Wastewater treatment and use in agriculture - FAO irrigation and drainage paper 47

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS Rome, 1992

M-56
ISBN 92-5-103135-5

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Preface

Wastewater Treatment and Use in Agriculture is presented as a guide to the use of treated effluent for irrigation and aquaculture. This document presents the latest views on health risks, environmental hazards and crop production potential associated with the use of treated wastewater. It draws on the WHO Guidelines for health protection measures considered appropriate under various conditions. It explains the basis for conventional wastewater treatment processes and introduces natural biological treatment systems as viable alternatives in developing countries, particularly in hot climate regions. Recharge of aquifers as a means of treatment and indirect use of wastewater is covered in some detail.

An important chapter of this Irrigation and Drainage Paper concentrates on wastewater irrigation and deals with water quality requirements for optimum crop production and potential impacts on soils and crops. Principles of irrigation drawn from Irrigation and Drainage Paper 29 (Rev. 1) are applied to the specific use of wastewater for crop irrigation. Site and crop selection are discussed and irrigation system selection for treated wastewater delivery is reviewed.

As a by-product of conventional wastewater treatment, sewage sludge is introduced as a potential agricultural resource in combination with wastewater irrigation. Sludge characteristics and treatment are summarized and the limitations of land application are discussed. Potential effects on soils and crops are considered and suggestions made for planting, grazing and harvesting constraints as well as environmental protection.

One chapter of the document is devoted to wastewater use in aquaculture. The concept of aquatic food chains is introduced and appropriate fish species and aquatic plants for wastewater aquaculture are reviewed. This chapter deals in some depth with the environmental conditions and fish management in aquaculture ponds and develops the health aspects of fish culture.

A brief discussion concerning the economic, institutional and policy issues of wastewater use in agriculture is presented. The need for national planning is stressed so that advantage can be taken of the resource potential of wastewater and sewage sludge. Alternatives for managing effluent use schemes are discussed in the context of strict control and long-term sustainability.

The final substantive chapter of the document reviews wastewater use experience in seven countries under different conditions. The success with advanced wastewater treatment in California is contrasted with the use of stabilization pond treatment in Jordan. Soil-aquifer treatment research in Arizona provides yet another alternative for wastewater treatment in effluent use schemes. Success with the combination of conventional wastewater treatment and human exposure control in Kuwait is presented as an example of the results of careful national planning for wastewater use in agriculture. Long experience in Mexico with crop restriction as the sole control measure points out the benefits and risks of this approach to wastewater irrigation. Finally, the long-term record of wastewater-fed aquaculture in Calcutta is reviewed.

A comprehensive list of references is provided at the end of the document.

This Irrigation and Drainage Paper is intended to provide guidance to national planners and decision-makers, agricultural and municipal managers, field engineers and scientists, health and agricultural field workers, wastewater treatment plant operators and farmers. Consequently, it covers a broad range of relevant material, some in considerable depth but some more superficially. It is meant to encourage the collection, treatment and use of wastewater in agriculture in a safe manner, with maximum advantage taken of this resource. Informal, unplanned and unorganized wastewater use is not recommended, nor is it considered adviseable from the health or agricultural points of view.

Acknowledgements

Before it was decided to proceed with this Irrigation and Drainage Paper in its present form, FAO commissioned a number of papers from different authors with a view to editing them into a suitable document. However, this approach did not achieve the range of coverage required and many of the original papers submitted were not used in the preparation of this document. Those that were used were edited to fit in with the needs of the Paper and are properly referenced in the text. FAO and the editor wish to acknowledge in particular the following contributors: Messrs. S.S. Al-Salem, T. Asano, H. Bouwer, H. Shuval and G. Tchobanoglous. A draft of this document was reviewed in an Expert Consultation on Safe and Efficient Irrigation with Treated Sewage Water organized by the FAO Regional Office for the Near East held in Rome in March 1991, and the comments and recommendations of the Expert Consultation have been incorporated into the text as appropriate.

The editor wishes to express his gratitude to Dr. A. Arar, former Senior Regional Officer of the Land and Water Development Division, FAO, for initiating the preparation of this document and his encouragement. Following Dr. Arar's retirement, Dr. A. Kandiah, Technical Officer of the Land and Water Development Division took on the responsibility for completion of the Paper and the editor is indebted to him for his encouragement and support. Dr. Kandiah also contributed significantly to Chapter 5.

The editor wishes to acknowledge the assistance of Ms. Alison Smith and Ms. Sandra Dodd, for without their dedication and hard work it would have been impossible to produce such a satisfactory document. Finally, acknowledgement is made to Ms. C.D. Redfern for preparing the material in final camera-ready copy to conform with the format of the FAO Irrigation and Drainage Paper series.

It is hoped that this document will make a positive contribution to the extension of wastewater use in agriculture and the improvement of wastewater use practices. The paper is dedicated to the agricultural workers and consumers of agricultural products who will benefit wherever wastewater might be used with greater control in the future.

1. Wastewater characteristics and effluent quality parameters

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1.1 Introduction

In many arid and semi-arid countries water is becoming an increasingly scarce resource and planners are forced to consider any sources of water which might be used economically and effectively to promote further development. At the same time, with population expanding at a high rate, the need for increased food production is apparent. The potential for irrigation to raise both agricultural productivity and the living standards of the rural poor has long been recognized. Irrigated agriculture occupies approximately 17 percent of the world's total arable land but the production from this land comprises about 34 percent of the world total. This potential is even more pronounced in arid areas, such as the Near East Region, where only 30 percent of the cultivated area is irrigated but it produces about 75 percent of the total agricultural production. In this same region, more than 50 percent of the food requirements are imported and the rate of increase in demand for food exceeds the rate of increase in agricultural production.

Whenever good quality water is scarce, water of marginal quality will have to be considered for use in agriculture. Although there is no universal definition of 'marginal quality' water, for all practical purposes it can be defined as water that possesses certain characteristics which have the potential to cause problems when it is used for an intended purpose. For example, brackish water is a marginal quality water for agricultural use because of its high dissolved salt content, and municipal wastewater is a marginal quality water because of the associated health hazards. From the viewpoint of irrigation, use of a 'marginal' quality water requires more complex management practices and more stringent monitoring procedures than when good quality water is used. This publication deals with agricultural use of municipal wastewater, which is primarily domestic sewage but possibly contains a proportion of industrial effluents discharged to public sewers.

Expansion of urban populations and increased coverage of domestic water supply and sewerage give rise to greater quantities of municipal wastewater. With the current emphasis on environmental health and water pollution issues, there is an increasing awareness of the need to dispose of these wastewaters safely and beneficially. Use of wastewater in agriculture could be an important consideration when its disposal is being planned in arid and semi-arid regions. However it should be realized that the quantity of wastewater available in most countries will account for only a small fraction of the total irrigation water requirements. Nevertheless, wastewater use will result in the conservation of higher quality water and its use for purposes other than irrigation. As the marginal cost of alternative supplies of good quality water will usually be higher in water-short areas, it makes good sense to incorporate agricultural reuse into water resources and land use planning.

Properly planned use of municipal wastewater alleviates surface water pollution problems and not only conserves valuable water resources but also takes advantage of the nutrients contained in sewage to grow crops. The availability of this additional water near population centres will increase the choice of crops which farmers can grow. The nitrogen and phosphorus content of sewage might reduce or eliminate the requirements for commercial fertilizers. It is advantageous to consider effluent reuse at the same time as wastewater collection, treatment and disposal are planned so that sewerage system design can be optimized in terms of effluent transport and treatment methods. The cost of transmission of effluent from inappropriately sited sewage treatment plants to distant agricultural land is usually prohibitive. Additionally, sewage treatment techniques for effluent discharge to surface waters may not always be appropriate for agricultural use of the effluent.

Many countries have included wastewater reuse as an important dimension of water resources planning. In the more arid areas of Australia and the USA wastewater is used in agriculture, releasing high quality water supplies for potable use. Some countries, for example the Hashemite Kingdom of Jordan and the Kingdom of Saudi Arabia, have a national policy to reuse all treated wastewater effluents and have already made considerable progress towards this end. In China, sewage use in agriculture has developed rapidly since 1958 and now over 1.33 million hectares are irrigated with sewage effluent. It is generally accepted that wastewater use in agriculture is justified on agronomic and economic grounds (see Example 1) but care must be taken to minimize adverse health and environmental impacts. The purpose of this document is to provide countries with guidelines for wastewater use in agriculture which will allow the practice to be adopted with complete health and environmental security.

EXAMPLE 1 - AGRONOMIC AND ECONOMIC BENEFITS OF WASTEWATER USE IN IRRIGATION

As an example, a city with a population of 500,000 and water consumption of 200 l/d per person would produce approximately 85,000 m^3/d (30 Mm^3/year) of wastewater, assuming 85% inflow to the public sewerage system. If treated wastewater effluent is used in carefully controlled irrigation at an application rate of 5000 m^3/ha.year, an area of some 6000 ha could be irrigated. In addition to the economic benefit of the water, the fertilizer value of the effluent is of importance. With typical concentrations of nutrients in treated wastewater effluent from conventional sewage treatment processes as follows:

Nitrogen (N) - 50 mg/l
Phosphorus(P) - 10 mg/l
Potassium (K) - 30 mg/l

and assuming an application rate of 5000 m^3/ha.year, the fertilizer contribution of the effluent would be:

N - 250 kg/ha. year
P - 50 kg/ha. year
K - 150 kg/ha. year

Thus, all of the nitrogen and much of the phosphorus and potassium normally required for agricultural crop production would be supplied by the effluent. In addition, other valuable micronutrients and the organic matter contained in the effluent will provide additional benefits.

1.2 Characteristics of wastewaters

Municipal wastewater is mainly comprised of water (99.9%) together with relatively small concentrations of suspended and dissolved organic and inorganic solids. Among the organic substances present in sewage are carbohydrates, lignin, fats, soaps, synthetic detergents, proteins and their decomposition products, as well as various natural and synthetic organic chemicals from the process industries. Table 1 shows the levels of the major constituents of strong, medium and weak domestic wastewaters. In arid and semi-arid countries, water use is often fairly low and sewage tends to be very strong, as indicated in Table 2 for Amman, Jordan, where water consumption is 90 l/d per person.

Table 1: MAJOR CONSTITUENTS OF TYPICAL DOMESTIC WASTEWATER

Constituent	Concentration, mg/l		
	Strong	Medium	Weak
Total solids	1200	700	350
Dissolved solids (TDS)[1]	850	500	250
Suspended solids	350	200	100
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6

Chloride[1]	100	50	30
Alkalinity (as $CaCO_3$)	200	100	50
Grease	150	100	50
BOD_5[2]	300	200	100

[1] The amounts of TDS and chloride should be increased by the concentrations of these constituents in the carriage water.

[2] BOD_5 is the biochemical oxygen demand at 20°C over 5 days and is a measure of the biodegradable organic matter in the wastewater.

Source: UN Department of Technical Cooperation for Development (1985)

Municipal wastewater also contains a variety of inorganic substances from domestic and industrial sources (see Table 3), including a number of potentially toxic elements such as arsenic, cadmium, chromium, copper, lead, mercury, zinc, etc. Even if toxic materials are not present in concentrations likely to affect humans, they might well be at phytotoxic levels, which would limit their agricultural use. However, from the point of view of health, a very important consideration in agricultural use of wastewater, the contaminants of greatest concern are the pathogenic micro- and macro-organisms.

Pathogenic viruses, bacteria, protozoa and helminths may be present in raw municipal wastewater at the levels indicated in Table 4 and will survive in the environment for long periods, as summarized in Table 5. Pathogenic bacteria will be present in wastewater at much lower levels than the coliform group of bacteria, which are much easier to identify and enumerate (as total coliforms/100ml). *Escherichia coli* are the most widely adopted indicator of faecal pollution and they can also be isolated and identified fairly simply, with their numbers usually being given in the form of faecal coliforms (FC)/100 ml of wastewater.

Table 2: AVERAGE COMPOSITION OF WASTEWATER IN AMMAN, JORDAN

Constituent	**Concentration mg/l**
Dissolved solids (TDS)	1170
Suspended solids	900
Nitrogen (as N)	150
Phosphorus (as P)	25
Alkalinity (as $CaCO_3$)	850

Sulphate (as SO_4)	90
BOD_5	770
COD[1]	1830
TOC[1]	220

[1] COD is chemical oxygen demand
[2] TOC is total organic carbon

Source: Al-Salem (1987)

Table 3: CHEMICAL COMPOSITION OF WASTEWATERS IN ALEXANDRIA AND GIZA, EGYPT

Constituent	**Alexandria**		**Giza**	
	Unit	**Concentration**	**Unit**	**Concentration**
EC	dS/m	3.10	dS/m	1.7
pH		7.80		7.1
SAR		9.30		2.8
Na_2^+	me/l	24.60	mg/l	205
Ca_2^+	me/l	1.50	mg/l	128
Mg	me/l	3.20	mg/l	96
K^+	me/l	1.80	mg/l	35
Cl^-	me/l	62.00	mg/l	320
SO_4^{2-}	me/l	35.00	mg/l	138
CO_3	me/l	1.10		
HCO_3^-	me/l	6.60		
NH_4^+	mg/l	2.50		
NO_3	mg/l	10.10		
P	mg/l	8.50		
Mn	mg/l	0.20	mg/l	0.7
Cu	mg/l	1.10	mg/l	0.4
Zn	mg/l	0.80	mg/l	1.4

Source: Abdel-Ghaffar *et al.* (1988)

Table 4: POSSIBLE LEVELS OF PATHOGENS IN WASTEWATER

Type of pathogen		Possible concentration per litre in municipal wastewater[1]
Viruses:	*Enteroviruses*[2]	5000
Bacteria:	Pathogenic *E. coli*[3]	?
	Salmonella spp.	7000
	Shigella spp.	7000
	Vibrio cholerae	1000
Protozoa:	*Entamoeba histolytica*	4500
Helminths:	*Ascaris Lumbricoides*	600
	Hookworms[4]	32
	Schistosoma mansoni	1
	Taenia saginata	10
	Trichuris trichiura	120

[?]Uncertain
[1]Based on 100 lpcd of municipal sewage and 90% inactivation of excreted pathogens
[2]Includes polio-, echo- and coxsackieviruses
[3]Includes enterotoxigenic, enteroinvasive and enteropathogenic *E. coli*
[4]*Anglostoma duedenale* and *Necator americanus*

Source: Feachem *et al.* (1983)

Table 5: SURVIVAL OF EXCRETED PATHOGENS (at 20-30°C)

Type of pathogen	Survival times in days			
	In faeces, nightsoil and sludge	In fresh water and sewage	In the soil	On crops
Viruses				
Enteroviruses	<100 (<20)	<120 (<50)	<100 (<20)	<60 (<15)*
Bacteria				
Faecal Coliforms	<90 (<50)	<60 (<30)	<70 (<20)	<30

				(<15)
Salmonella spp.	<60 (<30)	<60 (<30)	<70 (<20)	<30 (<15)
Shigella spp.	<30 (<10)	<30 (<10)	-	<10 (<5)
Vibrio cholerae	<30 (<5)	<30 (<10)	<20 (<10)	< 5 (<2)
Protozoa	<30 (<15)	<30 (<15)	<20 (<10)	<10 (< 2)
Entamoeba histolytica cysts	<30 (<15)	<30 (<15)	<20 (<10)	<10 (< 2)
Helminths	Many	Many	Many	<60 (<30)
Ascaris lunbricoides eggs	Months	Months	Months	

* Figures in brackets show the usual survival time.

Source: Feachem *et al.* (1983)

1.3 Quality parameters of importance in agricultural use of wastewaters

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1.3.1 Parameters of health significance

Organic chemicals usually exist in municipal wastewaters at very low concentrations and ingestion over prolonged periods would be necessary to produce detrimental effects on human health. This is not likely to occur with agricultural/aquacultural use of wastewater, unless cross-connections with potable supplies occur or agricultural workers are not properly instructed, and can normally be ignored. The principal health hazards associated with the chemical constituents of wastewaters, therefore, arise from the contamination of crops or groundwaters. Hillman (1988) has drawn attention to the particular concern attached to the cumulative poisons, principally heavy metals, and carcinogens, mainly organic chemicals. World Health Organization guidelines for drinking water quality (WHO 1984) include limit values for the organic and toxic substances given in Table 6, based on acceptable daily intakes (ADI). These can be adopted directly for groundwater protection purposes but, in view of the possible accumulation of certain toxic elements in plants (for example, cadmium and selenium) the intake of toxic materials through eating the crops irrigated with contaminated wastewater must be carefully assessed.

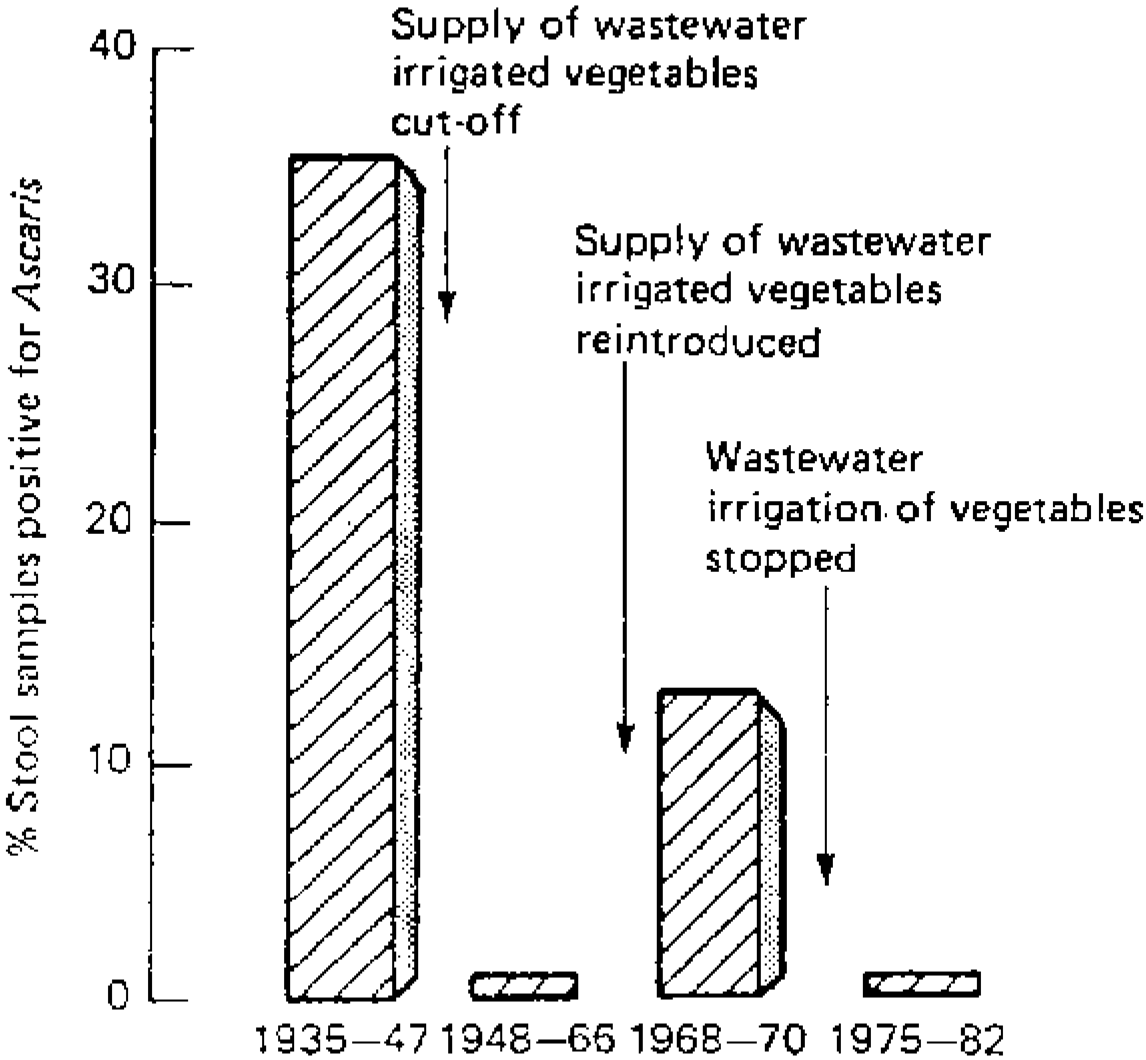
Table 6: ORGANIC AND INORGANIC CONSTITUENTS OF DRINKING WATER OF HEALTH SIGNIFICANCE

Organic	Inorganic
Aldrin and dieldrin	Arsenic
Benzene	Cadmium
Benzo-a-pyrene	Chromium
Carbon tetrachloride	Cyanide
Chlordane	Fluoride
Chloroform	Lead
2,4 D	Mercury
DDT	Nitrate
1,2 Dichloroethane	Selenium
1,1 Dichlorethylene	
Heptachlor and heptachlor epoxide	
Hexachlorobenzene	
Lindane	
Methoxychlor	
Pentachlorophenol	
Tetrachlorethylene	
2, 4, 6 Trichloroethylene	
Trichlorophenol	

Source: WHO (1984)

Pathogenic organisms give rise to the greatest health concern in agricultural use of wastewaters, yet few epidemological studies have established definitive adverse health impacts attributable to the practice. Shuval et al. (1985) reported on one of the earliest evidences connecting agricultural wastewater reuse with the occurrence of disease (Figure 1). It would appear that in areas of the world where helminthic diseases caused by *Ascaris* and *Trichuris* spp. are endemic in the population and where raw untreated sewage is used to irrigate salad crops and/or vegetables eaten uncooked, transmission of these infections is likely to occur through the consumption of such crops. A study in West Germany (reported by Shuval et al. 1986) provides additional evidence (Figure 2) to support this hypothesis and further evidence was also provided by Shuval et al. (1985; 1986) to show that cholera can be tranmitted through the same channel.

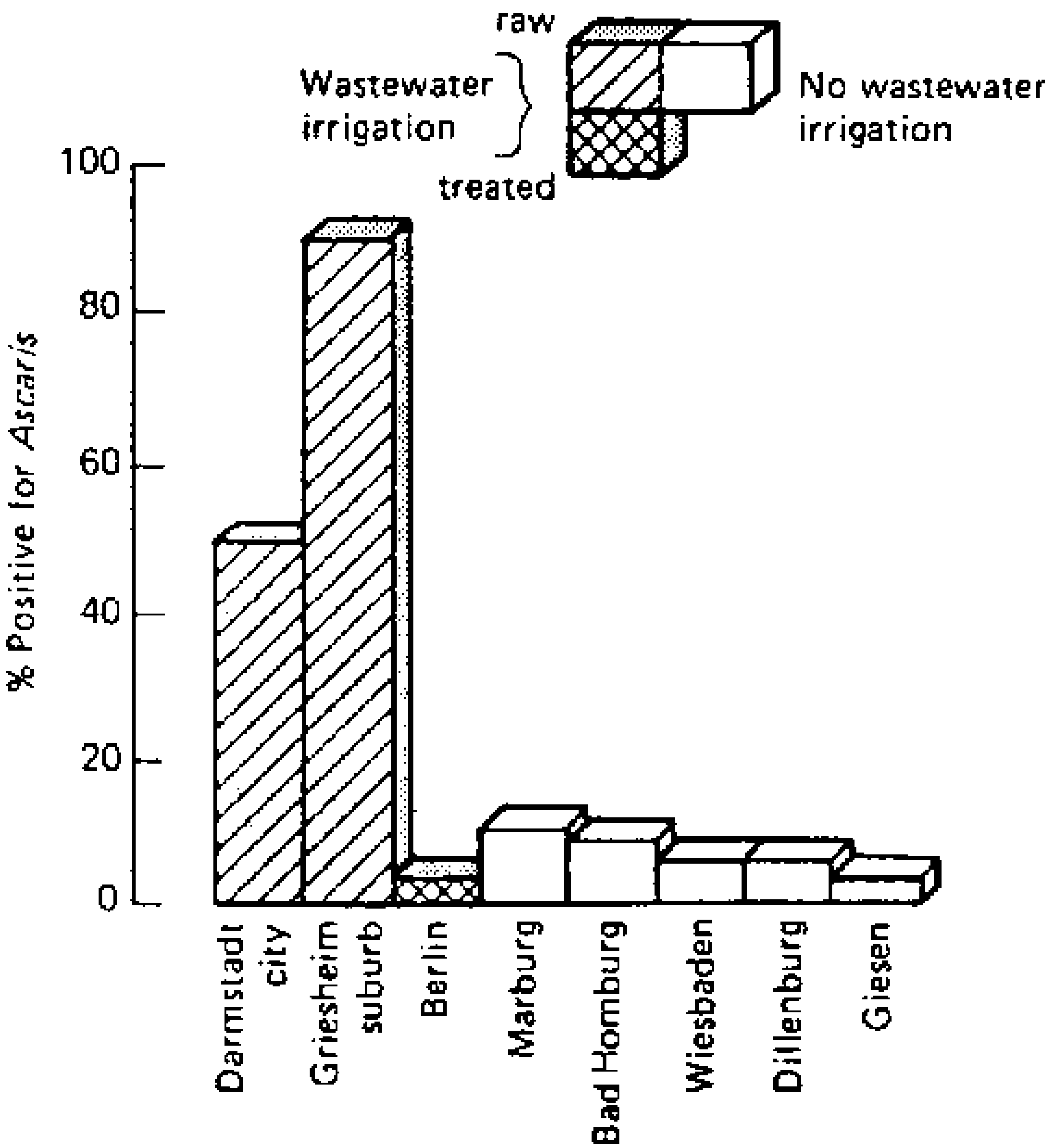
Figure 1: Prevalence of Ascaris-positive stool samples in West Jerusalem population during various periods, with and without supply of vegetables and salad crops irrigated with raw wastewater (Gunnerson, Shuval and Arlosoroff 1984)



There is only limited evidence indicating that beef tapeworm *(Taenia saginata)* can be transmitted to the population consuming the meat of cattle grazing on wastewater irrigated fields or fed crops from such fields. However, there is strong evidence from Melbourne, Australia and from Denmark (reported by Shuval *et al.* 1985) 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 (cysticerosis).

Indian studies, reported by Shuval et al. (1986), have shown that sewage farm workers exposed to raw wastewater in areas where *Ancylostoma* (hookworm) and *Ascaris* (nematode) infections are endemic have significantly excess levels of infection with these two parasites compared with other agricultural workers in similar occupations. Furthermore, the studies indicated that the intensity of the Ascaris infections (the number of worms infesting the intestinal tract of an individual) in the sample of sewage farm workers was very much greater than in the control sample. In the case of the hookworm infections, the severity of the health effects was a function of the worm load of individuals, which was found to be related to the degree of exposure and the length of time of exposure to the hookworm larvae. Sewage farm workers are also liable to become infected with cholera if practising irrigation with raw wastewater derived from an urban area in which a cholera epidemic is in progress (Shuval et al. 1985). Morbidity and serological studies on wastewater irrigation workers or wastewater treatment plant workers occupationally exposed to wastewater directly and to wastewater aerosols have not been able to demonstrate excess prevalence of viral diseases.

Figure 2: Wastewater irrigation of vegetables and *Ascaris* prevalence in Darmstadt and Berlin, compared with other cities in Germany not practising wastewater irrigation (Gunnerson, Shuval and Arlosoroff 1984)



No strong evidence has been adduced to suggest that population groups residing near wastewater treatment plants or wastewater irrigation sites are at greater risk from pathogens in aerosolized wastewater resulting from aeration processes or sprinkler irrigation. Shuval et al. (1986) suggest that the high levels of inmunity against most viruses endemic in the community essentially block environmental transmission by wastewater irrigation.

Finally, in respect of the health impact of use of wastewater in agriculture, Shuval et al. (1986) rank pathogenic agents in the order of priority shown in Example 2. They pointed out that negative health effects were only detected in association with the use of raw or poorly-settled wastewater, while inconclusive evidence suggested that appropriate wastewater treatment could provide a high level of health protection.

EXAMPLE 2 - RELATIVE HEALTH IMPACT OF PATHOGENIC AGENTS

High Risk (high incidence of excess infection)	Helminths (*Ancylostoma*, *Ascaris*, *Trichuris* and *Taenia*)
Medium Risk (low incidence of excess infection)	Enteric Bacteria *(Cholera vibrio, Salmonella typhosa, Shigella* and possibly others)
Low Risk (low incidence of excess infection)	Enteric viruses

The following microbiological parameters are particularly important from the health point of view:

i. <u>Indicator Organisms</u>

a. Coliforms and Faecal Coliforms. The Coliform group of bacteria comprises mainly species of the genera *Citrobacter, Enterobacter, Escherichia* and *Klebsiella* and includes Faecal Coliforms, of which *Escherichia coli* is the predominant species. Several of the Coliforms are able to grow outside of the intestine, especially in hot climates, hence their enumeration is unsuitable as a parameter for monitoring wastewater reuse systems. The Faecal Coliform test may also include some non-faecal organisms which can grow at 44°C, so the *E. coli* count is the most satisfactory indicator parameter for wastewater use in agriculture.

b. Faecal Streptococci. This group of organisms includes species mainly associated with animals *(Streptococcus bovis* and *S. equinus),* other species with a wider distribution (e.g. *S. faecalis* and *S. faecium,* which occur both in man and in other animals) as well as two biotypes *(S. faecalis var liquefaciens* and an a typical *S. faecalis* that hydrolyzes starch) which appear to be ubiquitous, occurring in both polluted and non-polluted environments. The enumeration of Faecal Streptococci in effluents is a simple routine procedure but has the following limitations: the possible presence of the non-faecal biotypes as part of the natural microflora on crops may detract from their utility in assessing the bacterial quality of wastewater irrigated crops; and the poorer survival of Faecal Streptococci at high than at low temperatures. Further studies are still warranted on the use of Faecal Streptococci as an indicator in tropical conditions and especially to compare survival with that of Salmonellae.

c. Clostridium perfringens. This bacterium is an exclusively faecal spore-forming anaerobe normally used to detect intermittent or previous pollution of water, due to the prolonged survival of its spores.

Although this extended survival is usually considered to be a disadvantage for normal purposes, it may prove to be very useful in wastewater reuse studies, as *Clostridium perfringens* may be found to have survival characteristics similar to those of viruses or even helminth eggs.

ii. Pathogens

The following pathogenic parameters can only be considered if suitable laboratory facilities and suitably trained staff are available:

a. *Salmonella* spp. Several species of *Salmonellae* may be present in raw sewage from an urban community in a tropical developing country, including *S. typhi* (causative agent for typhoid) and many others. It is estimated (Doran et al. 1977) that a count of 7000 *Salmonellae*/litre is typical in a tropical urban sewage with similar numbers of Shigellae, and perhaps 1000 *Vibrio cholera*/litre. Both *Shigella* spp and *V. cholera* are more rapidly killed in the environment, so if removal of *Salmonellae* can be achieved, then the majority of other bacterial pathogens will also have been removed.

b. *Enteroviruses.* May give rise to severe diseases, such as Poliomyelitis and Meningitis, or to a range of minor illnesses such as respiratory infections. Although there is no strong epidemiological evidence for the spread of these diseases via sewage irrigation systems, there is some risk and it is desirable to know to what extent viruses are removed by existing and new treatment processes, especially under tropical conditions. Virus counts can only be undertaken in a dedicated laboratory, as the cell culture techniques required are very susceptible to bacterial and fungal contamination.

c. *Rotaviruses.* These viruses are known to cause gastro-intestinal problems and, though usually present in lower numbers than *enteroviruses* in sewage, they are known to be more persistent, so it is necessary to establish their survival characteristics relative to *enteroviruses* and relative to the indicator organisms in wastewaters. It has been claimed that the removal of viruses in wastewater treatment occurs in parallel with the removal of suspended solids, as most virus particles are solids-associated. Hence, the measurement of suspended solids in treated effluents should be carried out as a matter of routine.

d. Intestinal Nematodes. It is known that nematode infections, in particular from the roundworm *Ascaris lumbricoides,* can be spread by effluent reuse practices. The eggs of *A. lumbricoides* are fairly large (45-70 μm x 35-50 μm) and several techniques for enumeration of nematodes have been developed (WHO 1989).

1.3.2 Parameters of agricultural significance

The quality of irrigation water is of particular importance in arid zones where extremes of temperature and low relative humidity result in high rates of evaporation, with consequent deposition of salt which tends to accumulate in the soil profile. The physical and mechanical properties of the soil, such as dispersion of particles, stability of aggregates, soil structure and permeability, are very sensitive to the type of exchangeable ions present in irrigation water. Thus, when effluent use is being planned, several factors related to soil properties must be taken into consideration. A thorough treatise on the subject prepared by Ayers and Westcot is contained in the FAO Irrigation and Drainage Paper No 29 Rev. 1 (FAO 1985).

Another aspect of agricultural concern is the effect of dissolved solids (TDS) in the irrigation water on the growth of plants. Dissolved salts increase the osmotic potential of soil water and an increase in osmotic pressure of the soil solution increases the amount of energy which plants must expend to take up water from the soil. As a result, respiration is increased and the growth and yield of most plants decline progressively as osmotic pressure increases. Although most plants respond to salinity as a function of the total osmotic potential of soil water, some plants are susceptible to specific ion toxicity.

Many of the ions which are harmless or even beneficial at relatively low concentrations may become toxic to plants at high concentration, either through direct interference with metabolic processes or through indirect effects on other nutrients, which might be rendered inaccessible. Morishita (1985) has reported that irrigation with nitrogen-enriched polluted water can supply a considerable excess of nutrient nitrogen to growing rice plants and can result in a significant yield loss of rice through lodging, failure to ripen and increased susceptibility to pests and diseases as a result of over-luxuriant growth. He further reported that non-polluted soil, having around 0.4 and 0.5 ppm cadmium, may produce about 0.08 ppm Cd in brown rice, while only a little increase up to 0.82, 1.25 or 2.1 ppm of soil Cd has the potential to produce heavily polluted brown rice with 1.0 ppm Cd.

Important agricultural water quality parameters include a number of specific properties of water that are relevant in relation to the yield and quality crops, maintenance of soil productivity and protection of the environment. These parameters mainly consist of certain physical and chemical characteristics of the water. Table 7 presents a list of some of the important physical and chemical characteristics that are used in the evaluation of agricultural water quality. The primary wastewater quality parameters of importance from an agricultural viewpoint are:

Table 7: PARAMETERS USED IN THE EVALUATION OF AGRICULTURAL WATER QUALITY

Parameters	Symbol	Unit
Physical		
Total dissolved solids	TDS	mg/l
Electrical conductivity	Ec_w	dS/m[1]
Temperature	T	°C
Colour/Turbidity		NTU/JTU[2]
Hardness		mg equiv. $CaCO_3$/l
Sediments		g/l
Chemical		
Acidity/Basicity	pH	
Type and concentration of anions and cations:		
Calcium	Ca^{++}	me/l[3]
Magnesium	Mg^{++}	me/l
Sodium	Na^{+}	me/l
Carbonate	CO_3^{--}	me/l
Bicarbonate	HCO_3^{-}	me/l
Chloride	Cl_{-}	me/l
Sulphate	SO_4^{--}	me/l
Sodium adsorption ratio	SAR	
Boron	B	mg/l[4]
Trace metals		mg/l
Heavy metals		mg/l
Nitrate-Nitrogen	NO_3-N	mg/l
Phosphate Phosphorus	PO_4-P	mg/l
Potassium	K	mg/l

[1] dS/m = deciSiemen/metre in SI Units (equivalent to 1 mmho/cm)

[2] NTU/JTU = Nephelometric Turbidity Units/Jackson Turbidity Units

[3] me/l = milliequivalent per litre
[4] mg/l == milligrams per litre = parts per million (ppm); also,
mg/l ~ 640 x EC in dS/m

Source: Kandiah (1990a)

i. Total Salt Concentration

Total salt concentration (for all practical purposes, the total dissolved solids) is one of the most important agricultural water quality parameters. This is because the salinity of the soil water is related to, and often determined by, the salinity of the irrigation water. Accordingly, plant growth, crop yield and quality of produce are affected by the total dissolved salts in the irrigation water. Equally, the rate of accumulation of salts in the soil, or soil salinization, is also directly affected by the salinity of the irrigation water. Total salt concentration is expressed in milligrams per litre (mg/l) or parts per million (ppm).

ii. Electrical Conductivity

Electrical conductivity is widely used to indicate the total ionized constituents of water. It is directly related to the sum of the cations (or anions), as determined chemically and is closely correlated, in general, with the total salt concentration. Electrical conductivity is a rapid and reasonably precise determination and values are always expressed at a standard temperature of 25°C to enable comparison of readings taken under varying climatic conditions. It should be noted that the electrical conductivity of solutions increases approximately 2 percent per °C increase in temperature. In this publication, the symbol EC_w, is used to represent the electrical conductivity of irrigation water and the symbol EC_e is used to designate the electrical conductivity of the soil saturation extract. The unit of electrical conductivity is deciSiemen per metre (dS/m).

iii. Sodium Adsorption Ratio

Sodium is an unique cation because of its effect on soil. When present in the soil in exchangeable form, it causes adverse physico-chemical changes in the soil, particularly to soil structure. It has the ability to disperse soil, when present above a certain threshold value, relative to the concentration of total dissolved salts. Dispersion of soils results in reduced infiltration rates of water and air into the soil. When dried, dispersed soil forms crusts which are hard to till and interfere with germination and seedling emergence. Irrigation water could be a source of excess sodium in the soil solution and hence it should be evaluated for this hazard.

The most reliable index of the sodium hazard of irrigation water is the sodium adsorption ration, SAR. The sodium adsorption ratio is defined by the formula:

(1)

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

where the ionic concentrations are expressed in me/l.

A nomogram for determining the SAR value of irrigation water is presented in Figure 3 (US Salinity Laboratory 1954). An exchangeable sodium percentage (ESP) scale is included in the nomogram to estimate the ESP value of the soil that is at equilibrium with the irrigation water. Using the nomogram, it is possible to estimate the ESP value of a soil that is at equilibrium with irrigation water of a known SAR value. Under field conditions, the actual ESP may be slightly higher than the estimated equilibrium value because the total salt concentration of the soil solution is increased by evaporation and plant trans-piration, which results in a higher SAR and a corres-pondingly higher ESP value.

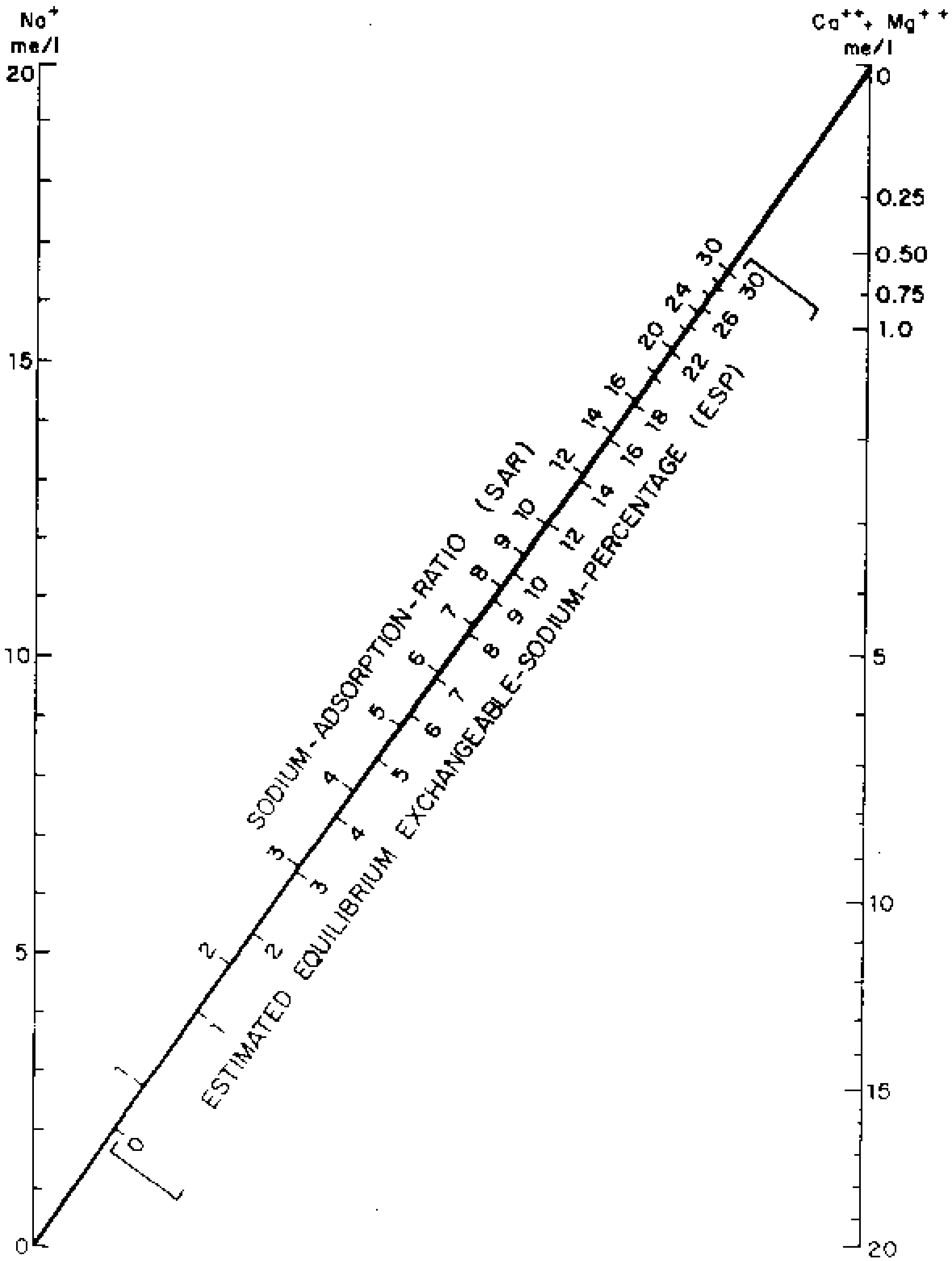
It should also be noted that the SAR from Eq 1 does not take into account changes in calcium ion concentration in the soil water due to changes in solubility of calcium resulting from precipitation or dissolution during or following an irrigation. However, the SAR calculated according to Eq 1 is considered an acceptable evaluation procedure for most of the irrigation waters encountered in agriculture. If significant precipitation or dissolution of calcium due to the effect of carbon dioxide (CO_2), bicarbonate (HCO_3^-) and total salinity (EC_w) is suspected, an alternative procedure for calculating an Adjusted Sodium Adsorption Ratio, SAR_{adj}. can be used. The details of this procedure are reported by Ayers and Westcot (FAO (1985).

iv. Toxic Ions

Irrigation water that contains certain ions at concentrations above threshold values can cause plant toxicity problems. Toxicity normally results in impaired growth, reduced yield, changes in the morphology of the plant and even its death. The degree of damage depends on the crop, its stage of growth, the concentration of the toxic ion, climate and soil conditions.

The most common phytotoxic ions that may be present in municipal sewage and treated effluents in concentrations such as to cause toxicity are: boron (B), chloride (Cl) and sodium (Na). Hence, the concentration of these ions will have to be determined to assess the suitability of waste-water quality for use in agriculture.

Figure 3: A nomogram for determining sodium adsorption ratio (US Salinity Laboratory 1954)



v. Trace Elements and Heavy Metals

A number of elements are normally present in relatively low concentrations, usually less than a few mg/l, in conventional irrigation waters and are called trace elements. They are not normally included in routine analysis of regular irrigation water, but attention should be paid to them when using sewage effluents, particularly if contamination with industrial wastewater discharges is suspected. These include Aluminium (A1), Beryllium (Be), Cobalt (Co), Fluoride (F), Iron (Fe), Lithium (Li), Manganese (Mn), Molybdenum (Mo), Selenium (Se), Tin (Sn), Titanium (Ti), Tungsten (W) and Vanadium (V). Heavy metals are a special group of trace elements which have been shown to create definite health hazards when taken up by plants. Under this group are included, Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg) and Zinc (Zn). These are called heavy metals because in their metallic form, their densities are greater than 4g/cc.

vi. pH

pH is an indicator of the acidity or basicity of water but is seldom a problem by itself. The normal pH range for irrigation water is from 6.5 to 8.4; pH values outside this range are a good warning that the water is abnormal in quality. Normally, pH is a routine measurement in irrigation water quality assessment.

2. Wastewater quality guidelines for agricultural use

2.1 Introduction

Health protection measures which can be applied in agricultural use of wastewater include the following, either singly or in combination:

- Wastewater treatment
- Crop restriction
- Control of wastewater application
- Human exposure control and promotion of hygiene

In the past, wastewater treatment has been widely adopted as the major control measure in controlled effluent use schemes, with crop restriction being used in a few notable cases. A more integrated approach to the planning of wastewater use in agriculture will take advantage of the optimal combination of the health protection measures available and allow for any soil/plant contraints in arriving at an economic system suited to the local sociocultural and institutional conditions.

A WHO (1989) Technical Report on 'Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture' discusses the integration of the various measures available to achieve effective health protection. Limitations of the administrative or legal systems in some countries will make some of these approaches difficult to apply, whereas shortage of skilled technical staff in other countries will place doubt upon reliance on wastewater treatment as the only control mechanism. To achieve greater flexibility in the use of wastewater application as a health protection measure, irrigation systems must be developed to be capable of delivering low quality wastewater and restrictions on irrigation technique and crops irrigated must become more common.

2.2 Human exposure control

Of the health protection measures mentioned above, only human exposure control is not dealt with in greater depth in later chapters of the Manual. The objective with this approach is to prevent the population groups at risk from coming into direct contact with pathogens in the wastewater or to prevent any contact with the pathogens leading to disease. Four groups are at risk in agricultural use of wastewater:

- agricultural workers and their families
- crop handlers
- consumers of crops, meat and milk
- those living near the areas irrigated with wastewater

and different methods of exposure control might be applied for each group.

Control measures aimed at protecting agricultural field workers and crop handlers include the provision (and insistence on the wearing) of protective clothing, the maintenance of high levels of hygiene and immunization against (or chemotherapeutic control of) selected infections. Examples of these measures are given in the WHO (1989) Technical Report mentioned. Risks to consumers can be reduced through cooking the agricultural produce before consumption and by high standards of food hygiene, which should be emphasized in the health education associated with wastewater use schemes. Local residents should be kept fully informed on the use of wastewater in agriculture so that they, and their children, can avoid these areas. Although there is no evidence to suggest that those living near wastewater-irrigated fields are at significant risk, sprinklers should not be used within 100 m of houses or roads.

Special care must always be taken in wastewater use schemes to ensure that agricultural workers or the public do not use wastewater for drinking or domestic purposes by accident or for lack of an alternative. All wastewater channels, pipes and outlets must be clearly marked and preferably painted a characteristic colour. Wherever possible, outlet fittings should be designed/selected so as to prevent misuse.

2.3 Effluent quality guidelines for health protection

Following several meetings of environmental specialists and epidemiologists, a WHO Scientific Group on Health Aspects of Use of Treated Wastewater for Agriculture and Aquaculture arrived at the microbiological quality quidelines for wastewater use in agriculture shown in Table 8. These guidelines were based on the consensus view that the actual risk associated with irrigation with treated wastewater is much lower than previously thought and that earlier standards and guidelines for effluent quality, such as the WHO (1973) recommended standards, were unjustifiably restrictive, particularly in respect of bacterial pathogens.

Table 8: RECOMMENDED MICROBIOLOGICAL QUALITY GUIDELINES FOR WASTEWATER USE IN AGRICULTURE[a]

Category	Reuse condition	Exposed group	Intestinal nematodes[b] (arithmetic mean no. of eggs per litre[c]	Faecal 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 parksd[d]	Workers, consumers, public	≤ 1	≤ 1000[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 faecal 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

[a] In specific cases, local epidemiological, socio-cultural and environmental factors should be taken into account, and the guidelines modified accordingly.

[b] *Ascaris* and *Trichuris* species and hookworms.

[c] During the irrigation period.

[d] A more stringent guideline (<200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.

[e] 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)

The new guidelines are stricter than previous standards in respect of the requirement to reduce the numbers of helminth eggs *(Ascaris* and *Trichuris* species and hookworms) in effluents for Category A and B conditions to a level of not more than one per litre. Also implied by the guidelines is the expectation that protozoan cysts will be reduced to the same level as helminth eggs. Although no bacterial pathogen limit is imposed for Category C conditions where farm workers are the only exposed population, on the premise that there is little or no evidence indicating a risk to such workers from bacteria, some degree of reduction in bacterial concentration is recommended for any effluent use situation.

The WHO Scientific Group considered the new approach to effluent quality would increase public health protection for the large numbers of people who were now being infected in areas where crops eaten uncooked are being irrigated in an unregulated, and often illegal, manner with raw wastewater. It was felt that the recommended guidelines, if adopted, would achieve this improvement and set targets which are both technologically and economically feasible. However, the need to interpret the guidelines carefully and modify them in the light of local epidemiological, sociocultural and environmental factors was also pointed out.

The effluent quality guidelines in Table 8 are intended as design goals for wastewater treatment systems, rather than standards requiring routine testing of effluents. Wastewater treatment processes achieving the recommended microbiological quality consistently as a result of their intrinsic design characteristics, rather than by high standards operational control, are to be preferred. In addition to the microbiological quality requirements of treated effluents used in agriculture, attention must also be given to those quality parameters of importance in respect of groundwater contamination and of soil structure and crop productivity.

Although heavy metals may not be a problem with purely domestic sewage effluents, all these elements are potentially present in municipal wastewater.

2.4 Water quality guidelines for maximum crop production

Traditionally, irrigation water is grouped into various quality classes in order to guide the user to the potential advantages as well as problems associated with its use and to achieve optimum crop production. The water quality classifications are only indicative guidelines and their application will have to be adjusted to conditions that prevail in the field. This is so because the conditions of water use in irrigation are very complex and difficult to predict. The suitability of water for irrigation will greatly depend on the climatic conditions, physical and chemical properties of the soil, the salt tolerance of the crop grown and the management practices. Thus, classification of water for irrigation will always be general in nature and applicable under average use conditions.

Many schemes of classification for irrigation water have been proposed. Ayers and Westcot (FAO 1985) classified irrigation water into three groups based on salinity, sodicity, toxicity and miscellaneous hazards, as shown in Table 9. These general water quality classification guidelines help to identify potential crop production problems associated with the use of conventional water sources. The guidelines are equally applicable to evaluate wastewaters for irrigation purposes in terms of their chemical constituents, such as dissolved salts, relative sodium content and toxic ions. Several basic assumptions were used to define the range of values in the guidelines and more detailed information on this is reported by Ayers and Westcot (FAO 1985).

The effect of sodium ions in irrigation water in reducing infiltration rate and soil permeability is dependent on the sodium ion concentration relative to the concentration of calcium and magnesium ions (as indicated by SAR) and the total salt concentration, as shown in the guidelines. It is graphically illustrated in Figure 4 which clearly indicates that, for a given SAR value, an increase in total salt concentration is likely to increase soil permeability and, for a given total salt concentration, an increase in SAR will decrease soil permeability. This illustrates the fact that soil permeability (including infiltration rate and surface crusting) hazards caused by sodium in irrigation water cannot be predicted independently of the dissolved salt content of the irrigation water or that of the surface layer of the soil.

Table 9: GUIDELINES FOR INTERPRETATION OF WATER QUALITY FOR IRRIGATION

Potential irrigation problem	Units	Degree of restriction on use		
		None	**Slight to moderate**	**Severe**
Salinity				
Ec_w[1]	dS/m	< 0.7	0.7 - 3.0	> 3.0
or				
TDS	mg/l	< 450	450 - 2000	> 2000
Infiltration				
SAR[2] = 0 - 3 and EC_w		> 0.7	0.7 - 0.2	< 0.2
3 -6		> 1.2	1.2 - 0.3	< 0.3
6-12		> 1.9	1.9 - 0.5	< 0.5
12-20		> 2.9	2.9 - 1.3	< 1.3
20-40		> 5.0	5.0 - 2.9	< 2.9
Specific ion toxicity				
Sodium (Na)				

Surface irrigation	SAR	< 3	3 - 9	> 9
Sprinkler irrigation	me/l	< 3	> 3	
Chloride (Cl)				
Surface irrigation	me/l	< 4	4 - 10	> 10
Sprinkler irrigation	m^3/l	< 3	> 3	
Boron (B)	mg/l	< 0.7	0.7 - 3.0	> 3.0
Trace Elements (see Table 10)				
Miscellaneous effects				
Nitrogen (NO_3-N)[3]	mg/l	< 5	5 - 30	> 30
Bicarbonate (HCO_3)	me/l	< 1.5	1.5 - 8.5	> 8.5
pH	Normal range 6.5-8			

[1] EC_w means electrical conductivity in deciSiemens per metre at 25°C
[2] SAR means sodium adsorption ratio
[3] NO_3-N means nitrate nitrogen reported in terms of elemental nitrogen

Source: FAO(1985)

Municipal wastewater effluents may contain a number of toxic elements, including heavy metals, because under practical conditions wastes from many small and informal industrial sites are directly discharged into the common sewer system. These toxic elements are normally present in small amounts and, hence, they are called trace elements. Some of them may be removed during the treatment process but others will persist and could present phytotoxic problems. Thus, municipal wastewater effluents should be checked for trace element toxicity hazards, particularly when trace element contamination is suspected. Table 10 presents phytotoxic threshold levels of some selected trace elements.

Table 10: THRESHOLD LEVELS OF TRACE ELEMENTS FOR CROP PRODUCTION

	Element	**Recommended maximum concentration (mg/l)**	**Remarks**
Al	(aluminium)	5.0	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
As	(arsenic)	0.10	Toxicity to plants varies widely, ranging from 12 mg/l

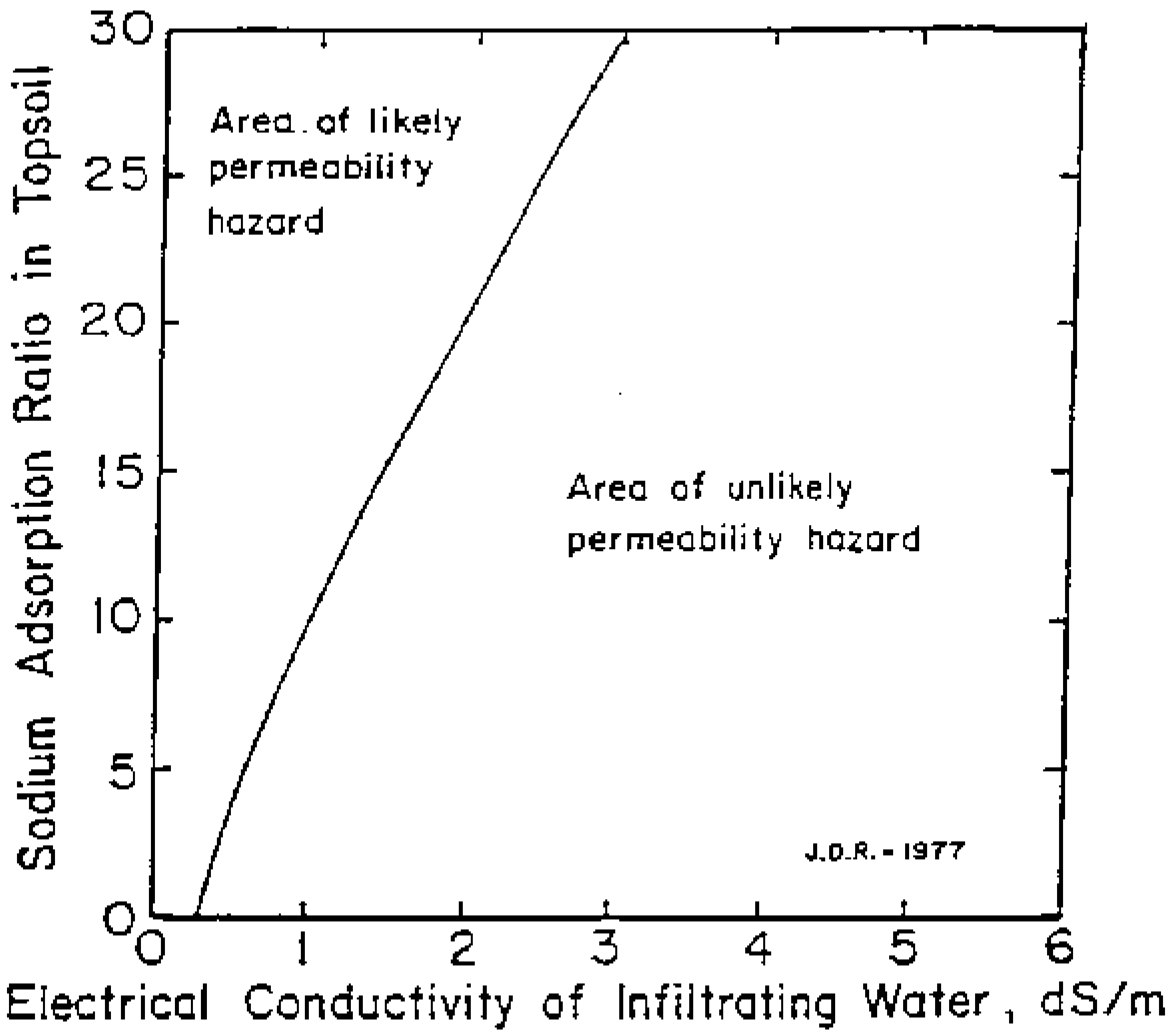
			for Sudan grass to less than 0.05 mg/l for rice.
Be	(beryllium)	0.10	Toxicity to plants varies widely, ranging from 5 mg/l for kale to 0.5 mg/l for bush beans.
Cd	(cadmium)	0.01	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/l in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co	(cobalt)	0.05	Toxic to tomato plants at 0.1 mg/l in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr	(chromium)	0.10	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on its toxicity to plants.
Cu	(copper)	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/l in nutrient solutions.
F	(fluoride)	1.0	Inactivated by neutral and alkaline soils.
Fe	(iron)	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Li	(lithium)	2.5	Tolerated by most crops up to 5 mg/l; mobile in soil. Toxic to citrus at low concentrations (<0.075 mg/l). Acts similarly to boron.
Mn	(manganese)	0.20	Toxic to a number of crops at a few-tenths to a few mg/l, but usually only in acid soils.
Mo	(molybdenum)	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Ni	(nickel)	0.20	Toxic to a number of plants at 0.5 mg/l to 1.0 mg/l; reduced toxicity at neutral or alkaline pH.
Pd	(lead)	5.0	Can inhibit plant cell growth at very high concentrations.
Se	(selenium)	0.02	Toxic to plants at concentrations as low as 0.025 mg/l and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. As essential element to animals but in very low concentrations.
Sn	(tin)		
Ti	(titanium)	-	Effectively excluded by plants; specific tolerance unknown.

W	(tungsten)		
C	(vanadium)	0.10	Toxic to many plants at relatively low concentrations.
Zn	(zinc)	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine textured or organic soils.

[1] The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10 000 m^3 per hectare per year). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates less than 10 000 m^3 per hectare per year. The values given are for water used on a continuous basis at one site.

Source: Adapted from National Academy of Sciences (1972) and Pratt (1972).

Figure 4: Threshold values of sodium adsorption ratio and total salt concentration on soil permeability hazard (Rhoades 1982)



2.5 Health protection measures in aquacultural use of wastewater

The measures which can be taken to protect health in aquacultural use of wastewater are the same as in agricultural use, namely wastewater treatment, crop restriction, control of wastewater application and human exposure control and promotion of hygiene. For the protection of workers in aquaculture ponds, the quality of the water is of paramount importance, as it is in respect of the contamination of fish or plants grown in excreta-fertilized or wastewater ponds. Transmission of pathogens can occur through persons handling and preparing contaminated fish or aquatic plants, which make human exposure control and hygiene important features of aquaculture programmes. Both the treatment applied to excreta, nightsoil or wastewater before introduction to an aquaculture pond and the rate of waste application will have an effect on the quality of water in the pond. In the past, these factors have not been controlled for health reasons but rather so as to ensure that a pond is not overloaded organically or chemically to the point where it will not support fish life or be suitable for the growth of aquatic plants. Reliance has been placed primarily on minimizing the risk of pathogen transmission through consumption by thorough cooking of the products. This has not always been satisfactory and, where the pond products are eaten uncooked, no health protection is provided. In some aquacultural practices, for example in rural Indonesia, depuration techniques are used in attempting to decontaminate fish in the period immediately preceding harvesting.

2.5.1 Special concerns in aquacultural use of human wastes

A number of human excreted helminthic pathogens, when released to aquaculture ponds, can involve fish or aquatic plants as intermediate hosts. Strauss (1985) has listed the following trematode infections as being capable of transmission in this way:

Clonorchis
Heterophys
Opistorchis
Metagonimus
Diphyllobothrium

However, he indicated that only clonorchiasis (liver fluke) and the closely related opistorchiasis have been transmitted through fish grown in excrete-fertilized or wastewater (freshwater) ponds. The first phase of development of these pathogens occurs in specific snails or copepods (minute crustaceans), with fish acting as a second intermediate host. These helminthic infections have significant public health importance in Asia, where fish are sometimes eaten raw. Strauss also pointed out that the helminthic pathogens *Fasciola* (sheep and cattle liver flukes) and *Fasciolopsis* (giant intestinal fluke) have the same pattern of life cycle but depend on aquatic plants, such as water chestnut, water cress and water bamboo, as secondary intermediate hosts onto which free-swimming cercariae become attached and where they encyst.

Aquatic snails also serve as intermediate hosts for the trematode-genus *Schistosoma* which is the causative agent of schistosomiasis (bilharzia). Transmission can occur when workers wade into aquaculture ponds in which infected snails are present and the larval schistosome penetrates the skin. This occupational hazard exists only where this disease is endemic and where snail hosts are present in aquaculture ponds. Schistosome infection, particularly *Schistosoma japonicum,* has been identified in excreta-fertilized fish ponds.

Fish grown in excreta-fertilized or wastewater ponds may also become contaminated with bacteria and viruses and serve as a potential source of transmission of infection if the fish are eaten raw or undercooked. Pathogenic bacteria and viruses may be passively carried on the scales of fish or in their gills, intraperitoneal fluid, digestive tract or muscle. Strauss (1985) reviewed the limited literature on excreted bacteria and virus survival in fish and concluded that:

- invasion of fish muscle by bacteria is likely to occur if the concentrations of faecal coliforms and salmonellae in the pond are greater than 10^4 and 10^5 per 100 ml, respectively;

- the potential for muscle invasion increases with the duration of exposure of the fish to contaminated pond water;

- little accumulation of enteric microorganisms and pathogens on, or penetration into, edible fish tissue occurs when the faecal coliform concentration in the pond water is below 10^3 per 100 ml;

- even at lower pond water contamination levels, high pathogen concentrations might be present in the digestive tract and the intraperitoneal fluid of the fish;

- pathogen invasion of the spleen, kidney and liver has been observed.

2.5.2 Quality guidelines for health protection in using human wastes for aquaculture

Because only limited experimental and field data on the health effects of sewage-fertilized aquaculture are available, the WHO Scientific Group on Health Aspects of Use of Treated Wastewater for Agriculture and Aquaculture could suggest only a tentative bacterial guideline for the quality of aquaculture pond water. The tentative bacterial guideline suggested is a geometric mean number of faecal coliforms of $\leq 10^3$ per 100 ml (WHO, 1989). Furthermore, in view of the dilution of wastewater which normally occurs in aquaculture ponds, this ambient bacterial indicator concentration could be achieved, the Scientific Group suggested, by treating wastewater fed to ponds to a level of 10^3-10^4 faecal coliforms / 100 ml. Such a guideline should ensure that invasion of fish muscle is prevented but pathogens might accumulate in the digestive tract and intraperitoneal fluid of fish. This might then create a health risk, through cross-contamination of fish flesh or other edible parts and transmission to consumers, if standards of hygiene in fish preparation are inadequate. High standards of hygiene during fish handling and, especially, gutting are necessary and cooking of fish is an important health safeguard. Similar considerations apply to the preparation and cooking of aquatic plants.

Table 11: BACTERIOLOGICAL QUALITY OF FISH FROM EXCRETA-REUSE SYSTEMS

Total aerobic bacterial concentration in fish muscle tissue, bacteria/g	**Fish quality**
0- 10	Very good
10- 30	Medium
> 50	Unacceptable

Source: Buras *et al.* (1987)

Buras et al. (1985, 1987) have questioned the value of faecal coliforms as bacterial indicators for fish muscle because, in their studies, they were not always detected, whereas total aerobic bacteria (standard plate count) were. They proposed that total aerobic bacteria should be the indicators on the grounds that, if they were detectable in the fish, there was a chance that pathogenic bacteria would also be present. Consequently, the bacteriological standards for fish raised in excreta-fertilized and wastewater ponds indicated in Table 11 were recommended by Buras et al. (1987). A more recent State-of-the-Art-Review of Reuse of Human Excreta in Aquaculture (Edwards, 1990) discussed this issue and suggested that it was unlikely that fish will be of an unacceptable bacteriological quality when raised in excreta-fed ponds that are well-managed from an aquacultural point of view to produce good fish growth. That is, fish ponds loaded with excreta at a level which leads to the development of a relatively large biomass of phytoplankton, serving as natural food for the fish, but with adequate levels of dissolved oxygen maintained in the water, for the fish, should produce fish with acceptable bacteriological quality.

Transmission of the helminthic infections clonorchiasis and fasciolopsiasis occurs only in certain areas of Asia and can be prevented only by ensuring that no trematode eggs enter the pond or by snail control. Similar considerations apply to the control of schistosomiasis in areas where this disease is endemic. The Scientific Group (WHO, 1989) recommended an appropriate helminth quality guideline for all aquacultural use of wastewater as the absence of viable trematode eggs.

3. Wastewater treatment

3.1 The problem

The principal objective of wastewater treatment is generally to allow human and industrial effluents to be disposed of without danger to human health or unacceptable damage to the natural environment. Irrigation with wastewater is both disposal and utilization and indeed is an effective form of wastewater disposal (as in slow-rate land treatment). However, some degree of treatment must normally be provided to raw municipal wastewater before it can be used for agricultural or landscape irrigation or for aquaculture. The quality of treated effluent used in agriculture has a great influence on the operation and performance of the wastewater-soil-plant or aquaculture system. In the case of irrigation, the required quality of effluent will depend on the crop or crops to be irrigated, the soil conditions and the system of effluent distribution adopted. Through crop restriction and selection of irrigation systems which minimize health risk, the degree of pre-application wastewater treatment can be reduced. A similar approach is not feasible in aquaculture systems and more reliance will have to be placed on control through wastewater treatment.

The most appropriate wastewater treatment to be applied before effluent use in agriculture is that which will produce an effluent meeting the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements (Arar 1988). Adopting as low a level of treatment as possible is especially desirable in developing countries, not only from the point of view of cost but also in acknowledgement of the difficulty of operating complex systems reliably. In many locations it will be better to design the reuse system to accept a low-grade of effluent rather than to rely on advanced treatment processes producing a reclaimed effluent which continuously meets a stringent quality standard.

Nevertheless, there are locations where a higher-grade effluent will be necessary and it is essential that information on the performance of a wide range of wastewater treatment technology should be available. The design of wastewater treatment plants is usually based on the need to reduce organic and suspended solids loads to limit pollution of the environment. Pathogen removal has very rarely been considered an objective but, for reuse of effluents in agriculture, this must now be of primary concern and processes should be selected and designed accordingly (Hillman 1988). Treatment to remove wastewater constituents that may be toxic or harmful to crops, aquatic plants (macrophytes) and fish is technically possible but is not normally economically feasible. Unfortunately, few performance data on wastewater treatment plants in developing countries are available and even then they do not normally include effluent quality parameters of importance in agricultural use.

The short-term variations in wastewater flows observed at municipal wastewater treatment plants follow a diurnal pattern. Flow is typically low during the early morning hours, when water consumption is lowest and when the base flow consists of infiltration-inflow and small quantities of sanitary wastewater. A first peak of flow generally occurs in the late morning, when wastewater from the peak morning water use reaches the treatment plant, and a second peak flow usually occurs in the evening. The relative magnitude of the peaks and the times at which they occur vary from country to country and with the size of the community and the length of the sewers. Small communities with small sewer systems have a much higher ratio of peak flow to average flow than do large communities. Although the magnitude of peaks is attenuated as wastewater passes through a treatment plant, the daily variations in flow from a municipal treatment plant make it impracticable, in most cases, to irrigate with effluent directly from the treatment plant. Some form of flow equalization or short-term storage of treated effluent is necessary to provide a relatively constant supply of reclaimed water for efficient irrigation, although additional benefits result from storage.

3.2 Conventional wastewater treatment processes

Conventional wastewater treatment consists of a combination of physical, chemical, and biological processes and operations to remove solids, organic matter and, sometimes, nutrients from wastewater. General terms used to describe different degrees of treatment, in order of increasing treatment level, are preliminary, primary, secondary, and tertiary and/or advanced wastewater treatment. In some countries, disinfection to remove pathogens sometimes follows the last treatment step. A generalized wastewater treatment diagram is shown in Figure 5.

Figure 5: Generalized flow diagram for municipal wastewater treatment (Asano *et al.* 1985)

3.2.1 Preliminary treatment

The objective of preliminary treatment is the removal of coarse solids and other large materials often found in raw wastewater. Removal of these materials is necessary to enhance the operation and maintenance of subsequent treatment units. Preliminary treatment operations typically include coarse screening, grit removal and, in some cases, comminution of large objects. In grit chambers, the velocity of the water through the chamber is maintained sufficiently high, or air is used, so as to prevent the settling of most organic solids. Grit removal is not included as a preliminary treatment step in most small wastewater treatment plants. Comminutors are sometimes adopted to supplement coarse screening and serve to reduce the size of large particles so that they will be removed in the form of a sludge in subsequent treatment processes. Flow measurement devices, often standing-wave flumes, are always included at the preliminary treatment stage.

3.2.2 Primary treatment

The objective of primary treatment is the removal of settleable organic and inorganic solids by sedimentation, and the removal of materials that will float (scum) by skimming. Approximately 25 to 50% of the incoming biochemical oxygen demand (BOD_5), 50 to 70% of the total suspended solids (SS), and 65% of the oil and grease are removed during primary treatment. Some organic nitrogen, organic phosphorus, and heavy metals associated with solids are also removed during primary sedimentation but colloidal and dissolved constituents are not affected. The effluent from primary sedimentation units is referred to as primary effluent. Table 12 provides information on primary effluent from three sewage treatment plants in California along with data on the raw wastewaters.

Table 12: QUALITY OF RAW WASTEWATER AND PRIMARY EFFLUENT AT SELECTED TREATMENT PLANTS IN CALIFORNIA

Quality parameters (mg/l, except as otherwise indicated)	City of Davis		San Diego		Los Angeles County Joint Plant	
	Raw wastewater	Primary effluent	Raw wastewater	Primary effluent	Raw wastewater	Primary effluent
Biochemical oxygen demand, BOD_5	112	73	184	134	-	204
Total organic carbon	63.8	40.6	64.8	52.3	-	-
Suspended solids	185	72	200	109	-	219
Total nitrogen	43.4	34.7	-	-	-	-
NH_3-N	35.6	26.2	21.0	20.0	-	39.5
NO-N	0	0	-	-	-	-
Org-N	7.8	8.5	-	-	-	14.9
Total phosphorus	-	7.5	-	10.2	-	11.2
Ortho-P	-	7.5	11.2		-	

pH (unit)	7.7	-	7.3	7.3	-	-
Cations:						
Ca	-	-	-	-	78.8	-
Mg	-	-	-	-	25.6	-
Na	-	-	-	-	357	359
K	-	-	-	-	19	19
Anions:						
SO_4	-		160		270	
Cl	-		120		397	
Electrical conductivity, dS/m	2.52	2.34			2.19	-
Total dissolved solids	-	-	829	821	1404	1406
Soluble sodium percentage, %	-		-		70.3	
Sodium adsorption ratio	-	-	-	-	8.85	6.8
Boron (B)	-	-	-	-	1.68	1.5
Alkalinity *($CaCO_3$)*	-	-	-		322	332
Hardness ($CaCO_3$)	-		-		265	

Source: Asano and Tchobanoglous (1987)

In many industrialized countries, primary treatment is the minimum level of preapplication treatment required for wastewater irrigation. It may be considered sufficient treatment if the wastewater is used to irrigate crops that are not consumed by humans or to irrigate orchards, vineyards, and some processed food crops. However, to prevent potential nuisance conditions in storage or flow-equalizing reservoirs, some form of secondary treatment is normally required in these countries, even in the case of non-food crop irrigation. It may be possible to use at least a portion of primary effluent for irrigation if off-line storage is provided.

Primary sedimentation tanks or clarifiers may be round or rectangular basins, typically 3 to 5 m deep, with hydraulic retention time between 2 and 3 hours. Settled solids (primary sludge) are normally removed from the bottom of tanks by sludge rakes that scrape the sludge to a central well from which it is pumped to sludge processing units. Scum is swept across the tank surface by water jets or mechanical means from which it is also pumped to sludge processing units.

In large sewage treatment plants (> 7600 m^3/d in the US), primary sludge is most commonly processed biologically by anaerobic digestion. In the digestion process, anaerobic and facultative bacteria metabolize the organic material in sludge (see Example 3), thereby reducing the volume requiring ultimate disposal, making the sludge stable (nonputrescible) and improving its dewatering characteristics. Digestion is carried out in covered tanks (anaerobic digesters), typically 7 to 14 m deep. The residence time in a digester may vary from a minimum of about 10 days for high-rate digesters (well-mixed and heated) to 60 days or more in standard-rate digesters. Gas containing about 60 to 65% methane is produced during digestion and can be recovered as an energy source. In small sewage treatment plants, sludge is processed in a variety of ways including: aerobic digestion, storage in sludge lagoons, direct application to sludge drying beds, in-process storage (as in stabilization ponds), and land application.

Example 3: Biological treatment biochemistry

3.2.3 Secondary treatment

The objective of secondary treatment is the further treatment of the effluent from primary treatment to remove the residual organics and suspended solids. In most cases, secondary treatment follows primary treatment and involves the removal of biodegradable dissolved and colloidal organic matter using aerobic biological treatment processes. Aerobic biological treatment (see Box) is performed in the presence of oxygen by aerobic microorganisms (principally bacteria) that metabolize the organic matter in the wastewater, thereby producing more microorganisms and inorganic end-products (principally CO_2, NH_3, and H_2O). Several aerobic biological processes are used for secondary treatment differing primarily in the manner in which oxygen is supplied to the microorganisms and in the rate at which organisms metabolize the organic matter.

High-rate biological processes are characterized by relatively small reactor volumes and high concentrations of microorganisms compared with low rate processes. Consequently, the growth rate of new organisms is much greater in high-rate systems because of the well controlled environment. The microorganisms must be separated from the treated wastewater by sedimentation to produce clarified secondary effluent. The sedimentation tanks used in secondary treatment, often referred to as secondary clarifiers, operate in the same basic manner as the primary clarifiers described previously. The biological solids removed during secondary sedimentation, called secondary or biological sludge, are normally combined with primary sludge for sludge processing.

Common high-rate processes include the activated sludge processes, trickling filters or biofilters, oxidation ditches, and rotating biological contactors (RBC). A combination of two of these processes in series (e.g., biofilter followed by activated sludge) is sometimes used to treat municipal wastewater containing a high concentration of organic material from industrial sources.

i. *Activated Sludge*

In the activated sludge process, the dispersed-growth reactor is an aeration tank or basin containing a suspension of the wastewater and microorganisms, the mixed liquor. The contents of the aeration tank are mixed vigorously by aeration devices which also supply oxygen to the biological suspension . Aeration devices commonly used include submerged diffusers that release compressed air and mechanical surface aerators that introduce air by agitating the liquid surface. Hydraulic retention time in the aeration tanks usually ranges from 3 to 8 hours but can be higher with high BOD_5 wastewaters. Following the aeration step, the microorganisms are separated from the liquid by sedimentation and the clarified liquid is secondary effluent. A portion of the biological sludge is recycled to the aeration basin to maintain a high mixed-liquor suspended solids (MLSS) level. The remainder is removed from the process and sent to sludge processing to maintain a relatively constant concentration of microorganisms in the system. Several variations of the basic activated sludge process, such as extended aeration and oxidation ditches, are in common use, but the principles are similar.

ii. *Trickling Filters*

A trickling filter or biofilter consists of a basin or tower filled with support media such as stones, plastic shapes, or wooden slats. Wastewater is applied intermittently, or sometimes continuously, over the media. Microorganisms become attached to the media and form a biological layer or fixed film. Organic matter in the wastewater diffuses into the film, where it is metabolized. Oxygen is normally supplied to the film by the natural flow of air either up or down through the media, depending on the relative temperatures of the wastewater and ambient air. Forced air can also be supplied by blowers but this is rarely necessary. The thickness of the biofilm increases as new organisms grow. Periodically, portions of the film 'slough off the media. The sloughed material is separated from the liquid in a secondary clarifier and discharged to sludge processing. Clarified liquid from the secondary clarifier is the secondary effluent and a portion is often recycled to the biofilter to improve hydraulic distribution of the wastewater over the filter.

iii. *Rotating Biological Contactors*

Rotating biological contactors (RBCs) are fixed-film reactors similar to biofilters in that organisms are attached to support media. In the case of the RBC, the support media are slowly rotating discs that are partially submerged in flowing wastewater in the reactor. Oxygen is supplied to the attached biofilm from the air when the film is out of the water and from the liquid when submerged, since oxygen is transferred to the wastewater by surface turbulence created by the discs' rotation. Sloughed pieces of biofilm are removed in the same manner described for biofilters.

High-rate biological treatment processes, in combination with primary sedimentation, typically remove 85 % of the BOD_5 and SS originally present in the raw wastewater and some of the heavy metals. Activated sludge generally produces an effluent of slightly higher quality, in terms of these constituents, than biofilters or RBCs. When coupled with a disinfection step, these processes can provide substantial but not complete removal of bacteria and virus. However, they remove very little phosphorus, nitrogen, non-biodegradable organics, or dissolved minerals. Data on effluent quality from selected secondary treatment plants in California are presented in Table 13.

Table 13: QUALITY OF SECONDARY EFFLUENT AT SELECTED WASTEWATER TREATMENT PLANTS IN CALIFORNIA

Quality parameter (mg/l except as otherwise indicated)	**Plant location**			
	Trickling filters		**Activated sludge**	
	Chino Basin MWD (No. 1)	**Chino Basin MWD (No. 2)**	**Santa Rosa Laguna**	**Montecito Sanitary District**
Biochemical oxygen demand, BOD_5	21	8	-	11
Chemical oxygen demand	-	-	27	-
Suspended solids	18	26	-	13
Total nitrogen	-	-	-	-
NH_3-N	25	11	10	1.4
NO_3-N	0.7	19	8	5
Org-N	-	-	1.7	-
Total phosphorus	-	-	12.5	-
Ortho-P	-	-	3.4	-
pH (unit)	-	-	-	7.6

Cations:					
	Ca	43	55	41	82
	Mg	12	18	18	33
	Na	83	102	94	-
	K	17	20	11	-
Anions:					
	HCO_3	293	192	165	-
	SO_4	85	143	66	192
	Cl	81	90	121	245
Electrical conductivity dS/m		-	-	-	1.39
Total dissolved solids		476	591	484	940
Sodium adsorption ratio		2.9	3.1	3.9	3.7
Boron (B)		0.7	0.6	0.6	0.7
Alkalinity ($CaCO_3$)		-	-	-	226
Total Hardness ($CaCO_3$)		156	200	175	265

Source: Asano and Tchobanoglous (1987)

3.2.4 Tertiary and/or advanced treatment

Tertiary and/or advanced wastewater treatment is employed when specific wastewater constituents which cannot be removed by secondary treatment must be removed. As shown in Figure 3, individual treatment processes are necessary to remove nitrogen, phosphorus, additional suspended solids, refractory organics, heavy metals and dissolved solids. Because advanced treatment usually follows high-rate secondary treatment, it is sometimes referred to as tertiary treatment. However, advanced treatment processes are sometimes combined with primary or secondary treatment (e.g., chemical addition to primary clarifiers or aeration basins to remove phosphorus) or used in place of secondary treatment (e.g., overland flow treatment of primary effluent).

An adaptation of the activated sludge process is often used to remove nitrogen and phosphorus and an example of this approach is the 23 Ml/d treatment plant commissioned in 1982 in British Columbia, Canada (World Water 1987). The Bardenpho Process adopted is shown in simplified form in Figure 6. Effluent from primary clarifiers flows to the biological reactor, which is physically divided into five zones by baffles and weirs. In sequence these zones are: (i) anaerobic fermentation zone (characterized by very low dissolved oxygen levels and the absence of nitrates); (ii) anoxic zone (low dissolved oxygen levels but nitrates present); (iii) aerobic zone (aerated); (iv) secondary anoxic zone; and (v) final aeration zone. The function of the first zone is to condition the group of bacteria responsible for phosphorus removal by stressing them under low oxidation-reduction conditions, which results in a release of phosphorus equilibrium in the cells of the bacteria. On subsequent exposure to an adequate supply of oxygen and phosphorus in the aerated zones, these cells rapidly accumulate phosphorus considerably in excess of their normal metabolic requirements. Phosphorus is removed from the system with the waste activated sludge.

Figure 6: Simplified flow diagram of Bardenpho-plant (World Water 1987)

Most of the nitrogen in the influent is in the ammonia form, and this passes through the first two zones virtually unaltered. In the third aerobic zone, the sludge age is such that almost complete nitrification takes place, and the ammonia nitrogen is converted to nitrites and then to nitrates. The nitrate-rich mixed liquor is then recycled from the aerobic zone back to the first anoxic zone. Here denitrification occurs, where the recycled nitrates, in the absence of dissolved oxygen, are reduced by facultative bacteria to nitrogen gas, using the influent organic carbon compounds as hydrogen donors. The nitrogen gas merely escapes to atmosphere. In the second anoxic zone, those nitrates which were not recycled are reduced by the endogenous respiration of bacteria. In the final re-aeration zone, dissolved oxygen levels are again raised to prevent further denitrification, which would impair settling in the secondary clarifiers to which the mixed liquor then flows.

An experimentation programme on this plant demonstrated the importance of the addition of volatile fatty acids to the anaerobic fermentation zone to achieve good phosphorus removal. These essential short-chain organics (mainly acetates) are produced by the controlled fermentation of primary sludge in a gravity thickener and are released into the thickener supernatent, which can be fed to the head of the biological reactor. Without this supernatent return flow, overall phosphorus removal quickly dropped to levels found in conventional activated sludge plants. Performance data over three years have proved that, with thickener supernatent recycle, effluent quality median values of 0.5-1.38 mg/l Ortho-P, 1.4-1.6 mg/l Total nitrogen and 1.4-2.0 mg/l nitrate-N are achievable. This advanced biological wastewater treatment plant cost only marginally more than a conventional activated sludge plant but nevertheless involved considerable investment. Furthermore, the complexity of the process and the skilled operation required to achieve consistent results make this approach unsuitable for developing countries.

In many situations, where the risk of public exposure to the reclaimed water or residual constituents is high, the intent of the treatment is to minimize the probability of human exposure to enteric viruses and other pathogens. Effective disinfection of viruses is believed to be inhibited by suspended and colloidal solids in the water, therefore these solids must be removed by advanced treatment before the disinfection step. The sequence of treatment often specified in the United States is: secondary treatment followed by chemical coagulation, sedimentation, filtration, and disinfection. This level of treatment is assumed to produce an effluent free from detectable viruses. Effluent quality data from selected advanced wastewater treatment plants in California are reported in Table 14. In Near East countries adopting tertiary treatment, the tendency has been to introduce pre-chlorination before rapid-gravity sand filtration and post-chlorination afterwards. A final ozonation treatment after this sequence has been considered in at least one country.

3.2.5 Disinfection

Disinfection normally involves the injection of a chlorine solution at the head end of a chlorine contact basin. The chlorine dosage depends upon the strength of the wastewater and other factors, but dosages of 5 to 15 mg/l are common. Ozone and ultra violet (uv) irradiation can also be used for disinfection but these methods of disinfection are not in common use. Chlorine contact basins are usually rectangular channels, with baffles to prevent short-circuiting, designed to provide a contact time of about 30 minutes. However, to meet advanced wastewater treatment requirements, a chlorine contact time of as long as 120 minutes is sometimes required for specific irrigation uses of reclaimed wastewater. The bactericidal effects of chlorine and other disinfectants are dependent upon pH, contact time, organic content, and effluent temperature.

3.2.6 Effluent storage

Although not considered a step in the treatment process, a storage facility is, in most cases, a critical link between the wastewater treatment plant and the irrigation system. Storage is needed for the following reasons:

> i. To equalize daily variations in flow from the treatment plant and to store excess when average wastwater flow exceeds irrigation demands; includes winter storage.
>
> ii. To meet peak irrigation demands in excess of the average wastewater flow.
>
> iii. To minimize the effects of disruptions in the operations of the treatment plant and irrigation system. Storage is used to provide insurance against the possibility of unsuitable reclaimed wastewater entering the irrigation system and to provide additional time to resolve temporary water quality problems.

Table 14: EFFLUENT QUALITY DATA FROM SELECTED ADVANCED WASTEWATER TREATMENT PLANTS IN CALIFORNIA[1]

Quality parameter (mg/l	Plant location

except as otherwise indicated)	Long Beach	Los Coyotes	Pomona	Dublin San Ramon	City of Livermore	Simi Valley CSD
Biochemical oxygen demand, BOD_5	5	9	4	2	3	4
Suspended solids	-	5	-	1	-	-
Total nitrogen	-	-	-	-	-	19
NH_3-N	3.3	13.6	11.4	0.1	1.0	16.6
NO_3-N	15.4	1.1	3	19.0	21.3	0.4
Org-N	2.2	2.5	1.3	0.2	2.6	2.3
Total phosphorus	-	-	-	-	-	-
Ortho-P	30.8	23.9	21.7	28.5	16.5	-
pH (unit)	-	-	-	6.8	7.1	-
Oil and grease	-	-	-	-	-	3.1
Total coliform bacteria, MPN/100 ml	-	-	-	2	4	-
Cations:						
Ca	54	65	58	-	-	-
Mg	17	18	14	-	-	-
Na	186	177	109	168	178	-
K	16	18	12	-	-	-
Anions:						
SO_4	212	181	123	-	-	202
Cl	155	184	105	147	178	110
Electrical conductivity, dS/m	1.35	1.44	1.02	1.27	1.25	-
Total dissolved solids	867	827	570	-	-	585
Soluble sodium, %	63.2	59.2	51.7	-	-	-
Sodium adsorption ratio	5.53	4.94	3.37	4.6	5.7	-
Boron (B)	0.95	0.95	0.66	-	1.33	0.6

Alkalinity ($CaCO_3$)	-	256	197	150	-	-
Total Hardness ($CaCO_3$)	212	242	206	254	184	-

[1]Advanced wastewater treatment in these plants follows high rate secondary treatment and includes addition of chemical coagulants (alum + polymer) as necessary followed by filtration through sand or activated carbon granular medium filters.

Source: Asano and Tchobanoglous (1987)

iv. To provide additional treatment. Oxygen demand, suspended solids, nitrogen, and microorganisms are further reduced during storage.

3.2.7 Reliability of conventional and advanced wastewater treatment

Wastewater reclamation and reuse systems should contain both design and operational requirements necessary to ensure reliability of treatment. Reliability features such as alarm systems, standby power supplies, treatment process duplications, emergency storage or disposal of inadequately treated wastewater, monitoring devices, and automatic controllers are important. From a public health standpoint, provisions for adequate and reliabile disinfection are the most essential features of the advanced wastewater treatment process. Where disinfection is required, several reliability features must be incorporated into the system to ensure uninterrupted chlorine feed.

3.3 Natural biological treatment systems

Natural low-rate biological treatment systems are available for the treatment of organic wastewaters such as municipal sewage and tend to be lower in cost and less sophisticated in operation and maintenance. Although such processes tend to be land intensive by comparison with the conventional high-rate biological processes already described, they are often more effective in removing pathogens and do so reliably and continuously if properly designed and not overloaded. Among the natural biological treatment systems available, stabilization ponds and land treatment have been used widely around the world and a considerable record of experience and design practice has been documented. The nutrient film technique is a fairly recent development of the hydroponic plant growth system with application in the treatment and use of wastewater.

3.3.1 Wastewater stabilization ponds

A recent World Bank Report (Shuval *et al.* 1986) came out strongly in favour of stabilization ponds as the most suitable wastewater treatment system for effluent use in agriculture. Table 15 provides a comparison of the advantages and disadvantages of ponds with those of high-rate biological wastewater treatment processes. Stabilization ponds are the preferred wastewater treatment process in developing countries, where land is often available at reasonable opportunity cost and skilled labour is in short supply.

Table 15: ADVANTAGES AND DISADVANTAGES OF VARIOUS SEWAGE TREATMENT SYSTEMS

	Criteria	Package plant	Activated sludge plant	Extended aeration activated sludge	Biological filter	Oxidation ditch	Aerated lagoon	Waste stabilization pond system
Plant performance	BOD removal	F	F	F	F	G	G	G
	FC removal	P	P	F	P	F	G	G
	SS removal	F	G	G	G	G	F	F
	Helminth removal	P	F	P	P	F	F	G
	Virus removal	P	F	P	P	F	G	G
Economic factors	Simple and cheap construction	P	P	P	P	F	F	G
	Simple operation	P	P	P	F	F	P	G
	Land requirement	G	G	G	G	G	F	P
	Maintenance costs	P	P	P	F	P	P	G
	Energy demand	P	P	P	F	P	P	G
	Sludge removal costs	P	F	F	F	P	F	G

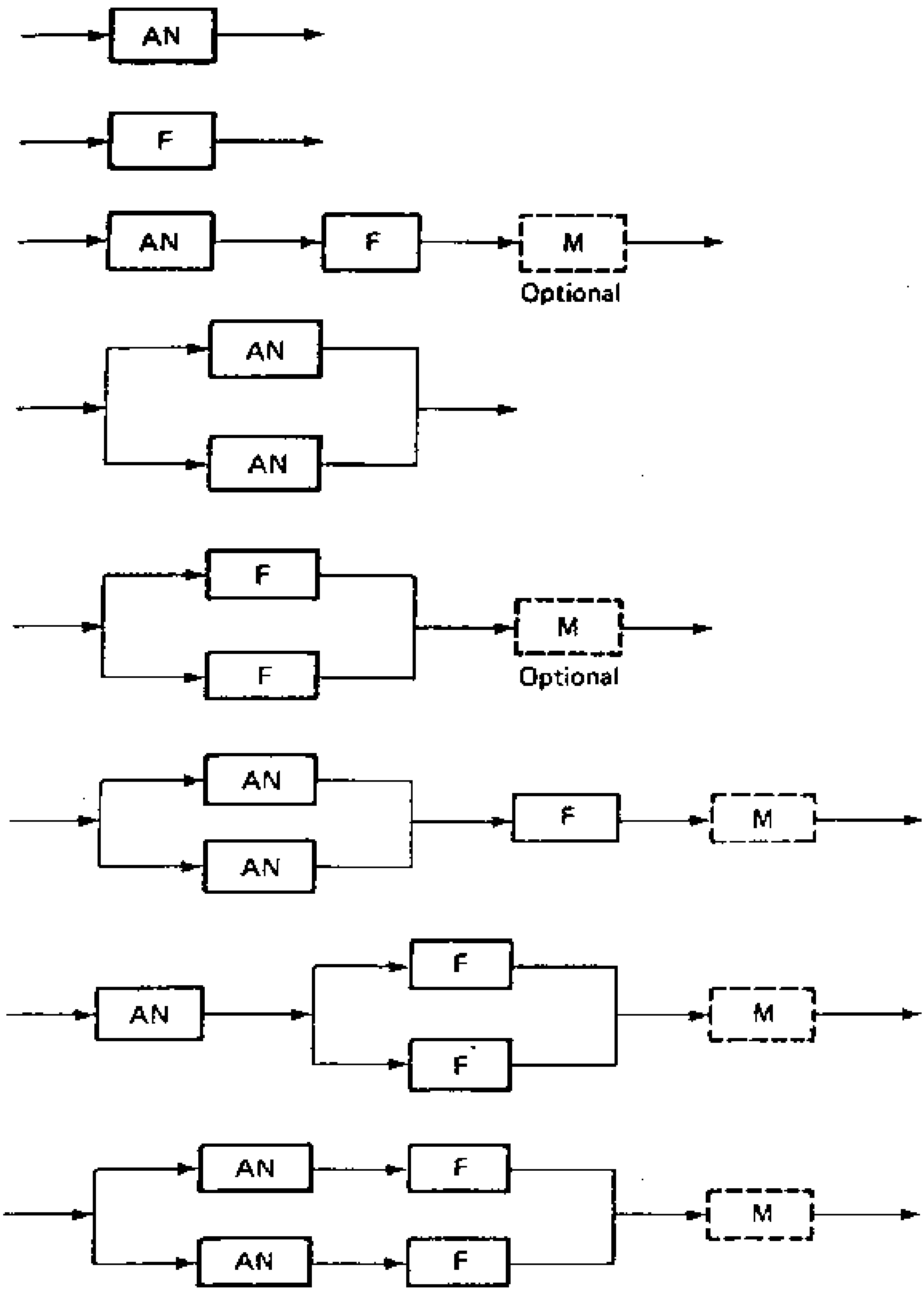
Key:

FC = Faecal coliforms;
SS = Suspended slids;
G = Good;
F = Fair;
P = Poor.

Source: Arthur (1983)

Wastewater stabilization pond systems are designed to achieve different forms of treatment in up to three stages in series, depending on the organic strength of the input waste and the effluent quality objectives. For ease of maintenance and flexibility of operation, at least two trains of ponds in parallel are incorporated in any design. Strong wastewaters, with BOD_5 concentration in excess of about 300 mg/l, will frequently be introduced into first-stage **anaerobic** ponds, which achieve a high volumetric rate of removal. Weaker wastes or, where anaerobic ponds are environmentally unacceptable, even stronger wastes (say up to 1000 mg/l BOD_5) may be discharged directly into **primary facultative** ponds. Effluent from first-stage anaerobic ponds will overflow into **secondary** facultative ponds which comprise the second-stage of biological treatment. Following primary or secondary facultative ponds, if further pathogen reduction is necessary **maturation** ponds will be introduced to provide tertiary treatment. Typical pond system configurations are given in Figure 7.

Figure 7: Stabilization pond configurations AN = anaerobic pond; F = facultative pond; M = maturation pond (Pescod and Mara 1988)



i. *Anaerobic Ponds*

Anaerobic ponds are very cost effective for the removal of BOD, when it is present in high concentration. Normally, a single, anaerobic pond in each treatment train is sufficient if the strength of the influent wastewater, L_i is less than 1000 mg/l BOD_5. For high strength industrial wastes, up to three anaerobic ponds in series might be justifiable but the retention time t_{an}, in any of these ponds should not be less than 1 day (McGarry and Pescod, 1970).

Anaerobic conditions in first-stage stabilization ponds are created by maintaining a high volumetric organic loading, certainly greater than 100g BOD_5/m^3 d. Volumetric loading, λ_v, is given by:

(2)

$$\lambda = \frac{L_i Q}{V}$$

where:

L_i = Influent BOD_5, mg/l,
Q = Influent flow rate, m^3/d, and
V = Pond volume, m^3

or, since V/Q = t_{an}, the retention time:

(3)

$$\lambda_v = \frac{L_i}{t_{an}}$$

Very high loadings, up to 1000g BOD_5/m^3d, achieve efficient utilization of anaerobic pond volume but, with wastewater containing sulphate concentrations in excess of 100 mg/l, the production of H_2S is likely to cause odour problems. In the case of typical municipal sewage, it is generally accepted that a maximum anaerobic pond loading of 400g BOD_5/m^3d will prevent odour nuisance (Meiring **et al.** 1968).

Table 16: BOD REMOVALS IN ANAEROBIC PONDS LOADED AT 250 g BOD_5/m^3d

Retention t_{an} days	BOD_5 removal %
1	50
2.5	60
5	70

Source: Mara (1976)

Anaerobic ponds normally have a depth between 2m and 5m and function as open septic tanks with gas release to the atmosphere. The biochemical reactions which take place in anaerobic ponds are the same as those occurring in anaerobic digesters, with a first phase of acidogenesis and a second slower-rate of methanogenesis (see Example 3). Ambient temperatures in hot-climate countries are conducive to these anaerobic reactions and expected BOD_5 removals for different retention times in treating sewage have been given by Mara (1976) as shown in Table 16. More recently, Gambrill **et al.** (1986) have suggested conservative removals of BOD_5 in anaerobic ponds as 40% below 10°C, at a design loading, λ_v, of 100 g/m³d, and 60% above 20°C, at a design loading of 300 g/m³d, with linear interpolation for operating temperature between 10 and 20°C. Higher removal rates are possible with industrial wastes, particularly those containing significant quantities of organic settleable solids. Of course, other environmental conditions in the ponds, particularly pH, must be suitable for the anaerobic microorganisms bringing about the breakdown of BOD.

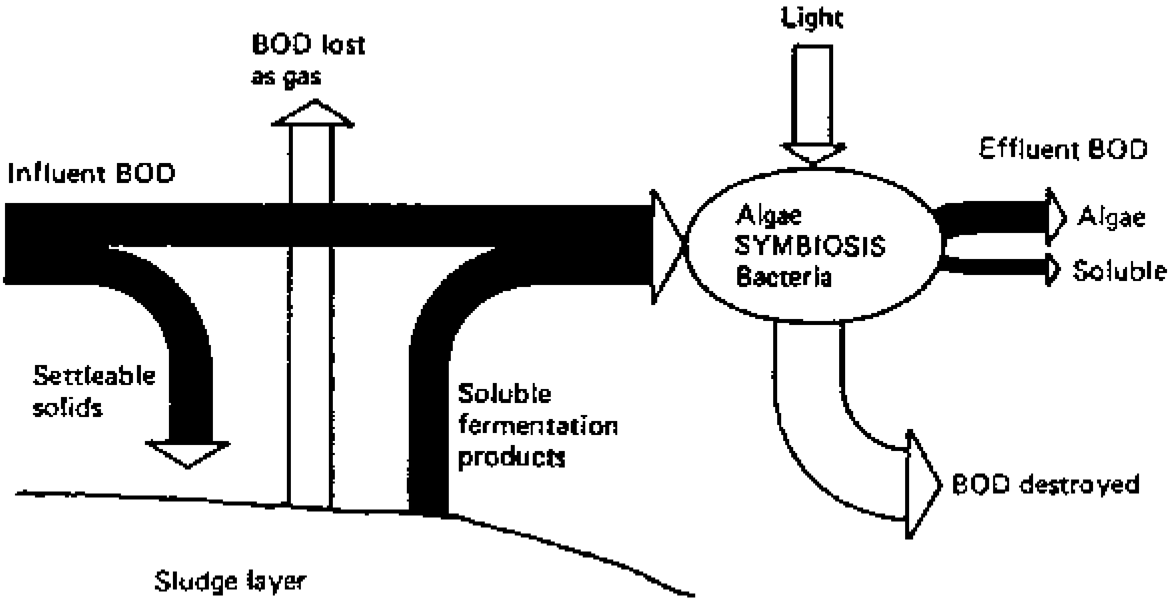
In certain instances, anaerobic ponds become covered with a thick scum layer, which is thought to be beneficial but not essential, and may give rise to increased fly breeding. Solids in the raw wastewater, as well as biomass produced, will settle out in first-stage anaerobic ponds and it is common to remove sludge when it has reached half depth in the pond. This usually occurs after two years of operation at design flow in the case of municipal sewage treatment.

ii. *Facultative Ponds*

The effluent from anaerobic ponds will require some form of aerobic treatment before discharge or use and facultative ponds will often be more appropriate than conventional forms of secondary biological treatment for application in developing countries. Primary facultative ponds will be designed for the treatment of weaker wastes and in sensitive locations where anaerobic pond odours would be unacceptable. Solids in the influent to a facultative pond and excess biomass produced in the pond will settle out forming a sludge layer at the bottom. The benthic layer will be anaerobic and, as a result of anaerobic breakdown of organics, will release soluble organic products to the water column above.

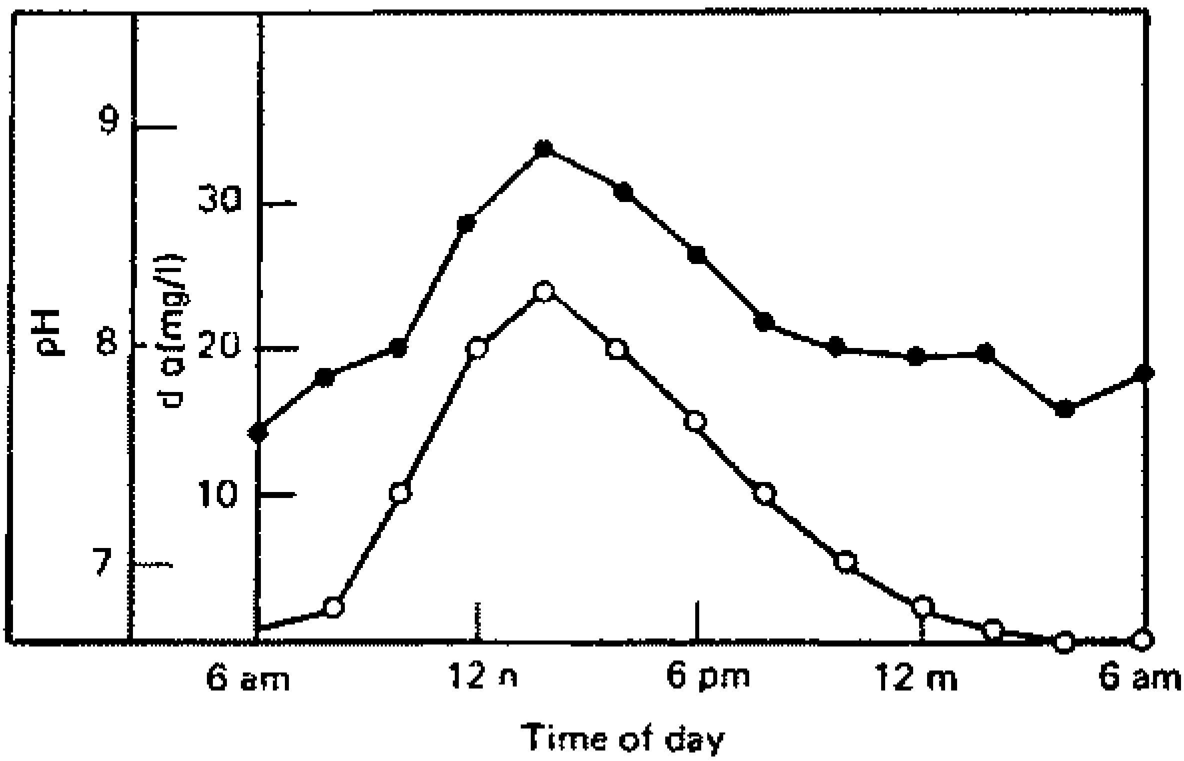
Organic matter dissolved or suspended in the water column will be metabolized by heterotrophic bacteria, with the uptake of oxygen, as in convential aerobic biological wastewater treatment processes. However, unlike in convential processes, the dissolved oxygen utilized by the bacteria in facultative ponds is replaced through photosynthetic oxygen production by microalgae, rather than by aeration equipment. Especially intreating municipal sewage in hot climates, the environment in facultative ponds is ideal for the proliferation of microalgae. High temperature and ample sunlight create conditions which encourage algae to utilize the carbon dioxide (CO_2) released by bacteria in breaking down the organic components of the wastewater and take up nutrients (mainly nitrogen and phosphorus) contained in the wastewater. This symbiotic relationship contributes to the overall removal of BOD in facultative ponds, described diagrammatically by Marais (1970) as in Figure 8.

Figure 8: Energy flows in facultative stabilization ponds (Marais 1970)



To maintain the balance necessary to allow this symbiosis to persist, the organic loading on a facultative pond must be strictly limited. Even under satisfactory operating conditions, the dissolved oxygen concentration (DO) in a facultative pond will vary diurnally as well as over the depth. Maximum DO will occur at the surface of the pond and will usually reach supersaturation in tropical regions at the time of maximum radiation intensity, as shown in Figure 9. From that time until sunrise, DO will decline and may well disappear completely for a short period. For a typical facultative pond depth, D_f, of 1.5m the water column will be predominantly aerobic at the time of peak radiation and predominantly anaerobic at sunrise. As illustrated in Figure 9, the pH of the pond contents will also vary diurnally as algae utilize CO_2 throughout daylight hours and respire, along with bacteria and other organisms, releasing CO_2 during the night.

Figure 9: Diurnal variation of dissolved oxygen and pH in facultative pond, pH: •, dissolved oxygen: o (Pescod and Mara 1988)



Wind is considered important to the satisfactory operation of facultative ponds by mixing the contents and helping to prevent short-circuiting. Intimate mixing of organic substrate and the degrading organisms is important in any biological reactor but in facultative ponds wind mixing is considered essential to prevent thermal stratification causing anaerobiosis and failure. Facultative ponds should be orientated with the longest dimension in the direction of the prevailing wind.

Although completely-mixed reactor theory with the assumption of first-order kinetics for BOD removal can be adopted for facultative pond design (Marais and Shaw, 1961), such a fundamental approach is rarely adopted in practice. Instead, an empirical procedure based on operational experience is more common. The most widely adopted design method currently being applied wherever local experience is limited is that introduced by McGarry and Pescod (1970).

A regression analysis of operating data on ponds around the world relating maximum surface organic loading, in lb/acre d, to the mean ambient air temperature, in °F, of the coldest month resulted in the following equation (now converted to metric units):

(4)

$$\lambda_{s(max)} = 60.3\,(1.099)^{T}$$

where:

λ_s = surface or arael organic loading, kg BOD_5/ha.d
T = mean ambient air temperature of coldest month, °C

Subsequently, Arthur (1983) modified this formula and suggested that best agreement with available operating data, including a factor of safety of about 1.5, is represented by the relationship:

(5)

$$\lambda_s = 20T - 60$$

This surface (or areal) BOD_5 loading can be translated into a mid-depth facultative pond area requirement (A_f in m^2) using the formula:

(6)

$$A_f = \frac{10 L_i Q}{\lambda_s}$$

Thus:

(7)

$$A_f = \frac{L_i Q}{2T - 6}$$

and the mean hydraulic retention time in the facultative pond (t_f in days) is given by:

(8)

$$t_f = \frac{A_f D_f}{Q}$$

The removal of BOD_5 in facultative ponds (λ_r in kg/ha d) is related to BOD_5 loading and usually averages 70-80% of λ_s. Retention time in a properly designed facultative pond will normally be 20-40 days and, with a depth of about 1.5m, the area required will be signficantly greater than for an anaerobic pond. The effluent from a facultative pond treating municipal sewage in the tropics will normally have a BOD_5 between 50 and 70 mg/l as a result of the suspended algae. On discharge to a surface water, this effluent will not cause problems downstream if the dilution is of the order of 8:1 and any live algae in the effluent might well be beneficial as a result of photo synthetic oxygen production during daylight hours.

Efficiently operating facultative ponds treating wastewater will contain a mixed population of flora but flagellate algal genera such as Chlamydomonas, Euglena, Phacus and Pyrobotrys will predominate. Non-motile forms such as Chlorella, Scenedesmus and various diatom species will be present in low concentrations unless the pond is underloaded. Algal stratification often occurs in facultative ponds, particularly in the absence of wind-induced mixing, as motile forms respond to changes in light intensity and move in a band up and down the water column. The relative numbers of different genera and their dominance in a facultative pond vary from season to season throughout the year but species diversity generally decreases with increase in loading. Sometimes, mobile purple sulphur bacteria appear when facultative ponds are overloaded and sulphide concentration increases, with the danger of odour production. High ammonia concentrations also bring on the same problem and are toxic to algae, especially above pH 8.0.

Maintenance of properly designed facultative ponds will be limited to the removal of scum mats, which tend to accumulate in downwind corners, and the cutting of grass on embankments. To ensure efficient operation, facultative ponds should be regularly monitored but, even where this is not possible, they have the reputation of being relatively trouble-free.

iii. *Maturation Ponds*

The effluent from facultative ponds treating municipal sewage or equivalent input wastewater will normally contain at least 50 mg/l BOD_5 and if an effluent with lower BOD_5 concentration is required it will be necessary to use maturation ponds. For sewage treatment, two maturation ponds in series, each with a retention time of 7 days, have been found necessary to produce a final effluent with BOD_5 < 25 mg/l when the facultative pond effluent had a BOD_5 < 75 mg/l.

A more important function of maturation ponds, however, is the removal of excreted pathogens to achieve an effluent quality which is suitable for its downstream reuse. Although the longer retention in anaerobic and facultative pond systems will make them more efficient than conventional wastewater treatment processes in removing pathogens, the effluent from a facultative pond treating municipal sewage will generally require further treatment in maturation ponds to reach effluent standards imposed for reuse in unrestricted irrigation. Faecal coliform bacteria are commonly used as indicators of excreted pathogens and maturation ponds can be designed to achieve a given reduction of faecal coliforms (FC). Protozoan cysts and helminth ova are removed by sedimentation in stabilization ponds and a series of ponds with overall retention of 20 days or more will produce an effluent totally free of cysts and ova (Feachem *et al.* 1983).

Reduction of faecal coliform bacteria **in any stabilization pond** (anaerobic, facultative and maturation) is generally taken as following first-order kinetics:

(9)

$$N_e = \frac{N_i}{1 + K_b t}$$

where:

N_e = Number of faecal coliforms/100 ml of effluent
N_i = Number of faecal coliforms/100 ml of influent
K_b = First-order rate constant for FC removal, d^{-1}
t = Retention time in any pond, d

For n ponds in series, Eq 8 becomes:

(10)

$$N_e = \frac{N_i}{(1+K_b t_{an})(1+K_b t_f)(1+k_b t_{m_1})\cdots(1+k_b t_{m_n})}$$

where:

$t_{m\,n}$ = Retention time in the nth maturation pond.

The value of KB is extremely sensitive to temperature and was shown by Marais (1974) to be given by:

(11)

$$K_{b(T)} = 2.6\ (1.19)^{T-20}$$

where:

$K_{b(T)}$ = value of KB at T°C

A suitable design value of N_i in the case of municipal sewage treatment is 1 x 10^8 faecal coliforms/100ml, which is slightly higher than average practical levels.

The value of N_e should be obtained by substituting the appropriate levels of variables in Eq 10 assuming a retention time of 7 days in each of two maturation lagoons (for sewage). If the calculated value of N_e does not meet the reuse effluent standard, the number of maturation ponds should be increased, say to three or more each with retention time 5 days, and N_e recalculated. A more systematic approach is now available whereby the optimum design for maturation ponds can be obtained using a simple computer programme (Gambrill *et al.* 1986).

Polprasert *et al.* (1983) have published an approach to the assessment of bacterial die-off which attempts to take into account the complex physical characteristics of ponds and biochemical reactions taking place in them. A multiple-regression equation involving parameters such as retention time, organic loading, algal concentration and ultra-violet light exposure has been suggested. The Wehner and Wilhelm (1956) non-ideal flow equation, including the pond dispersion number, was adopted to predict bacterial survival, in preference to the first order rate equation (Eq 9 and 10).

Maturation ponds will be aerobic throughout the water column during daylight hours and the pH will rise above 9.0. The algal population of many species of non-flagellate unicellular and colonial forms will be distributed over the full depth of a maturation pond. Large numbers of filamentous algae, particularly blue-greens, will emerge under very low BOD loading conditions. Very low concentrations of algae in a maturation pond will indicate excessive algal predation by zooplankton, such as Daphnia sp, and this will have a deleterious effect on pathogen die-off, which is linked to algal activity.

Saqqar (1988), in his analysis of the performance of the Al Samra stabilization ponds in Amman, Jordan, has shown that the coliform and faecal coliform die-off coefficients varied with retention time, water temperature, organic loading, total BOD_5 concentration, pH and pond depth. Total coliform die-off was less than the rate of faecal coliform die-off, except during the cold season. For the series of ten ponds, including at least the first five totally anaerobic, the faecal coliform die-off coefficient, k, for the temperature range 12 - 15°C increased through the pond sequence from 0.11 per day in the first anaerobic pond to 0.68 per day in the final two ponds, which operated as facultative ponds.

3.3.2 Overland treatment of wastewater

Apart from the use of effluent for irrigation of crops, termed 'slow rate' land treatment in the US Environmental Protection Agency's Process Design Manual for Land Treatment of Municipal Wastewaters (EPA 1977), and 'rapid infiltration' or 'infiltration percolation' of effluent discussed as soil-aquifer treatment in a later section of this document, the EPA manual deals with 'overland flow' as a wastewater treatment method. In overland flow treatment, effluent is distributed over gently sloping grassland on fairly impermeable soils. Ideally, the wastewater moves evenly down the slope to collecting ditches at the bottom edge of the area and water-tolerant grasses are an essential component of the system.

This form of land treatment requires alternating applications of effluent (usually treated) and resting of the land, to allow soil reaction and grass cutting. The total area utilized is normally broken up into small plots to allow this form of intermittent operation and yet achieve continuous treatment of the flow of wastewater. Although this type of land treatment has been widely adopted in Australia, New Zealand and the UK for tertiary upgrading of secondary effluents, it has been used for the treatment of primary effluent in Werribee, Australia and is being considered for the treatment of raw sewage in Karachi, Pakistan.

Table 17: SITE CHARACTERISTICS AND DESIGN FEATURES FOR OVERLAND FLOW TREATMENT OF WASTEWATER

Grade	Finished slope 2-8%
Field area required (ha)	6.55-44
Soil permeability	Slow (clays, silts and soils with impermeable barriers)
Annual application rate (m)	3-20
Typical weekly application rate (cm)	6-40

Source: EPA (1977)

Basic site characteristics and design features for overland flow treatment have been suggested by EPA (1977) as shown in Table 17. It was pointed out that steeper land slopes might be feasible at reduced hydraulic loadings. The ranges given for field area required and application rates cover the wastewater quality from raw sewage to secondary effluent, with higher application rates and lower land area requirements being associated with higher levels of preapplication treatment. Although soil permeability is not critical with this form of land treatment, the impact on groundwater should not be overlooked in the case of highly permeable soils.

The application rate for wastewaters will depend principally on the type of soil, the quality of wastewater effluent and the physical and biochemical activity in the near-surface environment. Rational design procedures, based on the kinetics of BOD removal, have been developed for overland flow systems by Middlebrooks *et al.* (1982). Slope lengths from 30 - 60 m are common in the US for overland flow systems.

The cover crop is an important component of the overland flow system since it prevents soil erosion, provides nutrient uptake and serves as a fixed-film medium for biological treatment. Crops best suited to overland flow treatment are grasses with a long growing season, high moisture tolerance and extensive root formation. Reed canary grass has a very high nutrient uptake capacity and yields a good quality hay; other suitable grasses include rye grass and tall fescue.

Suspended and colloidal organic materials in the wastewater are removed by sedimentation and filtration through surface grass and organic layers. Removal of total nitrogen and ammonia is inversely related to application rate, slope length and soil temperature. Phosphorus and trace elements removal is by sorption on soil clay colloids and precipitation as insoluble complexes of calcium, iron and aluminium. Overland flow systems also remove pathogens from sewage effluent at levels comparable with conventional secondary treatment systems, without chlorination. A monitoring programme should always be incorporated into the design of overland flow projects both for wastewater and effluent quality and for application rates.

3.3.3 Macrophyte treatment

Maturation ponds which incorporate floating, submerged or emergent aquatic plant species are termed *macrophyte ponds* and these have been used in recent years for upgrading effluents from stabilization ponds. Macrophytes take up large amounts of inorganic nutrients (especially N and P) and heavy metals (such as Cd, Cu, Hg and Zn) as a consequnce of the growth requirements and decrease the concentration of algal cells through light shading by the leaf canopy and, possibly, adherence to gelatinous biomass which grows on the roots.

Floating macrophyte systems utilizing water hyacinth and receiving primary sewage effluent in Florida have achieved secondary treatment effluent quality with a 6 day hydraulic retention time, water depth of 60 cm and hydraulic loading 1860 m^3/ha d (Reddy and Debusk 1987). The same authors suggested that similar results had also been observed for artificial wetlands using emergent macrophytes. In Europe, the land area considered to be necessary for treatment of preliminary-treated sewage is estimated at 2-5 m^2 per population equivalent to achieve a secondary effluent quality (Cooper et al. 1988).

i. *Floating Aquatic Macrophyte Systems*

Floating macrophyte species, with their large root systems, are very efficient at nutrient stripping. Although several genera have been used in pilot schemes, including *Salvinia, Spirodella, Lemna* and *Eichornia* (O'Brien 1981), *Eichornia crassipes* (water hyacinth) has been studied in much greater detail. In tropical regions, water hyacinth doubles in mass about every 6 days and a macrophyte pond can produce more than 250 kg/ha d (dry weight). Nitrogen and phosphorus reductions up to 80% and 50% have been achieved. In Tamil Nadu, India, studies have indicated that the coontail, *Ceratophyllum demersum,* a submerged macrophyte, is very efficient at removing ammonia (97%) and phosphorus (96%) from raw sewage and also removes 95% of the BOD_5. It has a lower growth rate than *Eichornia crassipes,* which allows less frequent harvesting.

In such macrophyte pond systems, apart from any physical removal processes which might occur (especially sedimentation) the aquatic vascular plants serve as living substrates for microbial activity, which removes BOD and nitrogen, and achieves reductions in phosphorus, heavy metals and some organics through plant uptake. The basic function of the macrophytes in the latter mechanism is to assimilate, concentrate and store contaminants on a short-term basis. Subsequent harvest of the plant biomass results in permanent removal of stored contaminents from the pond treatment system. Potential growth rates of selected aquatic macrophytes cultured in nutrient water are given in Table 18.

The nutrient assimilation capacity of aquatic macrophytes is directly related to growth rate, standing crop and tissue composition. The potential rate of pollutant storage by an aquatic plant is limited by the growth rate and standing crop of biomass per unit area. Water hyacinth, for example, was found to reach a standing crop level of 30 tonnes (dry weight)/ha in Florida, resulting in a maximum storage of 900 kg N/ha and 180 kg P/ha (Reddy and De Busk 1987).

Fly and mosquito breeding is a problem in floating macrophyte ponds but this can be partially alleviated by introducing larvae-eating fish species such as *Gambusia* and *Peocelia* into the ponds. It should be recognized that pathogen die-off is poor in macrophyte ponds as a result of light shading and the lower dissolved oxygen and pH compared with algal maturation ponds. In their favour, macrophyte ponds can serve a useful purpose in stripping pond effluents of nutrients and algae and at the same time produce a harvestable biomass. Floating macrophytes are fairly easily collected by floating harvesters. The harvested plants might be fed to cattle, used as a green manure in agriculture, composted aerobically to produce a fertilizer and soil conditioner, or can be converted into biogas in an anaerobic digester, in which case the residual sludge can then be applied as a fertilizer and soil conditioner (UN Economic and Social Commission for Asia and the Pacific 1981). Maximum removal by water hyacinth was 5850 kg N/ha year, compared with 1200 kg N/ha year by duckweed.

ii. *Emergent Macrophyte Treatment Systems*

In recent years, natural and artificial wetlands and marshes have been used to treat raw sewage and partially-treated effluents. Natural wetlands are usually unmanaged, whereas artificial systems are specially designed to maximize performance by providing the optimum conditions for emergent macrophyte growth. The key features of such reed bed treatment systems are:

- Rhizomes of the reeds grow vertically and horizontally in the soil or gravel bed, opening up 'hydraulic pathways'.

- Wastewater BOD and nitrogen are removed by bacterial activity; aerobic treatment takes place in the rhizosphere, with anoxic and anaerobic treatment taking place in the surrounding soil.

- Oxygen passes from the atmosphere to the rhizosphere via the leaves and stems of the reeds through the hollow rhizomes and out through the roots.

- Suspended solids in the sewage are aerobically composted in the above-ground layer of vegetation formed from dead leaves and stems.

- Nutrients and heavy metals are removed by plant uptake.

The growth rate and pollutant assimilative capacity of emergent macrophytes such as *Phragmites communis and Scirpus lacstris* are limited by the culture system, wastewater loading rate, plant density, climate and management factors.

Growth rates for emergent macrophytes are also provided in Table 18 as well as nutrient contents. High tissue N concentrations have been found in plants cultured in nutrient enriched (wastewater) systems and in plants analyzed in the early stages of growth. Maximum storage of nutrients by emergent macrophytes was found to be in the range 200-1560 kg N/ha and 40-375 kg P/ha in Florida (Reddy and DeBusk 1987). More than 50 percent of the nutrients were stored in below-ground portions of the plants, tissues difficult to harvest to achieve effective nutrient removal. However, because emergent macrophytes have more supportive tissue than floating macrophytes, they might have greater potential for storing the nutrients over a longer period. Consequently, frequent harvesting might not be so necessary to achieve maximum nutrient removal although harvesting above-ground biomass once a year should improve overall nutrient removal efficiency.

<u>Table 18:</u> GROWTH AND NUTRIENT (N & P) CONTENTS OF SELECTED MACROPHYTES

	Biomass		**Tissue composition**	
	Standing crop	**Growth rates**	**N**	**P**
	t (dw) ha^{-1}	**t ha^{-1} yr^{-1}**	**--- g kg^{-1} ---**	

FLOATING MACROPHYTES:				
Eichhornia crasspipes (water hyacinth)	20.0-24.0	60-110	10-40	1.4-12.0
Pistia stratiotes (water lettuce)	6.0-10.5	50-80	12-40	1.5-11.5
Hydrocotyle spp. (pennywort)	7.0-11.0	30-60	15-45	2.0-12.5
Alternanthera spp. (alligator weed)	18.0	78	15-35	2.0-9.0
Lemna spp. (duckweed)	1.3	6-26	25	4.0-15.0
Salvinia spp.	2.4-3.2	9-45		1.8-9.0
EMERGENT MACROPHYTES:				
Typha (cattail)	4.3-22.5	8-61	5-24	0.5-4.0
Juncus (rush)	22.0	53	15	2.0
Scirpus (bulrush)			8-27	1.0-3.0
Phragmites (reed)	6.0-35.0	10-60	18-21	2.0-3.0
Eleocharis (spike rush)	8.8	26	9-18	1.0-3.0
Saururus cernuus (lizardis tail)	4.5-22.5	-	15-25	1.0-5.0

Source: Reddy and De Busk (1987)

3.3.4 Nutrient film technique

The nutrient film technique (NFT) is a modification of the hydroponic plant growth system in which plants are grown directly on an impermeable surface to which a thin film of wastewater is continuously applied (Figure 10). Root production on the impermeable surface is high and the large surface area traps and accumulates matter. Plant top-growth provides nutrient uptake, shade for protection against algal growth and water removal in the form of transpiration, while the large mass of self-generating root systems and accumulated material serve as living filters. Jewell **et al.** (1983) have hypothesized the following mechanisms, taking place in three plant sections:

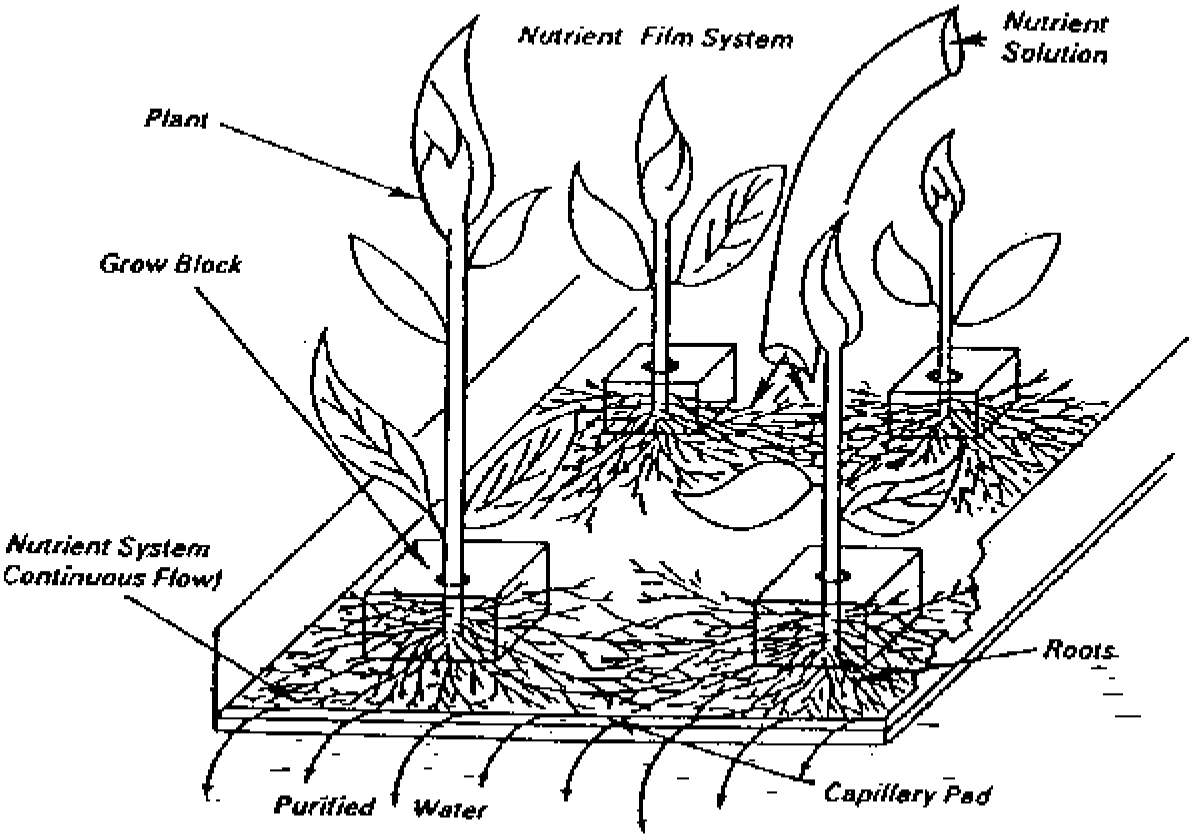
- Roughing or preliminary treatment by plant species with large root systems capable of surviving and growing in a grossly polluted condition. Large sludge accumulations, anaerobic conditions and trace metal precipitation and entrapment characterize this mechanism and a large portion of wastewater BOD and suspended solids would thereby be removed.

- Nutrient conversion and recovery due to high biomass production.

- Wastewater polishing during nutrient-limited plant production, depending on the required effluent quality.

A three year pilot-scale study by Jewell **et al.** (1983) proved this to be a viable alternative for sewage treatment. Reed canary grass was used as the main test species and resulted in the production of better than secondary effluent quality at an application rate of 10 cm/d of settled domestic sewage and synthetic wastewater. The highest loading rates achieved were equivalent to treating the sewage generated by a population of 10,000 on an area of 2 ha. Plants other than reed canary grass were also tested and those that flourished best in the NFT system were: cattails, bulrush, strawflowers, Japanese millet, roses, Napier grass, marigolds, wheat and phragmites.

Figure 10: Nutrient film technique variation of hydroponic plant production systems (Jewell *et al.* 1983)



4. Aquifer recharge with wastewater

4.1 Principles

4.1.1 Soil-aquifer treatment (SAT)

Where soil and groundwater conditions are favourable for artificial recharge of groundwater through infiltration basins, a high degree of upgrading can be achieved by allowing partially-treated sewage effluent to infiltrate into the soil and move down to the groundwater. The unsaturated or "vadose" zone then acts as a natural filter and can remove essentially all suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms. Significant reductions in nitrogen, phosphorus, and heavy metals concentrations can also be achieved.

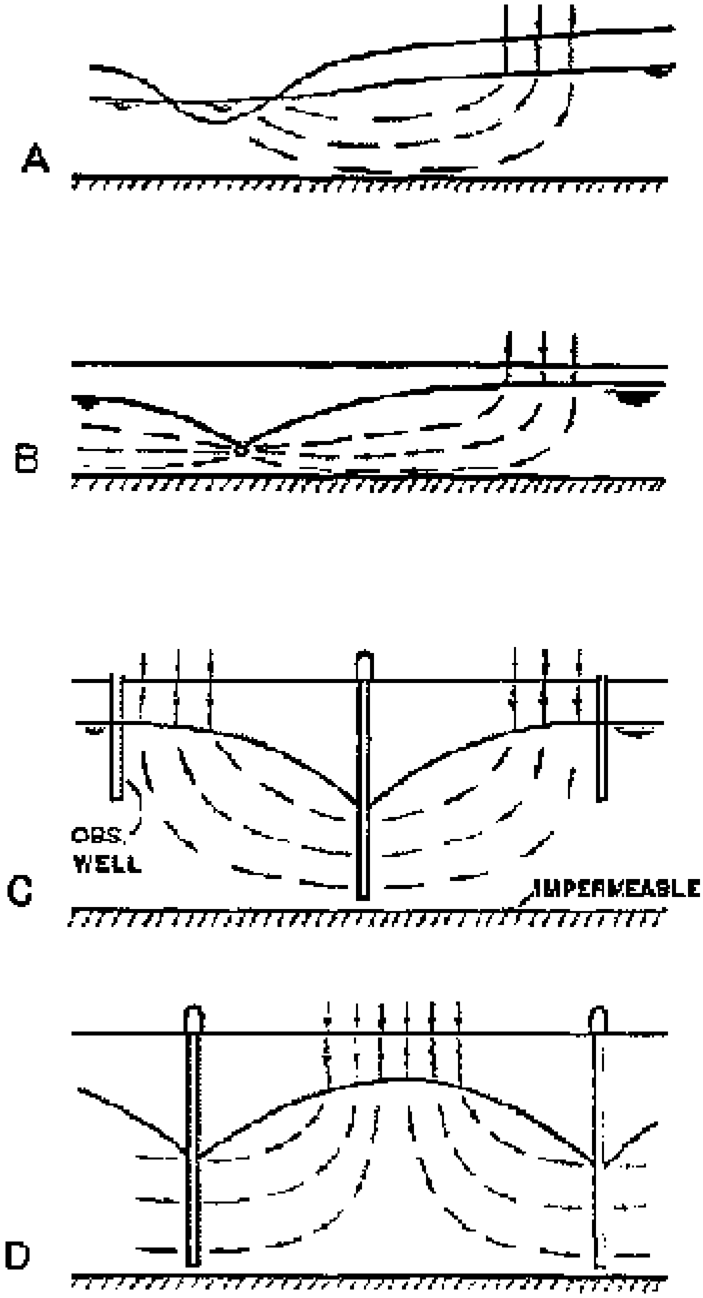
After the sewage, treated in passage through the vadose zone, has reached the groundwater it is usually allowed to flow some distance through the aquifer before it is collected (Figure 11). This additional movement through the aquifer can produce further purification (removal of microorganisms, precipitation of phosphates, adsorption of synthetic organics, etc.) of the sewage. Since the soil and aquifer are used as natural treatment, systems such as those in Figure 11 are called soil-aquifer treatment systems or SAT systems. Soil-aquifer treatment is, essentially, a low-technology, advanced wastewater treatment system. It also has an aesthetic advantage over conventionally treated sewage in that water recovered from an SAT system is not only clear and odour-free but it comes from a well, drain, or via natural drainage to a stream or low area, rather than from a sewer or sewage treatment plant. Thus, the water has lost its connotation of sewage and the public see it water more as coming out of the ground (groundwater) than as sewage effluent. This could be an important factor in the public acceptance of sewage reuse schemes.

4.1.2 SAT system layouts

Various types of SAT system are shown in Figure 11, the simplest being where the sewage effluent is applied to infiltration basins on high ground from where it moves down to the groundwater and eventually drains naturally through an aquifer into a lower area (Figure 11A). This lower area can be a natural depression or seepage area, a stream or lake, or a surface drain. SAT systems as in Figure 11A also serve to reduce the pollution of surface waters. Instead of discharging wastewater directly into streams or lakes, it is applied to infiltration basins at a higher elevation so that it receives soil-aquifer treatment before entering the stream or lake. The system shown in Figure 11B is similar to that shown in 11A but the treated sewage water, after SAT, is collected by underground, agricultural-type drains. Systems 11A and 11B have the advantage that the entire SAT process is accomplished without pumping.

Where the groundwater is too deep to collect the renovated sewage water by gravity, pumped wells must be used and there are two basic layouts. In one (Figure 11C), the infiltration basins are arranged in two parallel strips and the wells are located on the line midway between the two strips. In the other (Figure 11D), the infiltration basins are located close together in a cluster and the wells are on a circle around this cluster. The system of Figure 11C can be designed and managed so that the wells pump essentially all renovated sewage water and no native groundwater from the aquifer outside the SAT system. Systems as in Figure 11D are more likely to deliver a mixture of renovated sewage water and native groundwater. Systems 11C and 11D can be used both for seasonal underground storage of sewage water, allowing the groundwater mound to rise during periods of low irrigation water demand (winter), and for pumping the groundwater mound down in periods of high irrigation water demands (summer). The type of SAT system shown in Figure 11C would be suitable for small systems where there are only a few basins around a centrally located well (Figure 12).

Figure 11: Schematic of soil-aquifer treatment systems (Bouwer 1987)

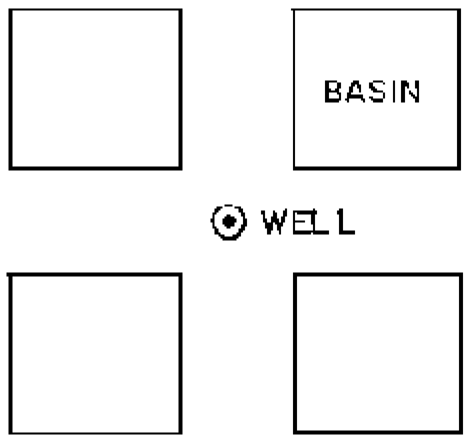


While SAT systems give considerable water quality improvement to the sewage effluent, the quality of the resulting renovated water is not often as good as that of the native groundwater. Thus, SAT systems should normally be designed and managed to prevent encroachment of sewage water into the aquifer outside the portion of the aquifer used for soil-aquifer treatment. For systems A and B in Figure 11, this could be achieved by ensuring that all the renovated water is intercepted by the surface or subsurface drain, which would result from excavating or installing the drain deeply enough to make sure that groundwater on the other side of the drain also moves toward the drain.

For system C in Figure 11, movement of renovated sewage water to the aquifer outside the SAT system can be prevented by managing infiltration and pumping rates so that the groundwater table below the outer boundaries of the infiltration strips never rises higher than the groundwater table outside the SAT system. This requires groundwater-level monitoring in a few observation wells installed at the outer edges of the infiltration strips (Figure 11C). In the case of system D in Figure 11, movement of renovated sewage water into the aquifer outside the circle of wells can be prevented by pumping the wells at sufficient rate so that there is movement of native groundwater outside the SAT system toward the wells.

Sewage water should travel sufficient distance through the soil and aquifer, and residence times in the SAT system should be long enough, to produce renovated water of the desired quality. While 100 m underground travel and one month underground retention time have been suggested as rule-of-thumb values, the actually required values depend on the quality of sewage effluent infiltrating into the ground, the soil types in the vadose zone and aquifer, the depth to groundwater, and the desired quality of the renovated water. Most of the quality improvement of sewage effluent moving through an SAT system occurs in the top 1m of soil. However, longer travel is desirable because it gives more complete removal of microorganisms and "polishing" treatment.

Figure 12: Schematic of four small infiltration basins with well in centre for pumping renovated sewage water from aquifer (Bouwer 1987)



4.1.3 Soil requirements

Infiltration basins for SAT systems should be located in soils that are permeable enough to give high infiltration rates. This requirement is important where sewage flows are relatively large, where excessive basin areas should be avoided (due to land cost) and where evaporation losses from the basins should be minimized. The soils, however, should also be fine enough to provide good filtration and quality improvement of the effluent as it passes through. Thus, the best surface soils for SAT systems are in the fine sand, loamy sand, and sandy loam range. Materials deeper in the vadose zone should be granular and preferably coarser than the surface soils. Soil profiles consisting of coarse-textured material on top and finer-textured material deeper down should be avoided because of the danger that fine suspended material in the sewage will move through the coarse upper material and accumulate on the deeper, finer material. This could cause clogging of the soil profile at some depth, where removal of the clogging material would be very difficult.

Vadose zones should not contain clay layers or other soils that could restrict the downward movement of water and form perched groundwater mounds. Aquifers should be sufficiently deep and transmissive to prevent excessive rises of the groundwater table (mounding) due to infiltration. Groundwater tables should be at least 1 m below the bottom of the infiltration basins during flooding. Above all, soil and aquifer materials should be granular. Fractured-rock aquifers should be protected by a soil mantle of adequate texture and thickness (at least a few metres). Shallow soils underlain by fractured rock are not suitable for SAT systems.

4.2 Operations

4.2.1 Hydraulic capacity and evaporation

Infiltration basins in SAT systems are intermittently flooded to provide regular drying periods, for restoration of infiltration rates and for aeration of the soil. Flooding schedules typically vary from 8 hours dry-16 hours flooding to 2 weeks dry-2 weeks flooding. Therefore, SAT systems should have a number of basins so that some basins can be flooded while others are drying. Annual infiltration amounts or "hydraulic loading rates" typically vary from 15 m/year to 100 m/year, depending on soil, climate, quality of sewage effluent, and frequency of basin cleaning. Thus, assuming a sewage production of 100 l/person day, a city of 100,000 people, and a hydraulic loading rate of 50 m/year, an SAT system for the entire sewage flow would require about 7.3 ha of infiltration basins. This shows that SAT systems do not necessarily require very large land areas, provided, of course, that the soils are permeable enough and the sewage is of such a quality (low suspended solids content) so as to allow high hydraulic loading rates to be maintained.

Evaporation losses from free water surfaces in dry, warm areas typically range between 1 and 2 m/year. Since the soil of infiltration basins will be mostly wet during drying, evaporation from intermittently flooded basins will be almost the same as that under continuous flooding conditions. Assuming an SAT system with a hydraulic loading rate of 50 m/year and evaporation losses of 1.5 m/year, evaporation losses would be 3% of all the sewage applied which would cause a 3 % increase in the concentration of dissolved salts in the sewage water.

4.2.2 Basin management

Bare soil is often the best condition for the bottom of infiltration basins in SAT systems. Occasional weeds are no problem but too many weeds can hamper the soil drying process, which delays recovery of infiltration rates. Dense weeds can also aggravate mosquito and other insect problems. Low water depths (about 20 cm) may be preferable to large water depths (about 1 m) because the turnover rate of sewage applied to shallow basins is faster than for deep basins of the same infiltration rate, thus giving suspended algae less time to develop in shallow basins. Suspended algae can produce low infiltration rates because they are filtered out on the basin bottom, where they clog the soil. Also, algae, being photosynthetic, remove dissolved carbon dioxide from the water, which increases the pH of the water. At high algal concentrations, this can cause the pH to rise to 9 or 10 which, in turn, causes precipitation of calcium carbonate. This cements the soil surface and results in further soil clogging and reduction of infiltration rates. Because suspended algae and soil clogging problems are reduced, shallow basins generally yield higher hydraulic loading rates than deep basins.

During flooding, organic and other suspended solids in the sewage effluent accumulate on the bottom of the basins, producing a clogging layer which causes infiltration rates to decline. Drying of the basins causes the clogging layer to dry, crack, and form curled-up flakes; the organic material also decomposes. These processes restore the hydraulic capacity so that when the basins are flooded again, infiltration rates are close to the original, high levels. However, as flooding continues, infiltration rates decrease again until they become so low that another drying period is necessary.

Depending on how much material accumulates on the bottom of infiltration basins, periodic removal of this material is necessary. Removing the material by raking or scraping is much better than mixing it with the soil with, for example, a disk harrow. The latter practice will lead to gradual accumulation of clogging materials in the top 10 or 20 cm of the soil, eventually necessitating complete removal of this layer, which could be expensive.

For clean secondary sewage effluent with suspended solids concentration of 10 to 20 mg/l, flooding and drying periods can be as long as 2 weeks each, and cleaning of basin bottoms may be necessary only once a year or once every 2 years. Primary effluent, with much higher suspended solids concentration, will require a schedule which might be 2 days flooding-8 days drying, and basin bottoms might be expected to require cleaning at the end of almost every drying period. The best schedule of flooding, drying, and cleaning of basins in a given system must be evaluated by on-site experimentation.

4.2.3 Pretreatment

The main constituent that must be removed from raw sewage before it is applied to an SAT system is suspended solids. Reductions in BOD and bacteria are also desirable, but less essential. In the USA, there are several hundred SAT systems and, prior to land application, the sewage typically receives conventional primary and secondary treatment because that is the treatment normally prescribed before anything can be done with the effluent. Secondary treatment removes mostly biodegradable material, as expressed by the BOD, but bacteria in the soil can also degrade organic material and reduce the BOD of the sewage to essentially zero. Thus, where pretreatment is followed by SAT, primary treatment would normally be sufficient. The primary effluent would have a higher BOD and suspended solids content than secondary effluent and this would result in somewhat lower hydraulic loading rates for the SAT system and would require more frequent basin cleaning (Rice and Bouwer 1984). However, elimination of the secondary step in conventional pretreatment of the effluent would result in very significant cost savings for the overall system.

4.3 Effects

As mentioned previously, the main constitutents that must be removed from sewage effluent before it can be used for unrestricted irrigation are pathogenic organisms. Nitrogen concentration might also have to be reduced and suspended solids and biodegradable materials should perhaps be removed to protect the irrigation system or for aesthetic reasons. If the renovated water is to be used for recreational lakes or discharged into surface water, phosphorus should also be removed to prevent algal growth in the receiving water. The following sections describe how these constituents are removed or reduced in SAT systems.

4.3.1 Suspended solids

After appropriate pretreatment, the suspended solids in sewage effluent are usually relatively fine and in organic form (sewage sludge, bacteria, floes, algal cells, etc.). These solids accumulate on the soil in the infiltration basins, requiring regular drying for infiltration recovery and periodic removal from the soil by raking or scraping. For loamy sands and sandy loams, few suspended solids will penetrate into the soil and then, usually, only for a short distance (a few cm, for example). In dune sands and other coarser soils, fine and colloidal suspended solids (including algal cells) can penetrate much greater distances. Except for medium and coarse uniform sands, soils are very effective filters, and suspended solids will be essentially completely removed from the sewage effluent after about 1m of percolation through the vadose zone. Additional details regarding suspended solids removal and clogging are given in Bouwer (1985) and Bouwer and Chaney (1974).

4.3.2 Organic compounds

Most organic compounds of human, animal or plant origin in sewage effluent are rapidly decomposed in the soil. Under aerobic conditions (intermittent flooding), breakdown is generally faster and more complete (to carbon dioxide, minerals and water) than under anaerobic conditions. The latter prevail in the soil profile during continuous or long-term flooding. Stable, non-toxic organic compounds such as humic and fulvic acids can be formed as products of reactions between proteins and carbohydrates (cellulose or lignin).

The BOD_5 of sewage varies from several hundred to about 1000 mg/l for raw sewage, and from about 10 to 20 mg/l for good quality secondary effluent. SAT systems can handle high BOD-loadings, probably hundreds of kg/ha day (Bouwer and Chaney 1974), and BOD levels are generally reduced to essentially zero after a few metres (often less) of percolation through soil. However, the final product water from SAT systems still contains some organic carbon, usually a few mg/l. This is probably mostly due to humic and fulvic acids but also to synthetic organic compounds in the sewage effluent that do not break down in the underground environment.

Halogenated hydrocarbons tend to be more resistant to biodegradation than non-halogenated hydrocarbons (Bouwer et al. 1984; Bouwer and Rice 1984). Synthetic organic compounds in the renovated water from SAT systems are generally present at very low concentrations, usually at the ppb (micrograms/l) level, and are not considered a problem when the water is used for irrigation. If it were to be used for drinking, however, additional treatment of the water by, for example, carbon filtration and reverse osmosis, would be necessary to remove the organic compounds. Additional details regarding BOD removal in SAT systems are given in Bouwer (1985) and Bouwer and Chaney (1974).

4.3.3 Bacteria and viruses

Pathogenic organisms in sewage effluent include salmonella, shigella, mycobacterium, and *vibrio comma.* Specific tests for these bacteria are not routinely carried out but, instead, the numbers of faecal coliform bacteria are normally determined. *Escherichia coli* are indicator organisms that are widely used to detect faecal contamination of water and the assumption is that if faecal coliform bacteria are present in a sample, then human pathogenic bacteria could also exist. It is also inferred that if faecal coliform bacteria are no longer present, pathogenic bacteria are also absent. Viruses in sewage effluent include entero- and adeno-viruses. Hepatitis viruses are of special concern. Viruses in renovated water from SAT systems are tested for by passing large volumes (1000 to 2000 l) through positively-charged filters to trap the viruses. Subsequently the viruses are determined in the laboratory as plaque-forming units (PFU's), which usually represent clusters of viruses. Specific viruses are tested for serologically. Other pathogens in sewage effluent include protozoa and helminth parasites, which are discussed elsewhere.

Soil is an effective filter to remove microorganisms from sewage effluent (except, of course, coarse soils such as sands and gravels, or fractured rock). Bacteria are physically strained from the water, whereas the much smaller viruses are usually adsorbed. This adsorption is favored by a low pH, a high salt concentration in the sewage, and high relative concentrations of calcium and magnesium over monovalent cations such as sodium and potassium. Human bacteria and viruses immobilized in the soil do not reproduce, and eventually die. Most bacteria and viruses die in a few weeks to a few months, but much longer survival times have also been reported. Many studies indicate essentially complete faecal coliform removal after percolation of 1 to a few metres through the soil. However, much longer distances of underground travel of microorganisms have also been reported. Usually, these long distances are associated with macropores, as may be found in gravelly or other coarse materials, structured or cracked clay soils, fractured rock, cavernous limestones, etc.

The best protection against breakthrough of pathogenic microorganisms in the renovated sewage water from SAT systems is to reduce bacterial levels in the sewage effluent before infiltration, to avoid coarse textured materials in the SAT systems, and to allow long underground travel distances and retention times. Additional information on this subject is provided in Bouwer (1985), Bouwer and Chaney (1974) and Gerba and Goyal (1985).

4.3.4 Nitrogen

Nitrogen levels in sewage can range from 20 to more than 100 mg/l, depending on in-house water use and diet of the local people and on the treatment of the sewage effluent prior to SAT. Nitrogen is primarily present as organic, ammonium, and nitrate nitrogen. The relative amounts of these nitrogen forms depend on the form of treatment prior to SAT. For secondary effluent, much of the nitrogen will often be in the ammonium form but some processes are designed to achieve nitrification and the effluent will then contain primarily nitrate-nitrogen. Raw sewage has considerable organic nitrogen.

The desirable form and concentration of nitrogen in the renovated sewage water from an SAT system depends on the nitrogen and water requirements of the crops to be irrigated, the need for preventing nitrate pollution of groundwater in the irrigated area due to excess nitrogen application to the crops, and on other possible uses of the water (including fish ponds, for which low concentrations of ammonium are required).

Control of the form and concentration of the nitrogen in renovated water from an SAT system is possible by properly selecting hydraulic loading rates and flooding and drying periods for the infiltration basins. For example, if the nitrogen in the sewage effluent is mostly in the ammonium form, short flooding periods and frequent drying of the infiltration basins (for example, 2 days flooding-5 days drying) will cause essentially complete nitrification of the ammonium in the soil, due to frequent aeration of the soil profile and resulting aerobic conditions. Thus, almost all the nitrogen in the renovated water from the SAT system will then be in the nitrate form and at concentrations about equal to the total nitrogen concentration in the sewage effluent applied to the basin. Long flooding and drying periods (for example, 1 month flooding-1 month drying) would eventually lead to complete breakthrough of ammonium in the renovated water because of anaerobic conditions in the soil and absence of nitrification. If flooding and drying periods are of intermediate length (for example, 1 to 2 weeks flooding-1 to 2 weeks drying), there will be a succession of aerobic and anaerobic conditions in the upper part of the soil profile, which stimulates nitrification and denitrification. The latter is an anaerobic bacterial process that reduces nitrate to free nitrogen gas and oxides of nitrogen that return to the atmosphere. With this process, about 75% of the nitrogen in sewage has been removed in an SAT system in Arizona, USA, with almost all of the remaining nitrogen in the renovated water occurring in the nitrate form.

Denitrification requires the presence of nitrate and organic carbon (an energy source for denitrifying bacteria) under anaerobic conditions. About 1 mg/l of organic carbon is required for each mg of nitrate nitrogen to be denitrified. If the nitrogen in the sewage is already mostly in the nitrate form and the water quite stabilized, organic carbon (as primary effluent, for example) may have to be added to the sewage effluent to achieve sufficient denitrification when the system goes anaerobic. Local experimentation is usually required to find the optimum schedule for flooding and drying, hydraulic loading, and organic carbon addition for stimulating denitrification. More information can be found in Bouwer (1985) and Bouwer and Chaney (1974).

4.3.5 Phosphorus

Sewage effluent can contain 5 to 50 mg/l phosphorus, depending on diet and water use of the local population. During pretreatment of the sewage, and in passage through the soil of the SAT system, organic phosphorus is biologically converted to phosphate. In calcareous soils and at alkaline pH, phosphate precipitates with calcium to form calcium phosphate. In acid soils, phosphate reacts with iron and aluminium oxides in the soil to form insoluble compounds. Sometimes, phosphate is initially immobilized by adsorption to the soil and then slowly reverts to insoluble forms, allowing more adsorption of mobile phosphate, etc. In clean sands with about neutral pH, phosphate can be relatively mobile. Further information is given in Bouwer (1985) and Bouwer and Chaney (1974).

4.3.6 Trace elements and salts

Sewage effluent contains a wide spectrum of other chemicals at low concentrations. These include heavy metals, fluorine, and boron. Unless these elements were already present in large concentrations in the drinking water or added to the sewage in significant amounts by industrial discharges, their concentrations in sewage are usually below the maximum limits for irrigation water (FAO 1985).

Metals are significantly retained in most soils but a high pH favours immobilization. Fluoride can form calcium fluoride, which has a very low solubility, in the soil and is also adsorbed by various soil components, especially hydrous aluminium oxides. Boron is mobile in sands and gravels but can be adsorbed on clay. Thus, SAT systems can significantly reduce the concentrations of trace elements in sewage effluent (Bouwer 1985; Bouwer and Chaney 1974).

Total salt concentrations in sewage effluent can be several hundred mg/l higher than in drinking water. Since SAT systems generally have sandy soils, hydraulic loading rates will be much higher than evaporation losses (for example, 50 m/yr vs 1.5 m/yr). Hence, the salt concentration in the renovated water from SAT systems will be about the same as (or slightly higher than) that of the sewage effluent. If clay or organic matter is present in the soil, there will be cation adsorption and ion exchange when the SAT system is first put into operation. However, eventually, the ionic composition of the renovated sewage water will be essentially the same as that of the sewage effluent going into the ground. SAT systems do not remove salts from sewage.

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5. Irrigation with wastewater

5.1 Conditions for successful irrigation

Irrigation may be defined as the application of water to soil for the purpose of supplying the moisture essential for plant growth. Irrigation plays a vital role in increasing crop yields and stabilizing production. In arid and semi-arid regions, irrigation is essential for economically viable agriculture, while in semi-humid and humid areas, it is often required on a supplementary basis.

At the farm level, the following basic conditions should be met to make irrigated farming a success:

- the required **amount** of water should be applied;
- the water should be of acceptable **quality;**
- water application should be properly **scheduled;**
- appropriate irrigation **methods** should be used;
- salt accumulation in the root zone should be prevented by means of **leaching;**
- the rise of water table should be controlled by means of appropriate **drainage;**

- plant **nutrients** should be managed in an optimal way.

The above requirements are equally applicable when the source of irrigation water is treated wastewater. Nutrients in municipal wastewater and treated effluents are a particular advantage of these sources over conventional irrigation water sources and supplemental fertilizers are sometimes not necessary. However, additional environmental and health requirements must be taken into account when treated wastewater is the source of irrigation water.

5.1.1 Amount of water to be applied

It is well known that more than 99 percent of the water absorbed by plants is lost by transpiration and evaporation from the plant surface. Thus, for all practical purposes, the water requirement of crops is equal to the evapotranspiration requirement, ET_c. Crop evapotranspiration is mainly determined by climatic factors and hence can be estimated with reasonable accuracy using meteorological data. An extensive review of this subject and guidelines for estimating ET_c, prepared by Doorenbos and Pruitt, are given in Irrigation and Drainage Paper 24 (FAO 1977). A computer program, called CROPWAT, is available in FAO to determine the water requirements of crops from climatic data. Table 19 presents the water requirements of some selected crops, reported by Doorenbos and Kassam (FAO 1979). It should be kept in mind that the actual amount of irrigation water to be applied will have to be adjusted for effective rainfall, leaching requirement, application losses and other factors.

5.1.2 Quality of water to be applied

Irrigation water quality requirements from the point of view of crop production have been discussed in Chapter 2. The guidelines presented are indicative in nature and will have to be adjusted depending on the local climate, soil conditions and other factors. In addition, farm practices, such as the type of crop to be grown, irrigation method, and agronomic practices, will determine to a great extent the quality suitability of irrigation water. Some of the important farm practices aimed at optimizing crop production when treated sewage effluent is used as irrigation water will be discussed in this chapter.

Table 19: WATER REQUIREMENTS, SENSITIVITY TO WATER SUPPLY AND WATER UTILIZATION EFFICIENCY OF SOME SELECTED CROPS

Crop	**Water requirements (mm/growing period)**	**Sensitivity to water supply (ky)**	**Water utilization efficiency for harvested yield, Ey, kg/m^3 (% moisture)**
Alfalfa	800-1600	low to medium-high (0.7-1.1)	1.5-2.0 hay (10-15%)
Banana	1200-2200	high (1.2-1.35)	plant crop: 2.5-4 ratoon: 3.5-6

			fruit (70%)
Bean	300-500	medium-high (1.15)	lush: 1.5-2.0 (80-90%) dry: 0.3-0.6 (10%)
Cabbage	380-500	medium-low (0.95)	12-20 head (90-95%)
Citrus	900-1200	low to medium-high (0.8-1.1)	2-5 fruit (85%, lime: 70%)
Cotton	700-1300	medium-low (0.85)	0.4-0.6 seed cotton (10%)
Groundnut	500-700	low (0.7)	0.6-0.8 unshelled dry nut (15%)
Maize	500-800	high (1.25)	0.8-1.6 grain (10-13%)
Potato	500-700	medium-high (1.1)	4-7 fresh tuber (70-75%)
Rice	350-700	high	0.7-1.1 paddy (15-20%)
Safflower	600-1200	low (0.8)	0.2-0.5 seed (8-10%)
Sorghum	450-650	medium-low (0.9)	0.6-1.0 grain (12-15%)
Wheat	450-650	medium high (spring: 1.15; winter: 1.0)	0.8-1.0 grain (12-15%)

Source: FAO(1979)

5.1.3 Scheduling of irrigation

To obtain maximum yields, water should be applied to crops before the soil moisture potential reaches a level at which the evapotranspiration rate is likely to be reduced below its potential. The relationship of actual and maximum yields to actual and potential evapotranspiration is illustrated in the following equation:

(12)

$$\left(1-\frac{Y_a}{Y_m}\right)=ky\left(1-\frac{ET_a}{ET_m}\right)$$

where:

Y_a = actual harvested yield
Y_m = maximum harvested yield
ky = yield response factor

ET_a = actual evapotranspiration
ET_m = maximum evapotranspiration

Several methods are available to determine optimum irrigation scheduling. The factors that determine irrigation scheduling are: available water holding capacity of the soils, depth of root zone, evapotranspiration rate, amount of water to be applied per irrigation, irrigation method and drainage conditions.

5.1.4 Irrigation methods

Many different methods are used by farmers to irrigate crops. They range from watering individual plants from a can of water to highly automated irrigation by a centre pivot system. However, from the point of wetting the soil, these methods can be grouped under five headings, namely:

i. **Flood irrigation -** water is applied over the entire field to infiltrate into the soil (e.g. wild flooding, contour flooding, borders, basins, etc.).

ii. **Furrow irrigation -** water is applied between ridges (e.g. level and graded furrows, contour furrows, corrugations, etc.). Water reaches the ridge, where the plant roots are concentrated, by capillary action.

iii. **Sprinkler irrigation -** water is applied in the form of a spray and reaches the soil very much like rain (e.g. portable and solid set sprinklers, travelling sprinklers, spray guns, centre-pivot systems, etc.). The rate of application is adjusted so that it does not create ponding of water on the surface.

iv. **Sub-irrigation -** water is applied beneath the root zone in such a manner that it wets the root zone by capillary rise (e.g. subsurface irrigation canals, buried pipes, etc.). Deep surface canals or buried pipes are used for this purpose.

v. **Localized irrigation -** water is applied around each plant or a group of plants so as to wet locally and the root zone only (e.g. drip irrigation, bubblers, micro-sprinklers, etc.). The application rate is adjusted to meet evapotranspiration needs so that percolation losses are minimized.

Table 20 presents some basic features of selected irrigation systems as reported by Doneen and Westcot (FAO 1988).

Table 20: BASIC FEATURES OF SOME SELECTED IRRIGATION SYSTEMS

Irrigation method	Topography	Crops	Remarks
Widely spaced	Land slopes capable of being	Alfalfa and other deep	The most desirable surface method for irrigating close-growing crops where

borders	graded to less than 1 % slope and preferably 0.2%	rooted close-growing crops and orchards	topographical conditions are favourable. Even grade in the direction of irrigation is required on flat land and is desirable but not essential on slopes of more than 0.5%. Grade changes should be slight and reverse grades must be avoided. Cross slops is permissible when confined to differences in elevation between border strips of 6-9 cm. Water application efficiency 45-60%.
Graded contour furrows	Variable land slopes of 2-25 % but preferable less	Row crops and fruit	Especially adapted to row crops on steep land, though hazardous due to possible erosion from heavy rainfall. Unsuitable for rodent-infested fields or soils that crack excessively. Actual grade in the direction of irrigation 0.5-1.5%. No grading required beyond filling gullies and removal of abrupt ridges. Water application efficiency 50-65%.
Rectangular checks (levees)	Land slopes capable of being graded so single or multiple tree basins will be levelled within 6 cm	Orchard	Especially adapted to soils that have either a relatively high or low water intake rate. May require considerable grading. Water application efficiency 40-60%.
Sub-irrigation	Smooth-flat	Shallow rooted crops such as potatoes or grass	Requires a water table, very permeable subsoil conditions and precise levelling. Very few areas adapted to this method. Water application efficiency 50-70%.
Sprinkler	Undulating 1->35% slope	All crops	High operation and maintenance costs. Good for rough or very sandy lands in areas of high production and good markets. Good method where power costs are low. May be the only practical method in areas of steep or rough topography. Good for high rainfall areas where only a small supplementary water supply is needed. Water application efficiency 60-70 %.
Localized (drip, trickle, etc.)	Any topographic condition suitable for row crop farming	Row crops or fruit	Perforated pipe on the soil surface drips water at base of individual vegetable plants or around fruit trees. Has been successfully used in Israel with saline irrigation water. Still in development stage. Water application efficiency 75-85 %.

Source: FAO (1988)

5.1.5 Leaching

Under irrigated agriculture, a certain amount of excess irrigation water is required to percolate through the root zone so as to remove the salts which have accumulated as a result of evapotranspiration from the original irrigation water. This process of displacing the salts from the root zone is called leaching and that portion of the irrigation water which mobilizes the excess of salts is called the leaching fraction, LF.

(13)

$$\text{Leaching Fraction (LF)} = \frac{\text{depth of water leached below the root zone}}{\text{depth of water applied at the surface}}$$

Salinity control by effective leaching of the root zone becomes more important as irrigation water becomes more saline.

5.1.6 Drainage

Drainage is defined as the removal of excess water from the soil surface and below so as to permit optimum growth of plants. Removal of excess surface water is termed surface drainage while the removal of excess water from beneath the soil surface is termed sub-surface drainage. The importance of drainage for successful irrigated agriculture has been well demonstrated. It is particularly important in semi-arid and arid areas to prevent secondary salinization. In these areas, the water table will rise with irrigation when the natural internal drainage of the soil is not adequate. When the water table is within a few metres of the soil surface, capillary rise of saline groundwater will transport salts to the soil surface. At the surface, water evaporates, leaving the salts behind. If this process is not arrested, salt accumulation will continue, resulting in salinization of the soil. In such cases, sub-surface drainage can control the rise of the water table and hence prevent salinization.

5.2 Strategies for managing treated wastewater on the farm

Success in using treated wastewater for crop production will largely depend on adopting appropriate strategies aimed at optimizing crop yields and quality, maintaining soil productivity and safeguarding the environment. Several alternatives are available and a combination of these alternatives will offer an optimum solution for a given set of conditions. The user should have prior information on effluent supply and its quality, as indicated in Table 21, to ensure the formulation and adoption of an appropriate on-farm management strategy.

Basically, the components of an on-farm strategy in using treated wastewater will consist of a combination of:

- crop selection,
- selection of irrigation method, and
- adoption of appropriate management practices.

Furthermore, when the farmer has additional sources of water supply, such as a limited amount of normal irrigation water, he will then have an option to use both the effluent and the conventional source of water in two ways, namely:

- by blending conventional water with treated effluent, and
- using the two sources in rotation.

These are discussed briefly in the following sections.

Table 21: INFORMATION REQUIRED ON EFFLUENT SUPPLY AND QUALITY

Information	Decision on irrigation management
Effluent supply	
The total amount of effluent that would be made available during the crop growing season.	Total area that could be irrigated.
Effluent available throughout the year.	Storage facility during non crop growing period either at the farm or near wastewater treatment plant, and possible use for aquaculture.
The rate of delivery of effluent either as m^3 per day or litres per second.	Area that could be irrigated at any given time, layout of fields and facilities and system of irrigation.
Type of delivery: continuous or intermittent, or on demand.	Layout of fields and facilities, irrigation system, and irrigation scheduling.
Mode of supply: supply at farm gate or effluent available in a storage reservoir to be pumped by the farmer.	The need to install pumps and pipes to transport effluent and irrigation system.
Effluent quality	
Total salt concentration and/or electrical conductivity of the effluent.	Selection of crops, irrigation method, leaching and other management practices.
Concentrations of cations, such as Ca^{++}, Mg^{++} and Na^{+}.	To assess sodium hazard and undertake appropriate measures.
Concentration of toxic ions, such as heavy metals, Boron and Cl^{-}.	To assess toxicities that are likely to be caused by these elements and take appropriate measures.
Concentration of trace elements (particularly those which are suspected of being phyto-toxic).	To assess trace toxicities and take appropriate measures.
Concentration of nutrients, particularly nitrate-N.	To adjust fertilizer levels, avoid over-fertilization and select crop.
Level of suspended sediments.	To select appropriate irrigation system and measures to prevent clogging problems.
Levels of intestinal nematodes and faecal	To select appropriate crops and irrigation systems.

coliforms.	

5.3 Crop selection

5.3.1 To overcome salinity hazards

Not all plants respond to salinity in a similar manner; some crops can produce acceptable yields at much higher soil salinity than others. This is because some crops are better able to make the needed osmotic adjustments, enabling them to extract more water from a saline soil. The ability of a crop to adjust to salinity is extremely useful. In areas where a build-up of soil salinity cannot be controlled at an acceptable concentration for the crop being grown, an alternative crop can be selected that is both more tolerant of the expected soil salinity and able to produce economic yields. There is an 8-10 fold range in the salt tolerance of agricultural crops. This wide range in tolerance allows for greater use of moderately saline water, much of which was previously thought to be unusable. It also greatly expands the acceptable range of water salinity (EC_w) considered suitable for irrigation.

The relative salt tolerance of most agricultural crops is known well enough to give general salt tolerance guidelines. Table 22 presents a list of crops classified according to their tolerance and sensitivity to salinity. Figure 13 presents the relationship between relative crop yield and irrigation water salinity with regard to the four crop salinity classes. The following general conclusions can be drawn from these data:

> i. full yield potential should be achievable with nearly all crops when using a water with salinity less than 0.7 dS/m,
>
> ii. when using irrigation water of slight to moderate salinity (i.e. 0.7-3.0 dS/m), full yield potential is still possible but care must be taken to achieve the required leaching fraction in order to maintain soil salinity within the tolerance of the crops. Treated sewage effluent will normally fall within this group,
>
> iii. for higher salinity water (more than 3.0 dS/m) and sensitive crops, increasing leaching to satisfy a leaching requirement greater than 0.25 to 0.30 might not be practicable because of the excessive amount of water required. In such a case, consideration must be given to changing to a more tolerant crop that will require less leaching, to control salts within crop tolerance levels. As water salinity (ECw) increases within the slight to moderate range, production of more sensitive crops may be restricted due to the inability to achieve the high leaching fraction needed, especially when grown on heavier, more clayey soil types,

Figure 13: Divisions for relative salt tolerance ratings of agricultural crops (Maas 1984)

Table 22: RELATIVE SALT TOLERANCE OF AGRICULTURAL CROPS

TOLERANT	
Fibre, Seed and Sugar Crops	
Barley	*Hordeum vulgare*
Cotton	*Gossypium hirsutum*
Jojoba	*Simmondsia chinensis*
Sugarbeet	*Beta vulgaris*
Grasses and Forage Crops	
Alkali grass	*Puccinellia airoides*
Alkali sacaton	*Sporobolus airoides*
Bermuda grass	*Cynodon dactylon*
Kallar grass	*Diplachne fusca*
Saltgrass, desert	*Distichlis stricta*
Wheatgrass, fairway crested	*Agropyron cristatum*
Wheatgrass, tall	*Agropyron elongatum*
Wildrye, Altai	*Elymus angustus*
Wildrye, Russian	*Elymus junceus*
Vegetable Crops	
Asparagus	*Asparagus officinalis*
Fruit and Nut Crops	
Date palm	*Phoenix dactylifera*
MODERATELY TOLERANT	
Fibre, Seed and Sugar Crops	
Cowpea	*Vigna unguiculata*
Oats	*Avena sativa*
Rye	*Secale cereale*
Safflower	*Carthamus tinctorius*

Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Triticale	*X Triticosecale*
Wheat	*Triticum aestivum*
Wheat, Durum	*Triticum turgidum*
Grasses and Forage Crops	
Barley (forage)	*Hordeum vulgare*
Brome, mountain	*Bromus marginatus*
Canary grass, reed	*Phalaris, arundinacea*
Clover, Hubam	*Melilotus alba*
Clover, sweet	*Melilotus*
Fescue, meadow	*Festuca pratensis*
Fescue, tall	*Festuca elatior*
Harding grass	*Phalaris tuberosa*
Panic grass, blue	*Panicum antidotale*
Rape	*Brassica napus*
Rescue grass	*Bromus unioloides*
Rhodes grass	*Chloris gayana*
Grasses and Forage Crops	
Ryegrass, Italian	*Lolium italicum multiflorum*
Ryegrass, perennial	*Lolium perenne*
Sudan grass	*Sorghum sudanense*
Trefoil, narrowleaf birdsfoot	*Lotus corniculatus tenuifolium*
Trefoil, broadleaf	*L. corniculatus arvenis*
Wheat (forage)	*Triticum aestivum*
Wheatgrass, standard crested	*Agropyron sibiricum*
Wheatgrass, intermediate	*Agropyron intermedium*

Wheatgrass, slender	*Agropyron trachycaulum*
Wheatgrass, western	*Agropyron smithii*
Wildrye, beardless	*Elymus triticoides*
Wildrye, Canadian	*Elymus canadensis*
Vegetable Crops	
Artichoke	*Helianthus tuberosus*
Beet, red	*Beta vulgaris*
Squash, zucchini	*Cucurbita pepo melopepo*
Fruit and Nut Crops	
Fig	*Ficus carica*
Jujube	*Ziziphys jujuba*
Olive	*Olea europaea*
Papaya	*Carica papaya*
Pineapple	*Ananas comosus*
Pomegranate	*Punica granatum*
MODERATELY SENSITIVE	
Fibre, Seed and Sugar Crops	
Broadbean	*Vicia faba*
Castorbean	*Ricinus communis*
Maize	*Zea mays*
Flax	*Linum usitatissimum*
Millet, foxtail	*Setaria italica*
Groundnut/peanut	*Arachis hypogaea*
Rice, paddy	*Oryza sativa*
Sugarcane	*Saccarum officinarum*
Sunflower	*Helianthus annuus palustris*
Grasses and Forage Crops	

Alfalfa	*Medicago sativa*
Bentgrass	*Agrostisstoloniferapalustris*
Bluestem, Angleton	*Dichanthium aristatum*
Brome, smooth	*Bromus inermis*
Buffelgrass	*Cenchrus ciliaris*
Burnet	*Poterium sanguisorba*
Clover, alsike	*Trifolium hydridum*
<u>Grasses and Forage Crops</u>	
Clover, Berseem	*Trifolium alexandrinum*
Clover, ladino	*Trifolium repens*
Clover, red	*Trifolium pratense*
Clover, strawberry	*Trifolium fragiferum*
Clover, white Dutch	*Trifolium repens*
Corn (forage) (maize)	*Zea mays*
Cowpea (forage)	*Vigna unguiculata*
Dallis grass	*Paspalum dilatatum*
Foxtail, meadow	*Alopecurus pratensis*
Grama, vlue	*Bouteloua gracilis*
Lovegrass	*Eragrostis sp.*
Milkvetch, Cicer	*Astragalus deer*
Oatgrass, tall	*Arrhenatherum, Danthonia*
Oats (forage)	*Avena saliva*
Orchard grass	*Dactylis glomerata*
Rye (forage)	*Secale cereale*
Sesbania	*Sesbania exaltata*
Siratro	*Macroptilium atropurpureum*
Sphaerophysa	*Spaerophysa salsula*

Timothy	*Phleum pratense*
Vetch, common	*Vicia angustifolia*
Vegetable Crops	
Broccoli	*Brassica oleracea botrytis*
Brussel sprouts	*B. oleracea gemmifera*
Cabbage	*B. oleracea capitata*
Cauliflower	*B. oleracea botrytis*
Celery	*Apium graveolens*
Corn, sweet	*Zea mays*
Cucumber	*Cucumis sativus*
Eggplant	*Solanum melongena esculentum*
Kale	*Brassica oleracea acephala*
Kohlrabi	*B. oleracea gongylode*
Lettuce	*Latuca sativa*
Muskmelon	*Cucumis melon*
Pepper	*Capsicum annum*
Potato	*Solanum tuberosum*
Pumpkin	*Cucurbita peop pepo*
Radish	*Raphanus sativus*
Spinach	*Spinacia oleracea*
Squash, scallop	*C. pepo melopepo*
Sweet potato	*Ipomoea batatas*
Tomato	*Lycopersicon lycopersicum*
Turnip	*Brassica rapa*
Watermelon	*Citrullus lanatus*
Fruit and Nut Crops	
Grape	*Vitis sp.*

SENSITIVE	
Fibre, Seed and Sugar Crops	
Bean	*Phaseolus vulgaris*
Guayule	*Parthenium argentatum*
Sesame	*Sesamum indicum*
Vegetable Crops	
Bean	*Phaseolus vulgaris*
Carrot	*Daucus carota*
Okra	*Abelmoschus esculentus*
Onion	*Allium cepa*
Parsnip	*Pastinaca sativa*
Fruit and Nut Crops	
Almond	*Prunus dulcis*
Apple	*Malus sylvestris*
Apricot	*Prunus armeniaca*
Avocado	*Persea americana*
Blackberry	*Rubus sp.*
Boysenberry	*Rubus ursinus*
Cherimoya	*Annona cherimola*
Cherry, sweet	*Prunus avium*
Cherry, sand	*Prunus besseyi*
Currant	*Ribes sp.*
Gooseberry	*Ribes sp.*
Grapefruit	*Citrus paradisi*
Lemon	*Citrus limon*
Lime	*Citrus aurantifolia*
Loquat	*Eriobotrya japonica*

Mango	*Mangifera indica*
Orange	*Citrus sinensis*
Passion fruit	*Passiflora edulis*
Peach	*Prunus persica*
Pear	*Pyrus communis*
Persimmon	*Diospyros virginiana*
Plum: Prune	*Prunus domestica*
Pummelo	*Citrus maxima*
Raspberry	*Rubus idaeus*
Rose apple	*Syzgium jambos*
Sapote, white	*Casimiroa edulis*
Strawberry	*Fragaria sp.*
Tangerine	*Citrus reticulata*

Source: FAO (1985)

iv. if the salinity of the applied water exceeds 3.0 dS/m, the water might still be usable but its use may need to be restricted to more permeable soils and more salt-tolerant crops, where high leaching fractions are more easily achieved. This is being practised on a large scale in the Arabian Gulf States, where drip irrigation systems are widely used.

If the exact cropping patterns or rotations are not known for a new area, the leaching requirement must be based on the least tolerant of the crops adapted to the area. In those instances, where soil salinity cannot be maintained within acceptable limits of preferred sensitive crops, changing to more tolerant crops will raise the area's production potential. If there is any doubt about the effect of wastewater salinity on crop production, a pilot study should be undertaken to demonstrate the feasibility of irrigation and the outlook for economic success.

5.3.2 To overcome toxicity hazards

A toxicity problem is different from a salinity problem in that it occurs within the plant itself and is not caused by water shortage. Toxicity normally results when certain ions are taken up by plants with the soil water and accumulate in the leaves during water transpiration to such an extent that the plant is damaged. The degree of damage depends upon time, concentration of toxic material, crop sensitivity and crop water use and, if damage is severe enough, crop yield is reduced. Common toxic ions in irrigation water are chloride, sodium, and boron, all of which will be contained in sewage. Damage can be caused by each individually or in combination. Not all crops are equally sensitive to these toxic ions. Some guidance on the sensitivity of crops to sodium, chloride and boron are given in Tables 23, 24 and 25, respectively. However, toxicity symptoms can appear in almost any crop if concentrations of toxic materials are sufficiently high. Toxicity often accompanies or complicates a salinity or infiltration problem, although it may appear even when salinity is not a problem.

The toxic ions of sodium and chloride can also be absorbed directly into the plant through the leaves when moistened during sprinkler irrigation. This typically occurs during periods of high temperature and low humidity. Leaf absorption speeds up the rate of accumulation of a toxic ion and may be a primary source of the toxicity.

In addition to sodium, chloride and boron, many trace elements are toxic to plants at low concentrations, as indicated in Table 10 in Chapter 2. Fortunately, most irrigation supplies and sewage effluents contain very low concentrations of these trace elements and are generally not a problem.

However, urban wastewater may contain heavy metals at concentrations which will give rise to elevated levels in the soil and cause undesirable accumulations in plant tissue and crop growth reductions. Heavy metals are readily fixed and accumulate in soils with repeated irrigation by such wastewaters and may either render them non-productive or the product unusable. Surveys of wastewater use have shown that more than 85 % of the applied heavy metals are likely to accumulate in the soil, most at the surface. The levels at which heavy metals accumulation in the soil is likely to have a deleterious effect on crops are discussed in Chapter 5. Any wastewater use project should include monitoring of soil and plants for toxic materials.

5.3.3 To prevent health hazards

From the point of view of human consumption and potential health hazards, crops and cultivated plants may be classified into the following groups:

Table 23: RELATIVE TOLERANCE OF SELECTED CROPS TO EXCHANGEABLE SODIUM

Sensitive	**Semi-tolerant**	**Tolerant**
Avocado	Carrot	Alfalfa
(Persea americana)	*(Daucus carota)*	*(Medicago sativa)*
Deciduous Fruits	Clover, Ladino	Barley
Nuts	*(Trifolium repens)*	*(Hordeum vulgare)*

Bean, green	Dallisgrass	Beet, garden
(Phaseolus vulgaris)	*(Paspalum dilatatum)*	*(Beta vulgaris)*
Cotton (at germination)	Fescue, tall	Beet, sugar
(Gossypium hirsutum)	*(Festuca arundinacea)*	*(Beta vulgaris)*
Maize	Lettuce	Bermuda grass
(Zea mays)	*(Lactuca sativa)*	*(Cynodon dactylon)*
Peas	Bajara	Cotton
(Pisum sativum)	*(Pennisetum typhoides)*	*(Gossypium hirsutum)*
Grapefruit	Sugarcane	Paragrass
(Citrus paradisi)	*(Saccharum officinarum)*	*(Brachiaria mutica)*
Orange	Berseem	Rhodes grass
(Citrus sinensis)	*(Trifolium alexandrinum)*	*(Chloris gayana)*
Peach	Benji	Wheatgrass, crested
(Prunus persica)	*(Mililotus parviflora)*	*(Agropyron cristatum)*
Tangerine	Raya	Wheatgrass, fairway
(Citrus reticulata)	*(Brassica juncea)*	*(agropyron cristatum)*
Mung	Oat	Wheatgrass, tall
(Phaseolus aurus)	*(Avena sativa)*	*(Agropyron elongatum)*
Mash	Onion	Karnal grass
(Phaseolus mungo)	*(Allium cepa)*	*(Diplachna fusca)*
Lentil	Radish	
(Lens culinaris)	*(Raphanus sativus)*	
Groundnut (peanut)	Rice	
(Arachis hypogaea)	*(Oryza sativus)*	
Gram	Rye	
(Cicer arietinum)	*(Secale cereale)*	
Cowpeas	Ryegrass, Italian	

(Vigna sinensis)	*(Lolium multiflorum)*	
	Sorghum	
	(Sorghum vulgare)	
	Spinach	
	(Spinacia oleracea)	
	Tomato	
	(Lycopersicon esculentum)	
	Vetch	
	(Vicia sativa)	
	Wheat	
	(Triticum vulgare)	

Source: Adapted from data of FAO-Unesco (1973); Pearson (1960); and Abrol (1982).

i. Food crops

- those eaten uncooked
- those eaten after cooking

ii. Forage and feed crops

- direct access by animals
- those fed to animals after harvesting

Table 24: CHLORIDE TOLERANCE OF SOME FRUIT CROP CULTIVARS AND ROOTSTOCKS

Crop	**Rootstock or Cultivar**	**Maximum permissible Cl^- without leaf injury**[1]	
		Root zone (Cl_e) (me/l)	**Irrigation water (Cl_w)**[2 3] **(me/l)**
	Rootstocks		
Avocado *(Persea americana)*	West Indian	7.5	5.0
	Guatemalan	6.0	4.0
	Mexican	5.0	3.3
Citrus *(Citrus spp.)*	Sunki Mandarin	25.0	16.6
	Grapefruit		

	Cleopatra mandarin		
	Rangpur lime		
	Sampson tangelo	15.0	10.0
	Rough lemon		
	Sour orange		
	Ponkan mandarin		
	Citrumelo 4475	10.0	6.7
	Trifoliate orange		
	Cuban shaddock		
	Calamondin		
	Sweet orange		
	Savage citrange		
	Rusk citrange		
	Troyer citrange		
Grape*(Vitis spp.)*	Salt Creek, 1613-3	40.0	27.0
	Dog Ridge	30.0	20.0
Stone Fruits *(Prunus spp.)*	Marianna	25.0	17.0
	Lovell, Shalil	10.0	6.7
	Yunnan	7.5	5.0
	Cultivars		
Berries *(Rubus spp.)*	Boysenberry	10.0	6.7
	Olallie clackberry	10.0	6.7
	Indian SUmmer	5.0	3.3
	Raspberry		
Grape*(Vitis spp.)*	Thompson seedless	20.0	13.3

	Perlette	20.0	13.3
	Cardinal	10.0	6.7
	Black Rose	10.0	6.7
Strawberry *(Fragaria spp.)*	Lassen	7.5	5.0
	Shasta	5.0	3.3

[1] For some crops, the concentration given may exceed the overall salinity tolerance of that crop and cause some reduction in yield in addition to that caused by chloride ion toxicities.

[2] Values given are for the maximum concentration in the irrigation water. The values were derived from saturation extract data (EC_e) assuming a 15-20 percent leaching fraction and $EC_d = 1.5\ EC_w$.

[3] The maximum permissible values apply only to surface irrigated crops. Sprinkler irrigation may cause excessive leaf bum at values far below these.

Source: Adapted from Maas (1984).

Table 25: RELATIVE BORON TOLERANCE OF AGRICULTURAL CROPS[1]

VERY SENSITIVE (<0.5 mg/l)	
Lemon	*Citrus limon*
Blackberry	*Rubus spp.*
SENSITIVE (0.5-0.75 mg/l)	
Avocado	*Persea americana*
Grapefruit	*Citrus X paradisi*
Orange	*Citrus sinensis*
Apricot	*Prunus armeniaca*
Peach	*Prunus persica*
Cherry	*Prunus avium*
Plum	*Prunus domestica*
Persimmon	*Diospyros kaki*
Fig, kadota	*Ficus carica*

Grape	*Vitis vinifera*
Walnut	*Juglans regia*
Pecan	*Carya illinoiensis*
Cowpea	*Vigna unguiculata*
Onion	*Allium cepa*
SENSITIVE (0.75-1.0 mg/l)	
Garlic	*Allium sativum*
Sweet potato	*Ipomoea batatas*
Wheat	*Triticum eastivum*
Barley	*Hordeum vulgare*
Sunflower	*Helianthus annuus*
Bean, mung	*Vigna radiata*
Sesame	*Sesamum indicum*
Lupine	*Lupinus hartwegii*
Strawberry	*Fragaria spp.*
Artichoke, Jerusalem	*Helianthus tuberosus*
Bean, kidney	*Phaseolus vulgaris*
Bean, lima	*Phaseolus lunatus*
Groundnut/Peanut	*Arachis hypogaea*
MODERATELY SENSITIVE (1.0-2.0 mg/l)	
Pepper, red	*Capsicum annuum*
Pea	*Pisum sativa*
Carrot	*Daucus carota*
Radish	*Raphanus sativus*
Potato	*Solanum tuberosum*
Cucumber	*Cucumis sativus*
MODERATELY TOLERANT (2.0-4.0 mg/l)	

Lettuce	*Lactuca sativa*
Cabbage	*B. oleracea capitata*
Celery	*Apium graveolens*
Turnip	*Brassica rapa*
Bluegrass, Kentucky	*Poa pratensis*
Oats	*Avena sativa*
Maize	*Zea mays*
Artichoke	*Cynara scolymus*
Tobacco	*Nicotiana tabacum*
Mustard	*Brassica juncea*
Clover, sweet	*Melilotus indica*
Squash	*Cucurbita pepo*
Muskmelon	*Cucumis melo*
TOLERANT (4.0-6.0 mg/l)	
Sorghum	*Sorghum bicolor*
Tomato	*L. lycopersicum*
Alfalfa	*Medicago sativa*
Vetch, purple	*Vicia benghalensis*
Parsley	*Petroselinum crispum*
Beet, red	*Beta vulgaris*
Sugarbeet	*Beta vulgaris*
VERY TOLERANT (6.0-15.0 mg/l)	
Cotton	*Gossypium hirsutum*
Asparagus	*Asparagus officinalis*

[1] Maximum concentrations tolerated in soil water without yield or vegetative growth reductions. Boron tolerances vary depending upon climate, soil conditions and crop varieties. Maximum concentrations in the irrigation water are approximately equal to these values or slightly less.

Source: Maas (1984)

iii. Landscaping plants:

- unprotected areas with public access
- semi-protected areas

iv. Afforestation plants:

- commercial (fruit, timber, fuel and charcoal)
- environmental protection (including sand stabilization)

In terms of health hazards, treated effluent with a high microbiological quality is necessary for the irrigation of certain crops, especially vegetable crops eaten raw, but a lower quality is acceptable for other selected crops, where there is no exposure to the public (see Table 8 in Chapter 2). The WHO (1989) Technical Report No. 778 suggested a categorization of crops according to the exposed group and the degree to which health protection measures are required, as shown in Example 4.

EXAMPLE 4 - CATEGORIZATION OF CROPS IN RELATION TO EXPOSED GROUP AND HEALTH CONTROL MEASURES

Category A:

- Protection required for consumers, agricultural workers, and the general public,

- Includes crops likely to be eaten uncooked, spray-irrigated fruits and grass (sports fields, public parks and lawns);

Category B:

- Protection required for agricultural workers only,

- Includes cereal crops, industrial crops (such as cotton and sisal), food crops for canning, fodder crops, pasture and trees,

- In certain circumstances some vegetable crops might be considered as belonging to Category B if they are not eaten raw (potatoes, for instance) or if they grow well above ground (for example, chillies), in such cases it is necessary to ensure that the crop is not contaminated by sprinkler irrigation or by falling on to the ground, and that contamination of kitchens by such crops, before cooking, does not give rise to a health risk.

5.4 Selection of irrigation methods

The different types of irrigation methods have been introduced in Section 5.1.4. Under normal conditions, the type of irrigation method selected will depend on water supply conditions, climate, soil, crops to be grown, cost of irrigation method and the ability of the farmer to manage the system. However, when using wastewater as the source of irrigation other factors, such as contamination of plants and harvested product, farm workers, and the environment, and salinity and toxicity hazards, will need to be considered. There is considerable scope for reducing the undesirable effects of wastewater use in irrigation through selection of appropriate irrigation methods.

The choice of irrigation method in using wastewater is governed by the following technical factors:

- the choice of crops,
- the wetting of foliage, fruits and aerial parts,
- the distribution of water, salts and contaminants in the soil,
- the ease with which high soil water potential could be maintained,
- the efficiency of application, and
- the potential to contaminate farm workers and the environment.

Table 26 presents an analysis of these factors in relation to four widely practised irrigation methods, namely border, furrow, sprinkler and drip irrigation.

Table 26: EVALUATION OF COMMON IRRIGATION METHODS IN RELATION TO THE USE OF TREATED WASTEWATER

Parameters of evaluation	Furrow irrigation	Border irrigation	Sprinkler irrigation	Drip irrigation
1 Foliar wetting and consequent leaf damage resulting in poor yield	No foliar injury as the crop is planted on the ridge	Some bottom leaves may be affected but the damage is not so serious as to reduce yield	Severe leaf damage can occur resulting in significant yield loss	No foliar injury occurs under this method of irrigation
2 Salt accumulation in the root zone with repeated applications	Salts tend to accumulate in the ridge which could harm the crop	Salts move vertically downwards and are not likely to accumulate in the root zone	Salt movement is downwards and root zone is not likely to accumulate salts	Salt movement is radial along the direction of water movement. A salt wedge is formed between drip points
3 Ability to maintain high soil water potential	Plants may be subject to stress between irrigations	Plants may be subject . to water stress between irrigations	Not possible to maintain high soil water potential throughout the growing season	Possible to maintain high soil water potential throughout the growing season and minimize the effect of salinity
4 Suitability to handle brackish wastewater without significant yield loss	Fair to medium. With good management and drainage acceptable yields are possible	Fair to medium. Good irrigation and drainage practices can produce acceptable levels of yield	Poor to fair. Most crops suffer from leaf damage and yield is low	Excellent to good. Almost all crops can be grown with very little reduction in yield

Source: Kandiah (1990b)

A border (and basin or any flood irrigation) system involves complete coverage of the soil surface with treated effluent and is normally not an efficient method of irrigation. This system will also contaminate vegetable crops growing near the ground and root crops and will expose farm workers to the effluent more than any other method. Thus, from both the health and water conservation points of view, border irrigation with wastewater is not satisfactory.

Furrow irrigation, on the other hand, does not wet the entire soil surface. This method can reduce crop contamination, since plants are grown on the ridges, but complete health protection cannot be guaranteed. Contamination of farm workers is potentially medium to high, depending on automation. If the effluent is transported through pipes and delivered into individual furrows by means of gated pipes, risk to irrigation workers will be minimum.

The efficiency of surface irrigation methods in general, borders, basins, and furrows, is not greatly affected by water quality, although the health risk inherent in these systems is most certainly of concern. Some problems might arise if the effluent contains large quantities of suspended solids and these settle out and restrict flow in transporting channels, gates, pipes and appurtenances. The use of primary treated sewage will overcome many of such problems. To avoid surface ponding of stagnant effluent, land levelling should be carried out carefully and appropriate land gradients should be provided.

Sprinkler, or spray, irrigation methods are generally more efficient in terms of water use since greater uniformity of application can be achieved. However, these overhead irrigation methods may contaminate ground crops, fruit trees and farm workers. In addition, pathogens contained in aerosolized effluent may be transported downwind and create a health risk to nearby residents. Generally, mechanized or automated systems have relatively high capital costs and low labour costs compared with manually-moved sprinkler systems. Rough land levelling is necessary for sprinkler systems, to prevent excessive head losses and achieve uniformity of wetting. Sprinkler systems are more affected by water quality than surface irrigation systems, primarily as a result of the clogging of orifices in sprinkler heads, potential leaf burns and phytotoxicity when water is saline and contains excessive toxic elements, and sediment accumulation in pipes, valves and distribution systems. Secondary wastewater treatment has generally been found to produce an effluent suitable for distribution through sprinklers, provided that the effluent is not too saline. Further precautionary measures, such as treatment with granular filters or micro-strainers and enlargement of nozzle orifice diameters to not less than 5 mm, are often adopted.

Localized irrigation, particularly when the soil surface is covered with plastic sheeting or other mulch, uses effluent more efficiently, can often produce higher crop yields and certainly provides the greatest degree of health protection for farm workers and consumers. Trickle and drip irrigation systems are expensive, however, and require a high quality of effluent to prevent clogging of the emitters through which water is slowly released into the soil. Table 27 presents water quality requirements to prevent clogging in localized irrigation systems. Solids in the effluent or biological growth at the emitters will create problems but gravel filtration of secondary treated effluent and regular flushing of lines have been found to be effective in preventing such problems in Cyprus (Papadopoulos and Stylianou 1988). Bubbler irrigation, a technique developed for the localized irrigation of tree crops avoids the need for small emitter orifices but careful setting is required for its successful application (Hillel 1987).

Table 27: WATER QUALITY AND CLOGGING POTENTIAL IN DRIP IRRIGATION SYSTEMS

Potential Problem	Units	Degree of Restriction on Use		
		None	**Slight to Moderate**	**Severe**
Physical				
Suspended Solids	mg/l	< 50	50- 100	> 100
Chemical				
pH		< 7.0	7.0 - 8.0	> 8.0
Dissolved Solids	mg/l	< 500	500-2000	> 2000
Manganese	mg/l	< 0.1	0.1 - 1.5	> 1.5
Iron	mg/l	< 0.1	0.1 - 1.5	> 1.5
Hydrogen Sulphide	mg/l	< 0.5	0.5 - 2.0	> 2.0
Biological	maximum			
Bacterial populations	number/ml	< 10000	10 000 - 50 000	> 50000

Source: Adapted from Nakayama (1982)

When compared with other systems, the main advantages of trickle irrigation seem to be:

i. increased crop growth and yield achieved by optimizing the water, nutrients and air regimes in the root zone,

ii. high irrigation efficiency - no canopy interception, wind drift or conveyance losses and minimal drainage losses,

iii. minimal contact between farm workers and effluent,

iv. low energy requirements - the trickle system requires a water pressure of only 100-300 k Pa (1-3 bar),

v. low labour requirements - the trickle system can easily be automated, even to allow combined irrigation and fertilization (sometimes terms fertigation).

Apart from the high capital costs of trickle irrigation systems, another limiting factor in their use is that they are only suited to the irrigation of row crops. Relocation of subsurface systems can be prohibitively expensive.

Clearly, the decision on irrigation system selection will be mainly a financial one but it is to be hoped that the health risks associated with the different methods will be taken into account. As pointed out in Section 2.1, the method of effluent application is one of the health control measures possible, along with crop selection, wastewater treatment and human exposure control. Each measure will interact with the others and thus a decision on irrigation system selection will have an influence on wastewater treatment requirements, human exposure control and crop selection (for example, row crops are dictated by trickle irrigation). At the same time the irrigation techniques feasible will depend on crop selection and the choice of irrigation system might be limited if wastewater treatment has already been decided before effluent use is considered.

5.5 Field management practices in wastewater irrigation

Management of water, soil, crop and operational procedures, including precautions to protect farm workers, play an important role in the successful use of sewage effluent for irrigation.

5.5.1 Water management

Most treated wastewaters are not very saline, salinity levels usually ranging between 500 and 200 mg/l (EC_w = 0.7 to 3.0 dS/m). However, there may be instances where the salinity concentration exceeds the 2000 mg/l level. In any case, appropriate water management practices will have to be followed to prevent salinization, irrespective of whether the salt content in the wastewater is high or low. It is interesting to note that even the application of a non-saline wastewater, such as one containing 200 to 500 mg/l, when applied at a rate of 20,000 m^3 per hectare, a fairly typical irrigation rate, will add between 2 and 5 tonnes of salt annually to the soil. If this is not flushed out of the root zone by leaching and removed from the soil by effective drainage, salinity problems can build up rapidly. Leaching and drainage are thus two important water management practices to avoid salinization of soils.

Leaching

The concept of leaching has already been discussed. The question that arises is how much water should be used for leaching, i.e. what is the leaching requirement? To estimate the leaching requirement, both the salinity of the irrigation water (EC_w) and the crop tolerance to soil salinity (EC_e) must be known. The necessary leaching requirement (LR) can be estimated from Figure 14 for general crop rotations reported by Ayers and Westcot (FAO 1985). A more exact estimate of the leaching requirement for a particular crop can be obtained using the following equation:

(14)

$$LR = \frac{EC_w}{5\,(EC_e - EC_w}$$

where:

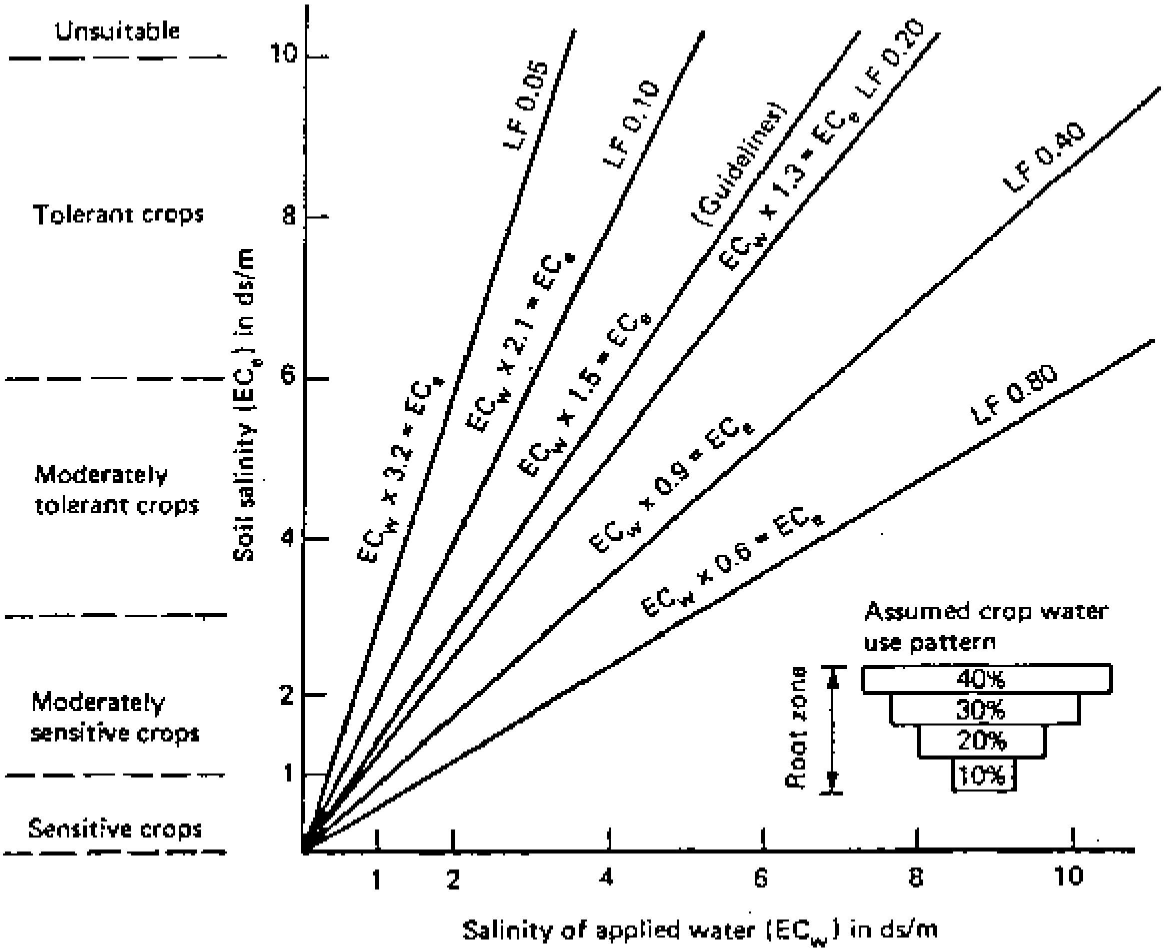
LR = minimum leaching requirement needed to control salts within the tolerance (EC_e) of the crop with ordinary surface methods of irrigation

EC_w = salinity of the applied irrigation water in dS/m

EC_e = average soil salinity tolerated by the crop as measured on a soil saturation extract. It is recommended that the EC_e value that can be expected to result in at least a 90% or greater yield be used in the calculation.

Figure 14 was developed using EC_e values for the 90% yield potential. For water in the moderate to high salinity range (>1.5 dS/m), it might be better to use the EC_e value for maximum yield potential (100%) since salinity control is critical in obtaining good yields. Further information on this is contained in Irrigation and Drainage Paper 29, Rev. 1 (FAO 1985).

Figure 14: Relationship between applied water salinity and soil water salinity at different leaching fractions (FAO 1985)



Where water is scarce and expensive, leaching practices should be designed to maximize crop production per unit volume of water applied, to meet both the consumptive use and leaching requirements. Depending on the salinity status, leaching can be carried out at each irrigation, each alternative irrigation or less frequently, such as seasonally or at even longer intervals, as necessary to keep the salinity in the soil below the threshold above which yield might be affected to an unacceptable level. With good quality irrigation water, the irrigation application level will almost always apply sufficient extra water to accomplish leaching. With high salinity irrigation water, meeting the leaching requirement is difficult and requires large amounts of water. Rainfall must be considered in estimating the leaching requirement and in choosing the leaching method.

The following practices are suggested for increasing the efficiency of leaching and reducing the amount of water needed:

i. leach during cool seasons instead of during warm periods, to increase the efficiency and ease of leaching, since the total annual crop water demand (ET, mm/year) losses are lower,

ii. use more salt-tolerant crops which require a lower leaching requirement (LR) and thus have a lower water demand,

iii. use tillage to slow overland water flow and reduce the number of surface cracks which bypass flow through large pores and decrease leaching efficiency,

iv. use sprinkler irrigation at an application rate below the soil infiltration rate as this favours unsaturated flow, which is significantly more efficient for leaching than saturated flow. More irrigation time but less water is required than for continuous ponding,

v. use alternate ponding and drying instead of continuous ponding as this is more efficient for leaching and uses less water, although the time required to leach is greater. This may have drawbacks in areas having a high water table, which allows secondary salinization between pondings,

vi. where possible, schedule leachings at periods of low crop water use or postpone teachings until after the cropping season,

vii. avoid fallow periods, particularly during hot summers, when rapid secondary soil salinization from high water tables can occur,

viii. if infiltration rates are low, consider pre-planting irrigations or off-season leaching to avoid excessive water applications during the crop season, and

ix. use one irrigation before the start of the rainy season if total rainfall is normally expected to be insufficient for a complete leaching. Rainfall is often the most efficient leaching method because it provides high quality water at relatively low rates of application.

Drainage

Salinity problems in many irrigation projects in arid and semi-arid areas are associated with the presence of a shallow water table. The role of drainage in this context is to lower the water table to a desirable level, at which it does not contribute to the transport of salts to the root zone and the soil surface by capillarity. What is important is to maintain a downward movement of water through soils. van Schilfgaard (1984) reported that drainage criteria are frequently expressed in terms of critical water table depths; although this is a useful concept, prevention of salinization depends on the establishment, averaged over a period of time, of a downward flux of water. Another important element of the total drainage system is its ability to transport the desired amount of drained water out of the irrigation scheme and dispose of it safely. Such disposal can pose a serious problem, particularly when the source of irrigation water is treated wastewater, depending on the composition of the drainage effluent.

Timing of irrigation

The timing of irrigation, including irrigation frequency, pre-planting irrigation and irrigation prior to a winter rainy season, can reduce the salinity hazard and avoid water stress between irrigations. Some of these practices are readily applicable to wastewater irrigation.

In terms of meeting the water needs of crops, increasing the frequency of irrigation will be desirable as it eliminates water stress between irrigations. However, from the point of view of overall water management, this may not always produce the desired results. For example, with border, basin and other flood irrigation methods, frequent irrigations may result in an unacceptable increase in the quantity of water applied, decrease in water use efficiency and larger amounts of water to be drained. However, with sprinklers and localized irrigation methods, frequent applications with smaller amounts may not result in decrease in water use efficiency and, indeed, could help to overcome the salinity problem associated with saline irrigation water.

Pre-planting irrigation is practised in many irrigation schemes for two reasons, namely: (i) to leach salts from the soil surface which may have accumulated during the previous cropping period and to provide a salt-free environment to germinating seeds (it should be noted that for most crops, the seed germination and seedling stages are most sensitive to salinity); and (ii) to provide adequate moisture to germinating seeds and young seedlings. A common practice among growers of lettuce, tomatoes and other vegetable crops is to pre-irrigate the field before planting, since irrigation soon after planting could create local water stagnation and wet spots that are not desirable. Treated wastewater is a good source for pre-irrigation as it is normally not saline and the health hazards are practically nil.

Blending of wastewater with other water supplies

One of the options that may be available to farmers is the blending of treated sewage with conventional sources of water, canal water or ground water, if multiple sources are available. It is possible that a farmer may have saline ground water and, if he has non-saline treated wastewater, could blend the two sources to obtain a blended water of acceptable salinity level. Further, by blending, the microbial quality of the resulting mixture could be superior to that of the unblended wastewater.

Alternating treated wastewater with other water sources

Another strategy is to use the treated wastewater alternately with the canal water or groundwater, instead of blending. From the point of view of salinity control, alternate applications of the two sources will be superior to blending. However, an alternating application strategy will require duel conveyance systems and availability of the effluent dictated by the alternate schedule of application.

5.5.2 Land and soil management

Several land and soil management practices can be adopted at the field level to overcome salinity, sodicity, toxicity and health hazards that might be associated with the use of treated wastewater.

Land development

During the early stages of on-farm land development, steps can be taken to minimize potential hazards that may result from the use of wastewater. These will have to be well planned, designed and executed since they are expensive and, often, one time operations. Their goal is to improve permanently existing land and soil conditions in order to make irrigation with wastewater easier. Typical activities include levelling of land to a given grade, establishing adequate drainage (both open and sub-surface systems), deep ploughing and leaching to reduce soil salinity.

Land grading

Land grading is important to achieve good uniformity of application from surface irrigation methods and acceptable irrigation efficiencies in general. If the wastewater is saline, it is very important that the irrigated land is appropriately graded. Salts accumulate in the high spots which have too little water infiltration and leaching, while in the low spots water accumulates, causing waterlogging and soil crusting.

Land grading is well accepted as an important farm practice in irrigated agriculture. Several methods are available to grade land to a desired slope. The slope required will vary with the irrigation system, length of run of water flow, soil type, and the design of the field. Recently, laser techniques have been applied to level land precisely so as to obtain high irrigation efficiencies and prevent salinization.

Deep cultivation

In certain areas, the soil is stratified, and such soils are difficult to irrigate. Layers of clay, sand or hard pan in stratified soils frequently impede or prevent free movement of water through and beyond the root zone. This will not only lead to saturation of the root zone but also to accumulation of salts in the root zone. Irrigation efficiency as well as water movement in the soil can be greatly enhanced by sub-soiling and chiselling of the land. The effects of sub-soiling and chiselling remain for about 1 to 5 years but, if long term effects are required, the land should be deep and slip ploughed. Deep or slip ploughing is costly and usually requires the growing of annual crops soon after to allow the settling of the land. Following a couple of grain crops, grading will be required to re-establish a proper grade to the land.

5.5.3 Crop management and cultural practices

Several cultural and crop management practices that are valid under saline water use will be valid under wastewater use. These practices are aimed at preventing damage to crops caused by salt accumulation surrounding the plants and in the root zone and adjusting fertilizer and agrochemical applications to suit the quality of the wastewater and the crop.

Placement of seed

In most crops, seed germination is more seriously affected by soil salinity than other stages of development of a crop. The effects are pronounced in furrow-irrigated crops, where the water is fairly to highly saline. This is because water moves upwards by capillarity in the ridges, carrying salts with it. When water is either absorbed by roots or evaporated, salts are deposited in the ridges. Typically, the highest salt concentration occurs in the centre of the ridge, whereas the lowest concentration of salt is found along the shoulders of the ridges. An efficient means of overcoming this problem is to ensure that the soil around the germinating seeds is sufficiently low in salinity. Appropriate planting methods, ridge shapes and irrigation management can significantly decrease damage to germinating seeds. Some specific practices include:

i. Planting on the shoulder of the ridge in the case of single row planting or on both shoulders in double row planting,

ii. Using sloping beds with seeds planted on the sloping side, but above the water line,

iii. Irrigating alternate rows so that the salts can be moved beyond the single seed row.

Figure 15 presents schematic representations of salt accumulation, planting positions, ridge shapes and watering patterns.

Figure 15: Schematic representations of salt accumulation and planting methods in ridge and furrow irrigation (Bernstein and Fireman 1957)

5.6 Planning for wastewater irrigation

5.6.1 Central planning

Government policy on effluent use in agriculture will have a deciding effect on what control measures can be achieved through careful selection of site and crops to be irrigated with treated effluent. A decision to make treated effluent available to farmers for unrestricted irrigation or to irrigate public parks and urban green areas with effluent will remove the possibility of taking advantage of careful selection of sites, irrigation techniques and crops in limiting the health risks and minimizing environmental impacts. However, if a Government decides that effluent irrigation will only be applied in specific controlled areas, even if crop selection is not limited (that is, unrestricted irrigation is allowed within these areas), public access to the irrigated areas will be prevented and some of the control measures described in Chapter 2 can be applied. Without doubt, the greatest security against health risk and adverse environmental impact will be achieved by limiting effluent use to restricted irrigation on controlled areas to which the public has no access but even imposing restrictions on effluent irrigation by farmers, if properly enforced, can achieve a degree of control.

Cobham and Johnson (1988) have suggested that the procedures involved in preparing plans for effluent irrigation schemes are similar to those used in most forms of resource planning and summarized the main physical, social and economic dimensions as in Figure 16. They also indicated that a number of key issues or tasks were likely to have a significant effect on the ultimate success of effluent irrigation, as follows:

> i. organizational and managerial provisions made to administer the resource, to select the effluent use plan and to implement it,
>
> ii. the importance attached to public health considerations and the levels of risk taken,
>
> iii. the choice of single-use or multiple-use strategies,
>
> iv. the criteria adopted in evaluating alternative reuse proposals,
>
> v. the level of appreciation of the scope for establishing a forest resource.

Adopting a mix of effluent use strategies is normally advantageous in respect of allowing greater flexibility, increased financial security and more efficient use of the wastewater throughout the year, whereas a single-use strategy will give rise to seasonal surpluses of effluent for unproductive disposal. Therefore, in site and crop selection the desirability of providing areas for different crops and forestry so as to utilize the effluent at maximum efficiency over the whole yearly cycle of seasons must be kept in mind.

Figure 16: Main components of general planning guidelines for wastewater reuse (Cobham and Johnson 1988)

5.6.2 Desirable site characteristics

The features which are critical in deciding the viability of a land disposal project are the location of available land and public attitudes. Land which is far distant from the sewage treatment plant will incur high costs for transporting treated effluent to site and will generally not be suitable. Hence, the availability of land for effluent irrigation should be considered when sewerage is being planned and sewage treatment plants should be strategically located in relation to suitable agricultural sites. Ideally, these sites should not be close to residential areas but even remote land might not be acceptable to the public if the social, cultural or religious attitudes are opposed to the practice of wastewater irrigation. The potential health hazards associated with effluent irrigation can make this a very sensitive issue and public concern will only be mollified by the application of strict control measures. In arid areas, the importance of agricultural use of treated effluent makes it advisable to be as systematic as possible in planning, developing and managing effluent irrigation projects and the public must be kept informed at all stages.

The ideal objective in site selection is to find a suitable area where long-term application of treated effluent will be feasible without adverse environmental or public health impacts. It might be possible in a particular instance to identify several potential sites within reasonable distance of the sewered community and the problem will be to select the most suitable area or areas, taking all relevant factors into account. The following basic information on an area under consideration will be of value, if available:

- a topographic map,
- agricultural soils surveys,
- aerial photographs,
- geological maps and reports,
- groundwater reports and well logs,
- boring logs and soil test results,
- other soil and peizometric data.

At this preliminary stage of investigation it should be possible to assess the potential impact of treated effluent application on any usable aquifer in the area(s) concerned. The first ranking of sites should take into account other factors, such as the cost and location of the land, its present use and availability, and social factors, in addition to soil and groundwater conditions.

The characteristics of the soil profile underlying a particular site are very important in deciding on its suitability for effluent irrigation and the methods of application to be employed. Among the soil properties important from the point of view of wastewater application and agricultural production are: physical parameters (such as texture, grading, liquid and plastic limits, etc.), permeability, water-holding capacity, pH, salinity and chemical composition. Preliminary observation of sites, which could include shallow hand-auger borings and identification of vegetation, will often allow the elimination of clearly unsatisfactory sites. After elimination of marginal sites , each site under serious consideration must be investigated by on-site borings to ascertain the soil profile, soil characteristics and location of the water table. Peizometers should be located in each borehole and these can be used for subsequent groundwater sampling. A procedure for such site assessment has been described by Hall and Thompson (1981) and, if applied, should not only allow the most suitable site among several possible to be selected but permit the impact of effluent irrigation at the chosen site to be modelled. When a site is developed, a long-term groundwater monitoring programme should be an essential feature of its management.

5.6.3 Crop selection issues

Normally, in choosing crops, a farmer is influenced by economics, climate, soil and water characteristics, management skill, labour and equipment available and tradition. The degree to which the use of treated effluent influences crop selection will depend on

Government policy on effluent irrigation, the goals of the user and the effluent quality. Government policy will have the objectives of minimizing the health risk and influencing the type of productivity associated with effluent irrigation. Regulations must be realistic and achievable in the context of national and local environmental conditions and traditions. At the same time, planners of effluent irrigation schemes must attempt to achieve maximum productivity and water conservation through the choice of crops and effluent application systems.

A multiple-use strategy approach will require the evaluation of viable combinations of the cropping options possible on the land available. This will entail a considerable amount of survey and resource budgeting work, in addition to the necessary soil and water quality assessments. The annual, monthly and daily water demands of the crops, using the most appropriate irrigation techniques, have to be determined. Domestic consumption, local production and imports of the various crops must be assessed so that the economic potential of effluent irrigation of the various crop combinations can be estimated. Finally, the crop irrigation demands must be matched with the available effluent so as to achieve optimum physical and financial utilization throughout the year. This process of assessment is reviewed by Cobham and Johnson (1988) for the case of effluent use in Kuwait, where afforestation for commercial purposes was found to offer significant potential in multiple-use effluent irrigation.

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6. Agricultural use of sewage sludge

6.1 Characteristics of sewage sludge

Most wastewater treatment processes produce a sludge which has to be disposed of. Conventional secondary sewage treatment plants typically generate a primary sludge in the primary sedimentation stage of treatment and a secondary, biological, sludge in final sedimentation after the biological process. The characteristics of the secondary sludge vary with the type of biological process and, often, it is mixed with primary sludge before treatment and disposal. Approximately one half of the costs of operating secondary sewage treatment plants in Europe can be associated with sludge treatment and disposal. Land application of raw or treated sewage sludge can reduce significantly the sludge disposal cost component of sewage treatment as well as providing a large part of the nitrogen and phosphorus requirements of many crops.

Very rarely do urban sewerage systems transport only domestic sewage to treatment plants; industrial effluents and storm-water runoff from roads and other paved areas are frequently discharged into sewers. Thus sewage sludge will contain, in addition to organic waste material, traces of many pollutants used in our modern society. Some of these substances can be phytotoxic and some toxic to humans and/or animals so it is necessary to control the concentrations in the soil of potentially toxic elements and their rate of application to the soil. The risk to health of chemicals in sewage sludge applied to land has been reviewed by Dean and Suess (1985).

Sewage sludge also contains pathogenic bacteria, viruses and protozoa along with other parasitic helminths which can give rise to potential hazards to the health of humans, animals and plants. A WHO (1981) Report on the risk to health of microbes in sewage sludge applied to land identified salmonellae and *Taenia* as giving rise to greatest concern. The numbers of pathogenic and parasitic organisms in sludge can be significantly reduced before application to the land by appropriate sludge treatment and the potential health risk is further reduced by the effects of climate, soil-microorganisms and time after the sludge is applied to the soil. Nevertheless, in the case of certain crops, limitations on planting, grazing and harvesting are necessary.

Apart from those components of concern, sewage sludge also contains useful concentrations of nitrogen, phosphorus and organic matter. The availability of the phosphorus content in the year of application is about 50% and is independent of any prior sludge treatment. Nitrogen availability is more dependent on sludge treatment, untreated liquid sludge and dewatered treated sludge releasing nitrogen slowly with the benefits to crops being realised over a relatively long period. Liquid anaerobically-digested sludge has high ammonia-nitrogen content which is readily available to plants and can be of particular benefit to grassland. The organic matter in sludge can improve the water retaining capacity and structure of some soils, especially when applied in the form of dewatered sludge cake.

The application of sewage sludge to land in member countries of the European Economic Commission (EEC) is governed by Council Directive No. 86/278/EEC (Council of the European Communities 1986). This Directive prohibits the sludge from sewage treatment plants from being used in agriculture unless specified requirements are fulfilled, including the testing of the sludge and the soil. Parameters subject to the provisions of the Directive include the following:

- Dry matter (%)
- Organic matter (% dry solids)
- Copper (mg/kg dry solids)
- Nickel (mg/kg dry solids)
- pH
- Nitrogen, total and ammoniacal (% dry solids)

- Phosphorus, total (% dry solids)
- Zinc (mg/kg dry solids)
- Cadmium (mg/kg dry solids)
- Lead (mg/kg dry solids)
- Mercury (mg/kg dry solids)
- Chromium (mg/kg dry solids)

To these parameters the UK Department of the Environment (1989) has added molybdenum, selenium, arsenic and fluoride in the recent 'Code of Practice for Agricultural Use of Sewage Sludge'. Sludge must be analyzed for the Directive parameters at least once every 6 months and every time significant changes occur in the quality of the sewage treated. The frequency of analysis for the additional four parameters may be reduced to not less than once in five years provided that their concentrations in the sludge are consistently no greater than the following reference concentrations: Mb - 3mg/kg dry solids, Se - 2mg/kg dry solids, As -2mg/kg dry solids and Fl - 200mg/kg dry solids.

6.2 Sludge treatment

Except when it is to be injected or otherwise worked into the soil, sewage sludge should be subjected to biological, chemical or thermal treatment, long-term storage or other appropriate process designed to reduce its fermentability and health hazards resulting from its use before being applied in agriculture. Table 28 lists sludge treatment and handling processes which have been used in the UK to achieve these objectives. The second edition of a 'Manual of Good Practice on Soil Injection of Sewage Sludge' has been produced by the Water Research Centre (1989) in the UK and describes suitable equipment and techniques for what is now the only method permissible within the EEC for applying untreated sludges to grassland.

Table 28: EXAMPLES OF EFFECTIVE SLUDGE TREATMENT PROCESSES

Process	Descriptions
Sludge Pasteurization	Minimum of 30 minutes at 70°C or minimum of 4 hours at 55° C (or appropriate intermediate conditions), followed in all cases by primary mesophilic anaerobic digestion
Mesophilic Anaerobic Digestion	Mean retention period of at least 12 days primary digestion in temperature range 35°C +/- 3°C or of at least 20 days primary digestion in temperature range 25°C + /- 3°C followed in each case by a secondary stage which provides a mean retention period of at least 14 days
Thermophilic Aerobic Digestion	Mean retention period of at least 7 days digestion. All sludge to be subject to a minimum of 55°C for a period of at least 4 hours
Composting (Windrows or Aerated Piles)	The compost must be maintained at 40°C for at least 5 days and for 4 hours during this period at a minimum of 55°C within the body of the pile followed by a period of maturation adequate to ensure that the compost reaction is substantially complete
Lime Stabilization of	Addition of lime to raise pH to greater than 12.0 and sufficient to ensure

Liquid Sludge	that the pH is not less than 12 for a minimum period of 2 hours. The sludge can then be used directly
Liquid Storage	Storage of untreated liquid sludge for a minimum period of 3 months
Dewatering and Storage	Conditioning of untreated sludge with lime or other coagulants followed by dewatering and storage of the cake for a minimum period of 3 months if sludge has been subject to primary mesophilic anaerobic digestion, storage to be for a minimum period of 14 days

Source: Department of the Environment (1989)

6.3 Sludge application

The concentrations of potentially toxic elements in arable soils must not exceed certain prudent limits within the normal depth of cultivation as a result of sludge application. No sludge should be applied at any site where the soil concentration of any of the parameters mentioned in Section 5.1, with the exception of molybdenum, exceed these limits. Maximum permissible concentrations of the potentially toxic elements in soil after application of sewage sludge (according to the UK Code of Practice) are given in Table 29. For zinc, copper and nickel, the maximum permissible concentrations vary with the pH of the soil because it is known that crop damage from phytotoxic elements is more likely to occur on acid soils. This Table also gives the maximum permissible average annual rates of addition of potentially toxic elements over a 10-year period.

Table 29: MAXIMUM PERMISSIBLE CONCENTRATIONS OF POTENTIALLY TOXIC ELEMENTS IN SOIL AFTER APPLICATION OF SEWAGE SLUDGE AND MAXIMUM ANNUAL RATES OF ADDITION

Potentially toxic element (PTE)	**Maximum permissible concentration of PTE in soil (mg/kg dry solids)**				**Maximum permissible average annual rate of PTE addition over a 10 year period (kg/ha)[3]**
	PH[1] 5.0 <5.5	**pH[1] 5.5<6.0**	**pH 6.0-7.0**	**PH[2] > 7.0**	
Zinc	200	250	300	450	15
Copper	80	100	135	200	7.5
Nickel	50	60	75	110	3
Cadmium	3[5]				0.15
Lead	300				15
Mercury	1				0.1
Chromium	400 (prov.)				15 (provisional)
*Molybdenum[4]	4				0.2

*Selenium	3				0.15
*Arsenic	50				0.7
*Fluoride	500				20

* These parameters are not subject to the provisions of Directive 86/278/EEC.

[1] For soils of pH in the ranges of 5.0 < 5.5 and 5.5 < 6.0 the permitted concentrations of zinc, copper, nickel and cadmium are provisional and will be reviewed when current research into their effects on certain crops and livestock is completed.

[2] The increased permissible PTE concentrations in soils of pH greater than 7.0 apply only to soils containing more than 5 % calcium carbonate.

[3] The annual rate of application of PTE shall be determined by averaging over the 10-year period ending with the year of calculation.

[4] The accepted safe level of molybdenum in agricultural soils is 4 mg/kg. However, there are some areas in the UK where, for geological reasons, the natural concentration of this element in the soil exceeds this level. In such cases there may be no additional problems as a result of applying sludge, but this should not be done except in accordance with expert advice. This advice will take account of existing soil molybdenum levels and current arrangements to provide copper supplements to livestock.

[5] For pH 5.0 and above

Source: Department of the Environment (1989)

When sludge is applied to the surface of grassland, the concentrations of potentially toxic elements should be determined in soil samples taken to a depth of 7.5 cm. The maximum concentrations of these parameters should not exceed the limits set out in Table 30. In order to minimize injestion of lead, cadmium and fluoride by livestock, the addition of these elements through sludge application to the surface should not exceed 3 times the 10 year average annual rates specified in Table 29. Sludge to be surface applied to grassland should not contain lead or fluoride individually in excess of 1200 and 1000 mg/kg dry solids, respectively.

Table 30: MAXIMUM PERMISSIBLE CONCENTRATIONS OF POTENTIALLY TOXIC ELEMENTS IN SOIL UNDER GRASS AFTER APPLICATION OF SEWAGE SLUDGE WHEN SAMPLES TAKEN TO A DEPTH OF 7.5 cm

Potentially toxic element (PTE)	Maximum permissible concentration of PTE in soil (mg/kg dry solids)			
	pH 5.0 <5.5	**pH 5.5<6.0**	**pH 6.0<7.0**	**PH[3] > 7.0**
Zinc[1]	330	420	500	750
Copper[1]	130	170	225	330
Nickel[1]	80	100	125	180
Cadmium[2]	3/5[5]			
Lead	300			
Mercury	1.5			
Chromium	600 (prov.)			
*Molybdenum[4]	4			
*Selenium	5			
*Arsenic	50			
*Fluoride	500			

* These parameters are not subject to the provisions of Directive 86/278/EEC.

[1] The permitted concentrations of these elements will be subject to review when current research into their effects on the quality of grassland is completed. Until then, in cases where there is doubt about the practicality of ploughing or otherwise cultivating grassland, no sludge applications which would cause these concentrations to exceed the permitted levels specified in Table 29 should be made in accordance with specialist agricultural advice.

[2] The permitted concentration of cadmium will be subject to review when current research into its effect on grazing animals is completed. Until then, the concentration of this element may be raised to the permitted upper limit of 5 mg/kg as a result of sludge applications only under grass which is managed in rotation with arable crops and grown only for conservation. In all cases where grazing is permitted no sludge applications which would cause the concentration of cadmium to exceed the lower limit of 3 mg/kg shall be made.

[3] See Table 29 (Note 3). The same values are valid for maximum permissible annual rate of PTE.

[4] See Table 29 (Note 4).

[5] For pH 5.0 and above.

Source: Department of the Environment (1989).

6.4 Effects of sludge on soils and crops

The natural background concentration of metals in the soil is normally less available for crop uptake and hence less hazardous than metals introduced through sewage sludge applications (Scheltinga, 1987). Research carried out in the U.K. (Carlton-Smith, 1987) has shown that the amounts of Cd, Ni, Cu, Zn and Pb applied in liquid sludge at three experimental sites could be accounted for by soil profile analyses five years after sludge applications, with the exception of Cu and Zn applied to a calcareous loam soil. These field experiments also determined the extent of transfer of metals from sludge-treated soil into the leaves and edible parts of six crops of major importance to UK agriculture and the effect of metals on yields of these crops.

Although all the plots received sufficient inorganic fertilizer to meet crop requirements for nutrients, the applications of sludge had some effects on crop yields. In 60% of the cases studied crop yields were not significantly affected but in 26% of the cases liquid sludge application resulted in significantly increased crop yields, attributed to the beneficial effects on soil structure. Reductions in wheat grain yield, from 6 - 10%, were noted on the clay and calcareous loam soils treated with liquid sludge and the sandy loam and clay soils treated with bed-dried sludge. However, this yield reduction was not thought to be due to metals but the most likely explanation was lodging of the crop as a result of excessive nitrogen in the soil.

Increases in metal concentrations in the soil due to sludge applications produced significant increases in Cd, Ni, Cu and Zn concentrations in the edible portion of most of the crops grown: wheat, potato, lettuce, red beet, cabbage and ryegrass. In most cases there was no significant increase of Pb in crop tissue in relation to Pb in the soil from sludge application, suggesting that lead is relatively unavailable to crops from the soil. The availability of metals to crops was found to be lower in soil treated with bed-dried sludge cake compared with liquid sludge, the extent being dependent on the crop. Even though the Ni, Cu and Zn concentrations in the soils treated with high rates of application of liquid and bed-dried sludges were close to the maximum levels set out in the EC Directive and the zinc equivalent of sludge addition exceeded the maximum permitted in U.K. guidelines, no phytotoxic effects of metals were evident, with one exception. This was in lettuce grown on clay soil, when Cu and Zn levels exceeded upper critical concentrations at high rates of sludge application.

6.5 Planting, grazing and harvesting constraints

To minimize the potential risk to the health of humans, animals and plants it is necessary to coordinate sludge applications in time with planting, grazing or harvesting operations. Sludge must not be applied to growing soft fruit or vegetable crops nor used where crops are grown under permanent glass or plastic structures (Department of the Environment, 1989). The EC Directive (Council of the European Communities, 1986) requires a mandatory 3-week no grazing period for treated sludge applied to grassland but prohibits the spreading of untreated sludge on grassland unless injected. Treated sludge can be applied to growing cereal crops without constraint but should not be applied to growing turf within 3 months of harvesting or to fruit trees within 10 months of harvesting. When treated sludge is applied before planting such crops as cereals, grass, fodder, sugar beet, fruit trees, etc., no constraints apply but in the case of soft fruit and vegetables, the treated sludge should not be applied within 10 months of crop harvesting. In general, untreated sludge should only be cultivated or injected into the soil before planting crops but can be injected into growing grass or turf, with the constraints on minimum time to harvesting as already mentioned.

6.6 Environmental protection

Care should always be taken when applying sewage sludge to land to prevent any form of adverse environmental impact. The sludge must not contain non-degradable materials, such as plastics, which would make land disposal unsightly. Movement of sludge by tanker from sewage treatment plant to agricultural land can create traffic problems and give rise to noise and odour nuisance. Vehicles should be carefully selected for their local suitability and routes chosen so as to minimize inconvenience to the public. Access to fields should be selected after consultation with the highway authority and special care must be taken to prevent vehicles carrying mud onto the highway.

Odour control is the most important environmental dimension of sludge application to land. Enclosed tankers should be used for transporting treated sludge, which tends to be less odorous than raw sludge. Discharge points for sludge from tankers or irrigators should be as near to the ground as is practicable and the liquid sludge trajectory should be kept low so as to minimize spray drift and visual impact. Untreated sludge should be injected under the soil surface using special vehicles or tankers fitted with injection equipment.

Great care is needed to prevent sludge running off onto roads or adjacent land, depending on topography, soil and weather conditions. On sloping land there is the risk of such runoff reaching watercourses and causing serious water pollution. Sludge application rates must be adjusted accordingly and, under certain circumstances, spreading might have to be discontinued. In addition to the problem of surface runoff, pollution may arise from the percolation of liquid sludge into land drains, particularly when injection techniques are used or liquid sludge is applied to dry fissured soils. In highly sensitive water pollution areas, sludge should be used only in accordance with the requirements of the pollution control authority as well as of good farming practice. Sludge storage on farms can optimize the transport and application operations but every effort must be made to ensure that storage facilities are secure.

7. Wastewater use in aquaculture

7.1 Biota in aquaculture ponds

7.1.1 Food chains

The objective in fertilizing an aquaculture pond with excreta, nightsoil or wastewater is to produce natural food for fish. Since several species of fish feed directly on faecal solids, use of raw sewage or fresh nightsoil as influent to fish ponds should be prohibited for health reasons. Edwards (1990) has represented the complex food chains in an excreta-fed fish pond as shown in Figure 17, involving ultimate decomposers or bacteria, phytoplankton, zooplankton and invertebrate detritivores. Inorganic nutrients released in the bacterial degredation of organic solids in sewage, nightsoil or excreta are taken up by phytoplankton. Zooplankton graze phytoplankton and small detritus particles coated with bacteria, the latter also serving as food for benthic invertebrate detritivores. Plankton, particularly phytoplankaton, are the major sources of natural food in a fish pond but benthic invertebrates, mainly chironomids, also serve as fish food, although they are quantitatively less important. To optimize fish production in a human waste fed pond, the majority of the fish should be filter feeders, to exploit the plankton growth.

Figure 17: Food chains in an excreta-fed aquaculture system (Edwards *et al.* 1988)

7.1.2 Fish species

A wide range of fish species has been cultivated in aquaculture ponds receiving human waste, including common carp *(Cyprinùs carpio),* Indian major carps (*Catla catlax, Cirrhina mrigala and Labeo rohita),* Chinese silver carp *(Hypophthalmichthys molitrix),* bighead carp *(Aristichthys nobilis),* grass carp *(Ctenopharyngodon idella),* crucian carp (*Carassius auratus),* Nile carp *(Osteochilus hasseltii),* tilapia *(Oreochromis spp.),* milkfish *(Chanos chanos),* catfish *(Pangasius spp.),* kissing gouramy *(Helostoma temmincki),* giant gourami *(Osphronemus goramy),* silver barb *(Puntius gonionotus)* and freshwater prawn *(Macrobrachium lanchesterii).* The selection reflects local culture rather than fish optimally-suited to such environments. For example, Chinese carps and Indian major carps are the major species in excreta-fed systems in China and India, respectively. In some countries, a polyculture of several fish species is used. Tilapia are generally cultured to a lesser extent than carps in excreta-fed systems although, technically, they are more suitable for this environment because they are better able to tolerate adverse environmental conditions than carp species. Milkfish have been found to have poorer growth and survival statistics compared with Indian major carps and Chinese carps in ponds fed with stabilization pond effluent in India.

Edwards (1990) gives a thorough review of current knowledge on the various fish species which can be cultured in ponds fed with human waste. It would appear that considerable confusion still exists with regard to fish feeding on natural food. Although fish are generally divided into types according to their natural nutritional habits - those that feed on phytoplankton, or zooplankton or benthic animals - several species are known to feed on whatever particles are suspended in the water. There is also uncertainty about the types of phytoplankton fed upon by filter-feeding fish. For example, although blue-green algae are thought to be indigestible to fish, Tilapia have been shown to readily digest these algae and there is evidence that silver carp can do the same.

7.1.3 Aquatic plants

Aquatic macrophytes grow readily in ponds fed with human waste and their use in wastewater treatment has been discussed in Section 2.3.3. Some creeping aquatic macrophytes are cultivated as vegetables for human consumption in aquaculture ponds and duckweeds are also cultivated, mainly for fish feed. Among the aquatic plants grown for use as vegetables are water spinach *(Ipomoea aquatica),* water mimosa (*Neptunia oleracea),* water cress *(Rorippa nasturtium-aquaticum)* and Chinese water chestnut *(Eleocharis dulcis).* The duckweeds *Lemna, Spirodela* and *Wolffia* are cultivated in some parts of Asia in shallow ponds fertilized with excreta, mainly as feed for Chinese carps but also for chickens, ducks and edible snails (Edwards 1990).

7.2 Technical aspects of fish culture

7.2.1 Environmental factors

In a successful aquaculture system there must be both an organismic balance, to produce an optimal supply of natural food at all levels, and a chemical balance, to ensure sufficient oxygen supply for the growth of fish and their natural food organisms and to minimize the build-up of toxic metabolic products (Colman and Edwards 1987). Chemical balance is usually achieved through organismic balance in waste-fed ponds because the most important chemical transformations are biologically mediated. It is now recognized that depletion of dissolved oxygen in fertilized fish ponds is due primarily to the high rates of respiration at night of dense concentrations of phytoplankton. Romaire et al. (1978)

introduced Eq. 15 to cover the factors influencing waste-fed fish pond dissolved oxygen (DO) at dawn:

(15)

$$DO_{dn} = DO_{dk} \pm DO_{df} - DO_m - DO_f - DO_p$$

where:

DO_{dn} = DO concentration at dawn
DO_{dk} = DO concentration at dusk
DO_{df} = DO gain or loss due to diffusion
DO_m = DO consumed by mud
DO_f = DO consumed by fish
DO_p = DO consumed by plankton

Bacterial respiration is not specifically mentioned in this equation but is included in the mud consumption of DO and in the planktonic DO consumption. In a well-managed waste-fed fish pond the DO in the morning should be only a few mg/l whereas in late afternoon the pond should be supersaturated with DO.

Mud respiration probably lowers DO by less than 1 mg/l overnight and a fish population weighing 3000 kg/ha would also lower DO by only about 1 mg/l overnight. Phytoplankton photosynthesis is the major source of oxygen during daylight hours and, during the night, the major cause of oxygen depletion is respiration. It has been estimated that respiration of plankton (bacterioplankton, phytoplankton and zooplankton) can lower pond DO by 8-10 mg/l overnight. By far the greatest proportion of the DO depletion overnight is caused by the respiration of the phytoplankton that develop as a result of the nutrients contained in the waste. Phytoplankton provide feed for the largest percentage of fish farmed in Asia (Edwards 1990). They also exhibit a positive net primary productivity on a 24-hour basis and are net oxygen contributors to a fish pond. The objective in a waste-fed fish pond should be to maintain an algal standing crop at an optimum level for net primary productivity by balancing the production of phytoplankton biomass, in response to waste fertilization, with the grazing of phytoplankton biomass by filter-feeding fish.

Fish mortality in a waste-fed pond can result from at least three possible causes. First, the depletion of oxygen due to bacterial oxygen demand caused by an increase in organic load. Second, the depletion of oxygen overnight due to the respiratory demand of too large a concentration of phytoplankton, having grown in response to an increase in inorganic nutrients, caused by an organismic imbalance. The third possible cause is high ammonia concentration in the waste feed. All three causes of fish mortality have been reported in respect of sewage-fertilized fish ponds. The sensitivity of fish to low levels of DO varies with species, life stage (eggs, larvae, adults) and life process (feeding, growth, reproduction). A minimum constant DO concentration of 5 mg/l is considered satisfactory, although an absolute minimum consistent with the presence of fish is probably less than 1 mg/l (Alabaster and Lloyd 1980). Fish cultured in waste-fed ponds appear to be able to tolerate very low DO concentrations, for at least short periods of time, with airbreathing fish (such as walking catfish *(Clarias batrachus)* being the most tolerant, followed in decreasing order of tolerance by tilapia, carps, channel catfish and trout. Reducing phytoplankton biomass to maintain a reasonable DO in the early morning hours might well depress fish growth more than exposure to a few hours of low DO. A wastewater fertilized aquaculture system might occasionally require a stand-by mechanical oxygenation system for use during periods when DO would otherwise be very low. However, if the system is well managed to avoid overloading, this expense can be avoided.

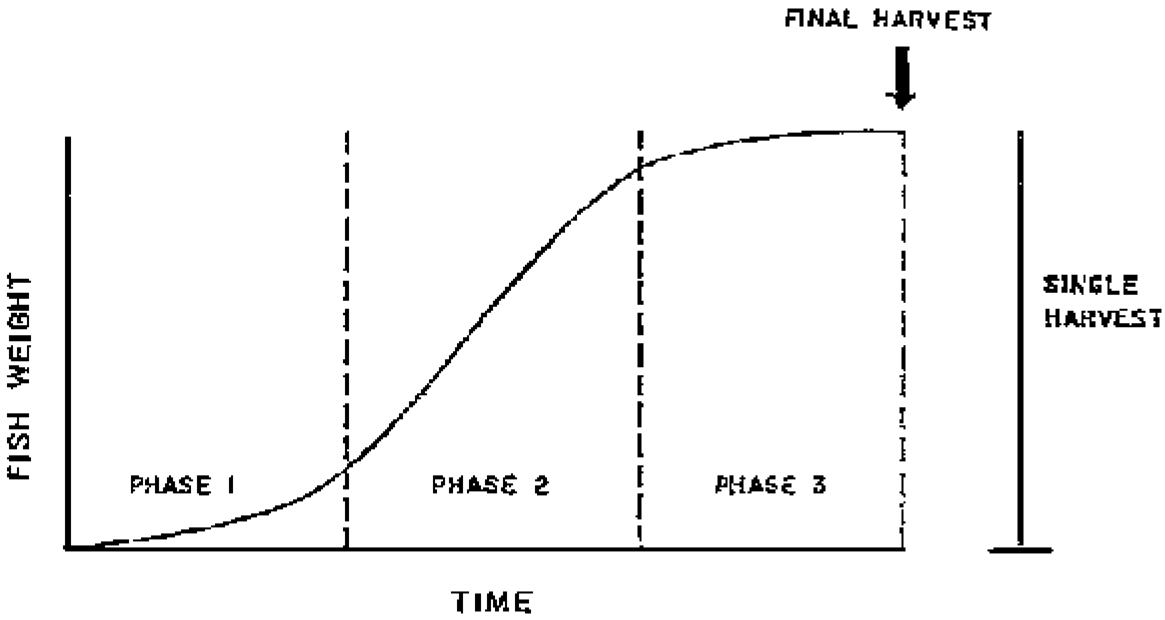
Unionized ammonia (NH_3) is toxic to fish in the concentration range 0.2 - 2.0 mg/l (Alabaster and Lloyd 1980). However, the tolerance of different species of fish varies, with tilapa species being least affected by high ammonia levels. Bartone et al. (1985) found that satisfactory growth and survival of tilapia was possible in fish ponds fed with tertiary effluent in Lima, Peru when the average total ammonia concentration was less than 2 mg N/l and the average unionized ammonia concentration was less than 0.5 mg N/l, with the latter only exceeding 2 mg N/l for short periods. In ponds receiving large quantities of organic matter, sediments tend to accumulate and release anaerobic breakdown products, such as methane and sulphides, which can inhibit fish growth. Bottom feeding fish, such as the common carp (*Cyprinus carpio),* are most affected by such conditions, especially if the macrozoobenthos disappear.

7.2.2 Fish yields and population management

A wide range of yields has been reported from waste-fed aquaculture systems, for example: 2-6 tons/ha yr in Indonesia, 2.7 - 9.3 tons/ha yr in China and 3.5 - 7.8 tons/ha yr in Taiwan. Although the majority of waste-fed fish ponds stocks carps, research in Peru and Thailand has demonstrated the potential of tilapia for such systems. Management of fish ponds can have a significant effect on fish yields but the maximum attainable yield in practice is of the order of 10 - 12 tons/ha yr (Edwards 1990).

Increase in weight of small fingerlings stocked in a pond follows a sigmoidal curve (Figure 18). The first phase of growth is slow, so a high stocking density can be adopted to better utilize the spatial and nutritional resources of the pond. Alternatively, this can be achieved by stocking with larger fish having a higher initial weight, following growth in nursery ponds. Fish yield is positively correlated with the size of the stocked fish at a given stocking density. In South China, tilapia are stocked once a year at rates of either 30g fish and $0.15/m^2$ or 1.3g fish at 2.3 - $3.0/m^2$ stocking density. An increase in weight of fish in a pond leads initially to an increase in yield or production but there is subsequently a reduction in the growth rate of individual fish because of the limitation of natural food production in the system. The third phase of slow growth in Figure 18 is because the total weight of fish in the pond is approaching the carrying capacity. Intermediate harvesting when the rapid growth ceases, at the end of phase 2, should lead to significant increases in total yield. The high yields of tilapia reported in South China sewage-fed ponds are due to high stocking density and frequent harvesting.

Figure 18: Fish growth cycle (Edwards 1990)



Clearly, the key to achieving high yields in a waste-fed pond is to determine the carrying capacity of the pond, the maximum standing stock of fish. This can be assessed by varying the waste load and determining the maximum production of natural food consistent with satisfactory water quality, sustainable through a fish culture cycle (Edwards 1990). Fish stocking density is related to carrying capacity according to the desired weight of individual fish at harvest, as follows:

(16)

$$\text{Fish stocking density (number / ha)} = \frac{\text{Carrying capacity (kg / ha)}}{\text{Harvestable weight of individual fish (kg)}}$$

Experience has shown that there is a limit to the fish yield attainable from a waste-fed fish pond. Higher yields can be achieved by addition of energy-rich supplementary feed, such as cereals, cereal brans or pelleted-feed. The highest yields are only achieved with a sufficiently high fish stocking density to benefit from the improvement in pond nutrition. There appears to be increased efficiency of utilization of supplementary feed by fish in ponds receiving sewage effluent.

Marketable weights of fish vary with species and local market preferences but, in general, desirable sizes of the following fish range from 0.25-0.6 kg for tilapia, 0.5-1.5 kg for Indian major carps (mrigal 0.5, rohu 1.0, catla 1.5 kg) and perhaps 1-2 kg for Chinese carps. Thus, for a particular carrying capacity, Chinese carps should be stocked at an intermediate density. The length of culture cycle, or frequency of harvesting, depends on the time it takes stocked fish to reach marketable size. It should be recognized that the size of individual fish is only significant if the product is to be consumed by humans. When fish are raised as high-protein feed for carnivorous fish or livestock, size is relatively unimportant. Nevertheless, it is now appreciated that sustainable yields of even high densities of small-size fish with a high specific growth rate are not significantly different from the yield of table fish for human consumption (6.2-7.8 tons/ha yr).

7.2.3 Health related aspects of fish culture

Although it is good practice to limit the discharge of toxic materials to sewerage systems, inevitably some of these materials gain access and heavy metals and pesticides are frequently present in municipal sewage. This gives rise to concern about bioaccumulation when sewage effluent is used in aquaculture. Algae are known to accumulate various heavy metals but, with the possible exception of mercury, fish raised in sewage-fed ponds have not been observed to accumulate high concentrations of these toxic substances. It would appear that the concentrations of heavy metals in the pond water may be accumulated at slower rates than new tissues develop in rapidly growing fish, such as tilapia. In the case of mercury, the position of fish in the food chain seems to be important in determining their mercury uptake, with carnivorous fish accumulating more than herbivores. Fish, apparently, have the ability to regulate the heavy metal content of their tissues, except for mercury, and tend to accumulate metals in parts other than muscle tissue. There is little information on the uptake of toxics other than heavy metals but a high phenol content in the sewage fed to fish ponds in Wuhon, China caused the fish flesh to become unpalatable due to the odour of phenol. Weis et al. (1989) have reported on the effects of treated municipal wastewater on the early life stages of three species of fish and indicated that moderately toxic effluent (organic fractions) caused cardiovascular and skeletal defects, depression of heart rate and poor hatching, larval and juvenile growth rates.

The health effects of aquacultural use of human wastes in respect of pathogenic organisms have been discussed in Section 2.5. Depuration was mentioned as a means to decontaminate fish grown in waste-fed aquaculture. It is generally believed that holding fish in clean-water ponds for several weeks at the end of the growing cycle will remove residual objectionable odours and pathogens and provide fish acceptable for market. However, there is a lack of data on depuration practice and experimental assessment. What little evidence there is suggests that depuration of heavily contaminated fish with bacteria in muscle tissue will not be effective. Relatively short depuration periods of one to two weeks do not appear to remove bacteria from the fish digestive tract. Considering the lack of verification of the effectiveness of depuration as a health protective measure, Edwards (1990) has not included it in his suggested strategies for safeguarding public health in aquaculture (Figure 19).

Figure 19: Aquacultural reuse strategies with different types of excreta to safeguard public health (Edwards 1990)

8. Economic, institutional and policy issues

While the overall benefits of wastewater use in agriculture are obvious and the technology and expertise exist to allow it to be achieved without detriment to public health or the environment, governments must be prepared to control the process within a broader framework of a national effluent use policy forming part of the national plan for water resources. Lines of responsibility and cost allocation formulae have to be worked out between the various sectors involved: local authorities responsible for wastewater treatment and disposal, farmers who will benefit from any effluent use scheme and the state which is concerned with the provision of adequate water supplies, protection of the environment and the promotion of public health. Sufficient attention must be given to the social, institutional and organizational aspects of effluent use in agriculture and aquaculture to ensure long-term sustainability.

8.1 Economic and financial implications

Although the responsibility for collecting, treating and disposing of urban wastewater will normally lie with a local water or sewerage authority or municipality, farmers wishing to take advantage of the effluent are often able and willing to pay for what they use but are not prepared to subsidize general disposal costs. They will base their decision on whether or not they will be better off paying for the effluent rather than doing without it, taking into account the quantity, timing, quality and cost of the treated effluent. The local sewerage authority should acknowledge their financial responsibility for the basic system to achieve environmental protection objectives and only charge farmers for any incremental costs associated with additional treatment or distribution required specifically for effluent use in agriculture or aquaculture. In practice, if the effluent use scheme is considered at the time the sewerage project is being planned, treatment costs might well be reduced over those normally required for environmental protection.

Payments by farmers might take the form of direct effluent use tariffs paid to the authority, or contributions to the capital and/or operating costs of the wastewater treatment plant and effluent conveyance system. Cost sharing can be by cash payments or in-kind contributions, such as land for siting treatment or storage facilities and labour for operation and maintenance. Bartone (1986) has indicated that benefit-cost studies made in Peru showed that the irrigation components in effluent irrigation schemes were economically viable even if land costs and operation and maintenance for wastewater treatment were charged to farmers but not if the full cost of investment in treatment facilities was charged against the agricultural component. In the latter case, feasibility depended on the alternative minimum cost of treatment required for disposal without reuse.

Since wastewater treatment is a major cost in effluent use systems, accepting that local authorities are fully responsible for wastewater collection, it is essential that treatment process selection is made in conjunction with decisions on crop and irrigation system selection. Only in this way can a minimal investment in treatment be achieved without compromising the health risks of an effluent use scheme. Once a decision on effluent quality has been taken, the required standard must be achieved consistently and the effluent treatment and conveyance system must be operated with complete reliability. Fluctuating production and demand for effluent created by seasonal and diurnal patters of water use, cropping and crop water needs must be accommodated at all times, even if the price of the effluent is varied, to be higher in the hot season.

8.2 Institutional organization

The scope and success of any effluent use scheme will depend to a large extent on the administrative skills applied. Wastewater collection and treatment and effluent use in agriculture and aquaculture span a wide range of both urban-based and rural-based interests at both local and regional levels and institutional responsibilities must be clearly defined. Decisions will have to be taken on:

- allocation of effluent among competing uses,
- maintenance of quality standards and system reliability,
- investment in supporting resources, especially managerial and technical staff, required to administer each component of an effluent use scheme.

Policy decisions should normally be taken by a national or regional body, with executive responsibilities in the hands of a regional organization. Such a regional organization would be responsible for project implementation and operation and would provide the criteria, framework and administrative mechanisms necessary for effective effluent utilization. However, they would also be responsible for effective monitoring and control of the crops irrigated, the quality of effluent and associated health and environmental impacts.

One of the most important features of a successful effluent use scheme is the supervision provided at all stages of the system. Strict control must be applied from the wastewater treatment plant, through the conveyance and irrigation systems to the quality of the resulting products, whether they are of commercial or environmental value. The management, monitoring and public relations procedures are as important as the technological hardware involved in the system and managers of regional organizations set up to administer effluent use projects must be firm if the schemes are to realise their full potential. Managerial and technical staff must be properly qualified and suitably trained to carry out their functions effectively. Treated effluent use in agriculture is a major resource development activity and requires an appropriate institutional structure, provided with adequate resources, to be successful.

8.3 Policy issues

The legislative framework for effluent use in agriculture can have a significant influence on project feasibility. Bartone (1986) has indicated that the authorities in Mexico are able to impose effective crop restriction measures in Irrigation Districts because they are empowered to withhold effluent from farmers not observing the regulations, whereas in Chile the sanitary authorities have little leverage. Chilean Water Law vests water rights in the farmers (landowners) and the authorities have never been successful in imposing crop restrictions, even though lettuce and other vegetables being irrigated with raw sewage have been implicated in annual typhoid epidemics in Santiago.

A coherent national policy for wastewater use in agriculture is essential. This must define the division of responsibilities among involved ministries and authorities and provide for their collaboration. Institutional mechanisms for implementation of the national policy must be established and legal backing provided for enforcement of regulations. Realistic standards must be adopted to safeguard public health and protect against adverse environmental impacts. Environmental issues associated with wastewater use are the main subject of a UNEP (1991) document. Provisions should be made to adequately staff and resource organizations charged with the responsibility for assessing, implementing, operating and monitoring effluent use schemes and enforcing compliance with regulations. A distinction between the upgrading of existing wastewater use schemes and the development of new schemes is drawn in Mari and Cairncross (1989). In addressing the former, it is stressed, attention should be paid not only to the technical improvements required or feasible but also to the need for better management of existing schemes and to their improved operation and maintenance.

A national and/or regional consultative committee will often be of value in developing policy guidelines. Serving on this committee should be a representative of all the main interest groups, including water resources planning, public health, public works (municipalities), agriculture and forestry, environmental protection, trade and commercial interests (including farmers' representatives). Policies emanating from such a committee should be free of local or partisan influences but, nevertheless, should be pragmatic. In particular, enforcement legislation must be unequivocal, unambiguous and addressed to the main problem areas. The committee should also be charged with assessing the epidemiological and agricultural impacts of effluent use schemes.

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9. Wastewater use case studies

9.1 Advanced wastewater treatment: California, USA

9.1.1 Reclaimed wastewater uses

Beneficial use of wastewater has been practised in California since the 1890s, when raw sewage was applied on 'sewer farms'. By 1987, more than 0.899 Mm^3/d of municipal wastewater (7-8% of the production) were being used for the applications indicated in Figure 20 (California State Water Resources Control Board 1990). Historically, agricultural use has dominated, and continues to do so, but over the past decade reclaimed wastewater has been increasingly used for landscape irrigation in urban areas and for groundwater recharge. Most of the reclaimed water (78%) is used in the Central Valley and South Coastal regions of California. Two hundred reclamation plants throughout California produce the volume of treated effluent indicated above and save 0.759 Mm^3/d of fresh water. The major wastewater reclamation systems are shown in Table 31. In agricultural use of treated effluent, at least twenty different food crops are being irrigated as well as at least eleven other crops and nursery products, as indicated in Table 32.

Figure 20: Types of reuse in California in 1987 (California State Water Resources Control Board 1990)

9.1.2 Wastewater reclamation criteria

Wastewater reclamation criteria have been in force in California since 1978, as issued by the California Department of Health Services (1978). For surface irrigation of food crops the requirement is for the effluent to be adequately disinfected and oxidized so that the median number of coliform organisms does not exceed 2.2 per 100 ml over 7 days, except that orchards and vineyards may be surface irrigated with effluent having a quality equivalent to that of primary effluent. Reclaimed wastewater use for spray irrigation of food crops must be at all times adequately disinfected, oxidized, coagulated, clarified, filtered wastewater with a bacteriological quality such that the 7-day median number of coliform organisms does not exceed 2.2 per 100 ml and the number of coliform organisms does not exceed 23 per 100 ml in more than one sample within any 30-day period. Exceptions to these quality requirements may be allowed by the State Department of Health on an individual case basis where the food crop is to undergo extensive commercial physical or chemical processing sufficient to destroy pathogenic agents before human consumption. For irrigation of fodder, fibre and seed crops the wastewater need only have received primary treatment. However, reclaimed wastewater used to irrigate pasture to which milking cows or goats have access must be at all times adequately disinfected and oxidized to achieve a median number of coliform organisms not exceeding 23 per 100 ml over 7-days.

Table 31: MAJOR WATER RECLAMATION SYSTEMS IN CALIFORNIA

Wastewater Treatment Plant Name	**Reclaimed water deliveries m^3/d**
San Jose Creek WRP	67 101
City of Bakersfield WTP #*2*	56875
Whittier Narrows WRP	53 648
City of Modesto	48 630
Fresno-Clovis Metropolitan Area Regional Wastewater Facilities	46284
Pomona WRP	32435
Laguna TP	31 560
Michelson WRP	29536
City of Bakersfield WTP #*3*	26447
City of Tulare WPCF	21 114
Lancaster WRP	18 539
South Tahoe PUD STP	17 184
Total	449 355
Percent of Statewide Total	50

The quality requirements for irrigation of golf courses, cemeteries, freeway landscapes and landscapes in other areas where the public has similar access or exposure are that the effluent should at all times be disinfected and oxidized to a median number of coliforms not exceeding 23 per 100 ml over 7 days and a number of coliforms not exceeding 240 per 100 ml in any two consecutive samples. More stringent quality requirements are applied to reclaimed wastewater used to irrigate parks, playgrounds, schoolyards and other areas where the public has similar access or exposure; here an adequately disinfected, oxidized, coagulated, clarified, filtered wastewater is required, or a wastewater treated by a sequence of unit processes assuming an equivalent degree of treatment and reliability. The effluent quality requirements are a median number of coliforms not exceeding 2.2 per 100 ml over 7 days and a limit of 23 coliforms per 100 ml in any sample. A similar quality is required for reclaimed wastewater used as a source of supply in nonrestricted recreational impoundments but in restricted recreational impoundments the wastewater should be disinfected and oxidized to a median number of coliforms not exceeding 2.2 per 100 ml over 7 days. Reclaimed water used as a source of supply in a landscape impoundment should be disinfected and oxidized to a median number of coliforms not exceeding 23 per 100 ml over 7 days.

For groundwater recharge of domestic water supply aquifers by surface spreading, the reclaimed wastewater must be at all times of a quality that protects public health. The State Department of Health Services advises Regional Water Quality Control Boards on an individual case basis for proposed groundwater recharge projects and for expansion of existing projects. Recommendations are based on all relevant aspects of each project, including treatment provided, effluent quality and quantity, spreading area operations, soil characteristics, hydrogeology, residence time and distance to withdrawal. A public hearing is held prior to making the final determination regarding the public health aspects of each groundwater recharge project.

Table 32: TYPES OF CROPS IRRIGATED WITH RECLAIMED WATER IN CALIFORNIA

Food crops		**Non-food crops**
Apples	Grapes	Alfalfa
Asparagus	Lettuce	Christmas trees
Avocados	Maize	Clover
Barley	Peaches	Cotton
Beans	Peppers	Eucalyptus trees
Broccoli	Pistachios	Flower seeds
Cabbage	Plums	Hay
Cauliflower	Squash	Maize
Celery	Sugarbeets	Sod
Citrus	Wheat	Trees
		Vegetable seeds

9.1.3 Wastewater treatment

The Office of Water Recycling of the California State Water Resources Control Board recognizes four levels of treatment beyond primary treatment, based on the unit processes and on the types of effluent use taking place:

i. Secondary treatment in stabilization ponds, including disinfection if provided

ii. Other secondary treatment, for example by the activated sludge process, including disinfection if provided

iii. Title 22 tertiary treatment, using filtration and other processes intended to comply with the requirement in the reclamation criteria, published in Title 22 of the California Code of Regulations (California Department of Health Services 1978) for adequately disinfected, oxidized, coagulated, clarified, filtered wastewater, or approved equivalent. Usually secondary effluent is treated by the approved equivalent of 'direct filtration', that is, coagulent addition and mixing directly followed by filtration.

iv. Other tertiary treatment, consisting of any process following secondary treatment, except tertiary treatment intended to comply with wastewater reclamation criteria in Title 22 of the California Code of Regulations.

In the survey reported in the review of California municipal wastewater reclamation in 1987 (California State Water Resources Control Board 1990) all the wastewater treatment plants producing effluents for beneficial uses were found to provide at least secondary treatment. With one exception, chlorination was believed to have been the sole method of disinfection applied. Tertiary treatment processes falling under category (iv) above were found to include filtration, carbon adsorption, denitrification, air stripping and reverse osmosis. A summary of the treatment levels provided for specific types of effluent use is given in Table 33.

9.1.4 Monterey wastewater reclamation study for agriculture

The Monterey Wastewater Reclamation Study for Agriculture (MWRSA) was a 10-year, US $7.2 million field-scale project designed to evaluate the safety and feasibility of irrigating food crops (many eaten raw) with reclaimed municipal wastewater (Sheikh et al. 1990). Demonstration fields at Castroville in the lower Salinas Valley, California were used to study full-scale farm practices using reclaimed municipal wastewater. Two 5 hectare experimental plots provided large amounts of data on crop response which were subjected to statistical analysis. On one plot artichokes were grown, while on the other a succession of broccoli, cauliflower, lettuce and celery was raised over a 5-year period starting in late 1980.

Secondary effluent from the 1500 m^3/d Castroville wastewater treatment plant of the Monterey Regional Water Pollution Control Agency was upgraded in a pilot tertiary reclamation plant before being used to irrigate the plots. Two parallel tertiary treatment processes were used, complete treatment in a 'Title 22' (T-22) process and a direct filtration process, termed the 'filtered effluent'

(FE) process, both systems being shown in Figure 21. The T-22 train included coagulation, clarification, filtration and disinfection, the full treatment process required for spray irrigation of food crops in the Wastewater Reclamation Criteria (California Department of Health Services 1978). Alum dosages of 50 to 200 mg/l and polymer dosage of 0.2 mg/l were applied in this process. In the FE process, low alum dosages between 0 and 15 mg/l and polymer dosages from 0 to 0.18 mg/l were applied with a combination of either static or mechanical rapid mixing and dual-media gravity filtration at 3.4 l/m^2s. The chlorine contact tank had a 90 minute theoretical retention time. Flocculation chambers were added to the FE process in October 1983 to enhance floe formation prior to filtration, producing a filtered effluent flow stream designated FE-F. Dechlorination of final effluent with sulphur dioxide was practised over the first three years but was discontinued in June 1983 to determine the effects, if any, of a chlorine residual on crops and to prevent microbial regrowth. No adverse effects of chlorine residual on crops was observed and further microbial regrowth in storage tanks and pipelines was prevented.

Table 33: LEVELS OF WASTEWATER TREATMENT PROVIDED IN CALIFORNIA FOR TYPES OF EFFLUENT USE

Type of effluent use	**Number of water reclamation plants providing indicated treatment**				
	Oxidation ponds	Other secondary	Title 22 tertiary	Other tertiary	Total
Agricultural Irrigation:					
Harvested feed, fibre and seed crops	12	20	1	1	34
Pasture	23	25	4	3	55
Orchards and vineyards	3	4	2	1	10
Tree crops (Christmas trees, firewood, pulp, etc.)	2	1	0	0	3
Nursery and sod crops	0	3	4	1	8
Food crops	0	2	1	0	3
Mixed, other or unknown types of agricultural products	11	19	3	3	36
Landscape Irrigation:					
Schools, playgrounds, parks where Title 22 tertiary effluent required	0	0	7	2	9
Freeway and highway landscape	0	0	8	4	12
Golf courses (including golf course	4	13	24	8	49

impoundments)					
Mixed, other or unknown types of landscape (including street landscape, slope cover,parks where tertiary effluent not required)	2	6	13	3	24
Landscape Impoundments (excluding golf courses)	0	0	1	0	1
Recreational Impoundment	0	1	3	0	4
Wildlife Habitat Enhancement, Wetlands	1	2	2	0	5
Industrial Use:					
Cooling water	0	1	2	2	5
Process water	0	0	1	0	1
Construction, dust control, washdown	1	1	1	1	4
Other or unknown types of industrial use	0	1	0	0	1
Groundwater Recharge	0	0	5	0	5
Miscellaneous or unknown types of use or mixed types of above uses	1	4	5	1	11
TOTAL	60	103	87	30	280[1]

[1] Total exceeds actual number of treatment plants because some plants serve several types of reuse.

Source: California State Water Resources Control Board 1990

Figure 21: Schematic diagrams of tertiary treatment systems used in the MWRSA (Sheikh *et al.* 1990)

A split plot experimental design allowed the study of two treatment variables: irrigation water type (T-22 effluent, FE effluent and well water) and fertilization rate (no fertilizer and 33%, 66% and 100% of full local fertilizer rate for the crop irrigated). The artichokes were fertilized four times a year and the fertilization regimes for the other row crops varied with each crop's requirements but all row crop areas received an application of fertilizer before planting. Analysis of variance was used to determine if significant differences could be detected between the characteristics of the soils and plants receiving different water types and fertilization rates.

The well water used to irrigate the plots was chemically satisfactory, consistently exhibiting adjusted SAR (SAR_{adj}) values of less than 4; for the soil at the MWRSA site (a 50% montmorillonite and 50% illite-vermiculite clay mixture) an SAR_{adj}, of 7 or less is considered to pose no problem, 7-12 would cause increasing problems and greater than 12 would potentially pose a severe problem. The T-22 effluent was generally within the SAR_{adj}, range 7-12, indicating increasing potential problems, while the FE effluent although usually in this range occasionally exceeded 12, with the potential for severe problems. Salinity in the reclaimed effluents was correspondingly high (611-1621 mg/l) but not so high as to cause soil permeability problems. The reclaimed effluents contained very low levels of heavy metals, an order of magnitude lower than the metal input from impurities in commercial fertilizers. All three types of irrigation water, including the well water, periodically exhibited high total coliform levels. Both the T22 and FE processes were capable of producing reclaimed water meeting the most stringent of the California Wastewater Reclamation Criteria (2.2 MPN coliforms/100 ml) most of the time. *Ascaris lumbricoides, Entamoeba histolytica* or other parasites were never detected in any of the irrigation waters. During the five years of the field study, the quality of both reclaimed effluents improved as a result of improving treatment plant operations and reclaimed water storage procedures.

In nearly all cases the relative values of chemical constituents of the soil followed the same relative value relationships in the irrigation waters. Chemical parameter concentrations were generally highest in the FE-irrigated soil samples and lowest in samples from the well water-irrigated soil. Higher fertilizer application rates were found to have effects on the concentrations of various soil chemical parameters similar to that of effluent irrigation. None of the data indicated that the soils irrigated with the three waters were being adversely affected and the reclaimed wastewater effluents did not have harmful effects on the soil. Heavy metals concentrations in the irrigated soils were not found to be a problem. The levels of total and faecal coliforms in soils irrigated with the two reclaimed effluents were similar to levels in the well water-irrigated soils and no parasites were ever detected in soil samples.

Analysis of plant edible tissues for heavy metals proved that there was no consistently significant difference between concentrations in plants irrigated with reclaimed wastewater effluents and in those irrigated with well water. In addition, the metal content of artichoke tissues from neighbouring fields showed no relationship with distance from the site of the plots. Analysis of residual tissues produced results similar to those for edible tissues except for accumulation of zinc (higher in edible tissues for all vegetables studied) and cadmium (higher in residual tissues). The levels of total and faecal conforms in plant tissues irrigated with all three waters were generally comparable. No consistently significant difference attributable to water type was observed and the same applied to the presence of parasites, which were detected in plant tissue only during the first year of the study.

Statistically significant differences in crop yield due to irrigation water type were observed in the cases of celery and broccoli, both crops giving higher yields with reclaimed wastewater irrigation. Yields of lettuce and celery showed interaction of water type and fertilization, with reclaimed wastewater irrigation improving yields in unfertilized plots but having little or no effect on plots receiving fertilizer. Artichoke yields were similar with all three irrigation water types. Yields of all five crops levelled off at or below 66% of the standard local fertilizer application rate and application of the full (100%) local fertilization rate did not improve yields further. It would appear that reductions of up to 33% of fertilizer application could be possible when reclaimed wastewater is used for irrigating these crops. Field inspection of crops showed no leaf damage due to residual chlorine in the effluents and no differences in appearance or vigour of plants irrigated with different water types. In cold storage tests for periods up to 4 weeks following harvest, no unexpected deterioration of produce was observed. The quality and shelf life of all the produce irrigated with the reclaimed wastewaters was as good as, and in some instances superior to, the produce irrigated with well water.

The results of this 5-year study have indicated that use of tertiary treated wastewater for food crop irrigation is safe and acceptable. No adverse impacts in terms of soil or groundwater quality degradation were observed. Conventional farming practices were shown to be adequate and the marketability of the produce did not appear to pose any problems. No project-related health problems were detected through medical examinations and the serum banking programme routinely conducted for the project personnel.

9.2 Wastewater treatment in stabilization ponds: Al Samra, Jordan

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The Al Samra Wastewater Stabilization Pond (WSP) System was commissioned in May 1985 and by 1986 was receiving approximately 57 000 m^3/d of domestic wastewater and septage from the Metropolitan Area of Greater Amman, Jordan. In addition to the WSP facility, which is about 40 kilometres northeast of Amman, the system comprises a septage receiving and pretreatment installation, an inverted siphon 38.6 kilometres long and a raw wastewater pumping station.

9.2.1 Septage pretreatment and wastewater transmission

Before wastewater from the Greater Amman area enters the siphon, a septage receiving and pretreatment installation allows the sludge removed from septic tanks and cesspits to be mixed with the wastewater. At Ain Ghazal, a site in Amman primarily occupied by an abandoned activated sludge treatment plant, an average of 5000 m^3/d of septage is discharged into an aerated grit chamber. A typical composition of the septage is 1600 mg/l BOD_5, 5700 mg/l COD and 2600 mg/l Suspended Solids. Also located at Ain Ghazal are large screening and grit removal devices for the wastewater. It is important during stormflow conditions to protect the siphon from damage from floating material, grit and large stones in the wastewater, which increases in volume to 148 000 m^3/d.

The transmission pipeline from Ain Ghazal to Al Samra is an inverted siphon of 1200 mm diameter with an inlet elevation of 688m, an outlet elevation of 580 m and an elevation of 460 m at its lowest point. It is made of welded steel 8.3 mm thick with a 25 mm concrete lining and has an ultimate capacity of 220,000 m^3/d. There are facilities at the low point for draining the siphon into a 50,400 m^3 emergency storage pond, which has a capacity larger than the 45,000 m^3 of wastewater in the pipe when it is flowing full. The siphon is equipped with blowoff and double acting air valves, line-size access points (at 4 km intervals), a line-size isolation valve at the low point and two flushing outlets, one on either side of the flushing valve. A foam swab and ball can be passed through the siphon from Ain Ghazal to the inlet works at Al Samra for cleaning purposes.

About 1 km upstream of the low point in the siphon a new wastewater pumping station allows wastewater from the Zarqa-Ruseifa area to be introduced into the pipeline. This pumping station had a peak pumping capacity of 14 000 m^3/d in 1987 but the ultimate capacity is 72 000 m^3/d.

9.2.2 Al Samra stabilization ponds

The general layout of the Al Samra wastewater stabilization ponds is shown in Figure 22 indicating three trains of ponds, each containing two anaerobic ponds, four facultative ponds and four maturation ponds. However, due to the high organic loading on the ponds, in practice the first eight ponds in each train are anaerobic and only the final two behave as facultative ponds. All the ponds are contained by embankments constructed of the indigenous soil, containing 10-20% clay, and no separate lining is provided. Details on the ponds are provided in Table 34.

Figure 22: Al Samra pond layout (Al-Salem 1987)

In order to reduce water losses by seepage and evaporation during the early phase of operation of the ponds, only two trains were used. After start-up in May 1985, effluent overflowed from the two trains by August 1985. Initially, in September 1985, the rate of seepage was estimated to be 8.54 mm/d but this declined to approximately 0.36 mm/d by December 1986. During 1986, loss of water by evaporation was 12.6%, with maximum rate of evaporation 14.4 mm/d in July and minimum 0.3 mm/d in November.

Table 34: EFFECTIVE POND SIZES AND RETENTIONS AT A FLOW RATE OF 68 000 m^3/d

Pond	Total depth (m)	Effective depth (m)	3 trains			2 trains		
			Area (ha)	Volume (m^3x10^5)	Retention (d)	Area (ha)	Volume (m^3x10^5)	Retention (d)
Al	5.0	3.0	9.5	2.85	4.2	6.3	1.90	2.8
A2	5.0	3.0	9.5	2.85	4.2	6.3	1.90	2.8

Fl	2.25	1.5	21.75	3.26	4.8	14.5	2.17	3.2
F2	2.0	1.5	21.75	3.26	4.8	14.5	2.17	3.2
F3	1.5	1.5	21.75	3.26	4.8	14.5	2.17	3.2
F4	1.5	1.5	21.75	3.26	4.8	14.5	2.17	3.2
Ml	1.25	1.25	18.75	2.34	3.4	12.5	1.56	2.3
M2	1.25	1.25	18.75	2.34	3.4	12.5	1.56	2.3
M3	1.25	1.25	18.75	2.34	3.4	12.5	1.56	2.3
M4	1.25	1.25	18.75	2.34	3.4	12.5	1.56	2.3
TOTAL			181.00	28.10	41.2	120.6	18.72	27.6

Source: Al-Salem (1987)

9.2.3 Performance of Al Samra stabilization ponds

The composition of the Amman wastewater as it enters the siphon at Ain Ghazal and as it discharges to the inlet works at Al Samra is shown in Table 35. Clearly, the transmission pipeline is acting as an anaerobic digester during the 18 hours travel time, with reductions in BOD_5, COD and SS of 14, 25 and 16%, respectively.

Table 35: COMPOSITION OF AMMAN WASTEWATER

Parameter	At entry to siphon (Ain Ghazal) mg/l	At Al Samra Inlet Works mg/l
BOD_5	766	623
TSS	899	754
COD	1829	1376
$CaCO_3$	848	645
TOC	224	193
TDS	1172	1127
Total N as N	150	103
NH_4-N	101	91
Total P as P	25	22
SO_4	93	60
H_2S	18.2	21.9

Source: Al-Salem (1987)

The performance of the Al Samra stabilization ponds ' is influenced by temperature, with an average water temperature of 15°C in the cold season (December-March) and 24°C in the hot season (August-November). Figure 23 shows the BOD_5 removal during 1986 for both the cold and the hot seasons. Pond loadings during this year were as shown in Table 36.

In terms of overall performance in 1986, the Al Samra ponds were highly efficient, removing 80% and 91% of the incoming BOD_5 on the basis of unfiltered and filtered final effluent samples, respectively. This was the situation with only two trains of ponds in operation when the design organic loading was being exceeded by 57% and the hydraulic loading was 25% greater than design. At the same time, a 4.6 log reduction in faecal coliforms was achieved in passage through the ponds (Al-Salem 1987).

Figure 23: Summary of BOD removal through the ponds (Al-Salem 1987)

Table 36: AL SAMRA POND ORGANIC LOADINGS - 1986

Pond No.	Hot season		Cold season	
	Vol. Loading g BOD_5/m^3d	Areal loading kg BOD_5/ha.d	Vol. loading g BOD_5/m^3d	Areal loading kg BOD_5/ha.d
A2-1	120	5925	120	5923
A2-2	50	2444	70	2376
F2-1		915		
F2-2		775 (408)		
F2-3		560 (307)		
F2-4		477 (176)		
M2-1		465 (164)		
M2-2		552 (121)		
M2-3		439 (118)		
M2-4		544 (95)		

() Figures in brackets denote loadings based on filtered BOD_5 samples.

Source: Al-Salem (1987)

The microbiological performance of the Al Samra ponds has been described in more detail for the period December 1986 to March 1987 by Saqqar and Pescod (1990). Table 37 shows total coliform and faecal coliform reductions through the pond series for the period concerned. It is clear that the final effluent (after Pond M4) did not meet the WHO (1989) guidelines figure of ≤ 1000 faecal coliforms/100 ml for most of the study period, in spite of having passed through the series of ponds with a minimum theoretical retention time of 34 days. The 4-month geometric means of the total and faecal coliform die-off coefficient (K_b) ranged from 0.22-0.76 and 0.11-0.68, respectively, with the level of K_b increasing through the pond sequence. Linear regression analysis of the data indicated that retention time, pond BOD_5 concentration, pH and depth had a significant effect on K_b. Data on nematode egg removal during January and February 1987 are given in Table 38, showing that nematode eggs were absent from the final effluent (Pond M4 outlet) over the period and indicating that the WHO (1989) guidelines value of ≤ 1/litre could be achieved with the theoretical retention time of 34 days, but not after 24.7 days (Pond F4 outlet).

Table 37: MONTHLY GEOMETRIC MEANS FOR TOTAL AND FAECAL COLIFORMS

Month	**DEC 1986**		**JAN 1987**		**FEB 1987**		**MARCH 1987**	
Average monthly water temp. °C	**12.1**		**11.8**		**14.9**		**15.1**	
Monthly geometric mean	Total coliforms No/100 ml	Faecal coliforms No/100 ml	Total coliforms No/100 ml	Faecal coliforms No/100 ml	Total coliforms No/100 ml	Faecal coliforms No/100 ml	Total coliforms No/100 ml	Faecal coliforms No/100 ml
Effluent of Pond AI	6.5×10^7	2.22×10^7	9.59×10^7	1.50×10^7	9.42×10^7	1.90×10^7	7.52×10^7	1.78×10^7
Effluent of Pond A2	2.59×10^6	9.20×10^5	4.28×10^7	6.18×10^6	5.57×10^7	1.0×10^7	3.23×10^7	7.94×10^6
Effluent of Pond F2	4.02×10^6	4.73×10^5	7.15×10^6	1.02×10^6	7.05×10^6	9.98×10^5	6.94×10^6	7.84×10^5
Effluent of Pond F4	6.38×10^5	6.53×10^4	1.24×10^6	1.76×10^5	8.78×10^5	1.12×10^5	6.30×10^5	9.65×10^4
Effluent of Pond M2	8.21×10^4	8180	2.36×10^5	31 020	1.28×10^5	17252	4.87×10^4	13924
Effluent of Pond M4	12289	1022	27838	4423	13 176	2631	3908	814

Source: Saqqar and Pescod (1991)

9.3 Soil-aquifer treatment: Arizona, USA

9.3.1 Project details

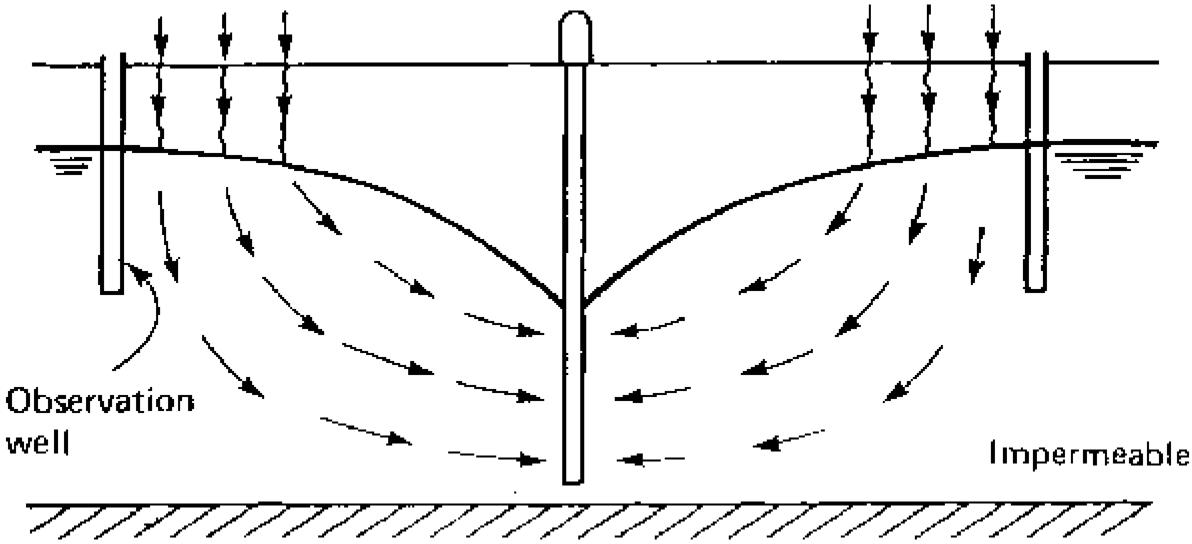
The city of Phoenix, in south-central Arizona, has been carrying out extensive testing of experimental soil-aquifer treatment (SAT) systems since 1967. Part of the effluent from the two major sewage treatment plants in the Phoenix area, both activated sludge plants with chlorination, was intended to be renovated by the SAT process and exchanged for high quality groundwater in a nearby irrigation district, which the city would then use to augment its municipal water supply. The Phoenix SAT system was to consist of a series of infiltration basins arranged in two parallel strips with wells on a line midway between the strips, as illustrated in Figure 24. To test the feasibility of the SAT system, a small test project was installed in 1967 followed by a larger demonstration project installed in 1975. The latter project was intended to form part of a future operational project with a basin area of 48 ha and a projected capacity of about 50 million m^3/year (Figure 25).

Table 38: NEMATODE* EGG COUNTS IN AL SAMRA PONDS SYSTEM

Date	**Sample location**			
	Raw wastewater eggs/l	**A2 outlet eggs/l**	**F4 outlet eggs/l**	**M4 outlet eggs/l**
24/1/1987	71	7	7	0
31/1/1987	53	10	7	0
7/2/1987	50	10	10	0
14/2/1987	141	36	24	0
20/2/1987	350	10	0	0
Geometric mean	99	12	6	0**
Removal efficiency	-	88%	94%	100%

* *Ascaris lumbricoides, Trichuris trichiura, Ancylostoma duedenale* and *Necator americanus.*
** Arithmetic mean
Source: Saqqar and Pescod (1991)

Figure 24: Infiltration basin SAT system (Bouwer 1987)



The first, test, project was installed in the Salt River bed at Flushing Meadows. It consisted of six parallel, long, narrow infiltration basins of about 0.13 ha each. The soil was about 1 m of loamy sand underlain by sand and gravel layers, with the groundwater table at a depth of around 3 m. Monitoring wells 6-9 m deep were installed at various points between the basins and away from the basins. A flooding and drying schedule of 9 days flooding - 12 days drying was adopted. Renovated water was sampled from the aquifer below the basins and after it had moved laterally for some distance through the aquifer. The scheme and results are reviewed in Bouwer et al. (1974) and in Bouwer et al. (1980).

The 23rd Avenue demonstration project (Bouwer and Rice 1984) was installed in 1975 on the north side of the Salt River bed. It consisted of the 16 ha area of lagoons, shown at the west side of Figure 25, split lengthwise into four infiltration basins of 4 ha each. Here, the soil lacks the loamy sand top layer of the Flushing Meadows site and, thus, the soil profile consists mostly of sand and gravel layers. The water table depth over the period of study ranged from 5 m to 25 m but was mostly about 15 m below ground level. Monitoring wells for sampling renovated water were installed at the centre of the project to depths of 18, 24 and 30 m, and on the north side of the basin complex to depths of 22 m. In addition, a large production well (capacity about 10 000 m^3/day) was drilled at the centre of the project with the casing perforated over the 30 to 54 m depth range.

A flooding and drying schedule of 14 days flooding - 14 days drying was mostly used and water depth in the basins was 15-20 cm. During flooding, infiltration rates were typically between 0.3 and 0.6 m/day, yielding a total infiltration or hydraulic loading rate of about 100 m/year. Initially, the sewage treatment plant effluent was allowed to flow through the 32 ha lagoon shown on the east of Figure 21 before entering the demonstration infiltration basins. However, this gave problems of soil clogging in the infiltration basins due to heavy growth of algae in the lagoon, especially during summer. Unicellular algae *Carteria klebsii* were particularly toublesome, not only forming a 'filter cake' on the bottom of the basins but also raising pH (due to CO_2 removal) and causing precipitation of $CaCO_3$, which further aggravated the soil clogging. Eventually, a bypass canal was constructed around the 32 ha lagoon, as shown on Figure 25, reducing the retention time from a few days to about half an hour. After the bypass channel was put into operation, hydraulic loading rates for the infiltration basins increased from 21 m/year to almost 100 m/year.

Figure 25: 23rd Avenue SAT project, Phoenix (Bouwer 1987)

At a loading rate of 100 m/year, 1 ha of infiltration basin can handle 10^6 m^3 of effluent/year. Hence, the 150 000 m^3/day of effluent from the 23rd Avenue wastewater treatment plant would require 55 ha of infiltration basins. Almost all the required area could be provided by converting the 32 ha lagoon into infiltration basins, as indicated in Figure 25. The resulting 48 ha could then handle 48 million m^3/year of effluent. Wells for pumping the renovated water from the aquifer could be located on the centreline through the project area (Figure 25). At a capacity of 10,000 m^3/day per well, 12 wells would be required in the operational full-scale project to remove renovated water at the same rate as wastewater infiltrates into the aquifer from the basins, thus creating an equilibrium situation.

9.3.2 Quality improvements

In both experimental projects, most improvements in effluent quality occurred in the vadose zone (the unsaturated zone between the soil surface and the groundwater table). The following details on quality improvements are taken from Bouwer (1987).

Suspended solids

The suspended solids content of the renovated water at the Flushing Meadows project was less than 1 mg/l. From the 23rd Avenue project it averaged about 1 mg/l for the large production well. Most of these solids probably were fine aquifer particles that entered the well through the perforations in the casing. The suspended solids content of the secondary effluent at the 23rd Avenue project averaged about 11 mg/l.

Total dissolved solids

The total salt content of the renovated water increased slightly as it moved through the SAT system (from 750 to 790 mg/l at the 23rd Avenue project). Evaporation from the basins (including from the soil during drying) should increase the TDS content by about 2%. The rest of the increase probably was due to mobilization of calcium carbonate due to a pH drop from 8 to 7 as the effluent moved through the vadose zone.

Nitrogen

At the Flushing Meadows project, nitrogen removal from the effluent as it seeped through the vadose zone to become renovated water was about 30% at maximum hydraulic loading (100-200 m/year), but 65% when the loading rate was reduced to about 70 m/year, by using 9-day flooding-12-day drying cyles, and by reducing the water depths in the basins from 0.3 to 0.15 m. The form and concentration of nitrogen in the renovated water sampled from the aquifer below the basins were slow to respond to the reduction in hydraulic loading (Bouwer et al. 1980). In the 10th year of operation (1977), the renovated water contained 2.8 mg/l of ammonium nitrogen, 6.25 mg/l nitrate nitrogen and 0.58 mg/l organic nitrogen, for a total nitrogen content of 9.6 mg/l. This was 65% less than the total nitrogen of the secondary sewage effluent, which averaged 27.4 mg/l (most as ammonium) in that year. At the 23rd Avenue project, the total N content in the secondary sewage effluent averaged about 18 mg/l, of which 16 mg/l was as ammonium. The 2-week flooding-drying cycles must have been conducive to denitrification in the vadose zone, because the total N content of the renovated water from the large centre well averaged about 5.6 mg/l, of which 5.3 mg/l was as nitrate, 0.1 mg/l as ammonium, 0.1 mg/l as organic nitrogen and 0.02 mg/l as nitrite. The nitrogen removal was thus about 70%. This removal was the same before and after the secondary effluent was chlorinated, indicating that the low residual chlorine of the effluent by the time it infiltrated into the ground apparently had no effect on nitrogen transformations in the soil.

The flooding and drying sequence that maximizes denitrification in the vadose zone depends on various factors and must be evaluated for each particular system. Pertinent factors include the ammonium and carbon contents of the effluent entering the soil, infiltration rates, cation-exchange capacity of soil, exchangeable ammonium percentage, depth of oxygen penetration in the soil during drying and temperature. The combined laboratory and field data from the Flushing Meadows experiments showed that, to achieve high nitrogen removal percentages, the amount of ammonium nitrogen applied during flooding must be balanced against the amount of oxygen entering the soil during drying. Flooding periods must be long enough to develop anaerobic conditions in the soil. Infiltration rates must be controlled to the appropriate level for the particular effluent, soil and climate at a given site. Most of the nitrogen transformations in the Flushing Meadows studies occurred in the upper 50 cm of the vadose zone.

Phosphate

Phosphate removal increased with increasing distance of underground movement of the sewage effluent. After 3 m of downward movement through the vadose zone and 6 m through the aquifer, phosphate removal at the Flushing Meadows project was about 40% at high hydraulic loading and 80% at reduced hydraulic loading. Additional lateral movement of 60 m through the aquifer increased the removal to 95% (that is, to a concentration of 0.51 mg/l phosphate phosphorus versus 7.9 mg/l in the effluent). After 10 years of operation and a total infiltration of 754 m of secondary effluent, there were no signs of a decrease in phosphate removal. At the 23rd Avenue project, phosphate phosphorus concentrations in the last few years of the research averaged 5.5 mg/l for the secondary effluent and 0.37 mg/l for the renovated water pumped from the centre well. The shallower wells showed a higher phosphate content, indicating that precipitation of phosphate continued in the aquifer. For example, renovated water sampled from the 22 m deep north well showed phosphate phosphorus concentrations that averaged 1.5 mg/l. Most of the phosphate removal was probably due to precipitation of calcium phosphate.

Fluoride

Fluoride removal paralleled phosphate removal, indicating precipitation as calcium fluoride. At the Flushing Meadows project, fluoride concentrations in 1977 were 2.08 mg/l for the effluent, 1.66 mg/l for the renovated water after it had moved 3 m through the vadose zone and 3-6 m through the aquifer and 0.95 mg/l after it had moved an additional 30 m through the aquifer. At the 23rd Avenue project, fluoride concentrations averaged 1.22 mg/l in the secondary effluent and 0.7 mg/l in the renovated water from the centre well.

Boron

Boron was not removed in the vadose zone or the aquifer and was present at concentrations of 0.5 to 0.7 mg/l in both effluent and renovated water. The lack of boron removal was due to the absence of significant amounts of clay in the vadose zone and aquifer.

Metals

At the Flushing Meadows project, movement of the secondary effluent through 3 m of vadose zone and 6 m of aquifer reduced zinc from 193 to 35 μ g/1, copper from 123 to 16 μ g/1, cadmium from 7.7 to 7.2 μ g/1 and lead from 82 to 66 μ g/1 (Bouwer, Lance and Riggs, 1974). Cadmium thus appeared to be the most mobile metal.

Faecal coliforms

The secondary effluent at the Flushing Meadows project was not chlorinated and contained 105-10^6 faecal coliforms/100 ml. Most of these were removed in the top metre of the vadose zone but some penetrated to the aquifer, especially when a new flooding period was started. The deeper penetration of faecal coliforms at the beginning of a flooding period was attributed to less straining of bacteria at the soil surface because the clogged layer had not yet developed. Also, the activity of native soil bacteria at the end of a drying period was lower, producing a less antagonistic environment for the faecal coliforms in the soil when flooding was resumed. Faecal coliform concentrations in the water after 3 m of travel through the vadose zone and 6 m through the aquifer were 10-500/100 ml when the renovated water consisted of water that had infiltrated at the beginning of a flooding period and 0-1/100 ml after continued flooding. Additional lateral movement of about 100 m through the aquifer was necessary to produce renovated water that was completely free of faecal coliforms at all times.

At the 23rd Avenue project, faecal coliform concentration in the secondary sewage effluent entering the infiltration basins was 10,000/100 ml prior to November 1980, when the effluent was not yet chlorinated but was first passed through the 32 ha lagoon. This concentration increased to 1.8 x 10^6/100 ml when the unchlorinated effluent was bypassed around the lagoon and flowed directly into the infiltration basins. It then decreased to 3500/100 ml after the effluent was chlorinated and still bypassed around the lagoon. The corresponding faecal coliform concentrations in the water pumped from the large centre well from a depth of 30-54 m averaged 2.3, 22 and 0.27/100 ml, respectively. The corresponding ranges were 0-40, 0-160 and 0-3/100 ml, respectively. Considerable faecal coliform concentrations were observed in the renovated water from the shallower wells, especially when the faecal coliform concentration of the infiltrating effluent was 1.8 x 10^6/100 ml. At that time, water from the 18 m deep well showed coliform peaks following the start of a new flooding period that regularly exceeded 1000/100 ml and at one time even reached 17,000/100 ml. Thus, a considerable number of faecal coliforms passed through the vadose zone. However, chlorination of the effluent with resulting reduction of the faecal coliform concentration to 3500/100 ml prior to infiltration, and additional movement of the water through the aquifer to the centre well, produced renovated water that was essentially free of faecal coliforms.

Viruses

At the Flushing Meadows project, the virus concentrations of unchlorinated secondary effluent averaged 2118 plaque-forming units (PFU)/100 l (average of six bimonthly samples taken for 1 year). They included poliovirus, echo virus, coxsackie and reoviruses. No viruses could be detected in renovated water sampled after 3 m of movement through the vadose zone and 3-6 m movement through the aquifer. At the 23rd Avenue project, virus concentrations in the renovated water from the centre well averaged 1.3 PFU/100 l before chlorination of the secondary effluent and 0PFU/100 l after chlorination of the secondary effluent. The combined effects of chlorination and SAT thus apparently resulted in complete removal of viruses.

Organic carbon

At the Flushing Meadows project, the biochemical oxygen demand (BOD_5) of the effluent water after moving 3 m through the vadose zone and 6 m through the aquifer was essentially zero, indicating that almost all biodegradable carbon was mineralized. However, the renovated water still contained about 5 mg/l total organic carbon (TOC), as compared to 10-20 mg/l of TOC in the secondary effluent. At the 23rd Avenue project, the TOC concentration of the secondary effluent averaged 12 mg/l where it entered the infiltration basins and 14 mg/l at the opposite ends of the basins. This increase was probably due to biological activity in the water as it moved through the basins. The renovated water from the 18 m well (intake about 5 m below the bottom of the vadose zone) had a TOC content of 3.2 mg/l and that from the centre well (which pumped from 30 to 54 m depth) had a TOC content of 1.9 mg/l, indicating further removal of organic carbon as the water moved through the aquifer. The TOC removal in the SAT system was the same before and after chlorination of the secondary effluent, indicating that chlorination had no effect on the microbiological processes in the soil.

The concentration of organic carbon in the renovated water of 1.9 mg/l was higher than the 0.2-0.7 mg/l typically found in unpolluted groundwaters, which contain mostly humic substances, such as fulvic and humic acids. The renovated water from the SAT process could thus contain a number of synthetic organic compounds, some of which could be carcinogenic or otherwise toxic.

Removal of trace organic compounds in the vadose zone

The nature and concentration of trace organics in the secondary sewage effluent and in the renovated water from the various wells of the 23rd Avenue project were determined by Stanford University's Environmental Engineering and Science Section, using gas chomatography and mass spectrometry. The studies were carried out for 2 months with unchlorinated effluent and then for 3 months with chlorinated effluent, taking weekly or biweekly samples. As could be expected, the results showed a wide variety of organic compounds, including priority pollutants, many in concentrations of the order of μ g/1 (Bouwer et al. 1984, and Bouwer and Rice 1984).

Chlorination had only a minor effect on the type and concentration of organic compounds in the sewage effluent. Of the volatile organic compounds, 30-70% were lost by volatilization from the infiltration basins. Soil percolation removed 50-99% of the non-halogenated organic compunds, probably mostly by microbial decomposition. Concentrations of halogenated organic compounds decreased to a lesser extent with passage through the soil and aquifer. Thus, halogenated organic compounds (including the aliphatic compounds chloroform, carbon tetrachloride, trichloroethylene and 1,1,1-trichloroethane and the aromatic dichlorobenzenes, trichlorobenzenes and chlorophenols) were more mobile and refractory in the underground environment than the non-halogenated compounds, which included the aliphatic nonanes, hexanes and octanes, and the aromatic xylenes, C3-benzenes, styrene, phenanthrene and diethylphthalate.

Other organic micropollutants

In addition to the aliphatic and aromatic compounds mentioned, other compounds tentatively identified in organic extracts of the samples of secondary sewage effluent and renovated water using gas chromatography-mass spectrometry were: fatty acids, resin acids, clofibric acid, alkylphenol polyethoxylate carboxylic acids (APECs), trimethylbenzene sulphonic acid, steroids, *n*-alkanes, caffeine, Diazinon, alkylphenol polyethoxylates (APEs) and trialkylphosphates. Several of the compounds were detected only in the secondary effluent and not in the renovated water. A few others - Diazinon, clofibric acid and tributylphosphate -decreased in concentration with soil passage but were still detected in the renovated water. The APEs appeared to undergo rather complex transformations during ground infiltration. They appeared to be completly removed by soil percolation during the prechlorination period but, after chlorination, two isomers were found following soil passage, while others were removed.

The results of these studies showed that SAT is effective in reducing concentrations of a number of synthetic organic compounds in the sewage effluent but that the renovated water still contains a wide spectrum of organic compounds, albeit at very low concentrations. Thus, while the renovated water is suitable as such for unrestricted irrigation and recreation, recycling it for drinking would require additional treatment, such as activated carbon filtration, to remove the remaining organic compounds. The water would also have to be disinfected and reverse osmosis may be desirable.

The Phoenix studies have proved that SAT can produce a renovated water meeting US public health, agronomic and aesthetic requirements for unrestricted irrigation, including irrigation of vegetable crops that are consumed raw. In these studies, chlorinated secondary effluent was applied to the infiltration basins because that was the effluent available. However, Bouwer (1987) asserts that the secondary, biological, treatment stage is not necessary because the SAT system can handle relatively large amounts of organic carbon. Instead, primary treated effluent, possibly with additional clarification through lime precipitation, might be satisfactory. Thus SAT might well provide a simple, low-cost method of producing an effluent suitable for agricultural use, where land is available and hydrogeological conditions are favourable.

9.4 Wastewater treatment and crop restriction: Tunisia

9.4.1 Current and future use of wastewaters in Tunisia

Wastewater use in agriculture has been practised for several decades in Tunisia and is now an integral part of the national water resources strategy. The volume of treated wastewater available in 1988 was 78 million m^3 and in the year 2000 it will probably exceed 125 million m^3 (Bahri 1988). In 1988, wastewater was being treated in 26 treatment plants, mainly located on the coast so as to prevent sea pollution, and by 1996 there should be 54 treatment plants. Of the existing sewage treatment plants, 16 are activated sludge, 2 trickling filters, 5 stabilization ponds and 3 oxidation ditches.

Use of treated effluents is seasonal in Tunisia (spring and summer) and the effluent is often mixed with groundwater before being applied to irrigate citrus and olive trees, forage crops, cotton, golf courses and hotel lawns. Irrigation with wastewater of vegetables that might be consumed raw is prohibited by the National Water Law (Code des Eaux). A regional Department for Agricultural Development (CRDA) supervises all irrigation water distribution systems and enforces the Water Code. At the present time, an area of about 1750 ha is being irrigated with treated wastewater, at the locations indicated in Table 39. The major irrigation areas around Tunis are shown on Figure 26. La Cherguia activated sludge plant receives sewage from part of the Tunis metropolitan area and discharges its effluent to the La Soukra irrigation area 8 kilometres away.

Figure 26: Current and future irrigation with treated wastewater in the Tunis metropolitan area (Strauss and Blumenthal 1989)

Table 39: ACTUAL AND FUTURE USE OF TREATED WASTEWATER IN TUNISIA

Location	Area ha	Wastewater treatment plant			Crops
		Name	System	Capacity m³/d	
Existing					
Tunis					
Soukra	600	Cherguia	AS	60000	Citrus trees
Nabeul					
Oued Souhil	250		As	14400	Citrus trees
		SE4			
Sousse					
Sousse North	43	Sousse N	AS	13 000	Golf course
Sousse South	205	Sousse S	TF	18700	Forage crops
Monastir					
Monastir		Monastir	TF	2600	Golf course
Under Implementation					
Tunis					Citrus trees
Soukra	200	Cherguia	AS	60000	Cereals
Cebala	2670	Choutrana	OD	43000	Forage crops
		Cotiere N	SP	15 800	Industrial crops
Mornag	940	Meliane S	OD	37 500	-
Nabeul	330	SE2	AS	3500	
		SE4	AS	14400	Citrus trees
		SE3	OD	3 500	
Hammamet	140	SE1	AS	6600	Golf course
Sousse					

Sousse North	120	Sousse N	AS	13 000	Forage, trees
Sousse South	200	Sousse S	TF	18700	Forage, trees
Sfax	270	Sfax	SP	24000	Forage, trees
Kairouan	240	Kairouan	AS	12000	Forage crops Industrial crops
Cafsa	157	Cafsa	SP	4500	Forage, trees
Planned					
Moknine	100	Moknine	SP	2400	
Sfax	130	Sfax	SP	24000	
Tunis	15000	Sedjoumi			

AS: Activated sludge;
TF: Trickling filters;
OD: Oxidation ditches;
SP: Stabilization ponds
Source: Bahri (1988)

Many new projects are now being implemented or planned and the wastewater irrigated area will be increased to 6700 ha, allowing 95% of the treated wastewater to be used in agriculture. The most important developments will take place around Tunis, where 60% of the country's wastewater is produced and 68% of the effluent-irrigated area will occur.

9.4.2 Studies of treated wastewater irrigation and sewage sludge application

In the period 1981 to 1987, the Ministries of Agriculture and Public Health, with assistance from the United Nations Development Programme (UNDP), carried out studies designed to assess the effects of using treated wastewater and dried, digested sewage sludge on crop productivity and on the hygienic quality of crops and soil. Treated wastewaters and dried, digested sludge from the La Cherguia (Tunis) and Nabeul (SE4) activated sludge plants were used in the studies and irrigation with groundwater was used as a control. At La Soukra, tests were conducted on sorghum *(Sorghum vulgare)* and pepper *(Capsicum annuum)* using flood irrigation and furrow irrigation, respectively. Clementine and orange trees were irrigated at Oued Souhil (Nabeul). In order to assess the long-term effects of irrigation with treated waste-water, investigations were carried out on the perimeter area of La Soukra, where irrigation with treated effluent had been practised for more than 20 years. The programme of studies not only produced useful results but was also valuable from the point of view of the training of specialists and technicians (Bahri 1988).

The average quality characteristics of the treated wastewater from La Cherguia and sewage sludge from Soukra and Nabeul are given in Tables 40 and 41. The effluent contains moderate to high salinity but presents no alkalization risk and trace element concentrations are below toxicity thresholds. The sewage sludge had a fertilizing potential, due to the presence of minerals and organic matter, but was of variable consistency. Evaluation of the fertilizing value of the effluent in relation to crop uptake suggests that the mean summer irrigation volume of 6000 m^3/ha would provide an excess of nitrogen (N) and potassium (K_2O) but a deficit of phosphorus (P_2O_5). The fertilizing value of 30 tonnes dry weight of sewage sludge per ha would be an excess of N and P_2O_5 and a deficit of K_2O. Application of treated effluent and sludge would balance the fertilizing elements but would provide an excess over crop requirements. Excess nitrogen would be of concern from the point of view of crop growth and in relation to groundwater pollution.

Table 40: AVERAGE CHARACTERISTICS OF TREATED WASTEWATERS (TW) AND WELL WATERS (WW) USED FOR IRRIGATION (in mg/l) IN LA SOUKRA COMPARED TO FAO RECOMMENDED MAXIMUM CONCENTRATIONS

Parameter	TW	WW	FAO
pH	7.6	7.6	6.5-8.5
EC	2.97	2.61	3.0
TDS (g/l)	1.82	1.71	2.0
SM	13.4	4.3	
COD	51	-	
HCO_3	370.0	228.5	600
SO_4	363.0	87.5	1000
Cl	554.0	648.0	1100
Ca	154.5	249.0	400
Mg	56.5	48.5	60
K	36.5	3.0	
Na	366.0	214.0	900
SAR	6.4	3.2	15
N (total)	2.5-43	-	30
NH_4	0.26-50.5	0.09	
NO_3	1.33-83.5	92.8	
NO_2	0.07-5.0	0.08	

P (total)	4.10	-	
PO_4	11.6	0.06	
Cd	-	-	0.01
Co	0.05	0.04	0.05
Cr	0.02	-	0.1
Cu	0.03	0.02	0.1
Fe	0.33	0.11	5
Mn	0.05	0.01	0.2
Ni	0.06	0.05	5
Pb	0.19	0.16	2
Zn	0.12	0.04	
TC/100 ml	10e4-10e6		
FC/100 ml	10e4-10e6		
FS/100 ml	10e4-10e6		
Salmonella	No		
Cholerae	No		

EC: electrical conductivity (in dS/m at 25°)
TDS: total dissolved solids
SM: suspended matter
COD: chemical oxygen demand
SAR: sodium adsorption ratio (in molalities)
TC: total coliforms
FC: faecal coliforms
FS: faecal streptococci
Source: Bahri (1988)

Application of treated wastewaters and sewage sludge at the La Soukra and Oued Souhil experimental stations, where the soils are alluvial and sandy-clayey to sandy, has not adversely affected the physical or bacterial quality of the soils. However, the chemical quality of the soils varied considerably, with an increase in electrical conductivity and a transformation of the geochemical characteristics of the soil solution from bicarbonate-calcium to chloride-sulphate-sodium (Bahri 1988). Trace elements concentrated in the surface layer of soil, particularly zinc (Zn), lead (Pb) and copper (Cu), but did not increase to phytotoxic levels in the short term of the study period. Rational use of sewage sludge would require standards to be developed for the specific soils, based on limiting concentrations of trace elements.

The use of treated wastewater resulted in annual and perennial crop yields higher than yields produced by groundwater irrigation. Sewage sludge application increased the production of sorghum and pepper and resulted in the crops containing higher concentrations of N, P and K and some minor elements (Fe, Zn and Cu). Bacterial contamination of citrus fruit picked from the ground irrigated with treated wastewater or fertilized with sewage sludge was significantly higher than the level of contamination of fruit picked from the trees. Natural bacterial die-off on sorghum plants was more rapid in summer than in autumn. Tests on pepper did not indicate particular contamination of the fruit.

Irrigation with treated wastewaters was not found to have an adverse effect on the chemical and bacteriological quality of shallow groundwater, although the initial contamination of wells was relatively high and subject to seasonal variation. Investigations on the peripheral area of La Soukra did not indicate significant impacts on soils, crops or groundwaters.

Table 41: AVERAGE CHEMICAL COMPOSITION OF THE SEWAGE SLUDGE (% DRY MATTER) COMPARED TO EUROPEAN STANDARDS

Parameter	Soukra-Nabeul sludge	AFNOR Standards 044-041
H_2O	25-50	
pH	7.2-7.9	
EC (1/5)	3.8-7.1	
VM %	17-42	
C (organic) %	10-20	
N (total) %	1-2.5	
C/N	6-8	
P (total) %	0.5-1.0	
Ca %	5-9	
Mg %	0.1-0.8	
K %	0.2-0.3	
Na %	0.1-0.4	
Cd ppm	4.0-7.0	20
Co ppm	16-30	
Cr ppm	51-78	1000

Cu ppm	150-320	1000
Fe %	7.6-18	-
Hg ppm	0.6-1.8	10
Mn ppm	103-320	-
Ni ppm	21-52	200
Pb ppm	192-526	800
Zn ppm	400-982	3000
Cr+Cu+Ni+Zn	560-1200	4000
FC/g fresh sludge	10e3-10e4	
FS/g fresh sludge	10e3-10e5	

EC: electrical conductivity (in dS/m at 25°)
VM: volatile matter
FC: faecal coliforms
FS: faecal streptococci
Source: Bahri (1988)

9.4.3 Legislation

The Tunisian Water Law, enacted in 1975, provides the legal framework for treated wastewater use. The Code prohibits the use of raw sewage in agriculture and the irrigation of vegetables that are eaten raw with treated wastewater. Another relevant legal document is an enactment, issued in 1985, regulating substances released to the environment, which refers to wastewater use. In 1989, an Act more specifically regulating the use of treated wastewater in agriculture was introduced. The implementation and enforcement of the Decree is the responsibility of the Ministries of Public Works, Agriculture, Economy and Public Health.

The 1989 Act requires that treated wastewater use in agriculture be authorized by the Ministry of Agriculture, after preliminary inquiry from the Ministry of Public Health and notification from the National Environmental Protection Agency (Bahri 1988). Specified in the document is the frequency of physico-chemical and biological analyses. Irrigation of vegetables and of any crop that might be consumed raw is forbidden. It also stipulates that crops irrigated with treated wastewater must be tested by the Ministry of Public Health. In areas where sprinkler irrigation is to be adopted, buffer zones surrounding the irrigated area must be created. Direct grazing on land irrigated with treated wastewater is prohibited. Quality standards have been issued in a separate document, in which the crops that might be irrigated with treated wastewater are specified (forage and industrial crops, cereals, trees) and the precautions that must be taken to prevent contamination of workers, residential areas and consumers are detailed.

9.5 Wastewater treatment and human exposure control: Kuwait

9.5.1 Background to treated effluent use in Kuwait

Untreated sewage has been used for many years to irrigate forestry projects far from the inhabited areas of Kuwait. Effluent from the Giwan secondary sewage treatment plant was used to irrigate plantations on an experimental farm from 1956 (Agriculture Affairs and Fish Resources Authority, Kuwait 1988). Following extensive studies by health and scientific committees within the country and by international consultants and organizations (WHO and FAO), the government of Kuwait decided to proceed with a programme of sewage treatment and effluent use. In all, by 1987 four sewage treatment plants were in operation: the 150 000 m^3/day Ardiyah sewage treatment plant (secondary stage) was commissioned in 1971, the 96 000 m^3/day coastal villages and the 65 000 m^3/day Jahra sewage treatment plants were commissioned in 1984 and a small (10 000 m^3/day) stabilization ponds treatment plant has also been installed on Failaka Island. The effluent from the Ardiyah, coastal villages and Jahra, activated sludge treatment plants was upgraded in the middle 1980s by the provision of tertiary treatment, consisting of chlorination, rapid gravity sand filtration and final chlorination.

Initially, the treated secondary effluent from the Ardiyah plant was distributed to the experimental farm of the Department of Agriculture at Omariyah. Trials were undertaken in the early 1970's to compare crop yields from irrigation with potable water, brackish water and treated effluent. An 850 ha farm was established in 1975 by the United Agricultural Production Company (UAPC), under Government licence, especially for the purpose of utilizing the treated wastewater. The directors of this close shareholding company represented the main private organizations involved in Kuwait agriculture, in particular the local dairy, poultry and livestock farming organization. In 1975, only part of the area was under cultivation, with forage (alfalfa) for the dairy industry the main crop, using side-roll sprinkler irrigation. However, aubergines, peppers, onions and other crops were grown on an experimental basis, using semiportable sprinklers and flood and furrow irrigation.

9.5.2 Master plan for effluent utilization

The Government strategy for implementation of the Effluent Utilization Project was to give the highest priority to development of irrigated agriculture by intensive cultivation in enclosed farm complexes, together with environmental forestry in large areas of low-density, low water-demand tree plantations. By 1976, however, the total cropped area in Kuwait was only 732 ha and the country relied heavily on food imports and imports of both fresh and dried alfalfa were considered to be unnecessarily high. In late 1977, the

Ministry of Public Works initiated the preparation of a Master Plan for effective use of all treated effluent in Kuwait, covering the period up to the year 2010 (Cobham and Johnson 1988).

The overall plan recommendations are shown in Table 42. For the western and northern sites (Jahra and Ardiyah effluents, respectively) it was suggested that the first priority should be devoted to developing an integrated system of forage (used in a high concentrate ration dairy enterprise) and extensive vegetable production on the UAPC farm, so that full utilization would be made of existing and potential facilities as soon as possible. This utilization should be based on: modern irrigation techniques, strengthening of shelter belts, provision of adequate effluent storage facilities, trial of different irrigation equipment, investigation of the relative merits of vegetable production on intensive and extensive scales and improvement of both management and technical husbandry skills. Second priority, it was recommended, should be given to developing fresh forage/hay production in rotation with vegetables on the other agricultural sites identified. Once the two major priorities had been achieved, as much prime and subsistence environmental protection forestry as possible should be planted. Provided that trials concerning commercial timber yielded positive results, it was suggested that an area of at least 213 ha of maximum production forestry should be included.

Table 42: THE MASTER PLAN - LAND USE IMPLICATIONS

	1980 (ha)	**2010 (ha)**
Western and northern sites		
Agriculture		
Forage: dairy enterprise	70	670
Forage: open market sale	149	589
Horticulture		
Extensive vegetables	50	200
Forestry		
'Maximum production' forestry	20	213
'Environmental protection' at recommended irrigation rate	3808	7826
'Environmental protection' forestry at subsistence irrigation rate	401	-
Others		
Existing trial site, vegetable areas	46	46
Subtotal	4544	9544

Coastal village sites		
Forestry		
'Maximum production' 'Environmental protection' forestry	52	787
	1673	1673
Subtotal	1725	2460
Failaka Island		
'Environmental protection' forestry	176	284
Total	6445	12288

Source: Cobham and Johnson (1988)

The resource implications of the Master Plan were assessed, including the tree nursery production required for the new forestry areas, the infrastructural requirements (including boundary walls and roads), the irrigation equipment and machining needs for forage, vegetables, etc. Construction of works for effluent utilization according to the Master Plan began in mid-1981 but delays in the provision of permanent power supplies to all 12 sites deferred commissioning of the project until 1985. A data monitoring centre receiving treated effluent from Ardiyah and Jahra has been provided and includes two 170 000 m^3 storage tanks, pumping station, administration building incorporating laboratories for monitoring effluents and soils and workshops for maintenance and stores.

9.5.3 Project outputs and controls

The ultimate project design provides for the development of 2700 ha of intensive agriculture and 9000 ha of environmental forestry (Agriculture Affairs and Fish Resources Authority, Kuwait 1988). In 1985, the treated effluent supplied to the experimental farm and irrigation project was used to irrigate the following:

Fodder plants - alfalfa, elephant grass, Sudan grass, field corn (maize), vetch, barley, etc.

Field crops - field corn (maize), barley, wheat and oats.

Fruit trees - date palms, olive, zyziphus and early salt-tolerant vines (sprinklers were not used for fruit trees).

Vegetables - potatoes, dry onions, garlic, beet and turnip were irrigated by any method; vegetables which are to be cooked before consumption, such as egg plant, squash, pumpkin, cabbage, cauliflower, sweetcorn, broad beans, Jews mallow, Swiss chard, etc., were irrigated in any way but not by sprinkler;

vegetables which are eaten raw, such as tomatoes, water melons and other melons, were irrigated with tertiary-treated sewage effluent by drip irrigation with soil mulching.

The yield of green alfalfa was 100 tonnes/ha per year and the total production from the agricultural irrigation project, using primarily treated sewage effluent, was 34,000 tonnes of vegetables and green fodder plants, including dehydrated alfalfa and barley straw. At this production level, a reasonable supply of some vegetables was made available to the local market, the total demand for green alfalfa for animals was satisfied and some of the needs for dehydrated fodder were met.

For forestry irrigation, the systems include storage tanks and pumping stations incorporating fertilizer injection. Treated effluent is supplied via control points to blocks of forestry. Header mains downstream of control points feed 12.5 mm polyethylene drip lines fitted with pressure-compensating drip emitters (two per tree) discharging 4 l/h operating over a 0.7-3.5 bar inlet pressure range. Up to now, only environmental protection forestry has been developed although there is the potential to produce high yields of commercial forestry using treated effluent irrigation. Annual productivity levels which can be achieved in irrigated sand areas have been estimated to range from 5-25 m^3/ha for *Prosopis* and *Tamarix* (Cobham and Johnson 1988).

In Kuwait, the decision was taken to exclude all amenity uses for the treated effluent and to restrict agricultural use to safe crops. Furthermore, areas of tree and shrub planting and the agricultural farm were to be fenced to prevent public access. An efficient monitoring system for the treated effluent, the soil and the crops has been implemented since the experimental farm was initiated. The guidelines for tertiary-treated effluent quality used in irrigation are:

Suspended solids	10 mg/l
BOD_5	10 mg/l
COD	40 mg/l
Cl_2 residual	about 1 mg/l after 12 hours at 20°C
Coliform bacteria	10 000/100 ml for forestry, fodder and crops not eaten raw 100/100 ml for crops eaten raw

Even the tertiary-treated effluent meeting these guidelines is not to be used to irrigate salad greens or strawberries. Cadmium was the only heavy metal of concern and special attention was given to monitoring the effluent and crops for this element and to measuring Cd in the kidneys of animals fed on forage irrigated with treated sewage effluent. Agricultural workers dealing with sewage effluent are medically controlled as a pre-employment measure and given periodic (6 monthly) examinations and vaccinations. No outbreaks of infectious disease have occurred since this procedure began in

1976. The impact of treated effluent irrigated vegetables on the consumer has not been possible to assess because no segregation of vegetables produced in this way is effected in the market.

9.6 Crop restriction for wastewater irrigation: Mexico

9.6.1 Historical use of sewage for irrigation

Use of raw sewage for irrigation in the Mezquital Valley of the Tula River Basin began in 1886 (Sanchez Duron 1988). However, it was not until 1945 that the Ministry of Agriculture and Water Resources established the Number 03 Mezquital Irrigation District to manage the distribution of wastewater from Mexico City for irrigation purposes. Irrigation is essential in this Irrigation District because rainfall is limited and poorly distributed over the year, most falling between July and September. Sewage from Mexico City mixed with variable proportions of surface water collected in reservoirs within the basin has enabled farmers in the Mezquital Valley to provide agricultural produce for the capital city.

Six Irrigation Districts currently make use of wastewater and surface runoff from urban areas and the Government has developed plans for wastewater use in 11 more, as indicated in Table 43. Four Irrigation Districts receive wastewater and runoff from Mexico City, which on average amounts to 55 m^3/sec. Irrigation District 03, the most significant, comprises 16 municipalities with a population of 300 000 in 1985. A complex network of canals serves the area, allowing intensive cultivation year round taking advantage of the supply of wastewater.

9.6.2 Mezquital valley irrigation district 03 experience

At different times and places in the District, the following types of irrigation water might be used separately or in combination:

River water	containing little or no contamination from urban wastewater.
Impounded river water	diverted from reservoirs, or river reaches downstream receiving spillway overflows, containing wastewater discharged into the reservoirs from the main collector canals.
Wastewater	from the main collector canals, composed of sewage and urban storm runoff.

Table 43: IRRIGATION DISTRICTS WITH CURRENT AND PLANNED USE OF WASTEWATER

Dist.No.	Name of district	State	Area irrigated (ha)	Total area which can be irrigated (ha)	Annual wastewater flow available as % of total irrigation water	Major crops grown

					supplied	
Wastewater reuse existing						
031	Tula[2]	Hidalgo	43000	48000	>100	Alfalfa, maize, wheat, oats, green tomatoes chillies
09	Cd. Juárez	Chihuahua	3000	17500	3.5	Cotton, alfalfa, oats, wheat
28[1]	Tulancingo	Hidalgo	300	1 100	54	Pasture, maize, alfalfa
30	Valesquillo	Puebla	17 600	33 800	58	Maize, alfalfa, beans, chillies
88[1]	Chiconautla-Chalco-Texcoco	Mexico	4 300	4300	> 100	Maize, alfalfa, oats, beet root
100[1]	Alfajayucan[3]	Hidalgo	14700	28900	> 100	Maize, beans, wheat, green tomatoes
Wastewater reuse planned						
10	Culican y Humaya	Sinaloa		223000	1.3	Wheat, sorghum, sugarcane
11	Alto Río Lerma	Guanajato		102000	5.6	Wheat, sorghum, maize, beans
14	Río Colorado	Baja California Norte		207000	1.5	Cotton, wheat, barley, alfalfa
16	Estado de Morelos			34 600	2.6	Rice, maize, green tomatoes, sugarcane
17	Región Lagunera	Coahuila & Durango		150000	2.1	Cotton, maize, wheat, alfalfa
20	Morelia y Querendaro	Michoacán de Ocampo		33900	7.2	Maize, wheat, sorghum, barley
26	Bajo Río San Juan	Tamaulipas		79500	1.5	Maize and sorghum
41	Río Yaqui	Sonora		93 800	1.3	Wheat, cotton, alfalfa

61	Zamora	Michoacán de Ocampo		17900	2	Wheat, peas, potatoes, strawberries
75	Valle del Fuerte	Sinaloa		223000	0.2	Cotton, knapweed, wheat, sugarcane
82	Ráo Blanco	Veracruz		1 600	2.6	Maize, watermelons, green tomatoes

[1] Using wwastewate and runoff from Mexico City
[2] 15 800 users in District
[3] 21 800 users in District
Source: Strauss and Blumenthal (1989)

Hence, the concentrations of chemical constituents and pathogenic organisms in the irrigation water will vary spatially and temporally. Large impounding reservoirs (such as Endho) providing relatively long retention times for wastewater will serve as treatment devices, settling out solids and reducing pathogen levels. Nevertheless, in general, faecal coliform levels in the irrigation water are 10^6-10^8/100 ml.

No treatment of sewage is provided before it is transported the 60 kilometres from Mexico City to Irrigation District 03 and, clearly, little improvement in faecal coliform levels has occurred before it is applied as irrigation water. In trying to achieve public health protection, reliance is placed on the application of crop restrictions rather than wastewater treatment. Every year, each farmer specifies the crops he is going to plant and irrigate with water allocated by the Irrigation District. The Ministry of Health sets the basic rules for crop restriction and the District's directing committee specifies in detail the crops which may not be cultivated under its jurisdiction (Strauss and Blumenthal 1989). In Irrigation District 03, banned crops are: lettuce, cabbage, beet, coriander, radish, carrot, spinach and parsley. Adherence to these restrictions is monitored mainly by the District's canal and gate operators, who are in close contact with farmers. Maize, beans, chili and green tomatoes, which form the staple food for the majority of the population, do not fall under these restrictions and neither does alfalfa, an important fodder crop in the area.

During the agricultural year 1983-84, 52 175 ha in Irrigation District 03 were harvested to produce 2 226 599 tonnes of food crops, with a value of more than US $33 million. The yields of the crops were greater than those obtained 10 years before, except for pasture, and it is believed that fertility conditions, measured on the basis of productivity, are better than before (Table 44). In addition, it is thought that the high content of organic matter and plant nutrients in the wastewater have improved the physical and chemical properties of the shallow soils in the District. The high rate of application of irrigation water has increased soil organic matter and systematically leached the soils, preventing the accumulation of soluble salts (Sanchez Duron 1988).

<u>Table 44:</u> CROPS, AREAS HARVESTED AND YIELDS IN IRRIGATION DISTRICT NUMBER 03

Crops		**Area harvested (ha) and yield (kg/ha)**			
		1970-71	**1975-76**	**1980-81**	**1983-84**
Maize (corn)	Harvested (ha)	17914	21 023	17907	18 371
	Yield (kg/ha)	3 938	3 896	4566	4581
Beans	Harvested (ha)	1 266	1 222	1 646	1 028
	Yield (kg/ha)	1 259	1 768	1 521	1 430
Wheat	Harvested (ha)	7293	2 634	2005	399
	Yield (kg/ha)	1 919	3 119	3 225	3 134
Alfalfa	Harvested (ha)	12708	15 206	20339	19515
	Yield (kg/ha)	95 300	89 154	91 175	96481
Oats	Harvested (ha)	2998	691	1 002	2489
	Yield (kg/ha)	18 150	19898	32470	25 348
Barley	Harvested (ha)	-	832	1 812	1 268
	Yield (kg/ha)	-	19620	19939	16823
Pastures	Harvested (ha)	13	11	65	109
	Yield (kg/ha)	142500	107000	44276	98 832

Source: Sanchez Duron (1988).

9.6.3 Health impacts

Mexican experience with raw wastewater irrigation suggests that successful enforcement of crop restriction has provided health protection for the general public, including crop consumers. Past studies on the health impact of the use of raw wastewater in agriculture in the Mezquital Valley have shown no consistent significant excess prevalence of gastrointestinal complaints or protozoan (apart from amoebiasis) or helminthic infections in children from communities irrigating with wastewater compared with children from a control community using clean water for irrigation. A study on the health effect of the use of wastewater on agricultural workers in Guadalajara concluded that a high prevalence of parasitic diseases in both exposed and control group workers was due to poor environmental sanitation, poor hygienic habits and lack of health education. However, a significant excess prevalence of infection in the exposed group was found for *Giardia lamblia* (17 per cent in exposed vs 4 per cent in control group) and *Ascaris* *lumbricoides* (50 per cent in exposed vs 16 per cent in control group). This led Strauss and Blumenthal (1989) to recommend further epidemiological studies on the increased health risk to farm workers and at least partial treatment of wastewater, to remove helminth eggs and protozoan cysts, in future wastewater use schemes in Mexico.

9.7 Wastewater use in aquaculture: Calcutta, India

9.7.1 The Calcutta system

The East Calcutta sewage fisheries are the largest single wastewater use system involving aqua-culture in the world. An historical account of the development of this system has been given by Edwards (1985 and 1990). Ghosh (1984) presented the data on the range of size and numbers of sewage fisheries in Calcutta as shown in Table 45. In 1945, the area of sewage-fed fish ponds was about 4628 ha, in a wetlands area of about 8000 ha, but the fish pond area had been reduced to about 3000 ha by 1987 due to urban reclamation and conversion of fish ponds to rice paddies. Ownership of the ponds is in the hands of about 160 city dwellers, who employ nearly 4000 families as fishermen, and there are several fishermens' cooperatives (Strauss and Blumenthal 1989).

Table 45: SIZE OF CALCUTTA SEWAGE FISHERIES BASED ON 1984 RECORD OF LICENSING, DIRECTORATE OF FISHERIES, WEST BENGAL

Size, ha	Number	Percent of total
<4	35	20
> 4-8	35	20
>8-12	43	24
>12-16	7	4
> 16-20	9	5
> 20-40	18	10
> 40-60	15	9
>60-80	9	5
>80	5	3
Total	176	100

Source: Ghosh (1984)

The fish ponds receive raw sewage from Calcutta on a batch basis and fishermen have developed appropriate operational techniques through experience. Olah *et al.* (1986) have described the technique adopted in operating 5.7 ha ponds, 0.7 m deep. Initially, screened raw sewage is allowed to flow into the ponds and after 12 days the pond contents is disturbed by repeated netting and manual agitation with split bamboos for oxidation, mixing and 'quick recovery' of water quality. After 25 days from initial filling with sewage, the ponds are ready to be stocked with fish. Thereafter, sewage is applied 7 days/month for 3 hours during the morning, to fertilize the ponds, at an estimated rate of 130 m^3 sewage/ha d. The ponds are stocked with a polyculture of fingerlings of catla *(Catla catla),* mrigal *(Cirrhinus mrigala),* rohu *(Labeo rohita),* common carp *(Cyprinus carpio)* and tilapia *(Oreochromis mossambicus)* ranging in size from 20-30 g at a total density of 3.5 fish/m^2 and total initial stocked weight of 869 kg. Intermediate harvesting is started after 120 days of rearing, using a seine net, and continued up to pond draining after 300 days, in March and April.

Estimates of total production and yield of fish from the Calcutta fisheries vary from 4,516 tonnes of fish from 6993 ha of fisheries in 1948 (approximately 0.6 tonnes/ha year) to 4-9 tonnes/ha year in 1984 (Edwards 1990). The fisheries supply the city markets with 10-20 tonnes offish per day, providing 10-20 per cent of the total demand. In addition, some degree of natural treatment is applied to the sewage and, in spite of the threat to the existing fisheries through urban development, workers on the wetlands project feel that much more sewage could be handled in this way and the greater part of Calcutta's demand for pond fish could be produced.

9.7.2 Health impacts

Total coliform counts of 10^5-10^6/100 ml in the influent sewage to the Calcutta fish ponds and 10^2-10^3/100 ml in the pond water have been reported. *Vibrio parahaemolyticus,* the second most important diarrhoea-causing agent (after *V. cholerae)* in the Calcutta area, has been found in the intestines offish from the sewage-fed ponds (Strauss and Blumenthal 1989). Nevertheless, no epidemiological studies have been carried out in Calcutta to assess the risk attributable to the use of sewage in aquaculture ponds.

Diarrhoeal diseases, typhoid fever and hepatitis A are the diseases of greatest concern, although protozoan cysts *(Giardia* and *Cryptosporidium)* are likely to be present in the upper layers of pond water and constitute a risk. With the relatively low levels of total coliforms in the pond water over the growing season, the fish are likely to be of good enough quality for human consumption providing they are well cooked and high standards of hygiene are maintained during their preparation (Strauss and Blumenthal 1989). Studies on *Vibrio parahaemolyticus* have indicated that it could be transmitted to fish consumers or fish farmers during the summer months. On the whole, the public health effects of sewage fertilization of aquaculture ponds in Calcutta remain unclear and further microbiological and epidemiological studies are required.

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