London, Manchester, and other major cities of the United Kingdom. By 1875 there were approximately 50 land treatment sites in Britain.

Widespread wastewater irrigation also became popular in other parts of Europe during the late 1800s and early 1900s. Paris, for example, had sewage farms as early as 1868, and by 1904 the great intercepting sewers of Paris had stopped discharging into the Seine altogether. All the dry weather wastewater flow was applied to sewage farms, which by then had a total area of 5,300 ha (see Fig. 1).

The city of Berlin established its first sewage farm in 1876. By 1910, Berlin had about 17,200 ha devoted to sewage farming and was treating about 310,000 m³ of wastewater per day. Melbourne, Australia, established its first large sewage farm--Werribbee Farm--in 1897 and grazed sheep and cattle on the grass grown in the sewage-irrigated plots. This well-managed farm is still in operation and today irrigates large areas of pasture with the effluent from its stabilization pond system, the world's largest. In 1904, planned sewage farming was established in Mexico City. An irrigation district was organized in the arid Valley of Mexico where the city's untreated wastewater was used to irrigate large areas. The program area has since been expanded under careful government control, and in 1988 approximately 100,000 ha were irrigated with wastewater.

Sewage irrigation was also under way in the United States in those early years. It was practiced as early as 1871 in Lenox and Worcester, Massachusetts, and in 1876 near Augusta, Maine. According to Fuller (1912), by 1904 the country had 14 municipal sewage farms or broad irrigation projects serving a population of about 200,000, and a number of institutional plants were in operation. Early municipal sewage irrigation projects near Chicago and Los Angeles had to be abandoned, however, because of the rapid growth of the two cities and their suburbs in the direction of sewage-irrigated lands. Apparently the health authorities intervened when the odor from these sites became a nuisance (Fuller 1912).

As in the United States, many of the early large irrigation and sewage farm projects in Europe were abandoned because urban development encroached upon the sewage farm areas. The problems with odor and concerns about public health--particularly fears about the possible transmission of disease from vegetable crops irrigated with raw sewage--were largely responsible for the decline of sewage farming. Another disadvantage in temperate areas with plentiful rainfall was that, with the cessation of sewage irrigation during heavy rainy seasons, raw sewage was frequently discharged into neighboring streams, or crops were harmed by oversaturation of the irrigated land areas. This was only a minor problem in the more arid western areas of the United States, however, and thus sewage farming has continued there up to the present.

By 1912 the trend away from sewage farming was already evident. According to Fuller, "The present outlook is that broad irrigation or sewage farming is decidedly on the wane with little prospects of adoption even in the arid districts except perhaps for an occasional project where local conditions are unusually favorable." Eventually sewage farming was almost completely abandoned in most areas of the highly urbanized industrial countries of the Western world.

All this changed after World War II, however, when scientific and engineering interest in wastewater reuse was revived in both the industrialized and the developing countries.

Present Status of Interest in Wastewater Reuse

After 1945, wastewater treatment and disposal through land application gained increasing attention as a means of preventing river pollution and increasing water resources in arid and semiarid areas. The more arid developing countries were particularly interested in utilizing wastewater for agricultural development.

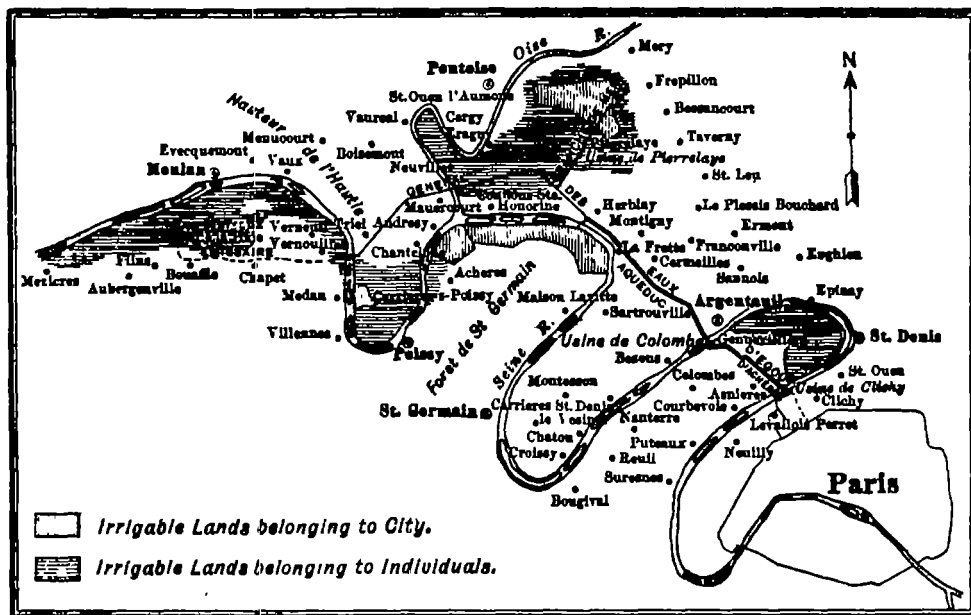


Fig. 1. Location of sewage farms of Paris in 1904.

Such countries have few flowing streams with sufficient capacity to serve as natural repositories, even for well-treated wastewater effluent. Thus, wastewater reuse in agriculture provided almost the only feasible, relatively low-cost method for sanitary disposal of municipal wastewater that minimized pollution of the region's waterways. These factors, coupled with

rapid urban growth and the need to increase agricultural production, made sewage farms attractive to the agricultural community and municipal planners.

Furthermore, the regulations developed by the State of California helped to reestablish the feasibility of wastewater reuse in agriculture in the western part of the United States (see Table 1). Soon thereafter a similar trend began in many of the rapidly developing countries faced with water shortages and with insufficient waterways to properly dilute and dispose of municipal wastewater.

The early strict California standards that were drafted to provide essentially a "zero risk" basis for reuse were copied in other areas of the United States and in countries throughout the world. However, those standards were not based on sound epidemiological criteria and have been accepted more on faith than on scientific evidence.

During the past hundred years, the concept of land application and wastewater reuse has passed through a complete cycle. Starting with the official blessing and enthusiastic initiation of land application and sewage farming projects in Europe and the United States, it soon became almost the sole method of disposing of municipal wastewater. In the early years of the twentieth century, however, projects were often ill-conceived, inadequately funded, and poorly regulated, and thus were eventually abandoned. Subsequently, the concept of reuse fell into disrepute. Today wastewater reuse is becoming widely accepted once again, but it is often based on highly restrictive and unenforceable health regulations.

A survey of current wastewater reuse practices in developing countries carried out by the World Bank-UNDP Program has estimated that some 80 percent of the wastewater flow from urban areas in developing countries is currently used for permanent or seasonal irrigation (Gunnerson et al. 1985).

In many areas (e.g., Santiago, Lima, Teheran, Bombay, and Kabul) untreated wastewater flows through channels and/or rivers to adjacent areas where it is diverted by subsistence farmers to small plots of unregulated vegetables and salad crops grown for nearby urban markets. The public health risks in such uncontrolled use of raw wastewater for irrigation are obvious.

In other areas government-controlled irrigation projects divert partly or fully treated wastewater to farming operations organized for the irrigation of controlled crops. Examples of such operations include a 2,800 ha greenbelt irrigated with treated wastewater at Khartoum; a 100,000 ha area of restricted grain and fodder crops irrigated with wastewater near Mexico City; 10,000 ha Werribbee Farm at Melbourne, where 50,000 sheep and 20,000 cattle graze on pasture irrigated with well-treated stabilization pond effluent; and a carefully controlled 9,000 ha farm near Kuwait City which is irrigated with well-treated wastewater effluent.

Most other cities in developing countries fall somewhere between being totally unregulated and being carefully and effectively controlled. Many governments have recognized the importance of wastewater recycling through irrigation and have developed national wastewater reuse programs as part of their water resources management policy. Such

programs have been established in Tunisia, Saudi Arabia, Israel, India, the Republic of South Africa, and some states in the United States (e.g., California, Arizona, and Florida).

Although wastewater reuse has been practiced more widely in developing countries over the past thirty years, much of it is unplanned and uncontrolled and poses a threat to public health. These risks must be fully understood and appropriate measures taken to provide technically feasible and economically attractive solutions so that the public can reap the full benefits of wastewater reuse without suffering harmful effects. Only then can such a practice become a truly successful development policy.

TABLE 1

California State Department of Health Standards for the Safe and Direct Use of Reclaimed Wastewater for Irrigation and Recreational Impoundments.

Description of minimum required wastewater characteristics				
Use of reclaimed wastewater	Primary ^a	Secondary and disinfected	Secondary coagulated filtered ^b and disinfected	Coliform MPN/100 ml median (daily sampling)
Irrigation				
Fodder crops	x			No requirement
Fiber crops	x			No requirement
Seed crops	x			No requirement
Produce eaten raw, surface-irrigated		x		2.2
Produce eaten raw, spray-irrigated			x	2.2
Processed produce, surface-irrigated	x			No requirement
Processed produce, spray-irrigated		x		23
Landscapes, parks, etc.		x		23
Creation of impoundments				
Lakes (aesthetic enjoyment only)		x		23
Restricted recreational lakes		x		2.2
Nonrestricted recreational lakes			x	2.2

^aEffluent not containing more than 1.0 ml/liter/hr settleable solids.

^bEffluent not containing more than 10 turbidity units.

Source: After Ongerth and Jopling in Shuval (1977), p. 230.

III. PUBLIC HEALTH RISKS ASSOCIATED WITH WASTEWATER IRRIGATION

Pathogenic Microorganisms in Wastewater

Enteric diseases of the human intestinal tract are caused by many types of pathogenic microorganisms, including bacteria, viruses, protozoa, and helminths.

These diseases are transmitted when pathogenic microorganisms are excreted to the environment by an infected person (the initial "host"), transported by a suitable vector, such as contaminated water or food, and ingested by another susceptible human "host." Large numbers of the disease-causing pathogens are excreted in the urine and feces of infected individuals, and these pathogens contaminate the wastewater which is dumped into the environment.

The concentration of pathogenic bacteria and viruses in the feces of an infected person usually ranges from 1 million to 100 million (10^6 - 10^8) organisms per gram of feces. The concentration of protozoa is about 10-100 thousand (10^4 - 10^5) per gram of feces, and the concentration of encysted helminth eggs ranges from 100 to 10,000 (10^2 - 10^4) per gram of feces.

The wastewater stream of a community carries the full spectrum of pathogenic microorganisms excreted by the diseased and infected individuals living in that community. The calculated concentration of pathogenic microorganisms in the wastewater stream is many millions per liter for bacteria, thousands per liter for viruses, and a few hundred per liter for some of the helminth eggs.

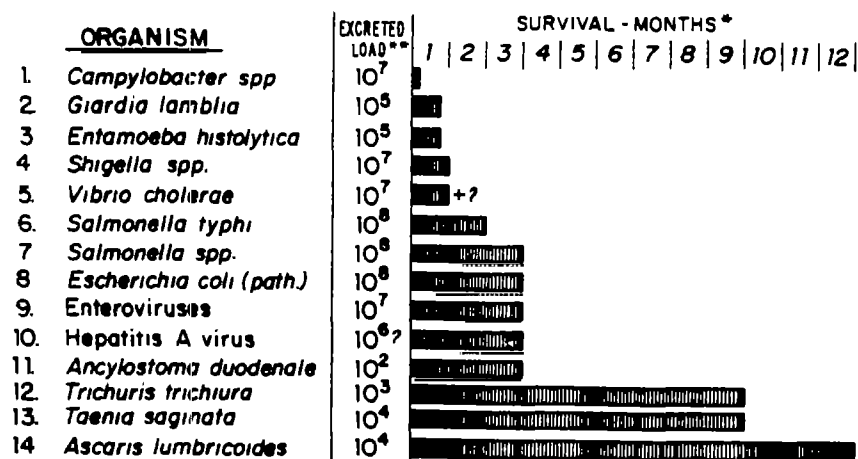
Survival of Pathogens in the Environment

In order for pathogens to infect a susceptible individual they must be 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 (see Fig. 2). 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 for one to three months. The highly resistant eggs of helminths such as Trichuris, Taenia, and Ascaris can survive for nine to twelve 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 sprinkler irrigation, but their concentration is greatly reduced by detrimental environmental factors such as sunlight and drying. Thus, most



* Estimated average life of infective stage at 20°-30°C

** Typical avg. number of organism/gm feces

Fig. 2. Persistence of selected enteric pathogens in water, wastewater, soil, and on crops. Source: Based on data from Feachem et al. (1983).

excreted pathogens can survive in the environment long enough to be transported by the wastewater to the fields. The crops they contaminate 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.

Proposed Model to Predict the Relative Effectiveness of Pathogens in Causing Infections Through Wastewater Irrigation

Theoretical analysis suggests that a number of epidemiological factors determine whether various groups of pathogens will cause infections in humans through wastewater irrigation. A model can be constructed to evaluate the empirical epidemiological data and to formulate control strategies.

The main factors that contribute to the effective transmission of pathogens by wastewater irrigation are:

1. Long persistence in the environment.

2. Low minimal infective dose.
3. Short or no immunity.
4. Minimal concurrent transmission through other routes such as food, water, and poor personal or domestic hygiene.
5. The need for a soil development stage.

Table 2 summarizes the epidemiological characteristics of the main groups of enteric pathogens as they relate to these five factors. 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 helminth (worm) diseases are the 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, 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, 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 reinfect individuals exposed to them again, for example, through wastewater irrigation. The transmission of bacterial and protozoan diseases through wastewater irrigation lies between these two extremes.

Theoretically, the pathogens can be ranked in the following descending order of risk:

1. High: Helminths (intestinal nematodes such as Ascaris, Trichuris, hookworm, and Taenia).
2. Lower: Bacterial infections (cholera, typhoid, and shigellosis) and Protozoan infections (amebiasis, giardiasis).
3. Least: Viral infections (viral gastroenteritis and infectious hepatitis).

We now turn to the available epidemiological evidence to determine if this theoretical model fits the empirical data.

TABLE 2

Epidemiological Characteristics of Enteric Pathogens vis-à-vis Their Effectiveness in Causing Infections 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 and food and water	no
Bacteria	short/medium	medium/high	short/medium	mainly home contact and food and water	no
Protozoa	short	low/medium	none/little	mainly home contact and food and water	no
Helminths	long	low	none/little	mainly soil contact outside home and food	yes

IV. EVALUATION OF THE EPIDEMIOLOGICAL EVIDENCE OF HUMAN HEALTH EFFECTS ASSOCIATED WITH WASTEWATER IRRIGATION

Existing Regulations Lack Epidemiological Basis

The strict health regulations governing wastewater reuse that have been developed in the industrial countries over the past 60 years have been based to a great extent on 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. 2). Most health authorities have concluded that, because pathogens can survive long enough to contaminate crops, even if their numbers are very low, they 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.

One of the primary goals of this study has been to reevaluate 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.

The following evaluation is based on available scientific papers published in recognized journals and on numerous unpublished government reports, university theses, and private papers obtained during an intensive worldwide search carried out with the help of international and national agencies and individuals. Over 1,000 documents, some more than 100 years old, were examined in the course of this study, but few offered concrete 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 paper is based (Shuval et al. 1986). The general conclusions of some of the more pertinent studies are presented below.

Population Groups Consuming Vegetables and Salad Crops Irrigated with Raw Wastewater

In areas of the world where the helminthic (worm) 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 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. 1984a) provided strong evidence that massive infections of both Ascaris and Trichuris may occur when salad and vegetable crops are

irrigated with raw wastewater. The disease almost totally disappeared from the community when raw wastewater irrigation was stopped (see Fig. 3). Two studies from Darmstadt, Germany (Krey 1949; Baumhogger 1949) provided additional support for this conclusion (see Fig. 4).

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 reinfection 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 vibrio. This possibility is of particular concern in nonendemic 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 (see Fig. 5; Fattal et al. 1986).

Similarly, evidence from Santiago, Chile, strongly suggests that typhoid fever can be transmitted by fresh salad crops irrigated with raw wastewater. As Figure 6 illustrates, the number of typhoid fever cases in Santiago rose rapidly 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 (Shuval et al. 1984b). 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.

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 and develop cysticercosis. 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.

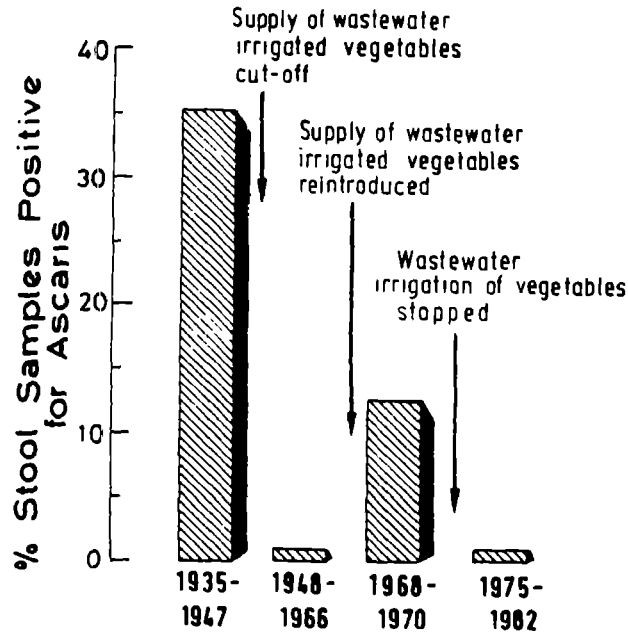


Fig. 3. Relationship between *Ascaris*-positive stool samples in population of western Jerusalem and supply of vegetables and salad crops irrigated with raw wastewater in Jerusalem, 1935-1982. Sources: Ben-Ari (1962), Jjumba-Mukabu and Gunders (1971), and Shuval, Yekutieli, and Fattal (1984).

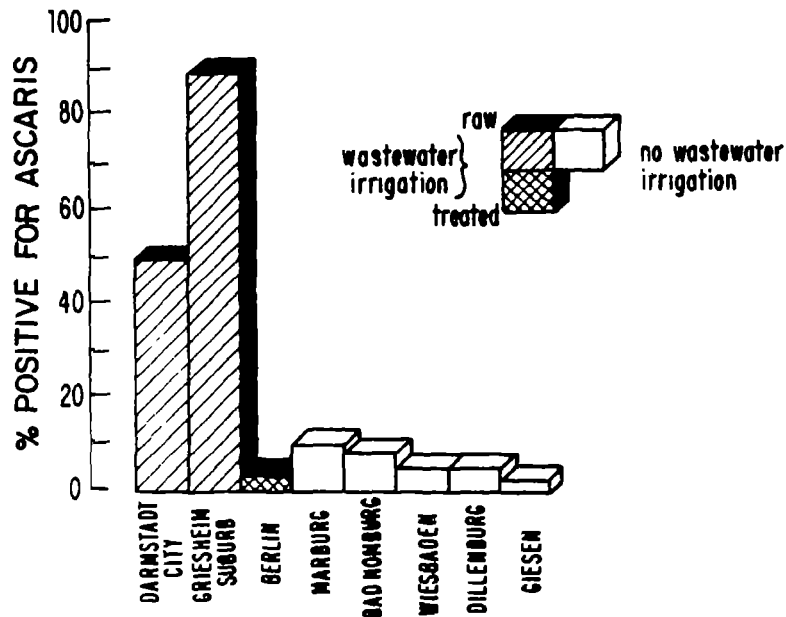


Fig. 4. Wastewater irrigation of vegetables and *Ascaris* prevalence in Darmstadt, Berlin, and other cities in Germany in 1949. Darmstadt used raw wastewater for irrigation. In Berlin, wastewater received biological treatment and sedimentation. Sources: Baumhogger (1949), Krey (1949), and Schlieper and Kalies (1949).

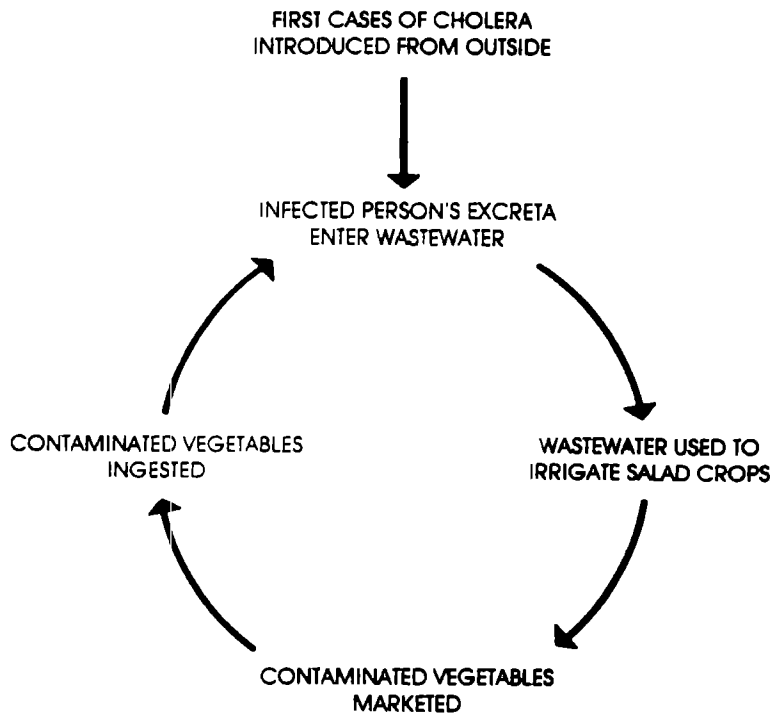


Fig. 5. Hypothesized cycle of transmission of *Vibrios cholerae* from first cholera carriers introduced from outside the city, through wastewater-irrigated vegetables, back to residents in the city.

Health Effects Among Sewage 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 (see Fig. 7; 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 anemia (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 nonexistent. This proved to be the case in the 1970 cholera outbreak in Jerusalem (Fattal et al. 1986).

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 occupationally 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 among wastewater irrigation workers in developing countries.

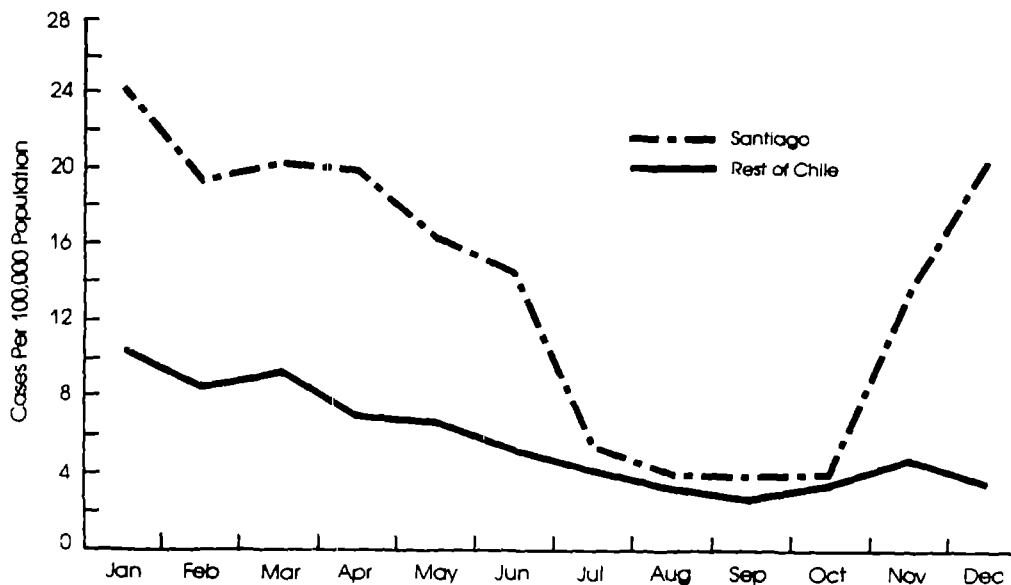


Fig. 6. Seasonal variation in typhoid fever cases in Santiago and the rest of Chile (average rates, 1977-1981). Source: Based on a field investigation carried out for the World Bank (Shuval 1984) and other published reports.

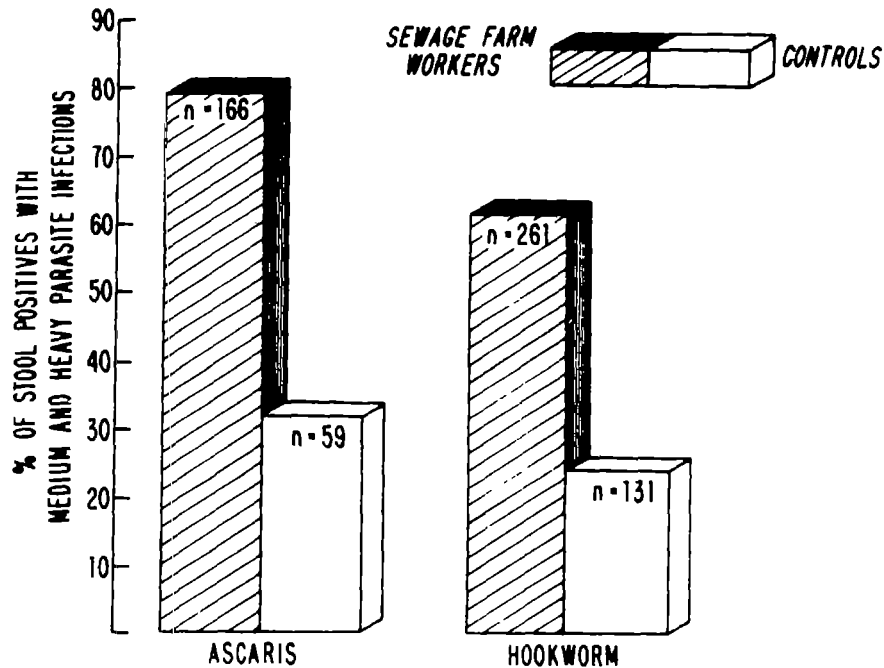


Fig. 7. Intensity of parasitic infection in sewage farm workers and controls in various regions of India. Source: Adapted from Krishnamoorthi, Abdulappa, and Anwikar (1973).

Health Effects Among Population Groups Residing Near Wastewater-Irrigated Fields

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 (Fattal et al. 1986; Shuval et al. 1987; and Shuval et al. 1989).

These findings support the conclusion that, in general, relatively high levels of immunity against most viruses endemic to 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.

Reduction in Negative Health Effects by Wastewater Treatment

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 (see Fig. 4).

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. Presumably, 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.

Furthermore, the absence of negative health effects in Lubbock, Texas (Camann et al. 1983), and 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 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 many thousands 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 but not total removal of the principal pathogens can provide a high level of health protection.

Implications for Developing Countries

In sum, epidemiological studies on the health effects of wastewater reuse in agriculture 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 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 poor-quality effluent is used.

Thus, the empirical evidence on disease transmission associated with wastewater irrigation in developing countries strongly suggests that helminths are the number one 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 declining order of 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 poorly 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 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 paper.

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, this study 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. No detrimental health effects were detected when well-treated wastewater of much higher coliform counts was used.

V. APPROPRIATE LOW-COST METHODS OF WASTEWATER TREATMENT FOR IRRIGATION

Goals of Wastewater Treatment for Irrigation

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 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, serious odors may develop and fish may die.

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, the conventional treatment systems 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; they must remove the pathogens with their own treatment systems using a series of highly efficient, technical, and costly processes (e.g., coagulation, sedimentation, filtration, and chemical disinfection). Table 3 shows the general range of pathogen removal efficiency for four conventional wastewater treatment processes (primary sedimentation, septic tanks, trickling filters, and activated sludge) and for low-cost waste-stabilization pond systems. The most effective conventional system is activated sludge, which removes 90-99 percent of the viruses, protozoa, and helminths, and 90-99.9 percent of the bacteria. Conventional processes cannot achieve higher levels of pathogen removal without great additional expense for chemical disinfection, such as chlorination, or for additional sand filtration. Further research and development are needed to improve the removal of helminths by conventional methods. As yet, little effort has been made to develop new and more effective methods.

In contrast, stabilization ponds are low in cost, easy to operate (and thus highly suitable for developing countries), and very effective against pathogens. Well-designed, multicell pond systems can remove 99.99-99.9999 percent ($4-6 \log_{10}$) of the bacteria and helminths from raw wastewater, and in warm climates can achieve an effluent quality of about 1,000 fecal coliform bacteria per 100 ml.

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. (Actual microbial standards or guidelines will be discussed later.) 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.

TABLE 3

Relative Efficiencies of Sewage Treatment Operations and Processes.

Treatment operation or process	Removal Efficiencies (%)			
	5-day, 20°C BOD	Suspended solids	Bacteria	COD
Fine screening	5-10	2-20	0	5-10
Chlorination of raw or settled sewage	15-30	--	90-95	--
Plain sedimentation	25-40	40-70	50-90 ^a	20-35
Chemical precipitation	50-85	70-90	40-80	40-70
Trickling filtration preceded and followed by plain sedimentation	50-95	50-92	80-95	50-80
Activated-sludge treatment preceded and followed by plain sedimentation	55-95	55-95	99 ^b	50-80
Stabilization ponds	90-95	85-95	≥99.9 ^c	70-80
Chlorination of biologically treated sewage	--	--	98-99	--

a. 3-6 hours' retention. May be down to 10 percent for shorter residence time.

b. Can decrease to 60 percent for poorly aerated AS systems and can reach 99.9 for extended aeration with hydraulic retention time ≥24 hours.

c. For series of three or more ponds with total retention time of 15-20 days or more.

Sources: Fair, Geyer, and Okun (1968); bacteria reduction data are based on Feachem et al. (1983), excluding chlorination and chemical precipitation data.

If the wastewater will be disposed of in a conventional system and discharged into a lake or river, then the primary goal is removal of the organic material (that is, lowering of the BOD) in order to prevent pollution of the natural waterways. Removal of pathogens, however, is only a secondary goal of conventional treatment systems. They are not designed to, and do not, remove pathogens as efficiently as the stabilization ponds which are used to treat wastewater prior to irrigation.

For sprinkler or drip irrigation systems, suspended particles must be removed to prevent clogging of the orifices in the irrigation equipment. In all cases, the large rapidly settleable solids must be removed to prevent sedimentation in irrigation canals.

To summarize, wastewater that is to be used for irrigation must be treated for the following reasons (in descending order of priority):

1. To remove pathogens, including helminths, bacteria, viruses, and protozoa.
2. To maintain aerobic conditions and prevent serious odors.
3. To ensure that nutrients of agricultural importance are not lost.
4. To remove large settleable solids to prevent irrigation channels from clogging and, in the case of sprinkler or drip systems, to remove suspended solids as required.

Stabilization Ponds--A Highly Efficient Wastewater Treatment Process

It is beyond the scope of this report to provide a full review of the science and technology of wastewater treatment that might meet all the criteria of agricultural irrigation. For further background information, the reader is referred to standard texts on the subject and to the full UNDP-World Bank report (Shuval et al. 1986).

The main emphasis of this report is on stabilization ponds because they are suitable for many situations in developing countries, cost little to use, require little or no mechanical equipment, and are robust and easy to operate. What is most important, they provide an exceptionally high degree of pathogen removal, better than that achieved by most conventional wastewater treatment processes.

Stabilization ponds are simple, natural waste treatment systems consisting of large open earthen lagoons or ponds, usually 1.5 to 2 meters deep. Typically, they hold the sewage flow for 20-25 days. Although many factors--for example, wastewater quantity and quality, climatic conditions, and the degree of treatment required--must be taken into account in the actual design of stabilization ponds, the pond area required for warm countries is about 3 m² per person; that is, 30 ha for a city with a population of 100,000 connected to the sewerage system.

The wastewater in stabilization ponds may be treated by a number of natural biological and physical processes without the need for the expensive concrete tanks, mechanical

equipment, energy, and chemicals that are usually required in conventional treatment plants. Sunlight, which serves as the main source of external energy, stimulates the natural biological processes, which in turn stabilize the organic wastes. Bacteria and other microorganisms break down the complex decomposable organic matter (which can become a nuisance if not removed) in the wastewater, and the nutrient components are taken up by the stable algae biomass. The bacteria also produce the CO_2 required by the algae. The algae in turn produce oxygen by photosynthesis which is used by the growing biomass of aerobic bacteria at work purifying the wastewater. The effluent from stabilization ponds is usually biologically stable, not objectionable in smell, green in color owing to the algae biomass, and rich in nutrients of value to agriculture.

The main physical process at work in wastewater stabilization ponds is sedimentation. Since wastewater is retained in the pond system for long periods of time, all of the rapidly settleable solids are removed, and a majority of the slower, more settleable suspended particles. In addition, most of the helminth eggs settle out in stabilization ponds. These eggs vary in size from 5 to 150 μm and their specific gravity is greater than water (it ranges from 1.055 to 1.18). The eggs of the largest (Schistosoma sp.) have a settling velocity of 12.5 m/hr and those of the smallest (Entamoeba histolytica) settle out in a 1.5 m deep pond in 214 hours, or about 9 days.

Field studies have shown that well-designed multicell stabilization ponds allowing 10-20 days of retention can remove almost 100 percent of the helminth eggs (Feachem et al. 1983; Mara and Silva 1986; Yanez et al. 1980).

Bacteria, viruses, and protozoa are often attached to larger fecal particles that settle out in pond systems. At best, however, only 90 percent can be removed by sedimentation. The most effective process for removing bacteria and viruses in stabilization ponds is die-away, 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 owing to the photosynthetic activity of the algae. Predatory or competing microorganisms may also affect die-away 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 25-day retention time usually reduces the fecal coliform concentration by 4-6 \log_{10} orders of magnitude--that is, by 99.99-99.9999 percent. Thus, if the initial concentration of fecal coli in the raw effluent is approximately 10⁷/100 ml, the effluent will contain 10-1,000/100 ml. The same pond will reduce enteric viruses by 2-4 \log_{10} orders of magnitude (i.e., from an initial concentration of about 1,000/100 ml to 10 or fewer/100 ml). Helminths will be removed completely, while the BOD will be reduced by about 80 percent. Figure 8 shows the generalized removal curves for BOD, helminth eggs, bacteria, and viruses in a multicell stabilization pond system in a warm climate.

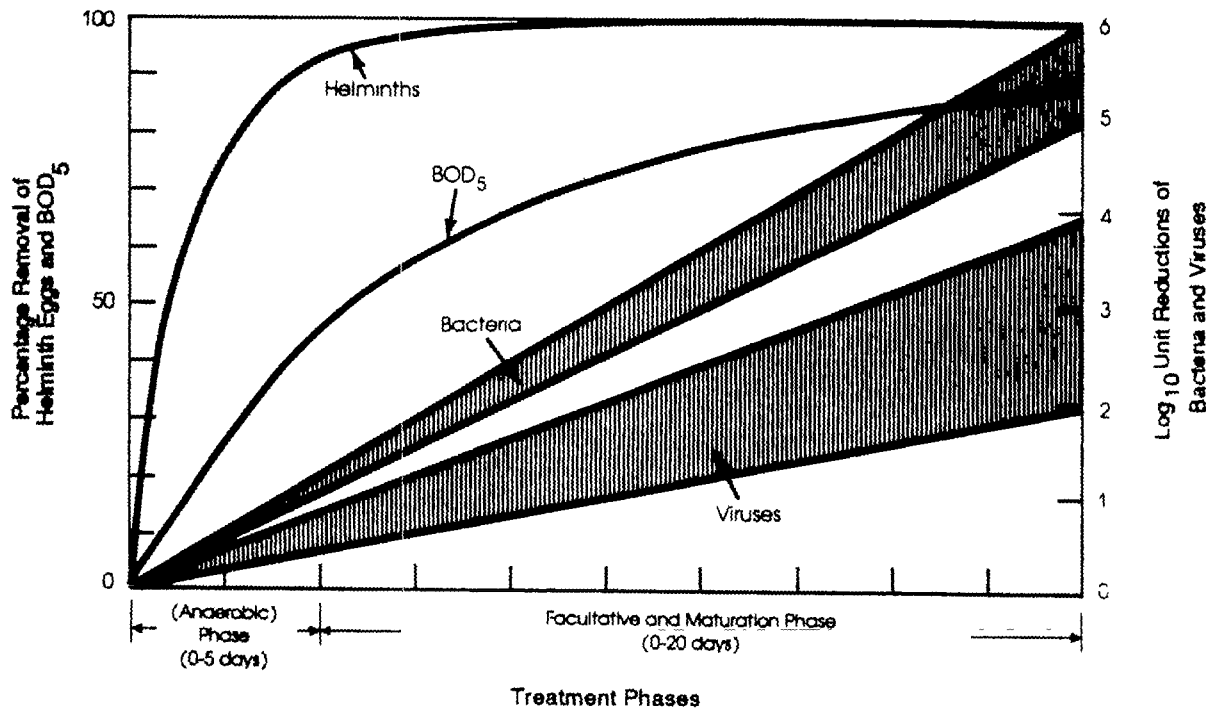


Fig. 8. Generalized removal curves for BOD, helminth eggs, excreted bacteria, and viruses in waste stabilization ponds at temperatures above 20°C.

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 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 not a serious obstacle. (This is discussed in a later section.)

Design Considerations for Stabilization Ponds

Detailed designs for stabilization ponds are provided in the full report on which this paper is based and in Arthur (1983). Figure 9 shows the layout of an oxidation pond system for effluent irrigation. Very often, the first plant unit is a Parshall flume (flow-measuring channel), which measures and monitors the wastewater flowing into the plant. The first

treatment unit is the three to four m deep anaerobic pond, which is usually designed for about two days of retention. A second similar anaerobic pond is placed in parallel with the first, and is used as an alternate so the ponds can be desludged each year. The typical maximum allowable BOD loading of the anaerobic ponds in areas with temperatures in excess of 20°C

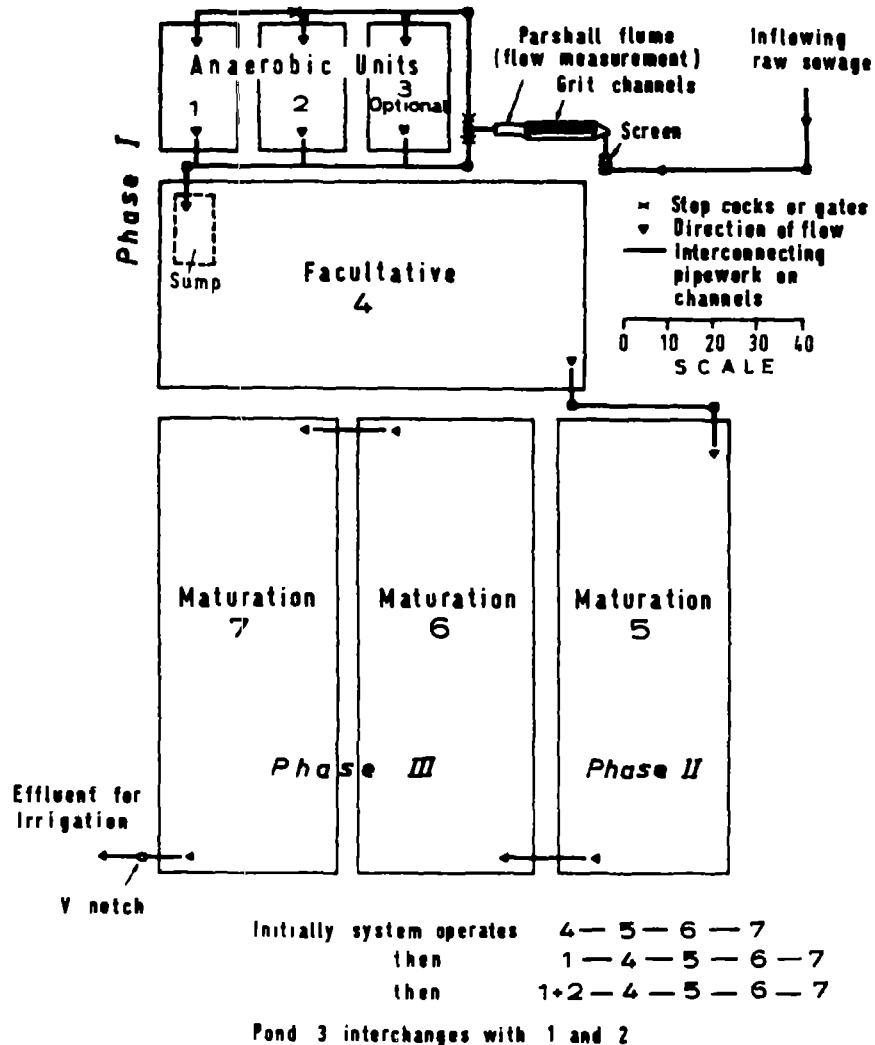


Fig. 9. Schematic layout of oxidation pond system for effluent irrigation and construction phases (after Arthur 1983).

would be 0.4 kg/m³/day. Assuming two days of retention, 4 m depth, and a wastewater flow of 200 l/c/d, the area required for the two anaerobic ponds would be about 0.2 m²/person. The expected BOD removal in a primary anaerobic pond of this type is 50-60 percent. Thus, first-stage anaerobic ponds can achieve a high degree of BOD removal in a relatively small area, thereby reducing the total area required for facultative ponds and lowering total plant costs.

If properly designed and operated, anaerobic ponds can be nuisance-free but should nonetheless be placed at some distance from residential areas.

The second treatment unit is the facultative pond, which is designed on the basis of BOD loading per unit area. It is used to ensure stable aerobic conditions and sufficient BOD removal. For a region with a mean water temperature of 20°C for the coldest month of the year, the recommended loading is about 280 kg/BOD/ha/day. With a BOD contribution of 40 gm/person/day to the wastewater and a 50 percent BOD removal in the primary anaerobic pond, the required area for the facultative pond would be 0.7 m²/person. The size of this pond is dependent solely on the BOD load; it is not influenced by the volume of flow. If wastewater flow is 200 l/c/d and pond depth 1.5 m, the facultative pond will provide 5.4 days of retention.

The third stage of the process consists of multicell maturation ponds, designed in accordance with the wastewater flow. Multiple cells are placed in series to ensure that retention time is adequate and to reduce short circuiting so that the required bacterial reduction can be achieved. For a wastewater flow of 200 l/c/d, a pond depth of 1.5 m, and a required retention period of 20 days in 4 cells, an additional 3 ponds with 14.6-day retention periods are required since the first facultative pond already provides 5.4 days of retention. The additional area required is 1.9 m²/person for a total of 2.8 m²/person. The actual plant size must be about 10 percent larger than the net pond area to allow for pond embankments, roads, and so on (i.e., total plant area should be about 3.1 m²/person). Of course, this is only an example, but it is representative of many areas. Less pond area might be required in warmer regions. Detailed design formulas and examples of stabilization pond designs are presented in the full report (Shuval et al. 1986). Among the many important design details to be considered are baffled effluent weirs that can provide significant increases in pond efficiency for helminth removal since they prevent suspended solids from breaking through.

Construction in Phases

When funds are limited, pond systems are often constructed in phases. An example of one possible phasing program is presented in Figure 9. Phase I includes the primary anaerobic units and the first facultative pond. This might require 50 percent of the ultimate design pond area. As shown in Figure 8, if such a system includes a single facultative pond with only a five-day retention time, then 99 percent of the helminth eggs will be removed, and about 99 percent of the bacteria, leaving an *E. coli* concentration of approximately 10⁵/100 ml. The BOD reduction would be about 65 percent, which would produce a sufficiently stable effluent to be acceptable from an aesthetic point of view. Such an effluent would be marginally suitable for the irrigation of nonedible crops. Recent studies indicate that a pond system for total helminth removal should include a minimum of one anaerobic pond followed by a five-day facultative pond and a five-day maturation pond (Mara and Silva 1986). Phase II would provide such a system by adding one maturation pond (pond number 5 in Figure 9). Phase III would add two more maturation ponds (ponds number 6 and 7). This system would remove all the helminths and 99.999 percent of the bacteria. The effluent would approach the microbial standard of 1,000 *E. coli*/100 ml recommended for unrestricted irrigation of all edible crops, but it might fluctuate around that goal.

In those cases where crop restrictions are feasible and cultivation of vegetables and salad crops normally eaten uncooked can be prevented, the lower degree of treatment achieved in the Phase II system would be acceptable as a long-term solution. Even in cases where edible crops are currently being irrigated with raw wastewater, major health benefits could be expected from the early introduction of a Phase I type plant, even if it did not provide the absolute safety that would be achieved by a plant with longer retention time and superior bacterial and viral removal rates. The Phase I plant would almost certainly interfere with the cycle of helminth diseases, which are often the primary problem in developing countries.

The Question of Large Land Requirements

As already indicated, the one disadvantage of stabilization ponds is that they require large areas of relatively flat land--approximately 30 ha for each 100,000 people in warm areas. A number of options exist to reduce the pond area required. For example, relatively simple equipment and energy-intensive treatment systems such as aerated lagoons or oxidation ditches can be used to reduce the area of the facultative pond. However, in many cases, the limiting design parameter is the area required to achieve adequate retention time (usually 15-25 days in warm climates) for removal of bacteria.

Where land shortages are severe owing to high prices or unsuitable topography in the vicinity of the urban area, an alternative is to transport the wastewater by pipeline to a more suitable site or to build a compact equipment-intensive conventional plant. However, since conventional treatment plants are less effective than stabilization ponds in removing pathogens, additional treatment units must be considered to ensure effective pathogen removal. Such processes might include chemical coagulation and sedimentation, sand filtration, and/or chemical disinfection and long-term storage reservoirs.

Table 4 presents the ratio of the construction cost of conventional treatment plants to the cost of stabilization ponds of the same capacity (Widmer 1981). According to these figures, a conventional activated sludge or trickling filter plant serving a population of 100,000 is five times more expensive to construct than a waste stabilization pond system. Arthur (1983) estimates that in 1983 construction costs of ponds without bottom sealing ranged from US\$15 to US\$30 per capita, whereas the costs of conventional plants ranged from US\$100 to US\$300 per capita. These figures exclude the cost of land, which can be a major factor in the case of oxidation ponds; but they do show the economic advantages of ponds in areas where land is inexpensive.

The operating costs of conventional plants are also much higher than those of stabilization ponds. Excluding capital costs, the operating costs are about \$1/capita/year for ponds versus \$15-\$20/capita/year for conventional plants. When operating costs and capitalization are combined, ponds cost about \$4/capita/year versus a minimum of \$25/capita/year for conventional plants without land costs.

Although the costs of stabilization ponds may increase when a large land area is required, the total is often much less than the cost of constructing and operating a conventional plant. For example, if land costs average about \$20,000 per hectare (\$2/m²) in urban fringe areas (Gunnerson et al. 1985) and pond area requirements are 3 m²/capita, the additional capital cost of land for ponds would be \$6/capita, or about \$0.60/capita/year. Even if land prices increased by a factor of 10 or 20 as urban transportation and services were brought in (Dorin-Dbubkin 1977), the incremental cost of ponds due to land alone would increase by \$6-\$12/capita/year compared with at least \$25/capita/year for conventional treatment.

Clare and Weiner (1961) conducted a survey of 262 treatment systems (160 stabilization ponds, 81 conventional treatment plants, and 21 other types) in the central United States (where land prices are not particularly low). They found that "In many cases the price of land may be 50 percent of the cost of the complete waste stabilization lagoon. The total cost has been equal to or less than the completed secondary treatment works. In numerous instances land costs could be double or triple the completed lagoon construction cost before equaling the conventional plant cost." This does not take into account the considerably higher operating cost of conventional plants.

TABLE 4

Ratio of Construction Cost of Conventional Treatment Plant to
Cost of a Pond Treatment Plant of the Same Capacity.

Design population	<u>ASP</u> WSP	<u>TFP</u> WSP	<u>PTP</u> WSP	<u>ITP</u> WSP
100	3.7	4.5	3.2	4.0
1,000	4.1	4.6	3.4	4.0
10,000	4.8	4.8	3.8	2.0
100,000	5.8	5.0	4.2	1.4

Note: ASP, activated sludge plant; TFP, trickling filter plant with separate sludge digestion; PTP, primary treatment plant with separate sludge digestion; ITP, Imhoff tank plant; WSP, waste stabilization pond plant. Removal efficiencies are not necessarily equivalent.

Source: Clare and Weiner (1965).

The claim that excessive land requirements and high land costs make ponds uneconomical can readily be disproved in most cases. Even if land values are expected to increase to a point where the ponds are no longer economical, it may still be prudent to build an inexpensive but efficient and land-extensive pond system for a 20-year period. The pond system can then be moved further out to cheaper land or be replaced by a more expensive land-intensive conventional system, with the excess released (and now high-priced) land being sold by the municipality to finance the more expensive mechanical system.

Interseasonal Wastewater 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 nonirrigation periods. If allowed to flow unrestricted, the effluent will contaminate the region's natural bodies of water.

A suitable solution is the large interseasonal storage reservoirs pioneered in Israel (Dor et al. 1986). These reservoirs are designed to store up to ten months of wastewater flow until the irrigation season. They are often preceded by conventional stabilization ponds, and may also be designed to catch surface runoff. Studies indicate that wastewater quality improves considerably in such reservoirs, with a major reduction in BOD and pathogens (see Fig. 10).

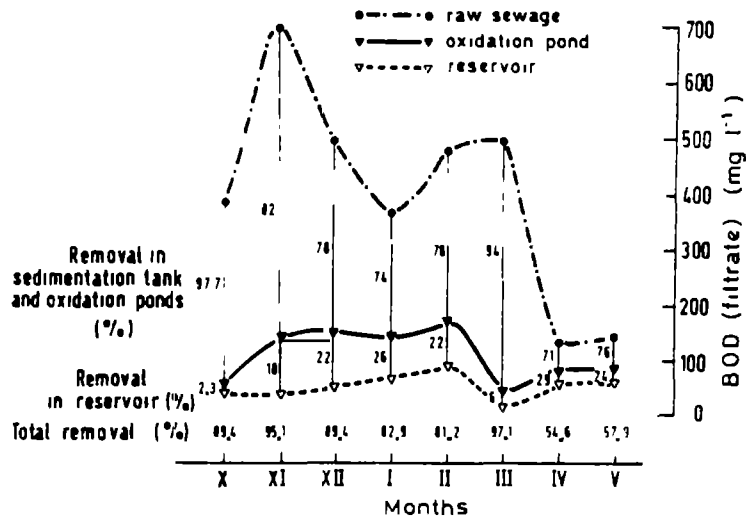


Fig. 10. Relative and total removal of BOD prior to and in the Naan wastewater reservoir, Israel. Source: Adapted from Dor and Berend (1982).

Another solution is to develop aquaculture in the final maturation ponds and/or additional storage reservoirs. Studies have shown that, when properly managed, such ponds have high fish yields, which can provide a low-cost source of protein.

Special Treatment for Drip Irrigation

Effluent from stabilization ponds is normally suitable for most equipment used in high-pressure sprinkler irrigation. The orifice of typical sprinkler nozzles ranges from 3 mm to more than 20 mm in diameter, but the smaller ones may become clogged by the solid particles in pond effluent. A minimum nozzle orifice of 5 mm has been found satisfactory for irrigation with pond effluent.

Drip irrigation systems use small tubes (25 mm in diameter) and low-rate drip applicators. The latter have pressure reducing emitters with narrow passages or orifices (typically 1 mm in diameter). Drip emitters are therefore inherently vulnerable to clogging, particularly if wastewater effluent is used.

Effluent from wastewater stabilization ponds has been used successfully for drip irrigation in Israel and Portugal, although special pretreatment of the effluent has been necessary. Various types of screen filters have been used which pass the effluent through a series of increasingly fine screens ranging from 60 mesh to 200 mesh.

At other installations, sand or gravel pressure filters with backwashing arrangements have been useful. Several problems surrounding effluent pretreatment for use in drip irrigation are yet to be solved satisfactorily and are still the subject of research (Adin 1986). However, technical solutions are expected. Work on the redesign of conventional drip irrigation emitters may help reduce clogging problems, although the recently developed bubbler irrigation has eliminated clogging altogether because the equipment has larger orifices (Hillel 1987).

VI. AGRONOMIC ASPECTS OF WASTEWATER REUSE

Agricultural Benefits

In arid and semiarid zones, the principal agricultural benefit of recycling municipal and/or industrial wastewater for land application is that water resources are conserved and more water is available to grow crops. In semiarid, or even in temperate zones that have a defined dry season during the summer, crop production may depend on supplemental irrigation with treated wastewater.

To determine the area that could be irrigated with the effluent from a city with a population of 500,000, suppose that the average water consumption rate is 175 liters per capita per day and there is an 85 percent return flow to the central sewerage system. In that case, the wastewater flow (150 l/c/d) would be 75,000 m³/day, or about 27 million m³/year. If we assume a well-controlled irrigation application rate of 10,000 m³/ha/year, then it would be possible to irrigate 2,700 ha with treated wastewater effluent from a city of 500,000. The crop yield of such an area might be 10,000 tons of cotton or 270,000 tons of tomatoes or other garden vegetables. The wholesale market value of these crops in 1986 would have been about \$6.5 million and \$27 million, respectively (Wiesel 1986).

Wastewater effluent also has significant fertilizer value. Typical concentrations of the nutrients in wastewater effluent are as follows:

Nitrogen (N)	=	40 g/m ³
Phosphorous (P)	=	10 g/m ³
Potassium (K)	=	30 g/m ³

Again, if effluent irrigation is applied at the rate of 10,000 m³/ha/year, nutrient applications would be as follows:

N	=	400 kg/ha/yr
P	=	100 kg/ha/yr
K	=	300 kg/ha/yr

Such fertilizer application rates supply all or more of the nitrogen normally required for agricultural crop production and much of the phosphorus and potassium. In addition, the organic matter in the effluent adds valuable micronutrients and humus to the soil, which help to improve water retention and soil structure. Studies in California, Portugal, and Israel have shown that many crops can thrive under wastewater irrigation without any additional chemical or organic fertilization.

Negative Effects of Wastewater Use in Agriculture

The chemical composition of municipal wastewater differs from that of municipal drinking water due to the addition of chemicals from household and industrial wastes. For example, it has been estimated that about 10 grams of sodium enter the sewerage system per person per day. If the wastewater flow is 150 l/c/d, the additional dissolved sodium concentration in the wastewater stream will be about 67 mg/l. This addition of sodium may be unimportant in areas with naturally low sodium concentrations in the incoming water supply, but may be of concern in areas with naturally high sodium concentrations in the water.

Excess sodium in irrigation water may cause soil aggregates to become dispersed and may reduce soil permeability. It may also affect the growth of certain plants that are sensitive to salt concentrations. Other dissolved salts, including toxic compounds from industrial sources, may enter the wastewater flow, particularly in large cities or communities serving industrial areas.

The relationship of soil properties, sodium concentration in water, and the concentration of total soluble salts is complex, and cannot be determined without careful evaluation of such parameters as the Sodium Adsorption Ratio (SAR) and the Cation Exchange Capacity (CEC). The potential impact of the chemical quality of the wastewater effluent to be used for irrigation should also be assessed by agricultural experts before a new wastewater irrigation project is initiated.

Boron, another chemical frequently found in municipal wastewater, can also become detrimental to agriculture. Boron is a common constituent of household and commercial laundry powder in the form of borax. Concentrations of boron commonly found in wastewater range from 0.1 to 1 mg/l. Citrus, avocados, and navy beans, for example, are sensitive to boron concentrations from 0.3 to 1.0 mg/l, whereas carrots, lettuce, and onions are quite tolerant and can grow in concentrations up to 3 mg/l. Since boron cannot be removed by normal treatment of wastewater, alternative compounds may have to be used in commercial laundry powders in areas where the boron in recycled wastewater has a deleterious effect on agriculture.

Wastewater irrigation also adds appreciable amounts of nitrogen to the soil. In some cases it may be in excess of that required for balanced plant growth and may stimulate excessive growth of the vegetative parts of the crops rather than the flowers or seeds. This may be a problem for crops such as cotton or fruits.

In areas where industrial wastewater makes up a major part of the wastewater flow, the chemical composition of the industrial discharges must be carefully evaluated to ensure that chemicals toxic to plant growth are not discharged to the sewerage system. Since it is difficult to treat or remove such chemicals, it is best to dispose of such industrial wastewater separately or to insist that the industry treat the chemicals so they will not be harmful to agriculture.

Another possible negative effect of wastewater irrigation is contamination of groundwater by both pathogenic microorganisms and chemical pollutants. This situation may arise in agricultural areas underlain by permeable soils that are connected to an aquifer which is used as a source of drinking water. Information must be collected on the local geology and on the aquifer and its use to determine if a major wastewater irrigation project could have a negative impact.

It should be noted here that all of the above potential negative effects of wastewater irrigation can be controlled with existing knowledge and technology. They are mentioned to emphasize that new projects must evaluate these possible effects in the early planning stages so that appropriate measures can be taken to safeguard against them.

The Effect of the Type of Irrigation System

Surface or Gravity Irrigation

It has been estimated that more than 95 percent of the irrigated land worldwide is served by surface irrigation. Notable exceptions include parts of Europe, Southern California, Israel, Cyprus, and selected areas of South America where surface irrigation has been replaced by sprinkler and drip irrigation systems as a result of unique local economic and social circumstances.

Surface irrigation systems--including wild flooding, border checks, and basin irrigation--usually lead to higher levels of water consumption than required. Whatever the system, the irrigation water, or in this case wastewater effluent, comes in direct contact with the growing plants. Thus, the edible crops will be exposed to direct and continuous contamination and the public health risk will be serious if raw or poorly treated wastewater is used.

Ridge-and-Furrow Irrigation

Furrow irrigation is used on row crops that are grown on raised ridges (see Fig. 11). Ridge crops are usually 10 to 25 cm above the surface of the water in the furrow and thus, even crops with low growth habits (e.g., peppers and tomatoes) will not come in contact with the effluent, provided they have erect stems or are supported by stakes and strings. Thus, the ridge-and-furrow method is safer for wastewater irrigation, but contact between low-lying crops and the wetted soil surface or water surface frequently occurs.

Sprinkler Irrigation

Sprinkler irrigation, although much more water-efficient than other methods, leads to direct contamination of all parts of the growing plants as they are hit by the effluent spray, whether they are garden crops or orchards. It is possible to design low-level under-tree sprinkler systems for orchards that can reduce or eliminate spraying of the actual fruit.

Drip Irrigation

In drip irrigation systems small-diameter (about 25 mm) plastic tubes are laid on the soil surface and low-velocity emitters deliver water directly to the root zone of each plant. There are several agronomic advantages to this system: it reduces water consumption, improves water regimes for plants, and improves yields. It also helps control plant disease connected with wetted foliage, and prevents contamination of vegetables by not allowing the wastewater to come in contact with the growing part of the plant (Sadovski et al. 1978). An effective way to protect crops from contact with wastewater-wetted soil in drip irrigation is to place a plastic sheet "mulch" overlay on top of the drip irrigation tubes. A small hole is cut in the sheet for each plant to grow through. This technique was developed for weed control but is highly effective in protecting crops from contamination. The disadvantage of the drip irrigation system is that special pretreatment of the effluent is necessary to prevent clogging.

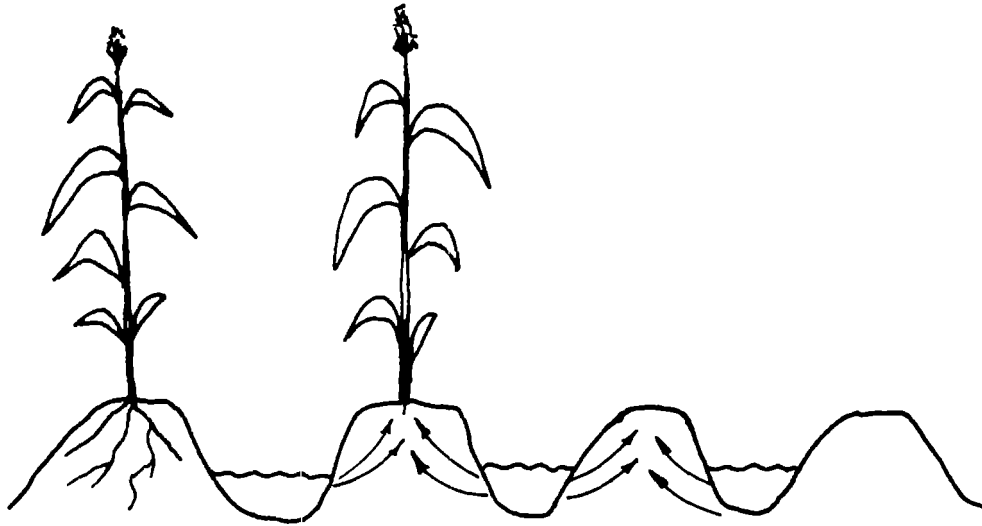


Fig. 11. Cross section of irrigation furrows showing flow path of water into ridges.

VII. TECHNICAL AND POLICY OPTIONS FOR REDUCING HEALTH RISKS ASSOCIATED WITH WASTEWATER IRRIGATION

The Need to Revise Guidelines for Effluent Irrigation

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 approximating that of drinking water (2 coliforms/100 ml), are usually not practical, even for developed countries. Such a standard is even less feasible for developing 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).

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 with raw or poorly treated wastewater. This usually occurs in the vicinity of major cities, particularly in semiarid regions.

Since the official effluent standards for vegetable irrigation are not within the obtainable range of common engineering practice, new projects to improve the quality of effluent are not usually approved. With the authorities insisting on unattainable and unjustifiable standards, farmers are practicing uncontrolled, unsafe widespread irrigation of salad crops with raw wastewater. The highly contaminated vegetables are supplied directly to the nearby urban markets, where such truck garden products can command high prices. This is a classic case in which official insistence on the "best" prevents 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 practiced in the United States 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 U.S. Environmental Protection Agency's water quality criteria for unrestricted irrigation with surface water is 1,000 fecal coliforms/100 ml (USEPA 1972). A WHO world survey of river water quality has indicated that most rivers have mean fecal coliform counts of 1,000-10,000/100 ml. And yet none of these industrialized countries have 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 United States, for example, microbial guidelines for recreational water have in the past ranged from 200-1,000 fecal

coliforms/100 ml, although there is currently a move to reduce those numbers. In Europe, guidelines vary from 100 coliforms/100 ml in Italy to 20,000 coliforms/100 ml in Yugoslavia. The European Economic Community has recommended a guideline of 10,000 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 United States 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 1,000/100 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 1,000-10,000 fecal coliforms/100 ml.

The Engelberg Report and the New WHO Guidelines

In July 1985 a group of environmental experts and epidemiologists meeting at Engelberg, Switzerland, under the auspices of the UNDP, World Bank, WHO, UNEP, and the International Reference Center for Waste Disposal formulated new tentative microbiological guidelines for treated wastewater reuse in agricultural irrigation (Engelberg Report 1985). The group reviewed the epidemiological evidence gathered in the UNDP-World Bank study (Shuval et al. 1986) and the epidemiological analysis prepared by Blum and Feachem (1985). The group accepted the main findings and recommendations of the UNDP-World Bank study 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, tentative guidelines recommended in the Engelberg Report and later recommended by the WHO Meeting of Experts (WHO 1989) are presented in Table 5. Since the possibility of transmitting helminth disease by wastewater irrigation of even nonedible crops was identified as the top health problem, a new, stricter approach to the use of raw wastewater was developed. The Engelberg 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 Engelberg 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 1,000/100 ml. This is a much more liberal coliform standard than the early California requirement of 2 total coliforms/100 ml (see Table 1, pg. 6) or even the 1973 WHO Guideline (see Table 6, p. 45) of 100 total coliforms/100 ml (WHO 1973).

In November 1987 an official WHO Meeting of Experts reviewed the earlier WHO wastewater irrigation microbial guidelines in light of the vast array of new evidence. After careful consideration, it adopted the Engelberg guidelines as the basis for the new authoritative WHO guidelines (WHO 1989). Thus, the highest international public health body has given its stamp of approval to this new approach.

An attractive feature of the new WHO (1989) effluent guidelines is that they can be readily achieved with low-cost, robust stabilization pond systems that are particularly suited to developing countries. The high levels of pathogen removal that can be achieved by such low-cost systems were shown in Figure 8.

TABLE 5Recommended Microbiological Quality Guidelines for Wastewater Use in Agriculture^a.

Category	Reuse conditions	Exposed group	Intestinal nematodes ^b (arithmetic mean no. of eggs per liter)	Fecal coliforms (geometric mean no. per 100 ml ^c)	Wastewater treatment expected to achieve the required microbiological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks ^d	Workers, consumers, public	≤ 1	≤ 1,000 ^d	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees ^e	Workers	≤ 1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and fecal coliform removal
C	Localized irrigation of crops in category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

- In specific cases, local epidemiological, sociocultural, and environmental factors should be taken into account, and the guidelines modified accordingly.
- Ascaris and Trichuris species and hookworms.
- During the irrigation period.
- A more stringent guideline (≤ 200 fecal coliforms/100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.
- In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

Source: WHO (1989).

Thus, after well over a century, health guidelines for wastewater reuse have gone through a complete cycle: from no regulation or control in the nineteenth 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.

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.

Available Control Measures

The primary findings of the UNDP-World Bank report concerning the identifiable and quantifiable health effects of wastewater reuse in agriculture indicate that irrigation with wastewater is much less hazardous (especially in developing countries) than originally assumed. At the same time, the use of raw wastewater can cause certain long-term health problems that may lead to economic hardship. These health problems are associated mainly with helminthic disease and, to a lesser extent, with bacterial and viral disease. They may affect the general public that consumes uncooked salad crops and vegetables that have been irrigated with raw wastewater. Sewage farmers, exposed to the raw wastewater, and their families may also be affected.

It is important to assess all reasonable technical and policy options and alternative remedial measures that can reduce or eliminate the negative health effects and economic burdens resulting from unregulated agricultural irrigation with raw wastewater. Only in this way can we develop socially feasible and cost-effective strategies for remedial action that will be appropriate for any given country. The types of remedial measures that should be evaluated include the following.

1. **Agronomic Techniques:** restrictions on the type of crops grown or modifications and control of irrigation techniques.
2. **Disinfection of Wastewater-Contaminated Crops:** disinfection of farm produce prior to marketing or in the home.
3. **Improving the Occupational Health of Sewage Farm Workers:** protective clothing and/or other measures to protect the health of farmers occupationally exposed.
4. **Wastewater Treatment:** wastewater treatment to eliminate or reduce the concentration of pathogens to acceptable levels.

Agronomic Techniques

The 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.

Restricting Crops. One of the earliest and still most widely practiced 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 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 semiarid areas, where subsistence farmers near major urban centers irrigate with raw wastewater, the market demand for salad crops and fresh vegetables is great. 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.

Modification and Control of Irrigation Techniques. As discussed earlier, basin or sprinkler irrigation of salad and vegetable crops usually results in direct contact of the crops with wastewater, thus introducing a high level of contamination. Well-controlled ridge-and-furrow irrigation reduces the amount of direct contact and contamination, and drip irrigation causes even less. Although none of these methods can completely eliminate direct contact of the wastewater with leafy salad crops and root crops, ridge-and-furrow and drip irrigation methods cause less contamination than the basin and sprinkler methods.

Many vegetables that grow on vines (e.g., 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, and especially drip irrigation, can provide a large degree of protection from direct contamination. Drip irrigation is the most costly form of irrigation, but its hygienic advantages make it attractive in certain cases.

Fruit groves 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, windfall picked from the ground will be in contact with wastewater-contaminated soil.

Another possible control measure is to discontinue irrigation with wastewater at a specified period 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.

All 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 under its control, such procedures can be of value.

Disinfection of Wastewater-Contaminated Crops

Point-of-Use-Disinfection. Numerous studies have been carried out, particularly by the United States Army, to evaluate the efficiency of various disinfection procedures for salad crops and vegetables fertilized with night soil or with wastewater irrigation. Most of these studies agree that disinfection of produce by the final consumer can be effective if it includes scrupulous cleansing of contaminated produce with detergent followed by disinfection for 15-20 minutes in strong solutions of chlorine, quaternary ammonia compounds, or other disinfectants.

In developing countries, household disinfection can be of value in the homes of the better-educated, higher-income groups, but it cannot be considered an effective public health measure for the larger low-income groups. It would require a tremendous educational effort with only limited chances of success among the majority of the population at the lower socioeconomic levels.

Central Market Disinfection Stations. Produce disinfection by stations at central vegetable markets has been considered, but apparently such procedures, even if carried out efficiently, would damage certain produce and reduce shelf-life. Since only limited experimental and field work has been carried out to evaluate this option, it is difficult to assess its feasibility at this time. Theoretically, if appropriate procedures are developed, this approach may provide a reasonable degree of protection for those who consume vegetables irrigated with raw wastewater.

Improving the Occupational Health of Sewage Farm Workers

All of the options discussed above are concerned only with protecting the general public from wastewater-irrigated produce. Even if the types of crops are strictly regulated and all health problems of the general public are controlled, the sewage farmers themselves would still be at risk. The main diseases affecting sewage farmers (hookworm, ascariasis, and to a lesser extent some enteric bacterial diseases) could theoretically be overcome if farmers wore boots or shoes to protect their feet from the penetration of hookworms and if they paid close attention to personal hygiene, particularly by washing their hands before eating.

Among farmers with higher levels of education and improved socioeconomic conditions, an educational program aimed at achieving such goals may have some effect. Such a program could be especially effective on centrally organized sewage farms, where boots could be provided by the management and washing facilities could be installed adjacent to special clean areas for rest and eating. Health education among the farmers could also be continued. However, in the case of hundreds of small, one-family marginal wastewater farms or plots common throughout the developing countries, such a program of improved occupational health would be difficult to carry out. Chemotherapy and prophylactic treatment of exposed sewage farm workers is a possible palliative measure until basic environmental improvements can be introduced. They cannot, however, be viewed as effective long-term control measures.

Wastewater Treatment

If wastewater can be effectively treated before it is used in agricultural irrigation, the negative health effects to sewage farm workers and to populations living in the vicinity can be reduced or eliminated totally.

Optimal Level of Treatment. Of the identifiable health effects associated with the use of wastewater for irrigation, those of greatest concern for most developing countries (as detected by this study) are those caused by the enteric helminths--Ascaris, Trichuris, hookworm, and under certain circumstances, the beef tapeworm. These pathogens can, over long periods, damage the health of both the general public consuming the crops irrigated with raw wastewater (or the meat of animals grazing on wastewater-irrigated pasture) and sewage farm workers and their families.

To a lesser extent, enteric bacteria and viruses can cause some acute problems, but these are generally of short duration. Thus, this study has shown that the bacterial pathogens rank second in importance to the helminths. The viruses pose the lowest health hazard of the three groups. An optimal wastewater treatment system should therefore be able to remove all helminths, while a lower degree of removal of bacteria and viruses might be tolerated. In addition, the effluent should be clear and odor-free. Odor nuisances, as noted earlier, are troubling to both farmers and people living near treatment plants and wastewater-irrigated fields. It might be possible to sell a high-quality attractive effluent to farmers at the full value of water, but it would be difficult to recover the full value of a less attractive effluent. However, where the need for fertilizer and water is great, the aesthetic quality of the effluent would be of secondary importance.

Of the wastewater treatment processes reviewed here, the most effective in meeting the new WHO (1989) recommended guidelines (see Table 5) is the simple, robust, and relatively low-cost stabilization pond system. The optimal system recommended for tropical areas would have an anaerobic first-stage pond with two days of retention, followed by about 20-25 days of retention in a series of 4-5 facultative and maturation ponds (see Figure 9).

The effluent from such ponds, with proper operation, will usually meet the geometric mean of 1,000 fecal coliforms/100 ml recommended by the WHO report (1989) and may often approach the bacterial standard of 100 total coliforms/100 ml.

Such an effluent would be suitable for irrigating all categories of crops, including the high-risk category vegetable and salad crops. Many countries may prefer not to require a specific bacterial standard for effluent since it might be difficult to administer or control. The simple pond treatment described above, or an equally effective alternative, appears to be the most appropriate approach for optimal wastewater irrigation projects involving unrestricted crops in the developing countries. However, if a standard or guideline is to be used for unrestricted irrigation of all crops--including vegetables eaten raw--then the new recommendations of the WHO (1989) report are most appropriate.

Lower Levels of Treatment. Crops of medium risk (those not eaten raw) should be irrigated with the effluent from an intermediate pond system comprising an anaerobic pond followed by two ponds in series with 10 days of retention (or an equivalent system). This treatment should remove almost all the helminths and about 99 percent of the bacteria and viruses (as compared with about 99.99-99.999 percent bacterial removal in a 20-25 day, 4-cell pond system). An intermediate pond system with such short retention periods and high organic loadings may not always produce effluent that is aesthetically acceptable or completely odor-free in colder periods. However, such ponds are easy to maintain and can provide a significant degree of effective pathogen removal and health protection, and fairly stable effluent quality.

Advantages of Centrally Managed, Engineered Environmental Interventions

History has proven that the broadest and most immediate health benefits can be obtained from remedial 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 breeding sites of malaria-carrying mosquitoes are well-known examples of success using this strategy. Any remedial action based on changing the personal behavior and lifestyle of the public through education, law enforcement, or both, is a much slower process and, in general, has succeeded only in areas with relatively high educational and living standards.

The wastewater treatment option reviewed above offers this type of centrally managed and engineered form of 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, 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 semiarid zones (as well as some humid areas) where irrigation is highly desirable, some consider it economically prudent to allow unrestricted wastewater irrigation of cash crops in high demand.

TABLE 6

Suggested Treatment Processes to Meet the Given Health Criteria for Wastewater Reuse.

	Irrigation		Recreation		Industrial reuse	Municipal reuse		
	Crops not for direct human consumption	Crops eaten cooked; fish culture	Crops eaten raw	No contact	Contact	Non potable	Potable	
Health criteria (see below for explanation of symbols)	A + F	B + F or D + F	D + F	B	D + G	C or D	C	E
Primary treatment	...	...	...	...	...	...	...	...
Secondary treatment		...	...	...	...	...	...	...
Second filtration or equivalent poisoning methods		.	.		...	.	...	..
Nitrification						.		...
Denitrification								..
Chemical clarification						.		..
Carbon absorption								..
Ion exchange or other means of removing ions						.		..
Disinfection		.	...	.	...	.	...	...

Health criteria:

- A - Freedom from gross solids; significant removal of parasite eggs.
- B - As A, plus significant removal of bacteria.
- C - As A, plus more effective removal of bacteria, plus some removal of viruses.
- D - Not more than 100 coliform organisms per 100 ml in 80 percent of samples.
- E - No fecal coliform organisms in 100 ml, plus no virus particles in 1,000 ml, plus no toxic effects on man and other drinking water criteria.
- F - No chemicals that lead to undesirable residues in crops or fish.
- G - No chemicals that lead to irritation of mucous membranes and skin.

In order to meet the given health criteria, processes marked ... will be essential. In addition, one or more processes marked .. will also be essential, and further processes marked . may sometimes be required.

Source: Reproduced with the permission of the WHO from: Reuse of Effluents: Methods of Wastewater Treatment and Health Safeguards, WHO Technical Report Series no. 517 (Geneva, 1973).

It is argued that with a high-quality effluent, the full value of the water used in irrigation will be more easily recoverable. Furthermore, a program based on the use of raw or minimally treated wastewater for restricted crops, even if successful, will not reduce exposure of the sewage farm workers. The same is true for any central disinfection scheme of the wastewater-irrigated produce. Improving personal hygiene for sewage workers is of definite value but of limited feasibility in most situations in the developing countries.

Effective Wastewater Treatment--The Best Control Strategy

At the present time, the control strategy with the widest benefits, in terms of controlling the quantifiable negative health effects of wastewater irrigation, is wastewater treatment by means of stabilization ponds (including anaerobic, facultative, and aerobic ponds in series with a total retention time of 20-25 days for warm climates). This method produces a stable and aesthetically acceptable effluent and can achieve essentially total removal of the high-priority helminths and reasonably efficient removal of the lower-priority enteric bacteria and viruses. This system is the recommended optimal system for tropical and semitropical areas where land availability and prices are suitable, because it is more effective in removing the priority pathogens identified in this study than conventional wastewater treatment processes. The stabilization pond system also happens to be best suited to most developing countries. The low construction and operating costs, the absence of complicated mechanical elements such as aeration devices and sludge-handling pumps, and the robust, almost fail-safe nature of the system make it superior to almost any other form of wastewater treatment requiring higher technology. Where pond systems are not suitable due to lack of land, alternative high technology treatment methods are available but may involve greater costs and are often less reliable.

VIII. ECONOMIC EVALUATION OF WASTEWATER REUSE IN IRRIGATION

The main difficulty in evaluating the economics of wastewater irrigation is the valuation of nonfinancial aspects such as reduction of environmental pollution nuisances or health risks. The other less difficult problem is the allocation of treatment costs between the wastewater producer and the agricultural user. Once these two problems have been resolved, the analysis of wastewater irrigation can be carried out using standard techniques of economic and social cost-benefit analysis, which are well documented. The main report (Shuval et al. 1986) presents a framework for the economic analysis of wastewater irrigation projects after making some simplifying assumptions to deal with the problems mentioned above.

The first step in the analysis should begin with the source of the wastewater and estimation of the least-cost disposal options that meet minimum environmental (health, sanitation, and pollution) standards. This set of cost estimates provides the logical breakpoint for allocation of costs to the generator of the wastewater. Costs above this amount should be allocated to the wastewater irrigation system. Then, assuming that irrigation is economically viable, investigations should be made to assess the demands for irrigation water in areas near the source of the wastewater. In general, there are four areas for reuse:

1. Rainfed (seasonal) agricultural areas.
2. Existing irrigation schemes.
3. Existing unplanned sewage irrigation.
4. Marginal lands currently not farmed.

Once land areas for potential reuse have been identified, the cost of conveying wastewater to the area should be estimated in addition to any incremental treatment costs required to make the effluent suitable for irrigation. (Note that incremental treatment costs may be nil or negative depending on the minimum environmental standards and the treatment technology required for the least-cost disposal alternative).

In analyzing the treatment costs of the preferred option for wastewater reuse—namely, stabilization ponds—the major factor to consider is the value of the land. In particular, the project analysis should consider using relatively low-valued land near the reuse area instead of high-valued land near the urban center. The land value should be determined from its market value or from some reasonable alternative economic use, such as agriculture (its net present value without the irrigation project). In many cases, treatment in a remote area will already have been identified as the least-cost option, depending on conveyance costs. (For a full discussion of the impact of land values on sewage treatment, see World Bank Technical Paper Number 7, Notes on the Design and Operation of Waste Stabilization Ponds in Warm Climates of Developing Countries, by J.P. Arthur, 1983.)

In addition, the economic value of irrigated agriculture should be determined by calculating the overall capital and operating costs of the system and detailed farm budgets for the various potential cropping patterns. The quality and quantity of the effluent are significant factors, since to a large extent they determine the potential cropping pattern and yields, and hence the potential farm revenues.

When developing the farm budgets, one should keep in mind that fertilizer requirements are lower with wastewater irrigation. Typical nutrient levels in wastewater are illustrated on page 33.

The estimated mean value of nutrients supplied in wastewater is US\$0.0255/m³ (2.55 cents/m³), based on 1984 prices. Assuming (1) irrigation at a rate of 10,000 m³/ha/yr, (2) no additional fertilizer requirement, and (3) all wastewater nutrients are needed and utilized; then the nutrient value of wastewater irrigation should be about US\$250/ha/yr. This may seem to be a small benefit, but it may be very meaningful to the marginal farmer in a developing country who is unable to afford the cash outlay involved in proper fertilizer applications. The real value of these nutrients to the farmer will vary with the current level of fertilization and the cropping pattern.

The other major economic consideration is the "without project" situation. In this case the existing use of the land is factored into the calculations so that the net impact of wastewater reuse can be determined. This aspect of the analysis is straightforward for rainfed agricultural areas (develop farm budgets for current situation) and areas that are not currently farmed (use market value) and only slightly more difficult in areas that are currently irrigated. In currently irrigated areas, the analysis should take into account whether present high-quality irrigation water is released for more highly valued uses, such as urban-domestic or industrial consumption.

If unplanned sewage irrigation is taking place, the analysis should not use the current net benefits of the area as a without project situation since it would not conform to accepted environmental and health standards. Rather, it should be assumed that the unplanned sewage irrigation would be discontinued or that very restrictive cropping limitations would be strictly enforced (effectively turning the area into an overland sewage treatment facility, the costs of which should be compared to other treatment methods). If it is assumed that the unplanned irrigation is to avoid the incremental costs of effluent irrigation, the least-cost treatment options are likely to be very low since the majority of the on-farm irrigation systems are already in place.

Economic returns to effluent irrigation can be substantial, particularly in areas where:

1. Water is a constraining factor to optimum agriculture.
2. Agricultural areas are nearby and effluent conveyance costs are low.

3. Wastewater does not contain toxic industrial or hazardous wastes.
4. Current wastewater disposal practices would require substantial investments to meet environmental, health, and social standards.
5. Low-cost land is available for stabilization ponds.
6. High-quality water is in short supply and can be released for higher-valued uses.

IX. SUMMARY AND CONCLUSIONS

Wastewater irrigation, based on up-to-date engineering technology and public health safeguards, is rapidly becoming a widely practiced strategy for conserving natural resources, developing agriculture, and protecting the environment. Furthermore, wastewater recycling is often the least-cost solution for wastewater treatment and disposal. This paper provides basic information on the latest developments in the field for administrators, planners, agricultural and public health officials, and engineers.

In arid and semiarid areas, the increase in water available for food production by agricultural irrigation and the added fertilizer value derived from the nutrients in the effluent are often sufficient incentives for wastewater irrigation. Additional benefits such as reducing stream pollution and protecting drinking water sources from chemical and microbial contamination can be important as well. This report has summarized the benefits of wastewater irrigation and the steps that must be taken to control any health risks that may be associated with the practice.

Studying the health effects of wastewater irrigation and remedial measures for their control shows that previous public health standards--which held that every excreted pathogen persisting in the environment, in soil, or on crops irrigated with wastewater is a potential cause of serious disease in man--is overly conservative, particularly when applied to developing countries. Credible, quantifiable health effects from wastewater irrigation, which in this study apply to developing countries, are limited. The major pathogenic agents--mainly helminths (disease-causing worms)--are partially removed if allowed to settle for two days and completely removed in 20-day, multicell stabilization ponds. This also reduces bacteria and viruses, and is a low-cost, highly efficient, robust treatment method, admirably suited to the needs of developing countries.

One way to reduce health risks associated with irrigation with poor quality wastewater is to restrict the type of crops irrigated to non-food crops or at least to those consumed cooked. This may be feasible in countries that have a well-organized infrastructure for inspection and law enforcement and a tradition of civic discipline. It may not be appropriate in many developing countries.

Removing pathogenic microorganisms by effective low-cost wastewater treatment can provide a high level of health protection for the public, as well as for farmers exposed to wastewater. Low-cost wastewater treatment prior to reuse is thus the control option of choice.

In light of the epidemiological evidence now available, it is recommended that the new guidelines for microbial quality of effluent used for unrestricted crop irrigation, recommended by the WHO/UNEP/UNDP/World Bank and adopted as the official WHO recommended guidelines (WHO 1989), of one or fewer helminth eggs per liter and a geometric mean of 1,000 fecal coli/100 ml, be adopted by countries interested in promoting wastewater reuse. These guideline qualities are attainable by well-designed stabilization pond treatment, and are thus feasible for developing countries. The consensus of the world public

health community today is that the new microbial guidelines provide a safe and rational basis on which countries can build a sound program of wastewater recycling and reuse, and reap the agricultural and environmental benefits.

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