Reuse of Human Wastes in Aquaculture

A Technical Review

by Peter Edwards

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The cover photo shows workers harvesting fish in an experimental pond in Rahara, West Bengal, India. All photos are by the author, except the following:

p. 46, Figure 2.18, Wolfgang Kasser
p. 95, Figure 4.6, drawn from an aerial photo by Janos Olah
p. 96, Figure 4.7, Elek Woynarovich

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Executive Summary

The reuse of human waste in aquaculture can produce significant benefits and achieve a variety of useful goals. In countries where nutrition requirements exceed food production, it can help close the gap by using valuable nutrients that would otherwise be squandered. In countries where water quality must be improved, it can lessen the harmful impact on watercourses from overpopulation. In arid regions, it can make an important contribution in the conservation of scarce water resources.

This UNDP-World Bank Water and Sanitation Program Report surveys past and current human waste reuse practices and systems. The first chapter gives a historical introduction and describes the context of the discussion for developing and developed countries.

The reuse of excreta in aquaculture is an age-old practice, particularly in Asia, and there are also commercial systems in operation in Europe, the best known being the Munich sewage fisheries. Chapter 2 describes excreta-based aquaculture systems in various societies in developing and developed countries.

Most developing countries would find cistern-flush toilets and conventional waterborne sewerage systems impractical, unaffordable, and unsustainable. Chapter 3 examines lower-cost, lower-technology sanitation options that can be linked to aquaculture.

Chapter 4 surveys past and current experimental excreta reuse involving cultivation of fish and/or vegetation in sewage effluents. Chapter 5 discusses design criteria for excreta reuse systems, the most feasible of which make use of night soil, septage, and existing or specially designed sewage stabilization-pond systems. Chapter 6 evaluates the potential for excreta reuse in brackish water and seawater.

The impact of excreta reuse on public health is an important perceived constraint to its development. Chapter 7 contains a discussion of the excreta-related pathogens that should be considered potential hazards in excreta-fed aquaculture. Reuse of human wastes may also encounter deep cultural prejudice, and Chapter 8 considers the sociological questions surrounding consumer acceptance of fish raised on excreta.

The economic benefits of excreta reuse can defray some of the costs of improved sanitation and produce fish at the same time. Since the implementation of an excreta reuse system may depend on a favorable economic appraisal, the all-important economic and financial aspects are examined in Chapter 9.

1. Introduction

The years 1981-1990 were declared the International Drinking Water Supply and Sanitation Decade by the United Nations. One of the Decade's stated goals was to provide the world's population with adequate human waste disposal facilities by 1990, a staggering task inasmuch as nearly two billion persons lacked adequate water supply and sanitation at the Decade's inception (Feachem 1981). According to Dale (1979), 25,000 persons per day -- 9.1 million per year -- die of preventable, waterborne disease, alone and in combination with malnutrition.

The indiscriminate discharge of human waste into the environment causes disease and squanders valuable nutrients that could augment food production and alleviate malnutrition. In 1974-76 the seriously undernourished of the world numbered about 435 million, and that appalling figure could approach 600 million by 2000 if historic trends of food consumption and income distribution continue (FAO 1981a). The amount of human waste potentially available for reuse in developing countries is prodigious and, if utilized effectively, could play a tremendous role in food production. McGarry (1972) estimated the production of excreta in Asia of about 30 million tons dry weight per year, containing 9.7 million tons of nitrogen, 1.4 million tons of phosphorus, and 1.9 million tons of potassium. Hanumanulu (1978) pointed out that in India the gap between food production and need could be reduced considerably by properly treating and recycling nutrients in human excreta. Rao (1977) suggested that it is ecologically expedient to recycle nutrients rather than to rely on nonrenewable resources to produce chemical fertilizers. Soermarwoto (1977) recommended that priority be given to research on nutrient recycling by traditional methods, including excreta-fed fishponds, to meet growing demand for food in Indonesia. China has set an example for other countries by making use of as much as 90 percent of its night soil in agriculture (AIT 1989).

Conventional sewerage systems do not remove nutrients efficiently (Tortell 1979, Mara and Pearson 1986), and there is concern that as the human population continues to grow, natural waters will be unable to assimilate nutrients without serious, far-reaching consequences. Alternative methods of waste treatment are needed to recycle nutrients into useful foods and to safeguard the environment (Mihursky 1969, Tortell 1979). A new philosophy is needed to protect the environment (Mihursky 1969). As the populations of many regions outgrow their water supplies, interest in wastewater reuse is increasing (Carpenter et al. 1974). Scarcity of water, particularly in arid climates, is a major incentive to optimize use of all water resources including wastewater (Buras 1977, Allen and Hepher 1979, Gaigher and Krause 1983).

The motives for developing and developed countries to reuse wastes in aquaculture are different (Henderson and Wert 1976, Duffer and Moyer 1978, Golueke 1979). For developing countries, the main motive is the production of food, while for developed countries it is wastewater treatment. For the former, the nutrients in the

wastewater are the recovered resource, while for the latter the water itself is the resource to be recovered and the environment protected. Millions of persons, particularly in Asia, depend on reuse for treatment of excreta and for the provision of food through agriculture and aquaculture.

New national goals in wastewater treatment in the United States of America place strong emphasis on the use of natural systems and improved biological processes. These goals encourage sewage reuse through agriculture, forestry, and aquaculture (Duffer 1982). However, the cultivation of fish in wastewater has been of interest in the United States for only a short time: from a practical point of view, it remains largely conceptual (Henderson 1982) and experimental (Ryther 1980). A major reason for recent interest in aquaculture in treating wastewater in the United States is its potential to reduce the energy requirements and the operation and maintenance costs of wastewater treatment (Reed et al. 1979). Aquaculture systems -- activated sludge and trickling filters, and tertiary treatment of effluents from secondary treatment systems using stabilization ponds -- might be cheaper, simpler alternatives to conventional secondary treatment (Henderson and Wert 1976, Duffer and Moyer 1978, Golueke 1979, Henderson 1982). Waste stabilization pond systems are receiving special attention because, unlike conventional sewage treatment involving activated sludge and trickling filters, they have the potential for nutrient reuse (Mara and Pearson 1986). The utilization of natural waste treatment systems such as aquaculture should reduce energy costs, and the reuse of nutrients in the production of biomass as a feedstuff should produce an economic revenue to offset part of the operating costs.

The possibility of generating revenue from fish culture in sewage stabilization ponds could also be a financial incentive for improved operation and maintenance of sewerage schemes (Meadows 1983). Thorslund (1971) discussed the relevance of aquaculture for the treatment of domestic wastewater in developing countries where there are problems in the construction and operation of conventional sewage treatment plants because of shortages of capital and technical expertise, and inadequate administration. He considers cultivation of fish in domestic wastewater to be logical both to control pollution and to obtain a cheap supply of protein.

Reuse of excreta or wastewater may be direct or indirect (Lund 1978a, Middleton and Gromiec 1978). Direct reuse is the planned and deliberate use of treated wastewater for aquaculture, compared to indirect reuse, where water that has already been used one or more times is discharged to the environment and then recovered and used again with or without recognition of its previous use. Wastewater is always employed in principle, even as drinking water, in the sense that water is not created but is continuously recirculated and reused. In the past, many societies were able to consider clean water a free and unlimited natural resource, but modern industrial societies are now forced to depend on water supplies that contain a large amount of previously used water (Allen and Hepher 1979). Wastewater is being reused unavoidably and unintentionally. According to Lund (1978a), "the reluctant consensus is that if we are to have sufficient water, it must be reused."

The indirect and unintentional reuse of wastewater is increasing in the United States. Wastewater makes up 20-40 percent of the low-flow volume of a number of rivers in some areas. The Thames River provides two thirds of the water supply for greater London, yet it contains about 14 percent sewage effluent at average flow (Middleton and Gromiec 1978). During summer in Holland, the Rhine River occasionally contains nearly 100 percent used water (Lund 1978a). The potential public health hazards from the direct reuse of wastewater may not differ appreciably from those faced by cities that use surface water heavily contaminated with municipal wastewater from upstream (WHO 1973). Reuse of excreta throughout the developing world is a reality, and economic demand often leads to spontaneous indiscriminate reuse. Public health authorities need to anticipate excreta reuse and implement adequate sanitary control measures. There may be a greater public health risk from not considering reuse as a viable option and failing to plan for it than having adequate safeguards and quality control through a defined excreta reuse system (Tortell 1979, Bartone 1985).

The reuse of excreta in aquaculture was developed initially in Asia. Sewage-fed fish culture in West Germany, carried out on a commercial scale for more than 50 years, was inspired by Asian practice (Liebmann 1960). Traditional methods of fish culture in Asia employ a wide variety of organic inputs, including excreta (Ling 1967, Prowse 1967). Aquaculture in the developed countries has evolved differently, partly because European and North American fish lack the ability to filter phytoplankton that develop in fertilized ponds (Opuszynski 1978, Colman and Edwards 1987). There is an increasing tendency in Europe, Japan, and North America to use formulated diets, particularly in pelleted form, and the feed costs usually represent more than 50 percent of the total operating costs of fish farms (Shang 1981). Furthermore, a fishpond fed with conventional pelleted feed containing fish meal as a protein source is a net consumer of protein, hardly a useful system to alleviate protein malnutrition in developing countries (Schroeder 1980a). Clearly, excreta reuse as organic fertilizer in fishponds in developing countries can provide both economic and protein-production benefits. The recent increased interest in the reuse of excreta in aquaculture is reflected in the considerable number of publications devoted in part or entirely to the subject. Allen (1969) prepared a preliminary bibliography on the utilization of sewage in fish culture. Reviews have been written by Allen (1972), Tsai (1975), Allen and Hepher (1979), Edwards (1980a, 1985), Edwards and Densem (1980), and Payne (1984). There have been conferences and seminars in India (Hora 1944), in the United States (EPA 1974, Devik 1976, Tourbier and Pierson 1976, Bastian and Reed 1979), in Italy (D'Itri 1977), and in South Africa (National Institute for Water Research 1980).

An account of past and existing aquaculture excreta reuse systems is presented in Chapter 2. Traditional excreta reuse systems should be studied to improve them and disseminate resource recovery information. Chapter 3 contains a brief account of various sanitation options, all of which can theoretically be linked to aquaculture, although certain technologies have greater potential than others for excreta reuse. There has been a considerable amount of research to date on excreta reuse, mainly involving sewage, and this is reviewed in Chapter 4. Preliminary design criteria for excreta reuse systems are discussed in Chapter 5. Most excreta reuse in aquaculture involves freshwater systems,

but the potential for excreta reuse in brackish water and seawater is reviewed in Chapter 6. A major perceived constraint to aquaculture excreta reuse is the potential threat to public health, the subject of Chapter 7. Sociological aspects of excreta reuse are examined in Chapter 8. The consumption of fish raised on human excreta is acceptable in certain societies but is not acceptable in many parts of the world. In the latter case, reuse of excreta in aquaculture should involve systems in which fish are cultured as high-protein feed for fish or livestock (Fig. 1.1). Excreta may also be used to cultivate duckweed for fish feed or for livestock feed (Edwards et al. 1984, 1987). Various authors have suggested that fish may be raised for animal feed or for fish-meal production, for bait for sports fishing, for raising fingerlings, and for raising juveniles of anadromous migratory species (Pillay 1973, Tapiador 1973, Duffer and Moyer 1978, Allen and Hepher 1979, Henderson 1982). The lengthening of the food chain by the cultivation of fish (or duckweed) as fish or livestock feed has sociological relevance because it may permit excreta reuse in societies in which it is traditionally unacceptable. The indirect reuse of excreta may also lead to an improvement in public health. The loss in biological efficiency caused by lengthening the food chain may be offset by the higher market value of the end product, for example, the culture of tilapia as feed for higher market-value carnivorous fish.
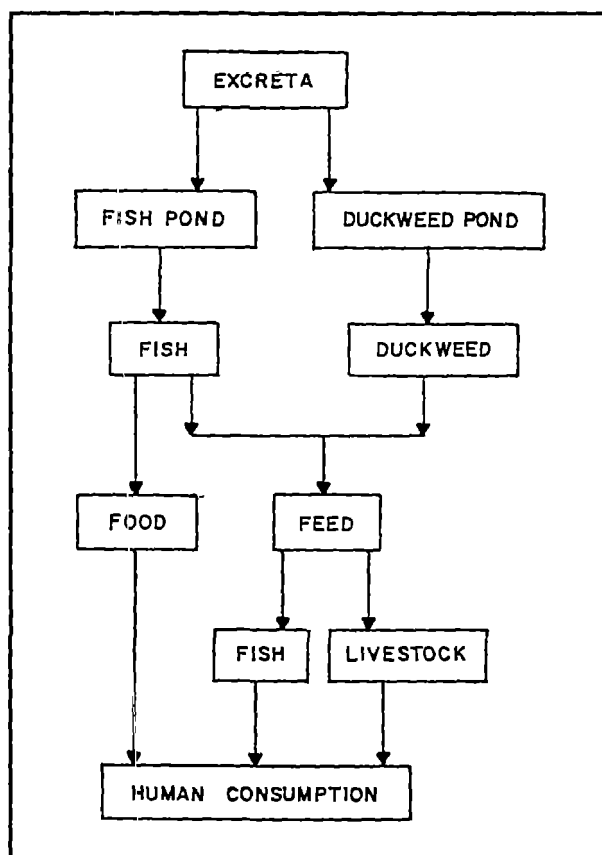
Figure 1.1 Excreta reuse strategies in aquaculture *Source:* Edwards et al. 1987

The important economic and financial aspects of excreta reuse in aquaculture are the subject of Chapter 9. The implementation of an excreta reuse system may well depend upon a favorable economic appraisal. Sponsorship by the World Bank has led to the publication of guidelines for the implementation of appropriate sanitation technologies for those who cannot afford expensive and relatively complicated conventional waterborne sewerage (Kalbermatten et al. 1982ab). However, the major problem remains that sanitation is, in most cases, not financially remunerative. Central and municipal governments may be morally committed to the improvement of sanitation but unable to finance sanitation systems indefinitely. Low-income householders in developing countries may be unwilling or unable to pay for adequate sanitation. Economic benefits from excreta reuse may at least help defray the costs of improved sanitation. Furthermore, economic benefits of excreta reuse are more tangible than benefits to public health and may provide a stronger motivation for further investments in sanitation.
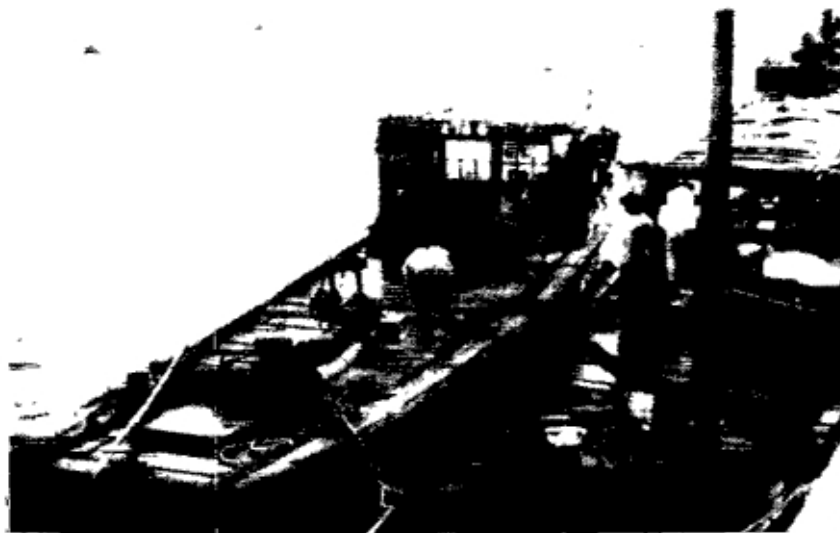
Figure 1.2 Night soil collected by vacuum trucks in Shanghai is discharged into riverside storage tanks

The Chinese experience indicates a real potential for excreta reuse. The Chinese use excreta more fully than any other culture. Night soil is collected in both rural and urban areas and transported manually or by carts, vacuum trucks, or boats. Most reuse is in agriculture, although significant amounts are used for fish culture. From 1952 to 1966, between 28 percent and 38 percent of the nutrients applied in agriculture came from night soil. In 1952, 176 million tons wet weight of night soil, about 70 percent of the total excreta in China, were recycled; this increased to 299 million tons wet weight, 90 percent of the total, by 1966 (McGarry 1976). The Chinese might not be able to maintain their agricultural production without excreta reuse. Perhaps the single most impressive example of excreta reuse in the world is Shanghai. Sewerage is still not widely available in the city, and 8,000 tons of excreta stored in night soil and septic tanks are pumped out daily by vacuum trucks, a total of 2.9 million tons per year (Ye 1984). A small amount of night soil is transported directly by vacuum trucks to the city outskirts, but most is sent
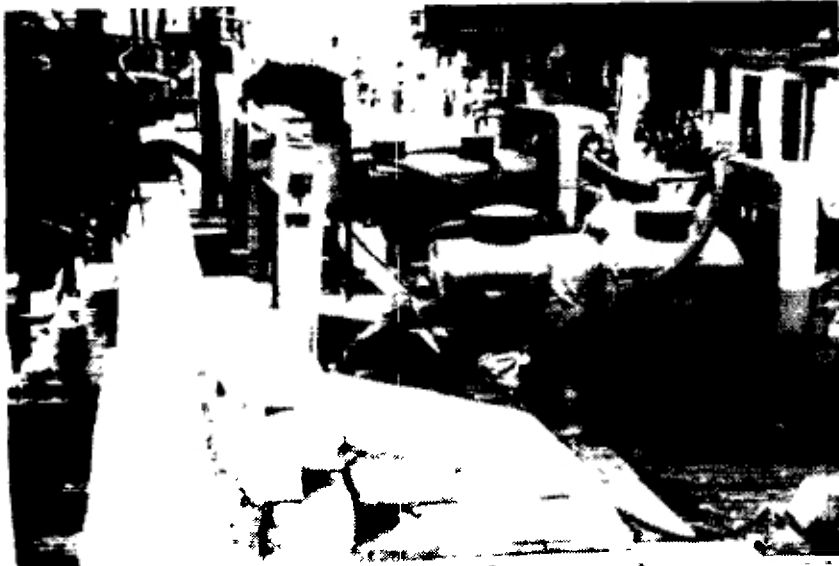
Figure 1.3 Night soil in Shanghai is pumped from riverside storage tanks into barges for transport to rural areas for reuse.

to 44 night-soil wharves along rivers. From there it is barged to the countryside (Figs. 1.2, 1.3). Night soil is stored in airtight tanks in which anaerobic decomposition takes place, and pathogens and helminth eggs are inactivated before it is used as fertilizer. However, reuse practices may not be hygienic and treatment is not always adequate. The total nitrogen content of Shanghai night soil is 2,800-4,750 mg/l; 8,176-13,870 tons of nitrogen are produced for agricultural reuse each year (Ye 1984). There is an obvious gap in applying the Chinese experience in excreta reuse to other developing countries. McGarry (1976) wrote, "the principle has, however, been proven in practice, the benefits are obvious, but the challenge has not been met."

There is reason to believe that excreta reuse will increase (Allen 1972), at least in developing countries where it is most urgently needed. An international group of experts recently convened by the World Health Organization stated that, where possible, reuse of wastewater should be the preferred method of wastewater disposal to minimize treatment costs and obtain maximum agricultural and aquacultural benefits from the nutrients contained in wastewater (WHO 1989). According to IRCWD (1985), excreta reuse in aquaculture will become an increasingly important form of waste disposal, water pollution control, and food production in the next two decades in many parts of the world. Sewage treatment plants of rapidly growing cities will become huge centers for food production (Borgstrom 1978), and the reuse of organic wastes from cities may eventually lead to the development of alternative agricultural systems that could surpass the contribution of the Green Revolution to world food production (Newcombe and Bowman 1978). If this review can stimulate the further application of aquaculture excreta reuse systems to fulfill even a small part of such optimistic predictions, it will have served its intended purpose.

2. Past and Current Excreta Reuse Aquaculture Systems

2.1 Introduction

The reuse of excreta in aquaculture is an age-old practice, particularly in Asia, but there are also systems in operation in Europe, the best known being the Munich sewage fisheries. A logical first step in assessing the potential for excreta reuse in aquaculture is a study of systems currently or recently in operation. This chapter describes excreta-based aquaculture reuse systems and demonstrates that excreta reuse in aquaculture is a viable commercial proposition for diverse societies in both developing and developed countries.

The various commercial systems of excreta reuse in aquaculture and the countries from which they have been reported in the literature are shown in Table 2.1. There is likely to be considerably greater excreta reuse than reported; because of widespread social opposition in many cultures, excreta reuse is not always readily discussed.

2.2 Unintentional reuse

The unintentional reuse of excreta in aquaculture, especially the use of fecally polluted surface water in fish ponds, is probably widespread, but it has rarely been documented.

Village tanks and natural depressions in rural areas in India function as waste stabilization ponds, and fort moats in urban areas (excavated ditches around old forts) often receive "sewage" from the town (Jhingran 1982). Fish cultivated in such water bodies derive nutrition from fertilization by excreta. Sreenivasan (1967) discussed fish production in various types of water bodies in Madras state in India. Fish were reported to grow well in fort moats characterized by permanent blooms of blue-green algae. Fish yields of over 1 ton/ha/yr were obtained by stocking milkfish (*Chanos chanos*), catla (*Catla catla*), mrigal (*Cirrhina mrigala*), *Cirrhina cirrhosa*, and common carp (*Cyprinus carpio*). Sreenivasan (1964) reported mean fish yields for 10 years of 1.6 tons/ha from Vellore fort moat and for 11 years of 1.3 tons/ha from Chinglepat fort moat, Madras State (Sreenivasan 1968). Only a few village fish ponds were reported to receive human excreta and sewage (Sreenivasan 1967).

There is a report of unintentional excreta reuse in Bangladesh (Ahmad 1979). A survey in Bangladesh revealed that night soil was not added directly to ponds; in fact, ponds were often used for bathing and washing kitchen utensils. However, latrines constructed in ditches behind houses remained almost dry in the dry season but filled with flood water during the monsoon season. Fish that entered the ditches with floodwater benefited from the eutrophic water, and night soil from the latrines continued to feed fish that grew in the ditches. The fish were harvested towards the end of the monsoon season when the water level fell. Consumers were generally reluctant to accept fish harvested from such ditches, but they would be unaware of the origin of such fish if they were sold on the market.

Table 2.1
Aquaculture Excreta Reuse Systems

	Unintentional	Overhung latrine	Cartage	—Fecally polluted surface water—				Sewage
				Pond	Cage	Raceway	Lake	
Africa								
Kenya								+
Malawi								+
South Africa								+
Zimbabwe								+
Asia								
Bangladesh	+							
Hong Kong		+	+					
India	+							+
Indonesia	+			+	+	+		+
Israel								+
Japan				+				
Malaysia		+	+					
China		+		+			+	+
Singapore		+	+					
Sri Lanka							+	
Taiwan			+	+	+			
Thailand		+						
Vietnam		+						
Europe								
Czechoslovakia								+
Poland								+
Russia								+
Germany								+

2.3 Overhung latrines

According to the literature, overhung latrines are widespread in Asia, particularly in China and countries where there are expatriate Chinese, and also in Indonesia and Vietnam.

2.3.1 China

There is a long history in China of the use of human excreta in aquaculture, but until recently, with the introduction of sewage fisheries, it was conducted mainly on a small scale (Zhou 1986). According to Lin (1974), there were over two million hectares of

freshwater ponds in China and most, especially those in the Pearl River and Yangtze River deltas, were heavily fertilized with "domestic sewage" (night soil). A more recent estimate of the area used for freshwater fish culture in China, including lakes and reservoirs, is three million hectares, with about one million hectares of ponds (Z. S. Zhong, personal communication 1989). There are numerous references in the literature to the use of overhung latrines on ponds in China from which feces drop directly into the pond (Turner 1894, Hoffmann 1934, Prowse 1967, FAO 1979, Edwards 1982, Ruddle et al. 1983). The latrines are usually brick structures built over the pond adjacent to the dike with a short bridge for access. They are particularly common in S. China (Fig. 2.1). Turner (1894) worked as a missionary in Guangdong Province for five years (1886-1891) and reported that fish were reared in ponds with overhung latrines. If the pond were adjacent to a road, passers-by contributed also to the fertility of the pond (Hoffmann 1934). Ponds in Guangdong Province were rented from private owners or from the public; for village ponds, the rent increased with the number of inhabitants and livestock because organic matter washed into ponds was the chief or sole source of added fish food. Usually feces dropped directly into the pond from an overhung latrine and were taken immediately by the fish, although rafts or night-soil boats were sometimes placed beneath the latrines. One opinion reported by Hoffmann (1934) was that common carp (*Cyprinus carpio*), bighead carp (*Aristichthys nobilis*), and silver carp (*Hypophthalmichthys molitrix*) fed on night soil, but another opinion was that only common carp ate night soil directly.

2.3.2 Hong Kong

Lin (1940) reported the presence of overhung latrines on ponds in Hong Kong.

2.3.3 Malaysia and Singapore

Ponds in Malaya (present-day Malaysia and Singapore) operated by overseas Chinese were reported to have overhung latrines (Prowse 1967). It was almost a universal feature of Chinese fish ponds in Malaya to have one or more latrines over the ponds for domestic use and "as a mute invitation to the passer-by" (Department of Fisheries, Colombo 1952). A recent survey of the status of night-soil reuse in freshwater ponds in three states of Peninsular Malaysia, with more than 80 percent of the country's freshwater fish-pond area, revealed that the use of organic manures in aquaculture was restricted to one ethnic group in the country, the Chinese; Malay and Indian fish farmers rarely fertilized their ponds (Seow et al. 1979). Overhung latrines on ponds were a frequent feature, although the impact of night soil was insignificant compared to the amount of pig and/or poultry manure entering most ponds from the integration of livestock with fish culture.

2.3.4 Thailand

The use of night soil is uncommon in Thailand. Edwards et al. (1983a) surveyed fish farms in Pathumthani province, central Thailand, and only about 5 percent of the farms surveyed utilized night soil in fish culture, usually through overhung latrines (Fig. 2.2). In most cases, the night-soil input from the use of an overhung latrine on the

Figure 2.1 Overhung latrine in Guangdong Province, China

pond was probably minor compared to other pond inputs. The average Thai farmer strongly objected to the use of human excreta in ponds, but in Bangkok ponds belonging to Thai of Chinese ancestry had overhung latrines (FAO 1949). Prowse (1967) reported that night soil was sometimes used in ponds in Thailand. Promising experimental results in fertilizing ponds with night soil were reported to have been obtained at Bangkhen Agricultural University, now Kasetsart University (FAO 1949), although they do not appear to have been published. According to Thiemmedh (1961), human feces proved to be a most effective fattening diet for silver striped catfish (*Pangasius pangasius*), although farmers probably sold such fish on the market rather than consuming them domestically, as was recently reported by a farmer with an overhung latrine on his pond (Edwards et al. 1983a).

2.3.5 Vietnam

Overhung latrines are common in the Mekong delta and some other areas in South Vietnam. Traditionally the overhung latrines are built on small ponds in which catfish (*Pangasius larnardi*) are raised. The ponds are connected by a small channel to the river, a screen prevents the escape of fish. This practice has polluted rivers that provide water for domestic use. An improved system has been designed with a small sedimentation pond linked to the fish pond (see Section 5.4).

2.3.6 Indonesia

Djajadiredja et al. (1979) carried out a detailed survey on the use of night soil in freshwater fish culture in West Java, Indonesia. About 50 percent of the total area of aquaculture in Indonesia was in West Java, and about 25 percent of freshwater ponds in West Java had latrines (Fig. 2.3). There were also overhung latrines on brackish water
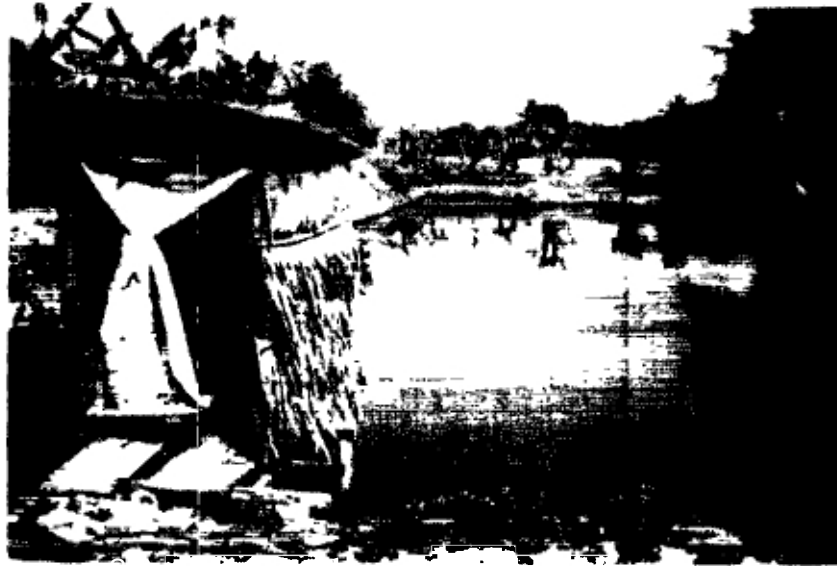
Figure 2.2 Overhung latrine in Thailand

ponds and rice fields. Most small-scale farmers with overhung latrines could not afford to purchase commercial inorganic fertilizers and supplementary fish feed. In most cases night soil and kitchen refuse were the main pond inputs, but supplementary feed was sometimes given: rice bran, cassava and soybean by-products, and cassava leaves and *Calocasia* leaves.

Kuhlthau (1979) described excreta disposal in Ciputat, a rural community situated near the border of Jakarta and West Java. Eighty-seven percent of households used overhung latrines on ponds located 10-100 m from the house, while 13 percent used pit latrines because they lived too far from a pond. However, in Cianjur there were very few latrines on ponds, but structures for bathing and washing clothes were common; defecation was mostly into running water streams (observation by the author, 1981). Night soil was so highly regarded by farmers as a pond input in the Bantul district of Yogyakarta that they scooped human feces from irrigation canals for use in their ponds (Djajadiredja et al. 1979).

The reuse of night soil in ponds in Indonesia is a major input in fish production and plays a role in the alleviation of the low protein intake of the rural population of Indonesia (Dajajadiredja et al. 1979). However, the reuse of night soil in aquaculture is declining slowly due to increasing pressures on land use for agricultural crops, urbanization and industrialization. Furthermore, the government has implemented a program to introduce improved latrines in rural areas.

Four prominent fish-culture areas in West Java were selected for a case study (Djajadiredja et al. 1979). The mean size of the total area of ponds was rather small in three upland districts (Bandung, Cianjur, Sukabumi), 500-1,000 m^2 per farmer with a mean size of individual ponds of 414-445 m^2. In the lowland district of Jakarta Selatan, the

fourth district studied, the mean size of the total pond holding was larger, 1,500-5,000 m^2 per farmer, although the mean individual pond size of about 405 m^2 was similar to the other three districts. Only 21 percent of the pond area of the three upland districts had latrines, but 90 percent of the lowland-district ponds had latrines. In the study by Kuhlthau (1979), the ponds ranged from 200-1,000 m^2 and were 1.5-2 m deep.

Figure 2.3 Overhung latrine in West Java, Indonesia

Two types of overhung facilities were built on separate ponds: toilets for bathing and washing clothes, and latrines for defecation. At least one latrine for private use was located on a pond, although some farmers built three to four public defecation latrines on their ponds to stimulate fish production (Dajajadiredja et al. 1979). The bathroom was essentially built above the pond. The polluted water in the pond was not used directly, but clean water was supplied by bamboo pipes from higher streams in upland areas (Soemarwoto 1977). It was estimated that 10-20 persons used each overhung latrine (Djajadiredja et al. 1979). If each contributed 250 g night soil per day, a 400 m^2 pond would receive 2.5-5 kg night soil per day. According to Kuhlthau (1979), one latrine usually served two to five families, and sometimes several latrines were built on a single pond. Djajadiredja et al. (1979) estimated that about 262 t of night soil per day were reused in fish culture in West Java. Detailed physicochemical measurements were made of water quality in the night-soil-fed ponds, but the data are of limited value because times of sampling were not given (Dajajadiredja et al. 1979, Hanafi and Sutarmat 1980). Surface-water dissolved-oxygen values were reported to range from about 3 mg/l to 16 mg/l during the day. Ponds with low daytime concentrations of dissolved oxygen were probably overloaded with organic matter.

Ponds were usually drained periodically and dried for a few days between fish culture cycles when use of the overhung latrine was discontinued. The mud from the ponds was periodically removed to fertilize land crops (Dajajadiredja et al. 1979). Fish harvest occurred once or twice per year, and the latrines were not used for three days prior

to harvest (Kuhlthau 1979). Sediment was removed from the pond bottom once a year. Mean fish yields in Java were reported by Dajajadiredja et al. (1979) to be 2.1 tons/ha/yr, but this figure included systems other than night-soil-fed ponds.

Overhung latrines were usually made of bamboo, but toilets for bathing and washing clothes were often brick or concrete. The latrines built by the pond owner were made of wood or bamboo with a 1 m² platform approximately 1.5-2 m above the water (Kuhlthau 1979). The latrines were built about two meters from the bank with a small bridge for access. Most village houses did not have indoor sanitary facilities, and the villagers performed their daily washing, bathing, and defecation in pond latrines, rivers, canals, ditches, or rice fields, although the use of pond latrines was reported to be most widely favored.

Most night-soil-fed ponds had a polyculture of at least five of the following six species: common carp (*Cyprinus carpio*), kissing gouramy (*Helostoma temmincki*), Java carp (*Puntius gonionotus*), nilem carp (*Osteochilus hasseltii*), giant gourami (*Osphronemus goramy*), and tilapia (*Oreochromis* spp.).

Fifty-five percent of respondents in a survey of night-soil-fed ponds revealed that fish feeding was the reason for the establishment of an overhung latrine on a pond, compared to 10 percent who cited reasons of sanitation. Of the 35 percent of respondents who gave both fish feeding and sanitation as motives, about equal numbers gave either fish feeding (43 percent) or sanitation (57 percent) as the priority motive (Djajadiredja et al. 1979). Clearly, overhung latrines were widely accepted because they provided both a practical method of excreta disposal and an economic way to increase fish production (Kuhlthau 1979).

The general sanitary condition of the villages was poor. Alimentary tract diseases were prevalent, although insufficient data were collected to determine if overhung latrines on ponds were a source of disease transmission (Djajadiredja et al. 1979). Most of the farmers were practicing Muslims; they were fastidious about the disposal of human excreta and were particularly offended by its presence and smell. They preferred to defecate in water, rather than on land or in pit latrines, to dispose of excreta "completely out of sight." A pond was usually the most convenient and most favored place for this purpose.

The use of ponds was suggested by Djajadiredja et al. (1979) as a relatively safe way to dispose of human excreta in rural areas lacking other sanitation facilities. Most villagers were conscious of the need to find clean water for their daily activities. Water for drinking and cooking came from wells or springs, while bathing and clothes washing were done in rivers or canals. Overhung latrines were usually located at some distance from village dwellings; water from night-soil-fed ponds was never used for bathing, cooking, or washing clothes. Furthermore, fish harvested from night-soil-fed ponds were held in a clean, running-water pond for a couple of days before sale or domestic consumption. Fish were scaled and eviscerated before cooking, and fish dishes were normally served well cooked, although half-cooked fish dishes were popular in certain

areas, notably West Java. Djajadiredja et al. (1979) reasoned that the potential for spreading disease from night-soil-fed ponds might be less with the existing system than if villagers defecated in other water bodies used for bathing and washing clothes. The government was promoting improved sanitation by advising villagers to build pit latrines; but in areas where night soil was the main source of fish nutrition, consideration needed to be given to the socioeconomic effects of improved sanitation on the fish farmers and on the protein the fish provided. Djajadiredja et al. (1979) suggested that sanitation might be improved more effectively by changing the traditional technique of night-soil reuse, both to increase fish production and to eliminate health hazards, rather than totally abolishing fish latrines. McGarry and Wing (1986) suggested that the overhung latrine pond system should be upgraded, perhaps by use of a Chinese three-tank system (see section 5.3).

2.4 Cartage

2.4.1 China

Cartage is probably a more important method of fertilizing ponds with night soil in China than the overhung latrine because cartage permits larger amounts of urban excreta to be reused in aquaculture (Fig. 2.4). Night soil was used very extensively and could be purchased in any city or village (Hoffmann 1934) at a price that was usually 2-3 times higher than pig manure and 10 times higher than cow manure. However, before 1985 in the Yangtze river basin, night soil was cheaper than pig manure (Z. S. Zhang, personal communication 1989). An experiment carried out in 1959 by the Tientsin Freshwater Aquaculture Research Station on the use of "rural domestic sewage" (probably night soil) in fish culture produced a fish yield of 6.5 tons/ha (IDRC 1973a). The traditional use of night soil in ponds in China continues today, but the system has been improved from a public health point of view by storage of excreta in a closed chamber prior to reuse (FAO 1977, 1979, 1983). The night soil is stored for either four or several weeks according to FAO (1977, 1983).

Li (1987) discussed a typical Chinese integrated fish farm, Nanhui Fish Farm in Shanghai. The traditional Chinese model embodies the principle of "three ponds combined in one" — the pond acts not only as the habitat for fish but also as a place where natural food is cultivated for fish and where oxygenation-decomposition of organic matter, including night soil, takes place. However, Chinese integrated fish farming is becoming more intensive with increasing substitution of organic fertilizers by inorganic fertilizers, increased inputs of supplementary feed, including pelleted feed, and a decrease in the proportion of filter-feeding fish such as bighead carp (*Aristichthys nobilis*), crucian carp (*Carassius auratus*), and silver carp (*Hypophthalmichthys molitrix*). Between 1982 and 1984 the use of pelleted fish feed increased 73 percent while the use of grass and urban night-soil fertilizers decreased by 24 percent and 33 percent, respectively (Li 1987).

Figure 2.4 Ferroconcrete barge used to transport night soil to fish farms in Wuxi, China

2.4.2 Taiwan

Night soil was commonly used to fertilize both freshwater and brackish ponds in Taiwan (Chen 1952, 1973; Tang and Chen 1957). There was also an attempt to promote integrated rice and fish farming in which night soil was one of the fertilizers. However, the system was not successful because it required increased labor, pesticides were toxic to fish, and poaching occurred (Chen 1953). According to Kuhlthau (1979), there were over 5,000 ha of ponds in the Tainan region of Taiwan in 1976, of which about 20 percent were freshwater and 80 percent were brackish ponds.

Night soil was collected by both private (illegal) operators and by the city authorities. Illegal operators started night soil collection early in the morning using dippers and buckets in conjunction with oxcarts, while the public system used vacuum trucks. Night soil was collected by both private and public collectors two to three times a month. Approximately 90 tons of night soil were collected daily by the public system from the city. Night soil was sold by both private and public collectors for reuse in agriculture and aquaculture. It was reported that all of the city's night soil was sold for aquaculture during 10 months of the year, January through October. According to McGarry (1972, 1976), night soil was collected in Taiwan by municipal collectors and purchased by farmers for feeding ponds. During the peak season, night soil was frequently stolen from vaults before the municipal collection; thus, there was effectively a black market for human excreta. From July 1977 to June 1978, the monthly output of night soil from Tainan city ranged from 2,244 tons to 2,900 tons, of which on average 72 percent was used to fertilize ponds (Lo 1979). The monthly rate of use of night soil was relatively uniform throughout the year, although the period of demand was different for freshwater (April-December) and brack ponds (January-March) (Table 2.2).

Table 2.2
Night Soil Collected in Tainan City and Used in Aquaculture

Date	Night soil output (tons)	Aquaculture use (tons)	Percent used
1977			
July	2,605	1,909	73
August	2,655	1,731	65
September	2,709	2,168	80
October	2,857	2,395	84
November	2,755	2,107	76
December	2,900	2,075	72
1978			
January	2,519	1,889	75
February	2,244	1,650	74
March	2,590	1,692	65
April	2,675	1,916	72
May	2,765	1.846	67
June	2,648	1,761	67
Total	**31,922**	**23,139**	**72**

Source: Lo 1979

Tang (1970) described freshwater fish production practices in Tainan Pond, a 6 ha pond in Taiwan which had been managed by experienced fish farmers for centuries. Management practices such as stocking fish, fertilization, and supplementary feeding were developed by farmers of past generations and had been used without modification for many years. Six species occupying different feeding niches were cultivated together in polyculture (Table 2.3). Fingerlings were stocked in February and March, except for the fish carnivore stocked after April, and fish were harvested the following December and January by draining the pond. The pond was fertilized periodically with chicken and pig manure as well as night soil, and rice bran was given as a supplementary feed late in the rearing season when the fish population was dense. Rice bran was given also at other times during the rainy season when natural food appeared to be insufficient for fish growth. A total of 10.9 tons dry matter of manure/ha/year were added to the pond, with night soil comprising 77 percent of the total amount. The mean moisture content of night soil was 78 percent, so 38 tons of fresh night soil/ha/yr were added to the pond. The mean gross

fish yield for three seasons was 7.3 tons/ha/yr. According to Lin (1968), the amount of night soil added to ponds varied widely but was up to 205 tons/ha/yr. Lo's (1979) survey of 300 fish farms in Chiayi and Tainan counties and Tainan city in 1978 included both freshwater and brackish ponds. The farmers added about 4.5 tons/ha of night soil at a time to freshwater ponds, four to six times during the fish culture cycle from April to December. No survey was made of fish productivity in ponds fertilized with night soil compared to those receiving no night soil.

Table 2.3
Fish (3-9 cm total length) Stocked in Tainan Pond

Common name	Scientific name	Feeding niche	Number stocked (per ha)	Percent mortality
Silver carp	*Hypophthalmichthys molitrix*	Phytoplankton	3,500	14
Grey mullet	*Mugil cephalus*	Detritus	9,000	33
Bighead carp	*Aristichthys nobilis*	Zooplankton	500	16
Grass carp	*Ctenopharyngodon idella*	Macrophytes	200	10
Common carp	*Cyprinus carpio*	Benthos	10,000	39
Sea perch	*Lateolabrax japonicus*	Fish carnivore	300	23
		Total	**23,500**	

Source: Tang (1970)

The use of organic fertilizers in agriculture has declined in Taiwan during the last 20-30 years because of abundant supplies of cheap chemical fertilizers and their convenience. Moreover, an increasing shortage of farm labor due to industrialization, has made transportation and application of bulky organic manures more expensive than in the past (Su 1983). According to information collected by the author on a 1985 visit to Taiwan, the use of night soil in aquaculture is now rare. The use of night soil in milkfish ponds ceased about 8-10 years ago, and rice bran is now the main fertilizer used to induce the development of benthic algae. Although Lin (1968) wrote that the use of night soil in freshwater ponds in Taiwan was declining as cheaper and more hygienic chemical fertilizers were becoming available, Chinese carps and tilapia are still raised in organically fertilized ponds. However, the fish are now raised in integrated systems with ducks and/or pigs. This practice eliminates the need to purchase, transport, and spread bulky night soil. The

decline in the reuse of night soil in aquaculture in Taiwan is due to the intensification of agriculture and the production of large amounts of by-products, particularly livestock manure, that can be conveniently recycled in aquaculture.

2.4.3 Hong Kong

Night soil was formerly used to fertilize ponds in Hong Kong and was bought from the city through an agent (Lin 1940). In 1947 Hickling described the fertilization of Tai Lee fish farm, a freshwater farm that used raw night soil in Hong Kong (unpublished notes of a study tour cited by Mortimer and Hickling 1954). The quantities of pond inputs varied monthly from pond to pond, but during the month prior to the visit, a mean of 48 cwt/acre of night soil (about 6.1 tons/ha) had been added. The ponds were a dense blue-green color. The water level was low because of the long dry season, and there had been some loss of fish due to suffocation at night. Fish yields were about 1.7 tons/ha/yr.

There appears to have been a decrease in the use of night soil in ponds in Hong Kong similar to the decrease in Taiwan, although specific data are lacking. Vegetables were fertilized with night soil until the late 1950s, but the practice has been discontinued (Newcombe and Bowman 1978). According to FAO (1981b), little night soil is now used by local farmers to fertilize their crops in Hong Kong; besides ocean dumping, night soil collected by the government is sold to China as fertilizer. Farmers in Hong Kong are discouraged from using organic fertilizers due to rising labor costs and are increasingly using inorganic fertilizers readily available at reasonable cost (Hui 1983). Furthermore, it has been estimated that 25 percent of all ponds in Hong Kong (about 490 ha) use chicken manure to fertilize the ponds (Hui 1983). The intensification of agriculture with the production of livestock in feedlots, as in Taiwan, may be the main cause for the cessation of the reuse of night soil in aquaculture because fish can be conveniently raised in integrated livestock and fish-farming systems with livestock manure available as a pond fertilizer.

2.4.4 Malaysia and Singapore

Birtwistle (1931) reported that night soil was occasionally used for carp culture in Malaya (present-day Malaysia and Singapore) but that it was too expensive for general use as a pond fertilizer as it was normally used in vegetable cultivation. Seow et al. (1979), in a recent survey of night-soil reuse in freshwater ponds in peninsular Malaysia, located only two farms (in Perak and in Selangor) that used a substantial amount of night soil to fertilize ponds with total water surfaces of 2 ha and 4 ha, respectively. The night soil was collected from households by night-soil collectors and transported to the farms (Fig. 2.5).

The loading rates of untreated night soil were 3.6-4.5 m³/month on the Perak farm and 7.9 m³/week on the Selangor farm. The two primary species reared were the bighead carp (*Aristichthys nobilis*) and grass carp (*Ctenopharyngodon idellus*). but mud carp (*Cirrhina molitorella*), silver barb (*Puntius gonionotus*), common carp (*Cyprinus carpio*),

Figure 2.5 In Malaysia, night soil is loaded into a pond using a wooden chute

and marble goby (*Oxyeleotris marmoratus*) were also stocked at lower densities. The farm in Perak depended solely on rainfall and had stagnant water ponds. However, the farm in Selangor had a constant flow of stream water into all ponds. This may explain the high night-soil loading rate on that farm. Napier and guinea grasses and cassava leaves were fed to the grass carp. Night-soil loading was regulated according to a visual inspection of the color of the water, and fish kills by depletion of dissolved oxygen were rare. Regular loading of night soil was suspended temporarily, or water was pumped into the ponds, if the ponds became too eutrophic. Night-soil loading was stopped for a month prior to harvest of fish on the Perak farm, but the Selangor farm did not undertake special measures before fish harvest. There was reported to be little chance of disease transmission from such fish because it is customary to cook fish thoroughly in Malaysia. Annual production on the Perak farm was estimated to be 5.1-6.8 tons/ha/yr and that on the Selangor farm, 6.1-7.6 tons/ha/yr.

The practice of using night soil as a basic pond input is disappearing in Malaysia. The traditional bucket latrine system is rapidly being replaced by sewerage, and municipalities do not issue permits for night-soil deliveries because of concern over public health. Furthermore, the vast majority of fish farms in Malaysia are integrated with livestock that provide organic fertilizer for the ponds.

2.4.5 Japan

Japan is another East Asian country in which the reuse of excreta was a traditional practice, and farmers had no prejudice against night soil. Traditional latrines in Japan had to be evacuated at regular intervals to avoid overflow; farmers were quite willing to remove toilet contents and were paid for the supply of nutrients they received (Takahashi

1978). The use of a water-tight storage privy was made compulsory by the order of a shogun (feudal lord) to maximize reuse of night soil as a fertilizer (Matsumoto and Hanaki 1988). Most night soil in large cities such as Tokyo and Osaka was collected. From 1908 to 1917, 38 percent of the 283,000 tons of nitrogen used on farmland was night soil, compared to 32 percent from straw and 30 percent from inorganic fertilizers. However, the old system of Japanese agriculture changed after World War II, chiefly due to rapid industrialization and rising labor costs. This caused a drastic increase in the cost of manures relative to inorganic fertilizer, and the use of night soil as an agricultural fertilizer was discontinued in 1967 (Yamamoto and Teramoto 1978).

Common carp (*Cyprinus carpio*) used to be cultured mainly in rice fields until about 1945, although the practice no longer continues because of increased use of insecticides and herbicides toxic to fish (Suzuki 1979). The former cultivation of fish in rice fields in Japan may be considered as a type of excreta reuse in aquaculture because night soil was probably used to fertilize the integrated system.

2.5 Fecally polluted surface water

The use of fecally polluted surface water is probably widespread wherever fish are cultured near human habitation lacking adequate sanitation. Direct defecation and discharge from toilets by pipes or channels both introduce fecal matter into surface waters. Fish culture systems involving fecally polluted surface water have been reported from Indonesia, Sri Lanka, and Taiwan.

2.5.1 Indonesia

There are various systems in Indonesia in which fecally polluted surface water is used for fish culture: ponds, running-water ponds or raceways, and cages. Many small rivers and streams in Java are essentially open sewers.

Ilan and Sarig (1952) reported the use of sewage water (presumably fecally polluted surface water) without any treatment prior to reuse for fish culture in the neighborhood of cities, and fish production of 4 tons/ha/yr. Milkfish were raised in the center of Java in ponds fed with dilute sewage (presumably fecally polluted surface water) in the ratio of one part sewage to two parts stream water, and both stocking and production were high (Huet 1972).

In 1981, the aukthor observed fish culture in shallow suburban ponds in Cianjur, West Java, that were fed with fecally polluted streams from the city. Fry and fingerlings of common carp were raised up to about 100 g in the ponds for stocking in fish cages, although small fish were eaten by poor people (Fig. 2.6). Ponds fed with fecally polluted streams and stocked with red tilapia for table fish were also observed in Muara, an urban area of Bogor, West Java (Fig. 2.7).

Figure 2.6 Culture of fingerlings in ponds fed with fecally polluted surface water, Cianjur, West Java

Fish were also stocked in raceways in Muara, Bogor (author's study tour 1981). These comprised small sections of narrow running-water streams in the urban area in which fish were retained by metal grills placed in the stream.

Vaas and Sachlan (1956) described the cultivation of common carp (*Cyprinus carpio*) in cages in fecally polluted streams in Bandung, West Java. The method was introduced about 1940 in the river Tjibunut, which ran through the city. The river divided into western and eastern branches, both about 4-5.5 m wide, although the water depth varied considerably due to rainfall from the minimum depth of 30-40 cm. The river was heavily contaminated by kitchen waste and human feces from dwellings on the river banks.

Bamboo cages were used in both branches of the river in 1952 — 34 cages in a stretch of 40 m in the western branch and 198 cages within a few kilometers in the eastern branch. Another 40 cages were added later in the eastern branch further upstream. These cages were placed so closely together that one could walk over them, and they obstructed the flow of the river.

Strong material was used to construct the cages to resist the force of wood or stones hurled against the cages during floods. The cages were rectangular in shape (1.5-3 m long, 0.9-1.5 m wide, and 0.6-0.75 m high) and were constructed of bamboo slats (2-3 cm wide with 0.5-1.5 cm spaces between slats). The cages lasted about two years. They were inserted at a slight angle into the river bed and normally protruded 15-20 cm out of the water, although they were completely submerged during flooding. Most cages were anchored by strong wooden poles or iron bars. There was a small door secured by a padlock in the middle of the upper side of the cage. The cages were cleaned daily of sand and gravel deposited by the flow of water. Leaves, twigs, and refuse that got stuck between the bamboo slats and reduced water circulation were also removed.

Figure 2.7 Culture of red tilapia in ponds fed with fecally polluted streams in Bogor, West Java

The cages were usually stocked with 8-12 cm common carp but sometimes with 5-8 cm fish, both at a density of 200-400 fish/cage. Little food was given except for some rice bran and stale bread because of the constant supply of natural food. It was difficult to assess the yield because farmers removed the largest fish for sale or to stock in separate cages with larger slits. However, the yield was reported to be 50-75 kg/cage/2-3 months.

There are two possible origins of the system, according to local fishermen and extension service personnel. It was either introduced by the Japanese during World War II as common carp were raised in running-water ponds in Japan; or it was developed by local vendors who often stored fish in small round woven baskets in the river and observed that carp left for some time increased in weight.

The river was contaminated by kitchen waste and human feces. Diurnal fluctuations of dissolved oxygen were the reverse of those in a fertile stagnant pond. Dissolved oxygen in the river was maximal at night and in the early morning, and decreased during the day. The respiratory activity of bacteria was lowest during the night because contamination with feces was minimal and the temperature was lower. Contamination was highest between 6 A.M. and 7 A.M., and oxygen consumption increased as the temperature rose during the day. Photosynthesis was completely overshadowed by respiration.

The silty, oxygen-deficient, rapidly flowing murky water was not a suitable environment for the development of plankton. However, the sewage fungus *Sphaerotilus* grew in thick tufts on the bamboo cages and many threads were floating in the water. The sewage fungi *Zoogloea* and *Beggiatoa*, the filamentous blue-green algae *Lyngbya* and

Oscillatoria, and sessile and free-living ciliated protozoa were also present on the cages in abundance. Enormous quantities of oligochaete worms were found among the threads of *Sphaerotilus* and blue-green algae, among leaves and grass strained out of the water, and especially in the sand and silt on the cage bottoms and along the shores. Besides worms, red chironomids (Tendipedidae) were also frequent. There were more chironomids and fewer oligochaete worms in the western branch of the river, where contamination was less heavy and the water less shaded. An analysis of the gut contents of carp revealed that the main sources of food were oligochaete worms and chironomids.

Following the success of cage culture in Bandung (Vaas and Sachla 1956), the extension service implemented a cage trial in the river Tjimaragas, a small river near the city of Garut, a less polluted river than the Tjibunut in Bandung. The residents of Garut then took up cage culture because of the success of the trial, and 88 cages were counted in 1954. The river was less polluted because it did not flow through the city, but it had similar water quality. Fish farmers constructed latrines near the cages, and the supply of feces was considerable. Some farmers relied only on human feces (on which the fish were often seen to feed voraciously), but others fed the fish twice daily with a mixture of rice bran, cooked rice, and stale bread.

The natural food production of the river was relatively unimportant as a source of fish food because of its infertile, sandy bottom and the large amount of suspended silt. The gut contents of all five fish sampled were mainly human feces (including a large number of eggs of human helminths *Ascaris lumbricoides*, *Ancylostoma duodenale*, and *Trichocephalus dispar*), and only a minor amount of natural food was present. Raising common carp in such a system was considered most economical.

Cage culture in fecally polluted streams in West Java was observed by the author in 1981. Only a few cages were seen in Bandung because they were prohibited by law: cages had previously filled the river, impeded water flow, and caused flooding. There were reported to be about 2,000 cages in Cianjur in the narrow stream running through the city. The stream was heavily polluted with fecal matter, kitchen waste, and waste from factories producing soybean and rice products (Figs. 2.8, 2.9). It was reported that 100-200 g common carp grew to 500 g in four months, a yield of 20 kg/m^3 of cage per year. A few cages were seen in a stream in Sukabumi, and a few also along the side of the main river in Bogor. They were reported to be much reduced in number in Bogor. The government declared them illegal because they impeded water flow.

Figure 2.8 Culture of common carp in cages in fecally polluted streams in Cianjur, West Java

Figure 2.9 A demonstration of the large-sized common carp cultured in cages in Cianjur

2.5.2 Sri Lanka

There is one well-documented case of the use of human excreta in aquaculture in Sri Lanka, in Colombo or Beira Lake (Mendis 1964, Costa and De Silva 1969). The 64 ha lake located in Colombo (Fig. 2.10) was rain fed, with a negligible amount of seawater entering the lake when the lock gates near the harbor were opened to allow the passage of boats. The lake was heavily polluted with fecal matter from several surface drains, the effluents of companies located along the lake, and also the domestic waste of numerous tenements that bordered the lake. The lake was characterized by virtually year-round blooms of phytoplankton, mainly blue-green algae. According to Mendis (1964), the lake was stocked with Mozambique tilapia (*Oreochromis mossambicus*) in 1952 and 1953. By 1957 the lake was teeming with this species, and a large number of fishers were engaged in its capture. He reported a yield of 2.3 tons/ha/yr in 1957. In addition to the large quantities of adult fish taken by commercial fishers, fry and fingerlings were also removed to stock other bodies of water. Mendis (1964) recommended the introduction of milkfish (*Chanos chanos*), a plankton feeder, because he believed that much of the lake plankton was not being utilized. He also recommended further exploitation of the existing tilapia.

Figure 2.10 Harvesting Mozambique tilapia (*Oreochromis mossambicus*) by gill net in Beira Lake, a fecally polluted lake in Colombo, Sri Lanka

Costa and Liyanage (1978) reported a detailed evaluation of the tilapia fishery over a 12 month period. Most fishers used gill nets for maximum efficiency of harvest, beating the water to drive fish into the nets. Usually two fishers in one boat set nets twice a day, morning and late evening. Most fishers contracted to supply buyers with prearranged quantities of fish. The commercial fishery produced about 90 percent *Oreochromis mossambicus*, and most of the remainder were native fish (*Etroplus suratensis* and *Glossogobius giuris*). In 1970-1971, the catch of tilapia was about 2.5 tons/ha/yr.

The author visited the lake in 1984 when it appeared to be much the same as described above. The water was blue-green from a dense growth of blue-green algae, probably *Microcystis*, and fishers were observed harvesting tilapia using gill nets.

2.5.3 Taiwan

Tilapia (probably *Oreochromis mossambicus*) were once cultivated in old milkfish ponds located adjacent to the seaward end of the city's sewage canal in Tainan (Huang 1968). As observed by the author in 1977, the sewage canal was an open channel containing water polluted by septic-tank effluent discharged directly into storm drains or sewers (Fitzgerald 1970). According to information collected by the author in Taiwan in 1985, the system no longer exists.

When in use, the ponds were prepared in winter, from the end of November to early March, for a new fish-culture cycle. The ponds were drained, and the pond bottom was allowed to dry until the mud cracked, about two weeks. Polluted surface water was pumped into the ponds at low tide to about 30 cm depth; at high tide the polluted water was diluted by seawater and its fertilizing value reduced. The pumped water was at first dark in color and offensive to smell. The stench disappeared in three to four days, and the water gradually became brownish as microorganisms developed. In two to three weeks the color of the water deepened to reddish brown, turbidity decreased, and benthic biomass developed. The clear water was drained or pumped out as much as possible, and more polluted water was pumped in. The process was repeated three to four times to ensure the accumulation of an adequate amount of organic matter and the development of a rich growth of benthos on the pond bottom.

A total weight of 300-400 kg/ha of young fish of about 20-28 g (about 1-2 fish/m²), which had been wintered in special ponds, were stocked about mid-March. The water was maintained at about 30-40 cm depth in spring and about 60-70 cm depth in summer. Polluted water was pumped into the ponds once every three days to maintain the water level and replenish nutrients. Supplementary feed was given only if a rich growth of natural food was not maintained. The cheapest supplementary feed was the green seaweeds *Enteromorpha* and *Chaetomorpha* collected from brackish-water areas, dried two to three days, and then thrown into the pond in several piles. Some of the decaying seaweed was eaten directly by the fish, and some functioned as a fertilizer.

Eight or nine intermediate harvests were carried out at about 25 day intervals during the growing season, from 40-45 days after stocking until the end of November. Larger fish were caught in the large-mesh seine nets, and the smaller fish were allowed to escape and continue growth. Small fish remaining at the end of November were transferred into the winter pond to serve as stock for the next year's cycle. Harvested fish ranged in size from 20 g to 80 g. Fish larger than 40 g were sold for human consumption, but those less than 30 g were sold as feed for chickens, ducks, and pigs. Wholesale prices were low: $0.19/kg for fish over 50 g, $0.15/kg for 40-50 g fish, and only $0.09/kg for fish less than 30 g. However, the average net profit was about $500/ha/yr because of the high yields.

Fish yields varied widely depending on the amount of polluted water available. Maximum yields of 6.5-7.8 tons/ha/yr were reported from ponds located where polluted water was abundant, but yields of 3.5-5.0 tons/ha/yr were obtained from ponds supplied with only moderate amounts of polluted water.

2.6 Sewage

Relatively few persons in developing countries are served by waterborne excreta collection systems or sewerage, but there are several commercially viable fish-culture systems that use sewage. India has the largest area of sewage-fed ponds in the world, and sewage fish culture occurs in several areas in China. The only other developing country in Asia to report sewage fish culture is Indonesia. Treated sewage is used in aquaculture in Israel, and perhaps the best-known example of sewage-fed aquaculture is the system in Munich. There are reports that sewage fish culture occurs in some countries in Eastern Europe. Only a small amount of sewage fish culture has been reported in Africa, and none in North, Central, and South America.

2.6.1 India

Sewage is reused in well-defined sewage fisheries in India, particularly in West Bengal, the only state in India where sewage is widely used for fish culture (Saha 1970, Saigal 1972, Jhingran 1974, Dehadrai and Ghosh 1977). It has been estimated that there are more than 132 sewage-fed fisheries in India covering about 12,000 ha.

Chacko and Ganapati (1949) reported that arrangements were being made to reuse Madura sewage for fish culture, and Ganapati and Chacko (1950) described a plan for a proposed sewage fish farm for the Madurai Municipality, Madras. The Madurai Municipality has built a sewage fish farm that functioned efficiently (Jayangoudar and Ganapati 1965), but no further information appears in the literature.

Ghosh et al. (1974) described the operation of a private sewage-fed fish farm at Khardah, situated near the sewage treatment plant of the Titagarh Municipality, West Bengal. The farm used sewage effluents from primary sedimentation. The ponds were fed with high initial doses of sewage effluent before the monsoon season. After the pond had been suitably diluted with rainwater during the monsoons, Indian major carp fingerlings were stocked at high densities. Sewage effluent was added periodically in small amounts to maintain the production of natural food. Ponds were frequently netted to remove fish of 250-800 g. Indian major carps were reported to be stocked in sewage-fed ponds in West Bengal, with mrigal dominating the polyculture. The total stocking density of carps in various ponds on the farm ranged from 5 to 7 fish/m^2, with mrigal usually 30-50 percent of the total. Mrigal, a bottom-feeder, was reported to feed directly on settled organic detritus.

Repeated netting operations were reported to be useful for oxygenation of pond water, particularly when sewage effluent was fed into the pond to restore plankton blooms.

Difficulties in feeding sewage effluents into ponds situated away from the main feeder canal occurred during the monsoon season due to the inundation of the subsidiary canals; total fish production in these ponds was 3-5 tons/ha/yr, lower than that of ponds nearer the main feeder canal (that could be fed with sewage effluent year-round). The fish yield in one pond adjacent to the main feeder canal was reported to be 7.7 tons/ha over seven months, or 13.2 tons/ha/yr.

Nair (1944a) reported that a pond on the estate of the Government Rifle Factory at Ishapore, near Calcutta, was fed with the effluent of an activated sludge plant. The cultivated fish were said to be of excellent quality.

The Calcutta sewage fisheries may be the largest single excreta-reuse aquaculture system in the world. They are described in some detail below (Figs. 2.11, 2.12). Calcutta has no sewage treatment plant, and two giant settling tanks at Bantala have not functioned for more than a decade (Ghosh 1984). The Calcutta sewage fisheries have been developed over the past 50 years by farmers who have gained experience in regulating the intake of raw sewage into ponds (Saha 1970, Saigal 1972, Ghosh 1983, Ghosh and Sen 1987). A reference to "sewage farming and fisheries" in the area dating back to 1865 suggests a much earlier origin of sewage-fed fish culture (Ghosh and Sen 1987).

The main sewers of Calcutta began to function in 1875. Sewage and storm water were discharged through an outfall into the Bidyadhari River about 8 km east of the city. Since the river was tidal, the sewage was stored in large reservoirs for up to eight hours and then emptied into the river when the water level went down sufficiently at ebb tide. In 1904 the first warnings were sounded that the sewage drainage outfall was seriously threatened. The river had silted up only about 3 km downstream to a height of 10 m; eight years later, the riverbed had silted up another 6 m. Beginning in 1918, attempts were made to revive the river by opening up spill areas and dredging, but by 1928 it was declared impossible to maintain the river (Bose 1944).

The main reason for the silting up of the Bidyadhari River was the conversion of the Salt Lakes, a vast area of waterlogged swamps that formed the spill area of the river, into saltwater ponds at the turn of the century (Bose 1944, Nair 1944b). The name Salt Lake was derived from the previous influence of tidal effects on the Bidyadhari River. The ponds, called *nona bheris*, were 80-400 ha in area. The shallow ponds were arranged on the sides of a canal from which they were fed during high tide through sluices with valves that opened inward. Young fish were able to enter the pond at high tide but were prevented from escaping when water was let out. Prawns, mullets, and sea bass were imprisoned in June and July and harvested periodically from July until the following January or February, when the ponds dried up.

Saltwater fish farming was initially very profitable because few costs were involved. But as the Bidyadhari became increasingly silty, new silt brought up on the high sidecould not be spread over the spill area and was deposited jon the river bed. The
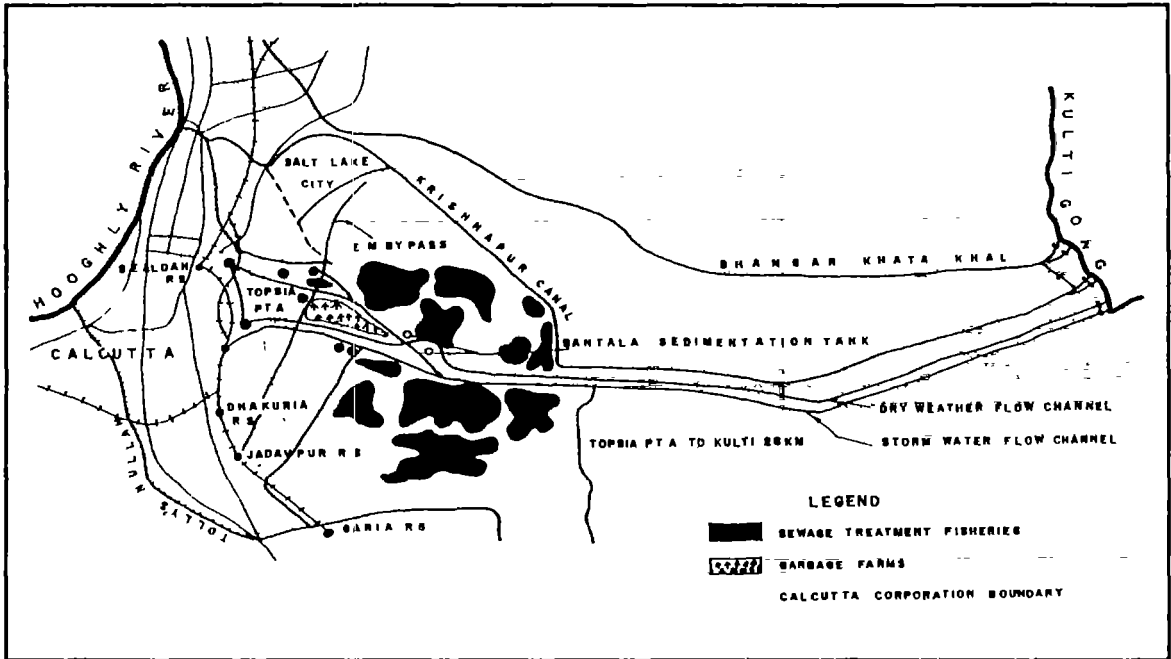
Figure 2.11 Calcutta sewage fisheries (*Source:* Ghosh 1984)

increased siltation in the river gradually made water exchange in the ponds difficult. Furthermore, due to the increased volume of sewage from city expansion and the reduced cross section of the river, water pollution increased and eventually reduced the growth of the fish.

Figure 2.12 The Calcutta sewage fisheries (The canal in the foreground distributes raw sewage to the ponds.)

The nutrients in the sewage undoubtedly led to high production of natural food and target organisms, but with increasing pollution it became difficult for fish to survive. The once powerful river dwindled so much in cross section that it became a high-level sewage channel. The once-profitable nona bheris became an undrainable swamp.

The following description of the subsequent development of the freshwater sewage fisheries is based largely on accounts by Bose (1944) and Saha (1970). In 1930, a landowner discovered he could cultivate carp by letting in small doses of sewage to the swampy area. The results were so good that within a short time the whole area was converted into a freshwater aquaculture system. However, difficulty was experienced in draining the ponds until the storm water channel was constructed from Bantala to Kulti in 1940. In 1935, two channels were constructed, one for sewage and the other for storm water, because of the deterioration of the Bidyadhari River. City sewage is taken through a network of sewers and sewage channels to the eastern side of the city and discharged into the dry-weather flow (DWF) channel that leads directly to two sedimentation tanks and associated sludge-drying lagoons at Bantala, near the old outfall on the east bank of the now-defunct Bidyadhari River, about 8 km from the city. The sedimentation tanks were built to avoid deposition of sewage solids along the 27 km DWF channel built to take clarified effluent to an outfall at Kulti, an estuarine tributary of the Royamangal River. As much as 60 percent of the water in the DWF channel was used for fish culture during the dry season (February-May). Two circular Pryss-type tanks removed more than 85 percent of settleable sewage solids from Calcutta sewage with a 1.5 hour retention time. With an internal tank diameter of 78 m, the tanks were the largest of their kind when constructed in 1943, but they are hopelessly inadequate to handle Calcutta's current volume of sewage. A storm-water flow (SWF) channel was also built adjacent to the DWF channel and has an outfall at Kulti. However, for practical purposes, the SWF channel is now another sewage channel because the DWF channel cannot handle the increasing volume of sewage from the expanding city. When the sewage drainage canals were completed in 1940, it was believed that dilution at the Kulti outfall would be sufficient to deal with the clarified effluent without impairing the river quality. However, due to the current overloading of the system, much crude sewage is discharged into the river. The discharged sewage oscillates without dissipating quickly because of tidal action, and about 45 km of the estuarine creek is a vast septic tank.

A rich natural fishery used to exist on the Kulti estuary but, with the exception of the air-breathing catfish *Pangasius pangasius* (David 1959), it disappeared due to sewage pollution after the outfall began operation. Natural stocking by tidal movement of brackish ponds with mullet, sea bass, and prawns has been adversely affected by sewage pollution, but the fertilizing effect of sewage leads to increased natural food production in properly managed brackish ponds (David 1959).

The construction of the DWF and SWF channels split the former Bidyadhari spill area into two sections, called the North and South Salt Lakes. The new drainage channels provide a gravity feed facility to the fish farmers for adding sewage to and draining water from the ponds. The DWF channel usually runs at a high level, and its level can also be adjusted by a regulator to ensure uninterrupted feeding of the ponds.

The SWF channel running parallel to the DWF channel is a low-level canal whose level can be kept about one meter lower than the adjacent ponds, even in the monsoon season: it is used for draining water from the ponds. When the system was constructed, simultaneous feeding and draining could be given only to the North Salt Lake ponds, although recommendations were made to improve sewage feeding to the South Salt Lake ponds.

Nair (1944a) described a sewage-fed fishery in the Dhapa area adjacent to a main sewage canal. It included one large (268 ha) and two small (27 ha and 94 ha) ponds, or bheris. Alternation of fish with rice took place only in the two smaller bheris because the larger had an uneven bottom unsuitable for rice cultivation. However, the large bheris served as a storage pond for smaller fish while the other two bheris were dewatered for rice cultivation. The large bheris was dewatered at the end of March or beginning of April and filled with brackish water from a seawater canal (0.2 percent) to a depth of about 15 cm. It was reported that salt water helped control external fish parasites. Sewage was then allowed to flow in to an average depth of about 1 m. The sewage was foul smelling and dark, and contained suspended solids. The bheris was left for 15-20 days to allow the suspended solids to settle and the water to lose its stench. A rich growth of algae appeared after a day or two. The bheris was subsequently fed sewage about once a month for four or five days to give a 1:4 ratio of sewage to water in the pond. The water depth was maintained at about one meter. The sewage was relatively dilute because considerable sedimentation of suspended solids took place in the approximately 5 km the sewage flowed to reach the bheris. The sewage flow was also diluted by fresh water flowing into the channel before it reached the bheris.

Fingerlings (about 50 g each) of Indian major carps (catla, mrigal, and rohu) were stocked at a total density of 0.1 fish/m^2. They attained marketable size by September, five to six months later, when harvesting began. Marketable sizes for catla, mrigal and rohu were about 1.5, 0.5, and 1.0 kg, respectively. Fish were harvested by seining from 9 A.M. to 2 P.M., but the catch was kept alive in a large submerged pocket of the net until 2 A.M. when the sale of fish began. Harvested fish under about 0.5 kg were put back in the bheris in the earlier part of the selling season. Harvesting continued until February, when the whole fishery was dewatered and left until March or April, when the cycle was repeated.

The cycle for the two smaller bheris was reported to be similar, but half of the 27 ha bheris was high land unsuitable for fish culture. The two smaller bheris were prepared for stocking fish in February, and the fish reached marketable size in June. Harvesting stopped in September when the small bheris were drained and undersized carp were transferred to the larger bheris. The dewatered bheris were then plowed and used to cultivate rice. Following rice harvest in December, the bheris were allowed to remain fallow until February, and the cycle was started again. Fish accounted for 70 percent and rice for 30 percent of the total net income in the 1943-44 season, when market prices for both fish and rice were high.

Considerable experience was required to operate a sewage-fed pond. Ponds were drained each year and the bottom exposed to the sun for a few months to reduce

bottom pollution. However, incidents of sewage overloading were reported, and continuous cloudy weather without the normal afternoon winds to aerate the pond water would also cause the fish to gasp for air at the surface and die in large numbers. To prevent mortality, clean water was let into the pond when indications of fish distress were observed. According to Basu (1948), sewage was fed once a month during the cool and hot seasons but the ponds were "drained off" -- that is, water was let out of the ponds during the monsoon season to prevent flooding. Sewage was allowed to enter against the direction of the wind and was mixed with pond water at a ratio of 1:3 or 1:4 over a period of five to ten days. The ponds were dried for one to two months to dry the bottom and clean out vegetation. Rice was sometimes cultivated as an alternating crop.

Various species of wild fish, ophicephalids, siluroids, anabantids, and minnows were caught in addition to the cultured carps (catla, *Catla catla*; mrigal, *Cirrhinus mrigala*; *Labeo bata*; *L. calbasu*; and rohu, *L. rohita*). Basu (1948) reported that in one year, 1-cm fry of catla, mrigal, and rohu attained weights of 0.8 kg, 0.5 kg, and 0.6 kg, respectively. Saha (1970) reported the growth of a polyculture of catla, mrigal, and rohu on the state sewage fish farm near Calcutta. Sewage was fed when necessary with a total of 3×10^6 gal/acre/yr (13,650 m^3/ha/yr), equivalent to 37 m^3/day with a year-round culture period, or 50 m^3/day assuming the more likely 9 month culture period.

A more recent description of a Calcutta sewage fisheries was presented by Olah et al. (1986). The sewage-fed ponds were 5.7 ha in water area with a mean water depth of 0.7 m. Two narrow, manually operated sluices were used as inlets and outlets. Raw sewage was allowed to flow into the ponds after preliminary screening of floating matter. After 12 days, the water was disturbed by repeated netting and manual agitation with split bamboos for oxidation, mixing, and quick recovery of the water quality. The ponds were usually ready to be stocked with fish 25 days after sewage introduction. The ponds were fertilized with sewage seven days per month for three hours during the morning. It was estimated that 130 m^3 sewage/ha/day were applied. The ponds were drained every year during March and April. Mustard-seed cake was applied at 250 ppm to kill fish, and 500 kg lime/ha were applied. The ponds were 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 g to 30 g with a total density of 3.5 fish/m^2, and total initial stocked weight of fish of 869 kg. Intermediate harvesting by seine net was started after 120 days. Harvest continued up to pond draining after 300 days.

Saha et al. (1958) analyzed the physicochemical properties of raw Calcutta sewage once a week for one year. Samples were collected from the outlet of a feeder channel of Calcutta Corporation from where sewage was drawn into the Government Fish Farm for pretreatment and for direct reuse in some adjoining private fisheries. Dissolved oxygen was zero, CO_2 was 20-96 mg/l, H_2S was 2.4-48 mg/l, free NH_3 was 12-63.6 mg NH_3-N/l, and albuminoid NH_3 was 1.1-16.0 mg N/l.

Ghosh (1984) presented a breakdown of the sizes of sewage fish farms (Table 2.4).

Table 2.4
Size of Calcutta Sewage Fisheries*

Size (ha)	Number	Portion of total (%)
Under 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
More than 80	5	3
Total	**176**	**100**

Source: Ghosh (1984)
* Based on 1984 record of licensing in the
  Directorate of Fisheries, West Bengal

Estimates of the total production and yield of fish from the Calcutta sewage fisheries vary. According to Basu (1948), there was an annual production of 4,516 metric tons of fish from the 6,993 ha of sewage fisheries, a mean of 0.6 ton/ha/yr. The Calcutta sewage fisheries supplied the city markets with about 10-12 tons fish/day (Saha et al. 1958). The annual fish production figures reported by Saha (1970) for the North and South Salt Lake fisheries were 5,222 and 1,849 metric tons, respectively, with the two areas supplying about 14.5 and 5 tons fish/day, respectively, to the Calcutta markets. However, Dehadrai and Ghosh (1977) reported that only about 1.5 tons of fish were collected daily by the Central Fisheries Corporation of India from the Calcutta sewage fisheries. The mean fish yields for the North and South Lakes were estimated to be 1.4 and 1.0 tons/ha/yr, respectively, from data given by Saha (1970), who also reported yields of catla, mrigal, and rohu in polyculture of 1.4-2.1 tons/ha/yr on the sewage-fed state fish farm near Calcutta. A higher annual production of 3.2 tons/ha was reported by Saigal (1972) with a polyculture of the three Indian major carps stocked at a total initial weight of 0.5 ton/ha in the government sewage-fed fish farm in West Bengal. Ghosh (1983) reported mean production of about 5 tons/ha/yr, and also fish production of 4-9 metric tons/ha/yr (Ghosh 1984). Fish production was 21.3 kg/ha/day over a 300-day growing period, equivalent to

7.8 tons/ha/yr, assuming a 365-day growth period in the study reported by Olah et al. (1986). Ghosh and Sen (1987) reported a yield of 838 kg/ha/yr in 1945, and that figure has increased to 2,471 kg/ha/yr today.

The area of the Calcutta sewage-fed ponds is decreasing due to urban reclamation and conversion of ponds to rice paddies (Ghosh 1984), but the extent is difficult to judge because of conflicting data. According to Basu (1948), the Salt Lakes sewage fisheries occupied 6,993 ha, although an additional 5,957 ha of marshy land could be converted to ponds. Saha et al. (1958) reported that the Calcutta sewage fisheries occupied about 4,000 ha. According to Saha (1970), the areas of the North and South Lakes sewage fisheries were 3,760 ha and 1,907 ha, respectively, a total of 5,667 ha, but a sizeable portion of the North Salt Lake area had been lost due to the Government of West Bengal Salt Lake Reclamation Scheme for Calcutta City expansion. More recent estimates were provided by Ghosh (1983): the area of sewage fisheries was 4,442 ha (North Salt Lake area, 2,447 ha; South Salt Lake area, 1,995 ha) in 1972, according to a survey by the Indian Institute of Management, but the latest figure from the State Fisheries Directorate indicated an area of 4,000 ha. According to Ghosh and Sen (1987), in 1945 the total area of wetlands was about 8,000 ha with about 4,628 ha of sewage-fed ponds; these have been reduced to about 3,000-3,200 ha today. They reported a large-scale conversion of 2,400 ha of sewage-fed ponds into rice fields in 1969. That change would reduce the 1945 area of ponds to only 2,228 ha, less than the area given for today.

The Calcutta sewage fisheries are a natural sewage treatment and reuse system for a city that lacks a conventional sewage treatment plant, a significant but little-known fact (Furedy and Ghosh 1984). However, suggestions have been made from the outset that the system should be organized on a rational basis. According to Nair (1944a), "if proper arrangements for irrigation and drainage could be made, a considerable area of low lying wasteland could be converted into sewage irrigated fisheries resulting [sic] in vastly increased supplies of carp for the Calcutta markets." He urged that the government of the corporation of Calcutta "must work together [to create] a big scheme of fishery development in this area so that the greater part of Calcutta's supply of pond fish can be secured from this source." Hora (1949) believed that the sewage-fed fisheries in the Salt Lakes area could be much more productive if arrangements could be made with the corporation of Calcutta for proper distribution of sewage to the fisheries. More recently, Chaudhuri and Basu (1976) suggested that the Calcutta Metropolitan District should develop a combined wastewater treatment and recycling system including fish production because a system based on solar energy and the fertilizing capacity of wastewater is ecologically sound and should generate enough money to pay back capital and running expenses.

Saha (1970) proposed that the South Salt Lake area, with only 1,907 ha of underdeveloped fisheries out of a total area of 3,800 ha, might be developed to compensate for the loss in fish supply from the North Salt Lake. He pointed out that only an autonomous organization specially set up for the purpose could deal effectively with such a large and complicated scheme.

Calcutta sewage fisheries are still threatened by the inevitable urban development conflicts (Furedy and Ghosh 1984, Ghosh and Sen 1987). The greatest threat to the sewage fisheries is urbanization: creeping sprawl at the urban edge and the systematic development of new towns. Infrastructure to service new towns has also encroached on the ponds. Land values are certain to increase near new roads and may render aquaculture uneconomic (Furedy and Ghosh 1984). Industrial pollution is an additional threat to the sewage fisheries. Tanneries are the main source of industrial pollution in Calcutta, and tannery wastes are threatening fish production in the wetlands (Furedy and Ghosh 1984). Calcutta sewage is reported to contain only a low concentration of heavy metals (Ghosh and Sen 1987).

In response to these threats, a call has been made for a national policy to protect and extend the Calcutta sewage-fed system and for international recognition (Ghosh and Sen 1987). It is now recognized that the fate of the Calcutta sewage fisheries has broad implications for all of India. The largest source of riverine pollution in the country is untreated municipal sewage discharge, according to the Central Pollution Board. The volume of sewage generated in cities along the Ganga Basin is about 3 million m³/day, of which less than 20 percent is treated; the rest is discharged into the river (Ghosh 1983). Ghosh (1983) proposed the establishment of sewage fisheries, including treatment and reuse in aquaculture as an economically feasible means of decreasing riverine pollution in the Ganga Basin. Conventional sewage treatment is considered too costly.

2.6.2 China

The predominant types of sanitation technology in China are "dry" systems, but sewerage is being installed in the larger cities. Some information concerning sewage-fed aquaculture was presented in the standard Chinese reference on aquaculture (IDRC 1973). Fertilization involves primary fertilization (Fig. 2.13) prior to stocking fish, followed by supplementary fertilization, the amount and frequency of which depends on water color and fish growth and activity. Better results are obtained with frequent applications of low dosages of fertilizer. Supplementary fertilization should be given three to five days after primary fertilization and as frequently as three to four times daily with low-fertility ponds or once or twice per day or every two days if the water is more fertile (IDRC 1973). The amount of domestic sewage used for primary fertilization should be 10-20 percent of the volume of the pond, while supplementary fertilization should follow after three to four days with a loading of about 35 kg BOD$_5$/ha/day.

Cultivation of fish in sewage effluents has been promoted in China since 1957. The total area was about 670 ha in 42 cities, according to a paper read at the 1964 Peking symposium entitled "Recent Progress of Municipal Wastewater Irrigation in China." A more recent national survey carried out by the Yangtze River Fishery Research Institute revealed that the total area of sewage fisheries has greatly increased. The economic benefits of increased fish production and treating sewage were recognized, but it was considered essential to pretreat the wastewater and adopt proper management to avoid adverse effects from pathogens and toxic substances (Kuo 1980). According to Wang (1987), there are now 20,000 ha of wastewater-fed fish farms in China.

Figure 2.13 Primary fertilization of a pond with raw
sewage in winter, Wuhan, China

There was a total of 270 ha of wastewater-fed ponds in Changsha, Hunan, in 1972, 25 percent of the total fishery area. They produced 1,065 tons of fish, almost 50 percent of the total fish yield of the city (Kuo 1980). The mean fish yield of wastewater ponds was three to four times greater than that of other freshwater ponds, and operating costs were halved. A 147 ha wastewater fishery station constructed by the Xianghu Commune produced 6 tons/ha/yr, excluding the area of fingerling ponds (Kuo 1980).

Kuo (1980) summarized the Changsha experience in wastewater fisheries. Pretreatment of municipal wastewater was combined with fish culture in the pond, which varied in depth from 0.7 m at one end to 2.5-3 m at the other end. The pond had three sections that varied in extent with wastewater flow conditions and the weather: primary sedimentation, purification, and utilization. The pond had advantages of lower capital cost and better utilization of the available capacity of the pond, but removal of sludge was not facilitated. A design with a centralized primary sedimentation pond with effluents subsequently distributed to several ponds was being studied. Two types of wastewater flow systems were in use, a continuous system at Chenjiahu suitable for more stable wastewater flow and larger ponds, and an intermittent system at Xianghu for unstable wastewater flow and smaller ponds. The size of the sewage-fed ponds must be large because it was advised that ponds too large for feeding or harvesting fish could be portioned into smaller ones of 4-7 ha. Detention time in the pond varied from 10 to 40 days, depending on water quality and other local conditions. More than 70-80 percent of the stocked fish were filter-feeding silver and bighead carp, with the remainder bottom-feeders. The recommended fish stocking size was larger than 17 cm at a density of about 1 fish/m^2. Fingerlings were stocked in the grow-out pond three to four times per year and harvested four to five times per year. The ponds were drained every two years in winter for

desludging and liming. With a 40 day detention period in the wastewater-fed pond, suspended solids decreased from 228 mg/l to 16 mg/l, and BOD_5 decreased from 301 mg/l to 18 mg/l. From a food sanitation point of view, there was little difference in fish flesh analysis between wastewater-raised fish and other freshwater fish.

Kuo (1980) also discussed a plan to raise the tropical fish tilapia in wastewater-fed ponds at Xiaotangshan near Beijing, where there was a hot spring. Three wells were dug to supply the warm water that would enable tilapia to be raised at such a northerly latitude.

Zhou (1986) described sewage-fed aquaculture in Changsha with a total area of 612 ha; this represented 45 percent of the total area used for aquaculture but it produced 68 percent of the suburban fish production. There were nine sewage fish farms with a total of 877 ponds and lakes. Xiang Lake and Xi Lake were typical farms that used sewage. Domestic sewage was the main source of sewage, with only 30-40 percent industrial sewage. The sewage was quite dilute with BOD_5 of about 50 mg/l and solids content of 89-282 mg/l. There was concern about copper, oil, and phenols in the mixture of domestic and industrial sewage.

Xiang Lake Fish Farm (142 ha) was founded in 1964. Pretreatment was initially used, but the sedimentation ponds worked for only a short period and were abandoned due to the inefficiency of the desludging system. More recently, sewage was partially treated in a canal before entering the ponds. The ponds were initially very large, some more than 33 ha, and fertility of the water was uneven. The ponds were remodeled as small, deep ponds of 0.67-5.3 ha, 2-2.5 m deep. Some high-load ponds were equipped with aerators. Fish production was highest in Changsha because of efficient management. From 1964 to 1983, 7,658 tons of fish were produced, equal to 2.7 tons/ha/year from the 142 ha farm.

Xi Lake Fish Farm (143 ha) was founded in 1972, and oeprations were initiated using 300 tons/day of sewage from Changsha Winery and 100 tons/day of domestic sewage. The initial sewage was fairly concentrated, with a mean BOD_5 of 1,514 mg/l and total solids of 1,141 mg/l. Toxic substances were at low levels except for mercury and phenol. The largest pond was 3.4 ha and mean depth was 2 m. Some high-production ponds were equipped with aerators. Fish production in 1983 was a mean of 3.9 tons/ha. The fish were considered high quality because of the concentration of distiller's grain in the sewage and because the fish were not tainted with a phenolic taste. Zhou (1986) also reported that two major sewerage systems in Changsha used to be discharged directly into the river Leu Yang. The construction of two large sewage fish farms in Xiang Lake, Hong She Fish Farms, and other farms in Chen Gia Lake and Xin River -- with a total area of 2.7×10^5 ha and receiving 1.5×10^5 tons sewage/day -- has played an important role in protecting the river since 1964.

The quality of the fish grown in Chen Gia Lake, Changsha, deteriorated in the 1960s and 1970s after a truck repair station and a train station began to discharge or leak oil into the sewage. Part of the problem may have been due to the lack of pretreatment of

sewage; the farm initially had a sedimentation system that silted up and was not emptied. Experimental ponds in Xiang Lake Fish Farm received the same sewage as the farm but better quality fish were obtained from the experimental ponds, possibly because oil was trapped by screens set in the pond inlets (Zhou 1986).

Sewage was not discharged into ponds for 10-15 days before fish harvest in Xiang Lake fish farm. Yao Jin Lake Fish Farm once harvested fish from ponds where sewage had been discharged the previous day and sold them to the market; the farm was strongly criticized by consumers.

The most desirable pond size was considered to be 3.3-6.7 ha. In larger ponds, fertility was uneven and harvesting difficult, but smaller ponds were sensitive to overloading, which often caused fish kills. Water depth was generally 2-3 m. Proper sewage pretreatment was considered essential, although there was considerable debate concerning the appropriate degree of pretreatment because of the cost involved. In general, screens and sedimentation ponds were considered necessary to remove oil, floating objects, and silt. Inlets and outlets to ponds were constructed on opposite sides to avoid short-circuiting, and they were fitted with screens and gates to prevent fish from escaping and to control the water level. Additional sewage distribution ditches were required to prevent overloading by diverting sewage from entering the pond. Water aerators to increased the oxygen transfer from the air, and pumps supplied fresh water when fish began to gulp at the surface.

A more recent account of sewage-fed fish culture in Changsha was given by Wang (1987). Sewage-fed fish culture began in 1957 and expanded rapidly: today about 250,000 m³/day of municipal sewage (75 percent of the city's total daily discharge) and 50,000 m³/day of agroindustrial and agricultural wastewater is treated in ponds. The city now has 1,430 ha of wastewater-fed ponds. Ponds are 0.5 ha to 2 ha in area and 2-2.5 m deep. Most are arranged in parallel, receiving raw wastewater and discharging treated wastewater periodically. Other ponds are arranged in series, and wastewater flows through them continuously. Ponds are equipped with floating mechanical aerators for use in case of oxygen deficiency. Fish yield is in the range of 4.5-6.0 tons/ha/yr.

Domestic sewage is used to fertilize lakes that are stocked with fish in China. Domestic sewage was used to fertilize a 427 ha lake in Wuhan, and the annual fish production increased from about 0.9 ton/ha/yr to about 1.2 tons/ha/yr after fertilization (IDRC 1973). Domestic sewage from Wuhan city has been used since 1951 to raise fish in lakes, and the yield has continued to increase with experience (Institute of Hydrobiology 1976). The Hankou Sewage Fishery pond area for raising table-size fish was 98.7 ha. Yields were 2.7 tons/ha in 1969, 3.2 tons/ha in 1970, 3.4 tons/ha in 1972, and 3.8 tons/ha in 1973. However, Hankou Sewage Fishery stopped using domestic sewage for fish farming in 1984 because it became contaminated with industrial wastes. During a visit to the farm by the author in 1984, small ponds were being used as nursery ponds (Fig. 2.14). It was reported that the farm had been experiencing difficulty marketing the fish because the flesh was unpalatable and the fish smelled of phenols. Higher fish yields were reported from other lakes in Wuhan, 5.8 tons/ha from the 10.7 ha North Lakes in 1972 and 9.3

tons/ha from the 13.3 ha Machine Marsh Lake in 1973 and 1975 (Institute of Hydrobiology 1976).

The following principles on rearing fish in waste-fed lakes were developed by the Institute of Hydrobiology (1976). More waste should be discharged into the lake in winter than at other seasons. Water temperatures are low in winter, and usually only a few large fish are present. The winter discharge of a large amount of waste supplies food not only for wintering fish but also for fish stocked during the next culture cycle. Smaller ponds may be drained at the end of the growing season and raw sewage added to the empty pond, as observed in Wuhan by the author (Fig. 2.13). Sewage should be added more frequently, but in smaller quantities, at other times of the year to keep the water fertile without risking anoxia. Weekly discharge of sewage will not cause adverse effects on the growth of fish. An amount of sewage equal to about 10 percent of the total volume of the pond can be added during the winter months, presumably before fish are stocked, but only 1-2 percent should be added in spring and autumn during the fish growth period. Large lakes, greater than 6.67 ha, can receive larger amounts of sewage than smaller lakes because a longer time is required for the sewage to disperse compared to the time required in smaller lakes.

The color of pond water is an important criterion: brown or dark green reflects the color of dominant diatoms and cryptomonads, and green algae, respectively. Black water indicates too much organic matter input, and the inflow of sewage should be reduced. Secchi-disc visibility can also be used as an index of sewage loading, with sewage added when visibility exceeds 20-30 cm. Sewage discharge should be made on clear days, not on cloudy or rainy days.

The growth and behavior of the fish are also important indicators of whether or not sewage should be added. If fish never swim near the surface, the water is infertile. If they float with their head inclined towards the water surface only in the early morning (before photosynthesis begins), then there is a balance between the dissolved oxygen and the concentration of phytoplankton. Sewage discharge should be suspended if fish swim near the surface throughout the day.

Attention needs to be paid to stocking the fish as well as to the rational use of sewage to obtain high fish yields. The yield is positively correlated with the size of stocked fingerlings. The yields in Machine Marsh Lake were 6.1, 5.1, and 9.3 tons/ha/year in 1969, 1971, and 1973, with the sizes of stocked fingerlings 10, 5, and 17 cm, respectively. Yield was also related to the stocking density: yields of 2.1, 3.2, and 5.8 tons fish/ha/yr resulted from stocking densities of 3.0, 3.4, and 1.5 fish/m^2 in 1968, 1970, and 1971, respectively. Higher stocking densities led to a decrease in fish yield.

The appropriate combination of silver carp and bighead carp depends on the composition of the plankton. If the plankton are predominantly phytoplankton, silver carp are more suitable than bighead, with bighead accounting for less than 15 percent of the stocked fish. In 1972, 5.8 and 4.2 tons/ha/year were obtained with bighead carp stocked

at 25 and 37 percent of the fish in two lakes, while another lake stocked at only 15 percent bighead carp yielded more than 7.5 tons/ha/year (Institute of Hydrobiology 1976).

Figure 2.14 Culture of fingerlings in Hankou sewage fishery, Wuhan, China

Jao and Zhang (1980) reported that Lake Dong Hu (East Lake), a large lake in Wuhan used for aquaculture, has become increasingly eutrophic over the past two decades. The abundance of phytoplankton increased several times and the species dominance changed from cryptomonads and diatoms to green and blue-green algae, with a marked increase in larger forms of the latter. The authors recommended that eutrophication of the lake be controlled to safeguard domestic water supply and recreation as well as aquaculture (Fig. 2.15).

2.6.3 Indonesia

Bandung is a major sewage reuse site. Sewage from the old city goes to Imhoff tanks at Bojongloa for sedimentation, but the tanks are hopelessly inadequate today for the volume of wastewater. Vaas (1957) conducted a study on fish culture in the Bojongloa area when common carp, kissing gourami and tilapia were raised in the ponds. The mean production ranged from 2-5 tons/ha/year in the 182.5 ha of ponds. According to Djajadiredja et al. (1979), the yields in the ponds in the Bojongloa area were 4-6 tons/ha/year. During a visit to the ponds by the author in 1981, the numerous sewage-fed ponds were observed to be shallow, only 0.4-0.6 m deep (Fig. 2.16). The ponds were being used as nursery ponds to raise common carp and Mozambique tilapia to 50 g size when they were sold for restocking in other aquaculture systems.

Figure 2.15 Fish harvest in eutrophic Lake Dong Hu (East Lake), Wuhan, China

Figure 2.16 Sewage-fed ponds used to raise fry and fingerlings in Bojongloa, Bandung, West Java

Vaas (1948) reported two isolated cases of sewage-fed fish culture in Indonesia. The effluent of a septic tank in Yogyakarta mixed with river water in a ratio of 1:3 filled a shallow 840-m² pond. A polyculture of common carp (*Cyprinus carpio*), silver barb,(Puntius gonionotus), snakeskin gourami (*Trichogaster pectoralis*), and kissing gourami (*Helostoma temmincki*) yielded about 4 tons/ha/yr. Vaas (1948) also reported a yield of 3 tons/ha/yr of common carp (*Cyprinus carpio*) and silver barb (*Puntius gonionotus*) in ponds fertilized with sewage from a lunatic asylum at Lawang, East Java.

2.6.4 Israel

The reuse of sewage in Israel is encouraged because conventional water resources are limited in the country's semiarid and arid climates (Feinmesser 1971, Hepher and Schroeder 1974). There is a general policy to integrate sewage treatment with agriculture and aquaculture. Crops can be irrigated with treated sewage only in the dry season in summer, so there is a need to impound and store sewage effluents at other times of the year. The use of the wastewater impoundments for fish culture could help defray costs through the production of fish for human consumption (Hepher and Schroeder 1974). According to Arthur (1983), it has been concluded that the ideal solution for sewage treatment and reuse in Israel, at least for smaller towns, is a properly designed anaerobic pond followed by a deep reservoir (4.5-8 m) to store effluent for irrigation. This has enabled practically all of the effluent to be used for irrigation.

There are several specific references in the literature to the reuse of sewage in aquaculture in Israel. Sewage stabilization-pond effluents are used after five days of detention as make-up water for ponds to balance losses from evaporation and seepage. The effluents are diluted with five times the quantity of fresh water (Watson 1962). The most common method of wastewater treatment prior to reuse is sewage stabilization ponds with five- to ten-day detention periods (Fattal 1983). According to Katzenelson et al. (1976), although wastewater is usually partially treated stabilization-pond effluent with a mean detention time of three to seven days, the levels of enteric microorganisms often approach those in raw domestic sewage. However, to prevent the spread of schistosomiasis, the Ministry of Health insists on five days of aerobic oxidation before sewage effluent may be added to the pond (Watson 1962). Sarig (1956) reported the cultivation of fish in a 1-ha reservoir at Rohama which received a daily inflow of about 3 m^3 sewage. The extrapolated net yield was 3.8 tons/ha/yr over a 220 day period. However, 3.8 tons of supplementary feed were also added, but it was reported that feed was added only as bait to facilitate capture of fish at approximately weekly intervals.

Katzenelson et al. (1976) reported that 19 kibbutzim with a population of about 10,000 used sewage in fish ponds, compared to 77 kibbutzim (population 36,465) registered with the Ministry of Agriculture as using wastewater for irrigation and 130 kibbutzim (population 46,360) that did not reuse wastewater.

Hepher and Schroeder (1977) estimated that there were about 50-100 ha of ponds in Israel that received wastewater, most in relatively small rural communities of 500-1,500 population and producing 100-600 m^3 of wastewater per day. The ponds were initially filled with fresh water, and sewage was used to replace losses from evaporation and seepage. The water loss lowered the water level by about 1-1.5 cm/day. The resulting dilution of wastewater within the pond was about 100- to 150-fold in the ponds of mean depth of 1.5 m. The wastewater added to the pond was about 250-300 mg BOD_5/l, which gave a range of organic loadings of 25-45 kg BOD_5/ha/day. According to Hepher and Schroeder (1977), the ponds could handle higher organic loadings because of supersaturation of oxygen produced by photosynthesis during daylight hours.

To demonstrate the benefits of wastewater aquaculture, Hepher and Schroeder (1977) also presented data from a kibbutz with 500 inhabitants and diverse agricultural operations, including a commercial fish farm. The total sewage effluent of 150 m³/day, including wastewater from the laundry, was used as the sole input to three ponds. The sewage effluent was channeled through a 24-m³ settling tank and diluted with two to four parts of fresh water before distribution to ponds. A fourth pond received liquid manure and washing water from the milking room of a 250-cow dairy. Data from two other ponds on the 60-ha kibbutz fish farm, which received neither sewage nor cow manure, are also presented in Table 2.5, which is a summary of data for the six ponds.

Table 2.5
Fish Production and Feed Conversion Factor

	No wastewater; chemically fertilized with ammonia and phosphate		Wastewater; no chemical fertilization			Liquid cow manure; chemically fertilized with ammonia and phosphate
Pond area (ha)	1.4	2.2	0.7	1.0	1.0	2.0
Fish yield (kg/ha/8 months)	4,700	4,700	8,000	8,600	8,100	7,500
Conversion coefficient (kg food/kg fish yield)	1.8	1.6	0.9	1.0	0.8	1.1

Source: Hepher and Schroeder (1977)

All ponds except those that received sewage were fertilized with liquid ammonia and superphosphate, each at a rate of 60 kg/ha/2 weeks and with 0.5 m³ sun-dried chicken manure/ha/2 weeks. All ponds received supplementary feed made up of about 50 percent sorghum grain and 50 percent pelleted feed with 25 percent total protein supplied six times per week at a rate of 4 percent of the carp biomass and 2 percent of the tilapia biomass in the pond at the time of feeding. Both sewage and liquid cow manure increased both the fish yield and the efficiency with which supplementary feed was converted into fish. The conversion coefficient (kg of feed/kg of fish yield) was lower in ponds that received liquid organic matter (wastewater or liquid cow manure). The yield per hectare was 70 percent higher in ponds that received liquid organic wastes and 40 percent less supplementary feed was required per kilogram of fish than in ponds that received no wastewater.

Schroeder and Hepher (1979) reported two examples of the reuse of sewage in ponds. In the first example, the sewage from a town of 5,000 fed directly into a 4-ha pond

that produced 2.8 tons/ha/6 months, equivalent to an annual yield of 5.6 tons/ha. In the second example (reported in more detail by Hepher and Schroeder 1977, discussed above) sewage from a kibbutz of 500 fed ponds with an area of 3 ha and yielded 8.6 tons/ha/8 months, although supplementary feed was also added at a daily rate of 3-4 percent of fish biomass.

Fattal (1983) noted that 10 kibbutzim used their own sewage and/or that of adjacent settlements to enrich their ponds year round.

Data on the extent of national reuse of sewage in aquaculture were presented by Feinmesser (1971) and Arthur (1983). According to Feinmesser (1971), a survey conducted by the Israeli Water Commission in 1967 was divided into two sections: sewage reuse from agricultural settlements and from the urban sector. No data were given for agricultural settlements, but 3,950 m³ municipal sewage per day were used in fish culture. According to Arthur (1983), 1,946,000 m³ sewage effluent – 18 percent of the total rural sector's effluent in 1980, were used in fish farming; most of it was treated in sewage stabilization ponds.

2.6.5 Europe

Sewage fish farming was developed in Germany during the first two decades of this century. Ponds were first constructed in 1887-88 in Dortmund, Munster, and Pankow behind sewage irrigation fields to monitor the quality of the drainage water. In 1899 wastewater was fed into shallow earth ponds, and various types of organisms were added to cultivate feed for carps and rainbow trout raised in separate systems. The idea was reported to be based on the use of overhung latrines in China and Java, where fish are raised without the addition of feed to the pond. The use of pretreated and diluted wastewater in one pond for simultaneous sewage treatment and fish culture, or sewage-fish farming, was first attempted in 1903 and 1905 (Liebmann 1960).

The first large-scale use of sewage-fed ponds was at Strasbourg, where raw sewage passed through a sieve-paddle wheel into a sedimentation basin. Half of this effluent was passed into a river, and the other half passed at 15-20 l/sec into a mixing plant for dilution three to four times with river water. The diluted sewage was passed along open wooden canals arranged in a horseshoe around three sides of 0.3-1.0 m deep ponds of about 5,000 m³ capacity. The diluted sewage was run into the ponds from the canals through funnel-shaped tubes 2-5 m long spaced at 10-15 m intervals with 12-15 tubes per pond. The diluted sewage remained in the ponds for 20-30 days. The sewage of 2,000 persons could be purified in a 1 ha pond. However, improper sedimentation caused problems of sludge accumulation.

Sewage-fed fish ponds were built in several places in Germany: Amberg, Bergedorf near Hamburg, Falkenberg and Grafenhainichen in Saxony, Grafenwohr, Konigsberg, Velbert in the Ruhr, and Zerbabelshof near Nurnberg. The largest plant was built in 1926-1929 in Munich. According to Kovacs and Olah (1984), several European countries including Czechoslovakia, Poland, and the Soviet Union have followed the

Munich sewage-fed pond system. Thorslund (1971) reported two case histories of sewage fish culture in Poland. Raw sewage was spread over grass fields at Legnica and then drained into 50 ha of ponds for 20 years to produce 0.5-0.7 tons of fish per hectare without supplementary feeding. Raw sewage was fed into a series of 55 ha ponds at Zaglowek; fish were not stocked in the first pond, but a yield of 3 tons per hectare was obtained in some ponds with supplementary feeding.
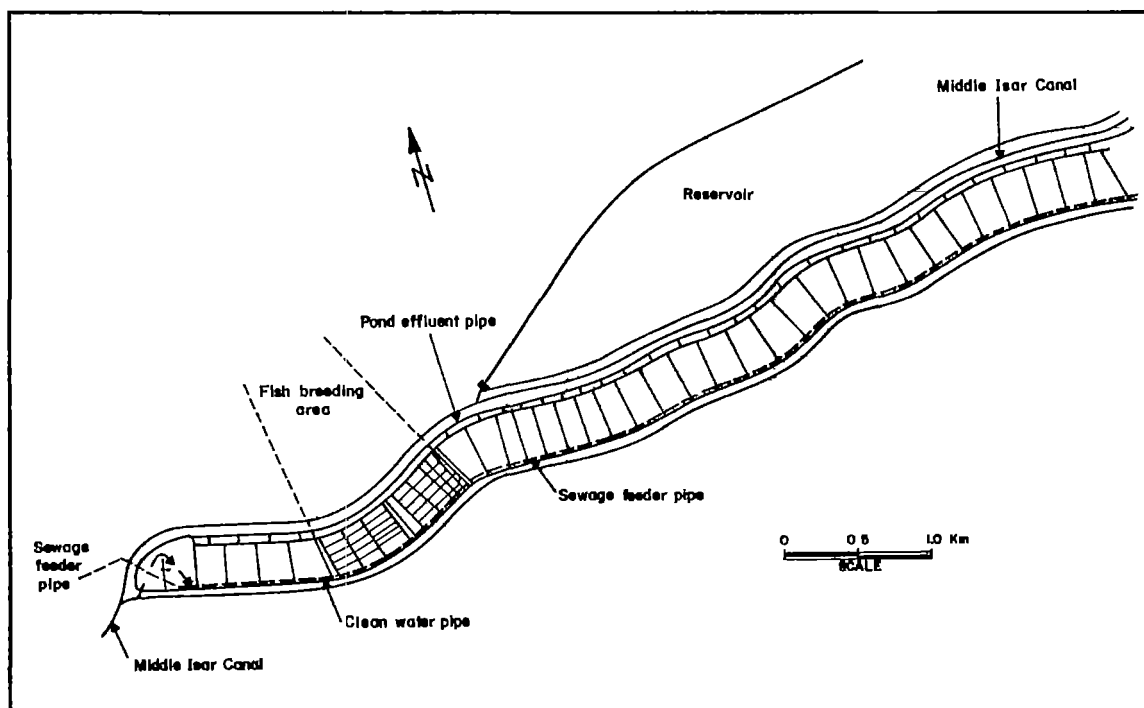
Figure 2.17 Layout of the Munich sewage-fed ponds (Modified from Schulte 1969)

The Munich sewage-fed ponds (Figs. 2.17, 2.18) are the largest in Germany and are described below based on accounts from Kisskalt and Ilzhofer (1937) and Scheuring (1939) as abstracted by Mortimer and Hickling (1954), and by Von Ammon and Stammer (1958), Liebmann (1960), Reichenbach-Klinke (1963), and Schulte (1969). Falck (1936) gave a brief introduction in English of the Munich sewage-fed system. More recent data on the Munich sewage fisheries were published by the Bavarian State Ministry for Land Development and Environmental Protection (1980).

The sewerage system was built in Munich in 1881, and by 1900, 75 percent of the city was connected. However, sewage treatment did not begin until 1925 when an Imhoff tank was used for settling of solids. Biogas was produced from the digestion of the solids. The raw sewage is relatively dilute due to large volumes of cooling water received from breweries. The sedimentation tanks retain 69 percent of the settleable solids, and the clarified effluent is pumped to the sewage-fed ponds, which started operation in 1929. The 233-ha pond complex was built on moorland of little agricultural value. An adjacent 615-ha reservoir for water storage for hydroelectricity generation receives the effluent from

Figure 2.18 Munich sewage-fed fish ponds

the ponds. The reservoir also receives the total wastewater flow when the ponds are dry during the winter. Water cannot be let out, and there has been a large accumulation of sludge over the years. Sludge accumulation along the shore has led to widespread mortality of shore birds because of *Clostridium botulinum*, which develops in anaerobic conditions (M. Bohl in discussion, Carpenter 1978).

The Munich sewage-fed ponds were designed to treat sewage following mechanical treatment. The fish ponds can accept the sewage of 500,000 persons, with a peak of 700,000, which is equivalent to approximately 2,000 population per hectare. With the increase in population of Munich, the sewage fishery was unable to cope with the total volume of sewage, and the excess was discharged into the Isar River, which became increasingly polluted. The sedimentation plant was extended between 1957 and 1960 with the construction of a parallel group of settling basins and a heated digester. In addition, two activated sludge units were built in 1967 and a third in 1974, although the sewage-fed pond complex still treated about 25 percent of the settled wastewater from Munich; from 1972 to 1975, a mean of 23.6 percent of the city's settled wastewater was treated. However, the system now functions as a polishing facility for tertiary treatment of activated sludge effluent. Since 1975, the ponds have not been fed with sedimented sewage (M. Prein, personal communication 1989). The mean organic loading to the 200 ha of ponds used for grow-out varied from a minimum of 7 tons to a maximum of 18 tons BOD_5/day between 1965 and 1975, equivalent to a mean yearly organic loading of 35-90 kg BOD_5/ha/day.

The fish-pond complex consists of ponds varying from 0.3 to 10 ha in size; 70 ha are divided into 12 ponds for growing second-summer carps, and 130 ha are divided into 18 ponds for third-summer carps (it takes three years to raise fish to marketable size

in the system). The ponds are rectangular in shape, with a length-to-width ratio of 3:1. The mean depth is 0.9 m, but the ponds vary in depth from 0.4 m at the inlet to 1.5-2 m at the outlet. Drainage and outflow of water are regulated at the outflow end of the large ponds. At the middle of the outlet is a monk (drainage structure) and 70 m on either side of the main monk are two small monks. The pond bottom has trenches for emptying the pond and harvesting the fish. There are also ponds for breeding, nursery, overwintering and storage of harvested fish prior to marketing.

The wastewater (150-200 mg BOD_5/l) is introduced at the small side of the 30 larger ponds by three sprinklers in each pond. They dilute the wastewater with river water at a ratio of sewage to river water of 1:3 in early summer and autumn, and 1:6 in summer. The wastewater is lifted by six centrifugal pumps to a level of 10 m and flows along the ponds in reinforced concrete pipes 2 m in diameter for 7.5 km. The river water is very cold, so it is introduced into two ponds at the western end of the pond complex to allow it to warm and to settle out the silt load. The wastewater is sprayed through a nozzle in each sprinkler and falls 2 m to the pond surface, above which there is a cascade of river water, which effects immediate mixing of sewage and river water. The dilution rate of wastewater can be regulated separately for each pond. The usual detention time in the pond is 42 hours, with a minimum of 20-30 hours. Over many years there has been a mean loading of 1.65 m^3/sec of wastewater and 9.5 m^3/sec of river water, with maximum loadings of 2.5 m^3/sec of wastewater and 10 m^3/sec of river water.

Common carp grow well at temperatures of 20-25°C. Because of low winter temperatures, fish are cultivated for only seven months, April to October. The ponds are filled with river water in March, and fish are stocked in mid-April. Wastewater is introduced into the ponds slowly to allow adaptation of the fish. The ponds are normally drained in October, but sometimes they are filled with water from October to December. A minimum dry period from December to March is sufficient to mineralize any sludge accumulation; there has been no sludge removal in 30 years of operation.

Wind action impedes the development of floating duckweeds. Submerged aquatic macrophytes cannot develop because common carp stir up the bottom. Emergent aquatic macrophytes must be cut.

The major cultivated species is common carp (*Cyprinus carpio*), and tench (*Tinca tinca*) is a secondary species. Common carp were reported to feed on bottom invertebrates such as chironomids and tubifex and also on zooplankton. The stocking density of year-old summer carps (150-250 g) is 400 fish/ha with 40 one-year summer tench/ha. The most favorable fish stocking density is about 500 fish/ha because fish are more susceptible to disease when stocked at a higher density. The final weight of marketable two- to three-year-old fish is 1.5 kg.

Rainbow trout (*Salmo gairdneri*) fry were introduced into the ponds in 1930 and grew to at least 250 g in one season. But trout swim close to the surface, and there was high mortality caused by fish-eating birds. Trout were also difficult to harvest because they were sensitive to the poorer quality of water in the harvesting pit.

In 1938, 30.1 tons of 2-year-old common carp, 1.4 tons of tench, and 1.1 tons of rainbow trout, a total of 32.6 tons of fish, were stocked in 201 ha of ponds. The harvests of common carp, tench, and rainbow trout for the same year were 80 tons (weighing 2-12.2 kg), 3.5 tons, and 8 tons, respectively, a total of 91.5 tons. The gross and net yields were 0.46 and 0.29 ton/ha, respectively. Common carp, tench, and rainbow trout were 92.3 percent, 4.3 percent and 3.4 percent of the stocked and 87.4 percent, 3.8 percent, and 8.7 percent of the harvested fish, respectively. The yields were usually stated to be about 0.5 ton/ha/growing season, but these appear to be gross yields. Net yields are about 0.3 ton/ha/growing season, or 0.5 ton/ha/year. Such yields dropped in years of low temperatures and high rainfall (Kurzmann 1933, cited by Mortimer and Hickling 1954). Fresh water is added two weeks before fish harvest to depurate the fish. The taste of the fish is reported to be good if the fish are held in clean water for a few weeks. The quality of the meat is good because the fish feed only on natural food.

If the ponds are operated well, the treatment efficiency is higher than that of trickling filters and activated sludge. The BOD_5 reduction is 70-75 percent, and that of nitrogen and phosphorus is higher; sometimes both are completely eliminated. There is a 99.6 percent reduction in the total bacterial count. Furthermore, the sale of fish reduces the cost of wastewater treatment. A disadvantage, because of the temperate climate, is that the ponds do not function in winter. Untreated sewage passes directly into the storage lake of the electricity power station, and later into the river. Sewage cannot be run through the ponds at a higher rate without reducing the growth rate of the fish, although sewage purification is not impaired. Therefore, it is not possible simultaneously to optimize both fish production and sewage disposal. People who live near the ponds also complain about a large production of chironomid flies.

2.6.6 Africa

There are relatively few reports of the cultivation of fish in sewage in Africa. Small-scale operations are reported in Kenya, Malawi, South Africa, and Zimbabwe.

Meadows (1983) discussed the feasibility of fish culture in sewage stabilization ponds in Kenya. Tilapia (probably *Oreochromis* spp.) and common carp (*Cyprinus carpio*) were reported to have been cultured continuously in sewage maturation ponds at Thika for over seven years, with two fish kills involving up to 50 percent of the carp but not tilapia. Tilapia were also reported to have grown in the secondary facultative and maturation ponds at Kisumu for six years without mortality.

In Malawi, Balarin (1987) reported the cultivation of the tilapias *Oreochromis shiranus* and *Tilapia rendalli* in a three-pond series of sewage stabilization ponds, total area 3.2 ha, on the Dwangwa sugar estate. The ponds received effluents from six worker villages on the estate. Yields were estimated at 4 tons/ha (growth period not specified), but the fish were reported not to be used for health reasons. Cross (1985) also described the production of 4-5 tons/ha/240-day growing season of the tilapia *Oreochromis shiranus* in sewage-fed lagoons on the sugar estate at Dwangwa. Domestic sewage from six estate-worker villages was passed along canals, settling out the large solids as it went, to six

three-pond stabilization systems, each covering 0.6 ha. The sewage loading was about 3,500 population per hectare of ponds. The first pond in each series was anaerobic, with phytoplankton blooming in the second and third ponds. Fish were stocked from a small hatchery pond into the third pond. The fish were kept for several weeks following harvest in a clean-water depuration system before cooking.

Several tons of *Tilapia melanopleura* (*T. rendalli*) and *T. mossambica* (*Oreochromis mossambicus*) were reported to be netted weekly from the maturation ponds of the Kwa Mashu sewage treatment works near Durban, South Africa, and distributed to the poor and needy. The ponds yielded 0.8-1.2 tons fish/ha/yr (Mackenzie and Livingstone 1968). However, wastewater is not generally used for fish production in South Africa (Gaigher and Cloete 1981) despite promising reports on the feasibility of sewage-fed aquaculture. The potential for sewage-fed aquaculture remains undeveloped in South Africa, according to a recent review by Wood (1986).

Hodgson (1964) reported that Mozambique tilapia (*Oreochromis mossambicus*) were stocked in 1961 in an aerobic sewage stabilization pond at Marandellas, in southern Rhodesia (Zimbabwe). The fish grew appreciably in size within two months but disappeared after four months, due primarily to predation and unauthorized fishing.

2.7 Aquatic macrophytes

Most excreta reuse systems involving aquaculture stock fish, but there are creeping aquatic macrophytes that are cultivated for human consumption in surface waters that may be incidentally or intentionally contaminated by fecal matter (Edwards 1980b). Duckweeds are also cultivated, mainly for fish feed.

2.7.1 Vegetables

Water spinach (*Ipomoea aquatica*) was reported to be cultivated in Hong Kong in flooded fields with heavy applications of night soil as a fertilizer (Edie and Ho 1969). Vegetables were fertilized with night soil in Hong Kong until the late 1950s (Newcombe and Bowman 1978), but the practice has been discontinued due to rising labor costs and ready availability of inorganic fertilizers at reasonable cost (Hui 1983). Water spinach in Thailand is usually cultivated in fecally polluted eutrophic canals and borrow pits (shallow ponds flanking roads and railways created by excavating soil to raise the level of the transportation system) (Edwards 1980b) (Fig. 2.19).

Water mimosa (*Neptunia oleracea*) is also cultivated in fecally polluted borrow pits and canals in Thailand (Edwards 1980b) (Fig. 2.20).

Watercress (*Rorippa nasturtium-aquaticum*), an emergent aquatic macrophyte native to Europe and north Asia, is cultivated in Hong Kong during the cooler months of the year in the fields used to raise water spinach in the summer (Edie and Ho 1969).
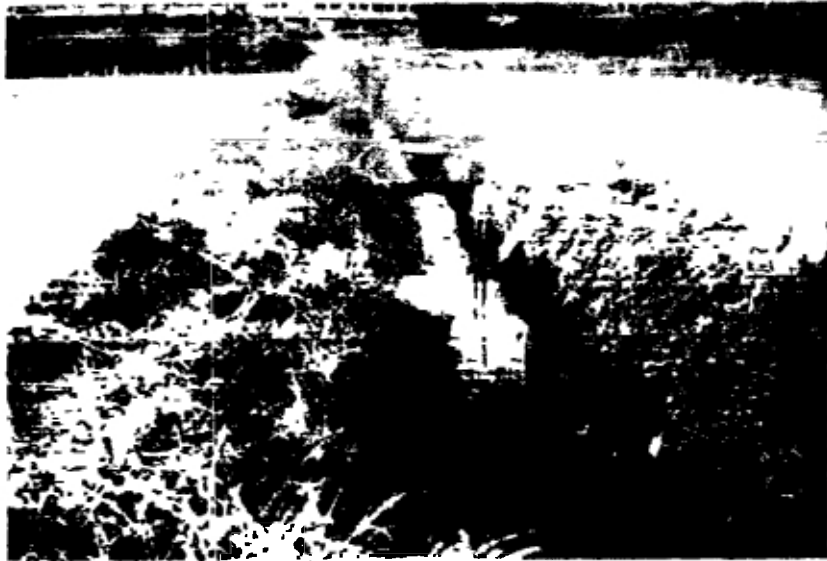
Figure 2.19 Cultivation and harvest of water spinach in a fecally polluted borrow pit in Thailand

Figure 2.20 Cultivation of water mimosa (*Neptunia oleracea*) in a fecally polluted borrow pit in Thailand

Chinese water chestnut (*Eleocharis dulcis*) has corms or tubers that are produced on underground rhizomes, and it is traditionally grown in China using heavy fertilization, which may include night soil (Edwards 1980b).

2.7.2 Duckweeds

The duckweeds *Lemna, Spirodela,* and *Wolffia* are cultivated in certain parts of Asia in shallow ponds fertilized with livestock manure or human excreta, mainly as feed for Chinese carps. Corner (1930) reported the cultivation of *Wolffia* in Singapore in small ponds that received drainage from the nearby Chinese communities.

More data concerning the cultivation of duckweeds are available from China. According to Ling (1967), *Wolffia* and *Lemna* were sometimes specially cultivated in fertile ponds or sections of canals. More information concerning the cultivation of *Spirodela* and *Wolffia* is given in the standard Chinese book on freshwater fish culture, although no details were given for *Lemna* (IDRC 1973). Chinese carp fry were reported to be fed initially on the smaller *Wolffia* and later, after reaching a size of 6-7 cm, they were fed the larger *Lemna* and *Spirodella*. *Wolffia* was cultivated in small ponds about 200-700 m² and 1-1.5 m deep fertilized with 150-375 kg (wet weight?)/ha/day of livestock manure or night soil. Fertilizers were added in small amounts at frequent intervals to maintain an optimal nutrient level. *Wolffia* was concentrated in dense masses using ropes and was harvested by nets. A maximum of 60 percent of the population was removed at each harvest. Yields were reported to be 50-57 kg/667 m²/day, equivalent to 14-16 tons dry matter/ha/year, assuming a *Wolffia* moisture content of 95 percent.

Spirodela was reported to be cultivated in ponds less than about 3,000 m², again using either livestock manure or night soil. Growth of *Wolffia* and *Spirodela* were both seasonal, and following a heavier primary fertilization when parent plants were first introduced, subsequent fertilization depended on the fertility of the water and the time of the year. Water was fertilized more frequently in spring and autumn when growth was more prolific, and smaller quantities were used in summer. The pond was dredged at regular intervals to facilitate nutrient release from the mud. *Spirodela* was harvested when the plants began to cover the entire surface of the pond and a maximum of 30 percent of the population was removed at each harvest. No yield data were given.

Chen (1976) reported that *Lemna* was cultivated in Taiwan as feed for grass carp fingerlings before they were old enough to eat larger and tougher aquatic and terrestrial plants. A more recent and detailed description of duckweed cultivation in Taiwan was given by Edwards et al. (1987). Duckweed – a mixture of *Lemna* and *Wolffia* – was cultivated in two areas in Taiwan, in Tainan and Chiai. About 100 ha were devoted to duckweed cultivation in Tainan, although the area was decreasing due to urban development. A total of about 20 ha were cultivated in Chiai, but the area was expanding at the expense of rice fields because duckweed cultivation was more profitable than rice. Duckweed was cultivated in shallow 0.1-0.5 ha earth ponds fed with fecally polluted surface water (Figs. 2.21, 2.22). Each pond was divided into small square or rectangular areas by floating bamboo poles secured by short vertical bamboo poles to prevent duckweed from moving to one side of the pond in response to wind. Duckweed was reported to grow year-round and was harvested weekly. Bamboo poles were used to move the floating duckweed to one corner of the pond where it was removed using a wicker basket. A maximum of 80 percent of the population was removed at each harvest to minimize the

Figure 2.21 Cultivation of duckweeds (*Lemna, Wolffia*) in shallow ponds using fecally polluted surface water in Taiwan

Figure 2.22 Harvesting duckweed (*Lemna, Wolffia*) in Taiwan

growth of phytoplankton, which reduced duckweed growth. The duckweed was cultivated mainly as feed for grass carp but also as feed for chickens, ducks, and edible snails. Yields reported by farmers were suspect because they varied by too large an extent and the ranges were at variance with yields reported from experimental work (see Section 4.12).

2.8 Summary

The vast majority of commercially viable excreta-reuse systems involving aquaculture are in Asia. There are few reports of excreta-reuse systems elsewhere; all involve sewage, and they are found in Africa and Europe. None are reported in North, Central, and South America. The Munich sewage-fed pond system in West Germany, which has operated for more than 50 years, is significant for the promotion of excreta reuse in developing countries because it occurs in a developed country.

Commercial reuse of excreta in aquaculture takes place almost entirely in freshwater systems. The only reported example of excreta reuse in saline water is the use of night soil to fertilize milkfish ponds in Taiwan, but their operation has been discontinued recently.

Most excreta reuse involves the culture of fish for human food, but small tilapia formerly raised in old milkfish ponds in Tainan, Taiwan, using fecally polluted surface water were sold as livestock feed (see Section 2.5.3). There is a limited amount of cultivation of aquatic macrophytes on excreta, mainly vegetables as human food and duckweeds as fish feed (see Section 2.7). The cultivation of fish and duckweed for animal feed, rather than as direct human food, may permit the reuse of excreta in those societies in which it is traditionally unacceptable.

There has recently been a decrease in the reuse of night soil in several countries in the Far East, where it has been traditionally acceptable — that is, Hong Kong, Japan, Malaysia, and Taiwan. This decrease is probably due to the rising cost of labor brought about by industrialization: the collection, transportation, and distribution of bulky night soil is uneconomic. Inorganic chemical fertilizers are readily available and relatively cheaper. They provide a more economically attractive option than the continued use of night soil, particularly in agriculture. Night soil as a pond fertilizer has been substituted by the increased supply of livestock manure brought about by the intensification of animal husbandry. Bulky livestock manures can be reused conveniently in ponds in integrated livestock-fish farming systems.

Most aquaculture wastewater-reuse systems use fresh or partially treated excreta. They do not appear to constitute a significant public health hazard (see Chapter 7). Sewage-fed fish culture, which is well developed in China and India, reuses raw or only primarily sedimented sewage. The Munich ponds are also fed with sewage that has received only primary sedimentation; clarified sewage effluent is mixed with river water as it is introduced into the ponds.

3. Aquaculture in Relation to Sanitation Technology Options

3.1 Introduction

Selection of appropriate sanitation technology for developing countries has been made especially difficult by the general acceptance in Western industrialized countries of the cistern flushed toilet and conventional sewerage or high-capacity septic tanks as the most satisfactory methods of excreta disposal (Pacey 1978). However, the World Bank's bibliographic search of literature relevant to low-cost waste disposal technologies has shown that there is no substance to the conventional wisdom that there are no viable technological alternatives between the extremes of the pit latrine and conventional sewerage (Kalbermatten et al. 1982ab). There are several practical alternatives to provide adequate sanitation at an affordable cost to the urban poor and rural communities in developing countries. This chapter appraises the feasibility of linking aquaculture to various sanitation options.

A generic classification system (Fig. 3.1: Open arrow shows movement of liquids; closed arrow, movement of solids.) shows the wide range of sanitation systems available. A key distinction in the figure is between those systems in which excreta are carried off-site by cartage or by water in sewers, and systems that treat and dispose of excreta on-site. A second distinction is between dry systems, in which water is not mixed with excreta, and wet systems, in which water is mixed with excreta during flushing. However, in all options except conventional sewerage, little flushing water is used and excreta are retained at least temporarily in a toilet receptacle or latrine.

It is technically feasible to link all these sanitation options, except chemical toilets, with aquaculture. The different kinds of excreta, fresh or after various types and degrees of treatment, may be added to a pond for resource recovery (Fig. 3.2). Similarly, sewage may be recycled in aquatic systems (Fig. 3.3). Although the septic tank with a cistern flush is usually considered a waterborne method of excreta disposal because excreta are carried by a pipe or sewer to the septic tank, it is included for the purpose of this review with low-cost sanitation technology options since sludge from the tank must be removed from the site by cartage.

It is useful to separate the process of collection and disposal of human waste into various stages: deposition, collection, transportation, treatment, reuse (which for the purpose of this report is aquaculture), and disposal. The pond into which the excreta may be added for reuse is referred to as a maturation pond because in most cases adequate levels of dissolved oxygen need to be maintained for fish growth. From a biological point of view, there is little difference between a maturation pond in a series of stabilization ponds stocked with fish, and a fish pond fertilized with various types of excreta.
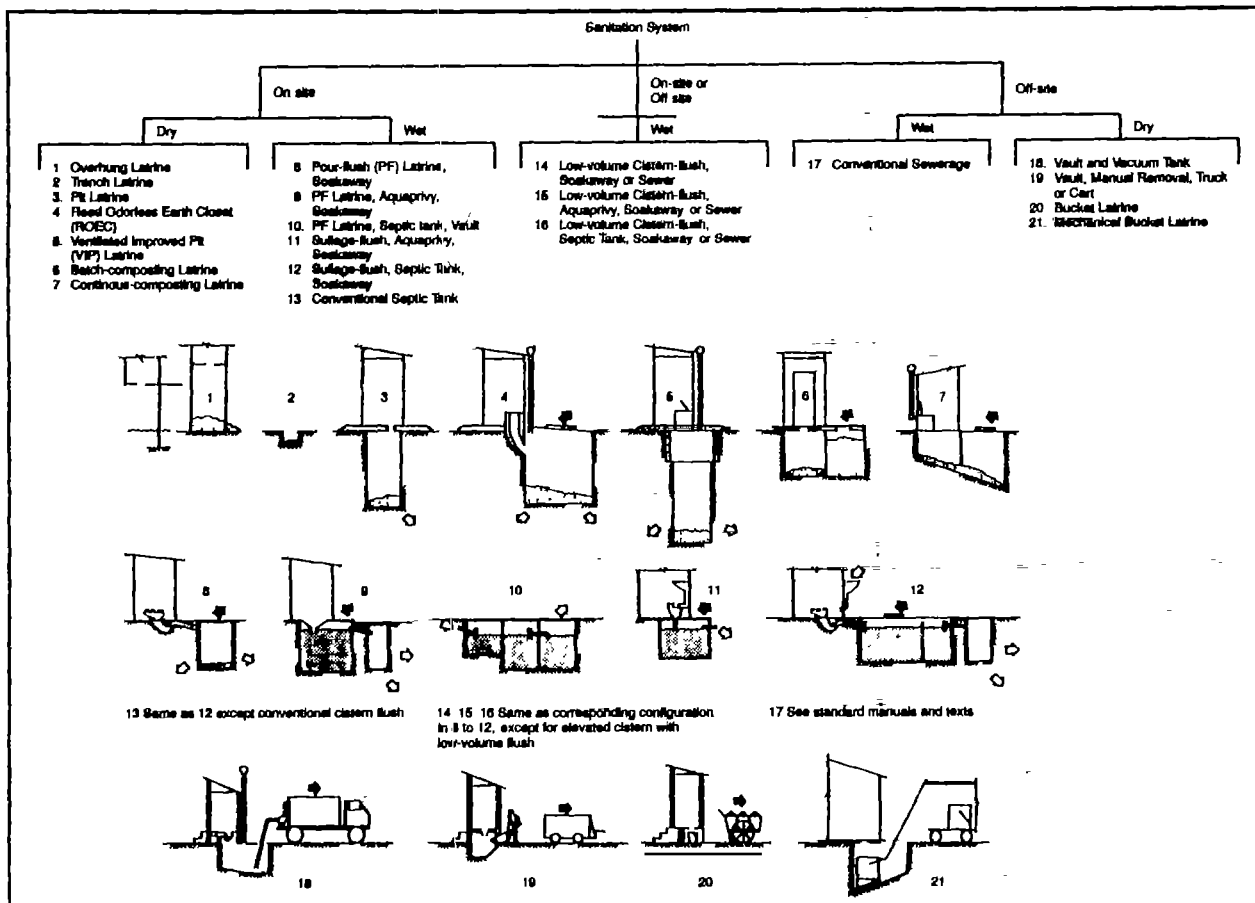
Figure 3.1 **Generic classification of sanitation systems** (*Source:* Kalbermatten et al. 1982a)

A brief outline is presented below of various sanitation options with comments of their potential linkage with aquaculture. For more detailed treatment of excreta disposal systems refer to Feachem and Cairncross (1978), Pacey (1978), Kalbermatten et al. (1982ab), and Cairncross and Feachem (1983).

3.2 Trench and overhung latrines

The trench latrine, a small and shallow pit dug into the ground into which defecation takes place, is designed for temporary use such as military camps and temporary building sites. It has little relevance for aquaculture.

The overhung latrine, a superstructure and floor built on wooden piles above water along the banks of rivers and in coastal areas, is common in Asia. Overhung latrines are common on ponds, particularly in southern China and Indonesia (see Chapter 2).
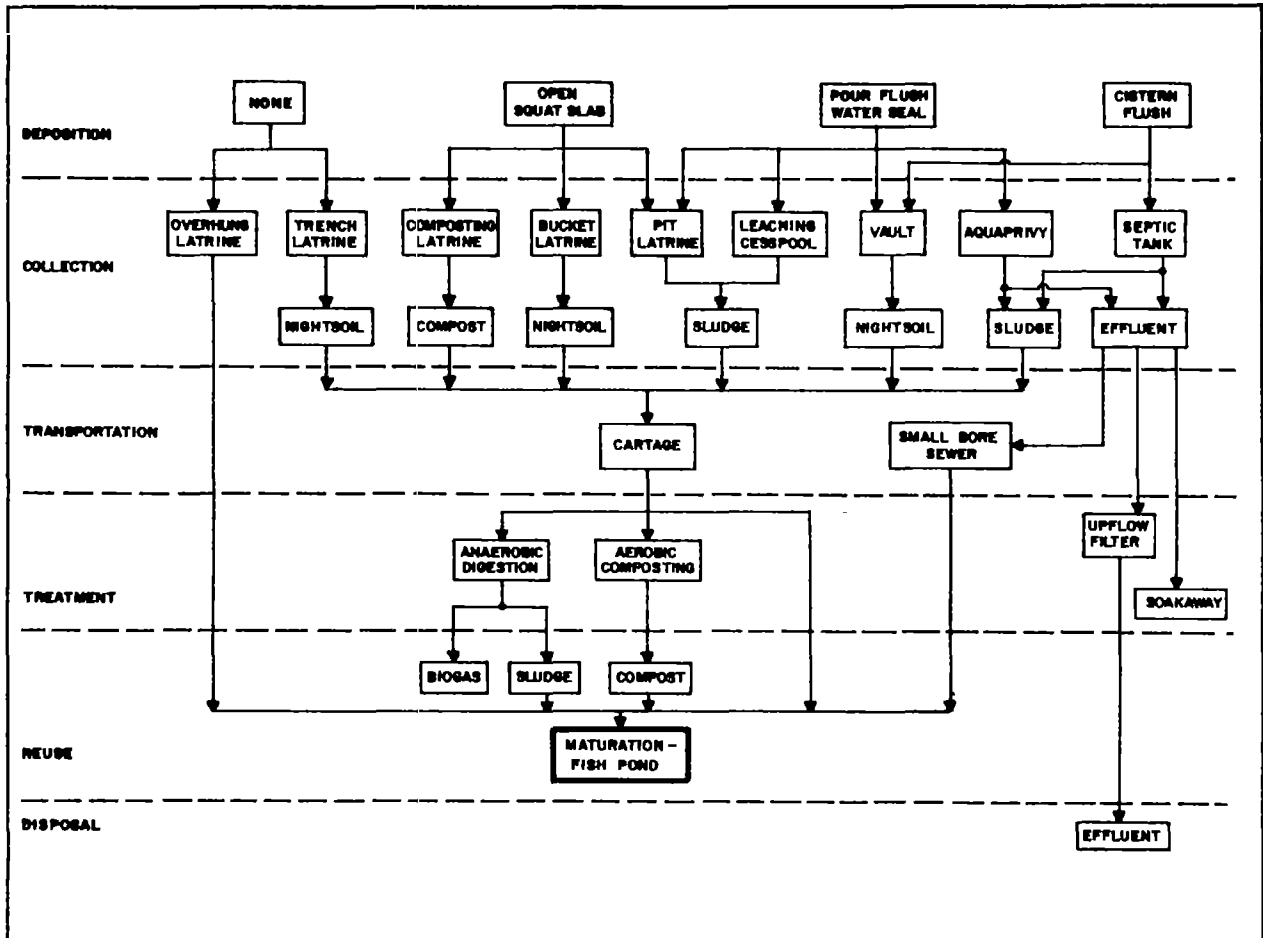
Figure 3.2 The relationship between low-cost sanitation technology options and agriculture (Adapted from Edwards 1985)

3.3 Composting latrine

There are two types of composting toilet, continuous and batch. Continuous-composting toilets, developed from a Swedish design known as the multrum, are extremely sensitive to the degree of user care. Even when the continuous-composting toilet is used properly, fresh excreta may slide into the pile of composted waste and cause a health hazard if recycled without further treatment (Fig. 3.4). The continuous-composting toilet is not recommended.

However, the double-vault composting (DVC) toilet, the most common type of batch-composting toilet, is safe if the compost is stored prior to use. The DVC is reported to be widely used in rural areas of Vietnam, and the compost is added to ponds. The Vietnamese double-vault composting toilet is a simple superstructure enclosing two vaults that are reached by two or three steps (Fig. 3.5). The two vaults have a squat hole on top with a groove to channel urine into a separate container. The urine is emptied daily as
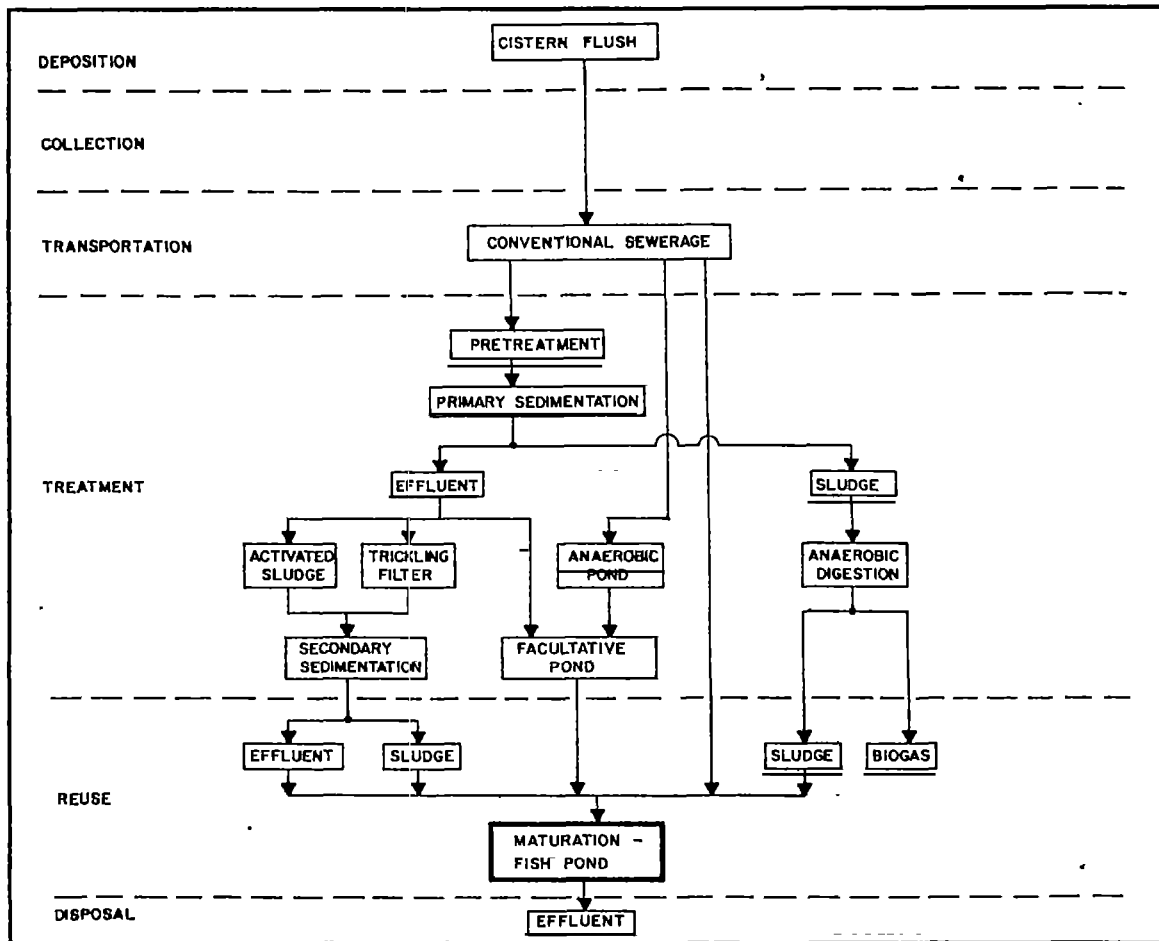
Figure 3.3 The relationship between conventional sewage and aquaculture
(*Source:* Edwards 1985)

fertilizer, and the vaults serve alternately as receptacles for defecation and composting. A vault is sealed when it is full, and the contents are allowed to compost for at least two months before use as fertilizer, while the adjacent vault is used for defecation.

3.4 Bucket latrine

The traditional bucket latrine is a squat slab and bucket located in a small vault below the slab (Fig. 3.6). The bucket is emptied manually into a larger collection bucket for transport to a treatment depot. The operation of bucket latrines is normally unsanitary, and it is difficult in practice to ensure that improved bucket latrine systems are operated satisfactorily in developing countries. Although improved bucket systems provide satisfactory service in parts of Australia and Singapore, even an improved bucket latrine
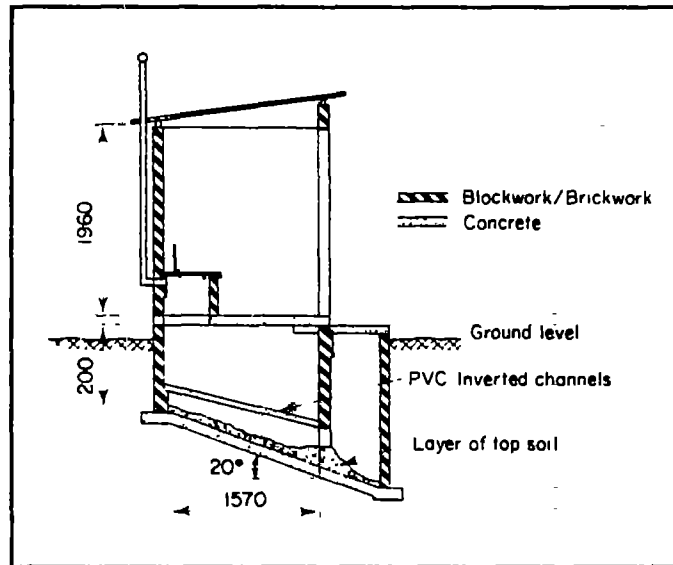
Figure 3.4 Composting latrine of the multrum type as used in the Botswana Low-Cost Sanitation Project (dimensions in millimeters; *Source:* Pacey 1978)

system cannot be recommended for new installations. However, a wooden bucket collection system is widely used in urban and rural China; the buckets are tipped into sealed carts or tanks and sanitary conditions are apparently maintained by a high degree of user care and motivation. Excreta collected in this way are used after a period of storage in sealed tanks.

3.5 Pit latrine

The most widely used method of excreta disposal in developing countries, in both rural and urban areas, is the pit latrine. It comprises a superstructure, a squat slab, and a pit into which excreta drop (Fig. 3.7). The pit latrine is likely to remain the most common means of excreta disposal, particularly in rural areas. An improved version, the ventilated, improved pit (VIP) latrine, in which air circulation removes odors and flies through a ventilation pipe, should receive even more widespread acceptance. Pit latrines can be desludged and the excreta recycled in aquaculture, preferably after the pit has been sealed and not used for at least 12 months by using each of two pits alternately: few *Ascaris* ova are likely to be viable after that length of time. Pit emptying can be done by householders, municipal agencies, or private contractors, and the contents can be sold as an input for ponds.
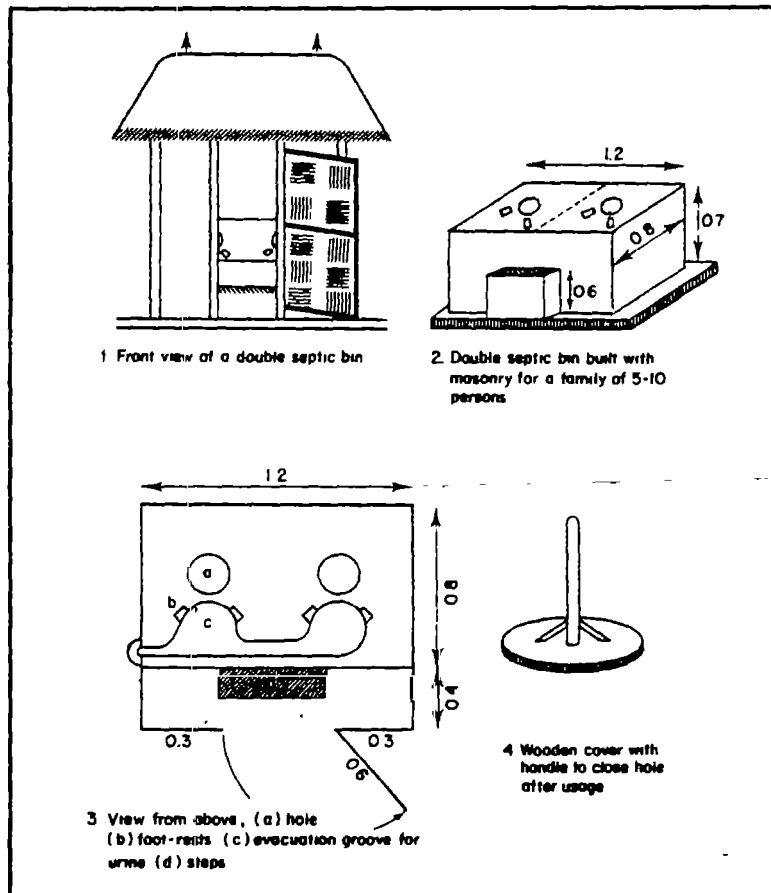
Figure 3.5 A double septic bin latrine as used in the countryside of northern Vietnam (*Source:* Pacey 1978)

3.6 Pour-flush toilet

Pour-flush toilets have a water seal beneath the squat slab. Only one to two liters of water are required for each flush. One type has direct discharge and is essentially a modification of the pit latrine in which the squat slab is provided with a water seal. A second type, widely used in India, Southeast Asia and some parts of Latin America, has one or two offset pits (Fig. 3.8). The pour-flush bowl is connected by a short pipe to an offset pit which may be a soakage pit, or a leaching cesspool which needs to be desludged periodically. The two-pit, pour-flush toilet, operated in the same manner as the double-pit VIP, allows waste to compost for 12 months or more. During that time, pathogens are inactivated and manual emptying of the pit can be done safely. However, septic tanks can also be used with low-volume, pour-flush latrines and are particularly suitable in areas of high water table, as a shallow leaching drain can be used instead of a soakaway pit. They are relatively low cost but require periodic removal of septage.

3.7 Vault

The removal of night soil or cartage from individual houses using manually carried buckets, carts or vacuum trucks was widely used in Europe until recently and is still widely practiced in Asia. Systems range from manual emptying of bucket latrines and small vaults in urban slums to mechanized emptying of large vaults in affluent urban areas in Japan (Fig. 3.9). Pradt (1971) described how the problem of the daily disposal of night soil in Japan led to the development of a unique technology involving the deposition of night soil in a watertight vault which is emptied every three to four weeks by vacuum truck. He concluded that, for less-developed communities, the Japanese night-soil collection system is a more practical approach than a Western-style, waterborne system.
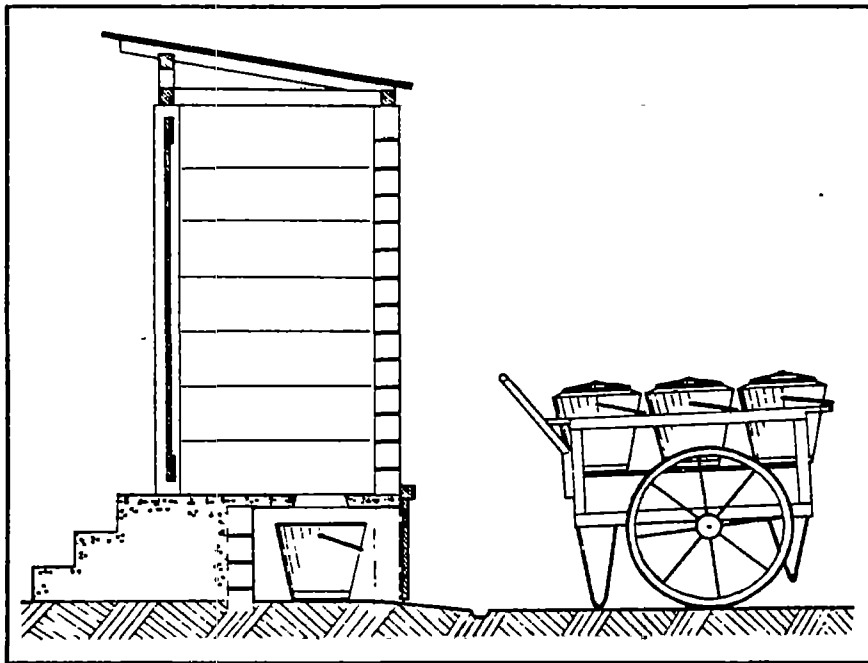
Figure 3.6 Bucket latrine with handcart for transport of buckets (*Source:* Pacey 1978)

Cartage can be operated at various levels of sophistication, from the daily collection of night soil by a person using a dipper and buckets to less frequent emptying of larger vaults using vacuum trucks. The latter type of system is widespread in urban areas in Asia, particularly in Japan and Taiwan: large areas of Tokyo are serviced by conservancy vaults and vacuum trucks. Vaults can be hygienic with a pour-flush, water-seal, or low-volume cistern flush. The frequency of excreta removal ranges from daily to monthly and depends on the size of the vault. Although night-soil cartage tends to have higher health risks than sewerage, particularly if vaults are emptied by hand using dippers, buckets and open carts, risks can be considerably reduced with well-designed systems such as in Japan.

There are advantages to the vault and vacuum-truck sanitation option. The water-seal bowl and vault can be manufactured locally and sold as a market commodity. A minimal amount of water is required, about 2-6 l/c/d. The option is suitable for densely populated urban areas because excreta can be removed readily by vacuum carts and trucks. Such a collection system is highly flexible, an important consideration in rapidly expanding urban areas in developing countries. Furthermore, the vault system can be easily upgraded by conversion to cistern-flush septic tanks with upflow filters or small-bore sewers, with a reduction in the frequency of the removal of the vault contents to once every few months. A key problem with the system is the organization of excreta removal because there is the fundamental need to remove night soil regularly. However, the vault is the best sanitation technology from the point of view of aquaculture reuse because there is the greatest degree of conservancy of excreta among the various sanitation options.
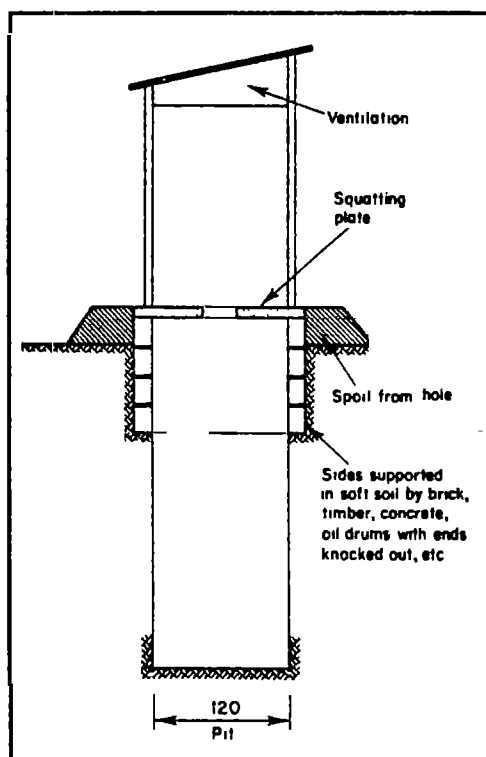
Figure 3.7 The basic components of a pit latrine (dimensions in centimeters; *Source:* Pacey 1978)

3.8 Aqua privy and septic tank

Septic tanks and aqua privies use anaerobic digestion of excreta in a tank of water: there is a separation of solid matter by sedimentation from a liquid effluent which flows out of the tank to soakaways (pits) or tile drain fields, or to small-bore sewers. The sludge deposited in the tank has a much lower volume than the original excreta (Fig. 3.10).
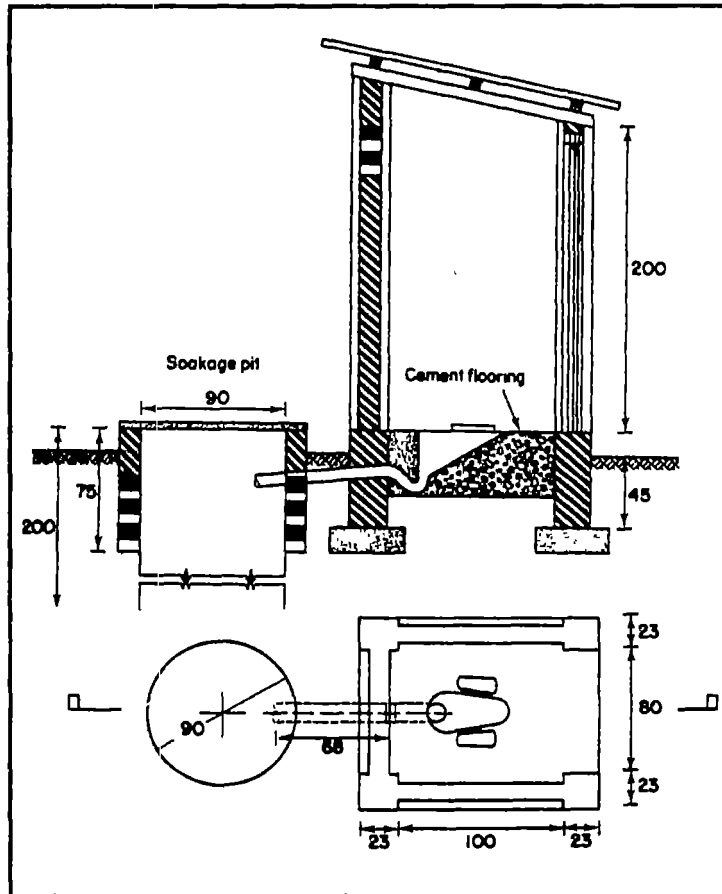
Figure 3.8 Hand-flushed, water-sealed latrine with offset pit designed by EERI, Nagpur, India
(dimensions in centimeters; *Source:* Pacey 1978)

The aqua privy is a low-cost technology intermediate between the pit latrine and flush toilet. It costs less to build than a septic tank and requires less water. Deposition of excreta from the squatting plate into the tank can be by a vertical drop-pipe with its lower end below the water level in the tank or by a low-volume pour-flush water seal.

The septic tank has relatively high construction cost and high water usage. Septic tanks provide modern water-borne excreta disposal on a small scale suited to rural areas where isolated houses are not connected to a reticulated sewerage system.

Many cities in Asia rely on septic tanks, which can lead to pollution of the surrounding area from either insufficient land for effluent disposal or impermeable soil. Leaching cesspools with outlet pipes are commonly installed in Asian cities, so that the surrounding soil may act as a soakaway. However, in dense urban areas the soil pores soon become blocked, and leaching cesspools then function like a septic tank. To safeguard the environment from pollution, "septic tanks" in Asian cities could be equipped with anaerobic upflow filters to treat the effluent further, or they could be converted to
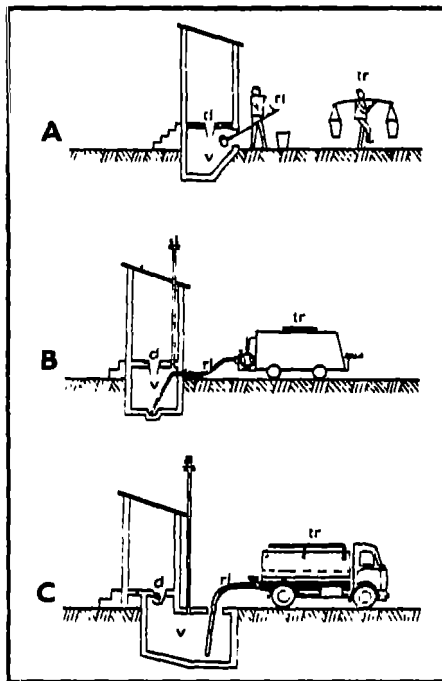
Figure 3.9 Incremental improvements made to latrines with vaults and to the cartage system serving them
(*Source:* Pacey 1978)

watertight vaults with more frequent removal of the contents. The latter would provide more excreta for reuse in aquaculture. The effluent of aqua privies and septic tanks could be removed by small-bore sewers which could feed a maturation pond.

3.9 Conventional sewerage

In conventional sewerage, excreta are mixed with large volumes of water from a cistern flush and are removed from the house in a flow along pipes or sewers, ideally to a treatment plant. The major advantages of conventional sewerage, in addition to safeguarding public health, are a high degree of user convenience. However, there are technical and financial constraints which often make it an unsuitable option for developing countries (Mara 1976, Rybczynski et al. 1978).

Per capita costs for the installation of sewerage systems range from $150 to $650, too costly for many areas in developing countries with average yearly incomes can be less than $200 (Dale 1979). Sewerage systems require large amounts of water, but only 13 percent of the population of developing countries have piped water, and its supply may be seasonal or sporadic because of climatic or operational difficulties.
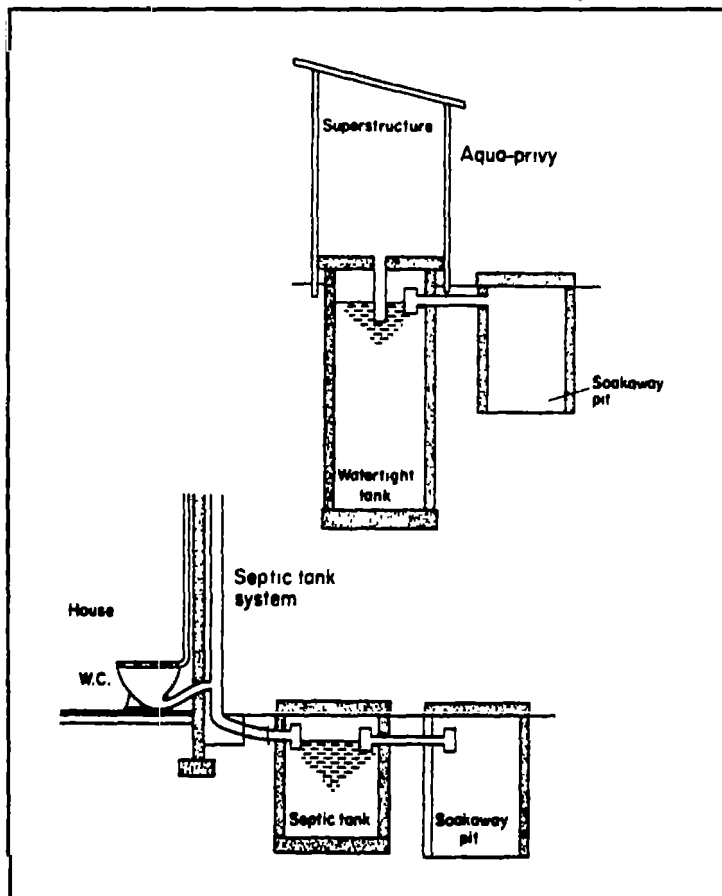
Figure 3.10 Comparison of the principle of the aquaprivy and the principle of the septic tank
(*Source:* Pacey 1978)

The construction of sewerage systems is ill-suited to incremental implementation in densely populated areas and may require as much as a decade to plan and implement. Over that much time, the percentage of the population served by sewerage systems may actually decline due to population growth. At present, 93.5 percent of the population of the tropics is not served by sewers and, according to a WHO survey, the fraction of the urban population of developing countries that had sewage connections decreased from 27 percent in 1970 to 25 percent in 1976, while 25 percent of the urban population had no access to any sanitary facility (Rybczynski et al. 1978).

Following preliminary treatment to remove large floating objects, sand, and grit, suspended sewage solids are removed by primary sedimentation in sedimentation tanks. The sludge is hazardous to health, highly odorous when fresh, and should be treated by digestion before reuse. The three major types of secondary sewage treatment are trickling filters, activated sludge, and stabilization ponds. The first two are the least suitable for developing countries because of their cost and high maintenance requirements. In addition,

the effluents may remain hazardous to health and may contain significant amounts of nutrients.

If land is available at reasonable cost, stabilization ponds are recommended for treating sewage in the tropics: they are cheaper to build and maintain than trickling filters and activated sludge plants, and they are vastly superior from a public health point of view (Mara 1976). A properly designed series of ponds with a minimum detention time of 25 days can produce a final effluent with no protozoa and helminth ova and a very low survival rate of bacteria and viruses (Feachem et al. 1983). Stabilization ponds can be maintained by unskilled workers with minimum supervision. Conventional sewage treatment plants require large drying beds or sophisticated disposal facilities for regular sludge removal. However, anaerobic ponds require desludging only every two to three years, but facultative and maturation ponds can usually function more than 20 years before sludge removal is needed (Arthur 1983). The reasons for installing sewage stabilization ponds are persuasive where sufficient land is available at reasonable cost and in an appropriate location. According to Arthur (1983), when sewerage is the most appropriate sanitation technology, stabilization ponds should be proposed as the first treatment option.

There are reports of effluents from both trickling filters and activated sludge plants being further treated in maturation ponds and used for aquaculture following secondary sedimentation. Sewage sludge has also been used for the experimental feeding of fish. However, most data relating sewage and aquaculture pertain to fish cultivation in sewage stabilization ponds. A series of conventional stabilization ponds normally consists of an anaerobic pond that functions as a septic tank to allow sedimentation of sewage solids, followed by facultative and maturation ponds. These latter two contain high densities of phytoplankton suitable for feeding fish, but dissolved oxygen levels are normally suitable for aquaculture only in maturation ponds. From a sanitary engineering point of view, anaerobic and facultative ponds are designed for five-day biochemical oxygen demand (BOD_5) removal and maturation ponds for pathogen removal, but the latter are suitable for aquaculture. As shown in Figure 3.3, there are various options for sewage reuse in a series of stabilization ponds. The choice among these options depends on the strength of the raw sewage. Aquaculture should be considered to defray sewage treatment operating costs.

3.10 Sanitation sequences

An important result of the World Bank study was the development of the concept of sanitation sequences, step-by-step improvements which can be implemented as the socioeconomic status of a community increases (Kalbermatten et al. 1982a). It is important to note that none of the sanitation sequences leads to conventional sewerage. Even in urban areas, the final upgrading is generally to low-volume cistern-flush toilets connected to a vault that overflows into a small-bore sewer. This finding has implications for aquaculture, which would lead to more complete reuse of the nutrients contained in the excreta. In general, low-cost sanitation technology options have greater potential for linkage with aquaculture than does conventional sewage.

4. Experimental Excreta Reuse

4.1 Introduction

Most experimental work on excreta reuse in aquaculture has focused on fish cultivation in sewage effluents. In contrast to the commercially viable, sewage-fed ponds found in Asia (India, Israel, and China) and to a lesser extent in Europe (mainly Germany), experiments in sewage-fed fish culture have been reported widely: from Africa, North and South America and the Caribbean, Asia, Australia, and Europe. The major features of research studies on fish culture with sewage are presented in Table 4.1, and a discussion of each study is presented below.

Research has also been conducted on the use of septage, biogas slurry, and composted night soil as fish-pond nutrients in Asia. Most research has involved fish, and duckweeds have also been studied.

4.2 Sewage stabilization ponds: Africa

Research in Africa has been centered in South Africa, and there is one report from Kenya.

4.2.1 Kenya

Tilapia nilotica (*Oreochromis niloticus*) grew well over a 20 week period with a survival of 95 percent in experimental cages in the secondary facultative ponds (diurnal dissolved oxygen range 1.2-26 mg/l) at Thika, Kenya (Meadows 1983).

4.2.2 South Africa

Research was conducted by Hey (1955) to evaluate the feasibility of fish culture in sewage effluent. Effluent from the sewage treatment plant at Athlone (primary sedimentation, two-stage biological filtration, and final sedimentation) was allowed to filter through a field of grass to remove organic matter, then channelled to a balancing pond, and finally directed to four ponds that were fed with sufficient flow to compensate for evaporation and seepage. The ponds were also planted with submersed aquatic macrophytes: *Lagarosiphon* sp., *Myriophyllum persapinacoides* and *Vallisneria spiralis*. A variety of fish was stocked after the ponds developed a rich biota including chironomids, snails, zooplankton, and insect larvae. Largemouth bass (*Micropterus salmoides*) grew better than smallmouth bass (*M. dolomieu*) and spotted bass (*M. punctulatus*). Bluegill sunfish (*Lepomis macrochirus*) also grew well. Heavy mortalities of bass and bluegills, which occurred twice, were attributed to nighttime depletion of dissolved oxygen from

Table 4.1
A Summary of Experimental Studies on Sewage in Fish Culture

Conti-nent	Country	Reuse system	Species	Comments	Citation
Africa	Kenya	Cages in secondary facultative ponds	Nile tilapia[a]	Good growth	Meadows (1983)
	South Africa	Four ponds after biological filtration	Largemouth bass[b], smallmouth bass[c], spotted bass[d], blue-gill sun fish[e], Euro-pean perch[f], Mo-zambique tilapia[g], Tilapia sparramani	Good growth of largemouth bass, bluegill sunfish and Mozambique tilapia, slower growth of European perch. Estimated production of tilapia 1.1 t/ha/yr	Hay (1955)
	South Africa	Reservoir fed with treated domestic sewage effluent	Mozambique tila-pia[g], Tilapia ren-dalli, common carp[h], catfish[i], black bass[b], silver carp[j]	Catfish and black bass stocked to control reproduction of tilapia. Potential yield 1 t/ha/yr	Ferreira and Schoonbee (1983)
	South Africa	Single cage in concrete pond fed with matura-tion pond effluent	Mozambique tilapia[g]	Good growth	Gaigher and Krause (1983)
	South Africa	Cages in ponds fed with trickling filter effluent	Mozambique tilapia[g]	Good growth when system functions properly	Gaigher and Torien (1985)
Amer-ica	Domini-can Repub-lic	Tilapia raised in sewage stabilization ponds fed live to large-mouth bass in experimental cages	Tilapia		Davies (1982)
	Peru	A single tertiary sewage stabilization pond and two quaternary and a single quintenary pond fed with tertiary effluent	Nile tilapia[a], com-mon carp[h], giant freshwater prawn[k]	Good growth of tilapia and common carp but poor growth of giant freshwater prawn	Moscosco and Nava (1984), Bartone (1985), Bartone et al. (1985), Cointreau (1987)
	United States	Ponds fed with activated sludge effluent treated further by sand and gravel filters	Channel catfish[l], Malacca tilapia hybrid[m], rainbow trout[n]	Reuse of sewage effluents for sports fishing. Channel catfish and tilapia grew well but survival of ranibow trout was low. Fish yield 0.8 t/ha/yr	Hallock and Ziebell (1970)
	United States	Ponds fed with trickling filter effluent	Fathead minnow[o]	Reuse of sewage effluents for bait fish for sports fishing	Konefes and Bachmann (1970)
	United States	Ponds fed with activated sludge effluent	Blue tilapia[p]		Buros (1977)

Table 4.1
Continued

Conti-nent	Country	Reuse system	Species	Comments	Citation
	United States	Cages in sewage stabilization ponds equipped with aerators	Hybrid tilapia[m]	Extrapolated yield of 206 t/ha/yr	Suffern et al. (1978)
	United States	Four sewage stabilization ponds in series fed with effluent from two aerated lagoons in series	Channel catfish[i], gold shiner[q], tilapia (probably[r]), fathead minnow[s]	Tilapia grew well but winter temperatures caused mortality. Channel catfish grew well only when young. Golden shiner and fathead minnow grew well but yields were low, possibly due to predation by wild catfish. Species used not considered ideal.	Coleman et al. (1974), Carpenter et al. (1976), Carpenter (1978), Henderson (1982)
Asia	Hong Kong	Two ponds fed with activated sludge effluent and/or high rate biological filter effluent	Mozambique tilapia[e]	Good growth and survival. Extrapolated net yields 1.5 and 2.1 t/ha/yr	Sin and Chiu (1987a)
	Hong Kong	Two ponds in series to those used to culture Mozambique tilapia (above)	Bighead carp[r], common carp[k], grass carp[j], silver carp[j]	Good growth of bighead, common and silver carp, poor growth of grass carp. Mass mortalities. Extrapolated net yield 2.0 t/ha/yr	Sin and Chiu (1987b)
	India	Fenced-off section of a sewage effluent canal	*Etroplus suratensis, Barbus sarana, Labeo fimbriatus, Cirrhina reba, Osphromenus goramy*	Good growth	Ganapati and Chacko (1950)
	India	One pond fed with sewage stabilization pond effluent with 2 day detention period	Common carp[k]	Extrapolated yield 7.7 t/ha/yr	Muthuswamy et al. (1974)
	India	Two ponds in series fed with sewage stabilization pond effluent with about 3 day detention period	Common carp[k], mrigal[t], rohu[u], *Labeo finbriatus*	Extrapolated yield 11.5 t/ha/yr	Muthuswamy et al. (1978)
	India	Tanks fed with sewage stabilization pond effluent	Common carp[k], rohu[u]	Common carp grew better than rohu but occasional mortality.	Krishnamoorthi et al. (1975), Krishnamoorthi and Abdulappa (1979)

Table 4.1
A Summary of Experimental Studies on Sewage in Fish Culture (continued)

Conti-nent	Country	Reuse system	Species	Comments	Citation
	India	Tanks fed with sewage stabilization pond effluent	Walking catfish[v]	Lower growth rate than common carp but much higher survival rate	Krishnamoorthi et al. (1975), Krishnamoorthi and Abdulappa (1979)
	India	Sewage stabilization ponds	Catla[w], rohu[u]	Good growth	Chatterjee et al. (1967)
	India	Commercial pond fed with sewage effluent following primary sedimentation	Catla[w], rohu[u], silver carp[j]	Good growth. Extrapolated yield 13.2 t/ha/yr	Anon (1973b), Ghosh et al. (1973, 1974)
	India	Sewage-fed pond	Nile tilapia[a]	Good growth. Estimated (extrapolated) yield 9.4 t/ha/yr	Anon (1976)
	India	Sewage-fed pond	Walking catfish[v], Nile tilapia[a]	Good growth	Ghosh et al. (1976)
	India	Sewage-fed pond	Catla[w], mrigal[f], rohu[u], common carp[b], silver carp[j]	Good growth. Extrapolated net yield 7.6 t/ha/yr	Dehadrai and Ghosh (1977)
	India	Four ponds fed with sewage stabilization pond effluent	Indian major carps, Chinese carps, milkfish[x]	Extrapolated yields of 8.4 and 4.3 t/ha/yr in two ponds which received effluent directly, and 3.3 and 3.5 t/ha/yr in two ponds which received effluent from the two ponds	Kutty (1979, cited by Jhingran 1982)
	Israel	Four ponds fed with extended aeration effluent	Blue tilapia[e], common carp[b], silver carp[j]	Determination of tolerance levels of different species to ammonia	Buras et al. (1987)
Aus-tral-asia	New Zealand	One pond fed with raw sewage to compensate for water loss	Rainbow trout[c], gold fish[y], common smelt[z]	Good growth of rainbow trout and gold fish but poor growth of common smelt	Slack (1974), Teoh (1974)
Eu-rope	France	Ponds fed with sewage stabilization pond effluent in batch culture	Bighead carp[r], Common carp[b], silver carp[j], Nile tilapia[a]	Good growth but some mortality due to ammonia and low dissolved oxygen	Bailly (1978, 1979)
	Hungary	Sewage sprayed into ponds after primary treatment	Bighead carp[r], common carp[b], grass carp[t], silver carp[j]	Good growth. Net yield 1.8-2.0 t/ha/120 day growing season or 5.5-6.1 t/ha/yr	Kovacs and Olah (1984)
	Hungary	Sewage sprayed into ponds after primary treatment	Common carp[b], silver carp[j]	Good growth. Net yield 12 kg/ha/day over 120 day growing season or 4.4 t/ha/yr	Olah et al. (1986)

Table 4.1
Continued

Conti-nent	Country	Reuse system	Species	Comments	Citation
	Poland	Ponds fed with activated sludge effluent	Crucian carp[a]	Good growth. Yield 1.3 t/ha/yr	Wolny (1964, 1966), Thorslund (1971)
	Poland	Ponds fed with activated sludge effluent	Common carp[b], grass carp[c], silver carp[d]	Good growth.	Klekot (1978)
	Russia	Fish cultured in last three ponds of cascading series of six ponds fed with raw sewage	Carp (common?)		Mayenne (1933, cited by Mortimer and Hickling 1954)
	United King- dom	Cages in polishing pond of conventional diffused air plant	Common carp[b]	Good growth	Williams et al. (1973), Noble (1975)

[a]*Oreochromis niloticus*; [b]*Micropterus salmoides*; [c]*Micropterus dolomieu*; [d]*Micropterus punctulatus*; [e]*Lepomis macrochirus*; [f]*Perca fluviatilis*; [g]*Oreochromis mossambicus*; [h]*Cyprinus carpio*; [i]*Clarias gariepinus*; [j]*Hypophthalmichthys molitrix*; [k]*Macrobrachium rosenbergii*; [l]*Ictalurus punctatus*; [m]*Oreochromis hornorum* x *O. mossambicus*; [n]*Salmo gairdneri*; [o]*Pimephales promelas*; [p]*Oreochromis aureus*, [q]*Notemigonus crysoleucas*; [r]*Aristichthys nobilis*, [s]*Ctenopharyngodon idella*; [t]*Cirrhina mrigala*; [u]*Labeo rohita*; [v]*Clarias batrachus*; [w]*Catla catla*; [x]*Chanos chanos*; [y]*Carassius auratus*; [z]*Retropinna retropinna*; [aa]*Carassius carassius*

blooms of *Scenedesmus*. Both largemouth bass and bluegills later inexplicably disappeared from the ponds, despite breeding. European perch (*Perca fluviatilis*) were considered to be totally unsuitable, presumably due to a lack of growth. Mosquito fish (*Gambusia affinis*), introduced to control mosquitoes, did exceptionally well. Both *Tilapia mossambica* (*O. mossambicus*) and *T. sparrmani* grew and bred satisfactorily. *O. mossambicus* were judged best suited to the local system and productivity based on ten years of experience (although without accurate records) was estimated to be about 1.1 tons/ha/yr. The results with tilapia were so promising that it was reported that attempts were being made to use the fish as human food, particularly for lower-income groups, following depuration in running water for 24 hours and dipping in dilute chlorinated water. The fish were distributed to institutions known to prepare fish under hygienic conditions. Plans were made to use 4.8 ha of ponds for raising fish on an economic scale if the existing prejudice against consumption of sewage-raised fish could be overcome.

Fish were cultured in a 25 ha reservoir used as a storage pond for cooling water from a steam electric-power generating plant at Orlando, Johannesburg, South Africa (Ferreira and Schoonbee 1983). The reservoir supported considerable phytoplankton growth because the water supply to the reservoir mainly comprised treated domestic sewage

effluent. *Oreochromis mossambicus* and *Tilapia rendalli* were introduced to control phytoplankton and aquatic macrophytes, respectively. Common carp (*Cyprinus carpio*), sharp-tooth catfish (*Clarias gariepinus*), and black bass (*Micropterus salmoides*) were also stocked, the latter in an unsuccessful attempt to control overpopulation of *O. mossambicus*. More recently, silver carp (*Hypophthalmichthys molitrix*) were stocked to help to control phytoplankton blooms. Fish were reported to grow well in the reservoir because of the rich growth of phytoplankton and the relatively high year-round temperatures (22-30°C) due to recirculation of the entire water volume of the reservoir through the power station every 16 hours. Furthermore, oxygenation of pond water occurred during the cooling process when some of the water was sprayed into the air through a system of nozzles; oxygen saturation of water near the bottom of the approximately 4 m deep reservoir never fell below 8 percent. A study of *O. mossambicus* and *H. molitrix* showed that their diets were similar but that the ratio of detritus to phytoplankton was much higher in the former than the latter. The need to suppress phytoplankton blooms by application of copper sulphate diminished gradually following the introduction of silver carp. However, continual harvesting of fish was required because predators such as black bass and catfish could not control the population growth of *O. mossambicus* in the reservoir. The authors stated that the reservoir had the potential to produce an average of 1 ton fish/ha/yr without any supplementary feeding.

In an attempt to ease the difficulty of harvesting fish in sewage stabilization ponds, Mozambique tilapia (*Oreochromis mossambicus*) were cultured in a floating cage (Gaigher and Krause 1983). Cage culture was also to overcome predation by sharp-tooth catfish (*Clarias gariepinus*). The single circular floating cage with a diameter and depth of 0.9 m (volume 0.57 m^3) was suspended in a 500 m^2 concrete pond fed continuously with the effluent from the final maturation ponds of the Bloemfontein Sewage Works. The pond contained a rich population of zooplankton. The stocking density was 17 fish/m^3 of cage volume. The fish grew rapidly from a mean initial weight of 10.1 g to a mean final weight of 130.6 g in about three months, although the growth rate decreased toward the end of the study. The economic viability of growing tilapia in cages suspended in sewage stabilization pond effluents was considered to depend on whether fish stocked at high density would reach marketable size in the warm season growing period.

A later study by Gaigher and Toerien (1985) substantiated the conclusion of Gaigher and Krause (1983) that *O. mossambicus* grew rapidly in cages suspended in treated sewage effluents. The fish were cultivated in 2 m^3 floating cages in ponds 4 and 5 in a series of five ponds which received treated sewage from trickling filters at the Phuthaditjhaba sewage system. A preliminary study showed that only the fifth, and possibly the fourth pond, would be suitable for fish because of high concentrations of un-ionized ammonia. Fish were stocked at densities varying from 50 to 200 fish/m^3 of cage volume. All fish stocked in pond 4 died within the first month. The tilapia in all cages in pond 5 grew rapidly during the first month, but large numbers of fish died and the growth of surviving fish ceased after raw settled sewage was let directly into the maturation ponds for several days because of problems encountered with the trickling filters. Growth later increased as environmental conditions improved. However, fish mortality was observed on sampling dates. It was concluded that tilapia should grow from 20 g to a

marketable size of 100 g when stocked at high densities in cages within a summer growing season, provided conditions remained stable. Periodic organic overloading led to high mortality and reduced growth, probably due to low dissolved oxygen and high un-ionized ammonia concentrations. At the pH and temperatures recorded in the study in pond 5, the calculated un-ionized ammonia never exceeded 0.9 mg/l, with the exception of the occasion when raw sewage was let into the maturation pond series and total ammonia reached 10 mg/l.

4.3 Sewage stabilization ponds: The Americas

Research in the Americas has been reported from the Dominican Republic, Peru, and the United States.

4.3.1 Dominican Republic

Live tilapia harvested from sewage stabilization ponds in the Dominican Republic were used to feed largemouth bass raised in experimental cages (Davies 1982). Consumers refused fish harvested from wastewater, but the bass commanded an extremely high price.

4.3.2 Peru

The San Juan de Miraflores sewage-reuse project located in Lima, Peru, began in 1961 with the construction of 21 experimental sewage stabilization ponds (Moscoso and Nava 1984, Bartone 1985, Bartone et al. 1985, Cointreau 1987). Extensive studies of the quality of treated sewage have been carried out since 1977 by the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS) in conjunction with Peruvian health authorities to evaluate the effectiveness of sewage stabilization ponds in the tropics. The experimental ponds have provided valuable design data since they began operating in 1964.

There has been a comprehensive research program on sewage reuse in San Juan since 1977, partially funded by the World Bank, UNDP and GTZ. The first phase of research began in 1977 with an engineering appraisal of the sewage stabilization ponds. The ponds were designed originally as two-cell facultative ponds with mean depths of 1.3-1.5 m. The 21 ponds are arranged in two batteries, the upper of 10 ponds and the lower of 11. The main purpose of the first phase was to evaluate sewage stabilization ponds under a range of organic loadings in tropical conditions, and the second phase to evaluate pathogen reduction. In a third phase, the production of Nile tilapia (*Oreochromis niloticus*), common carp (*Cyprinus carpio*), and giant freshwater prawn (*Macrobrachium rosenbergii*) were studied in polishing ponds receiving treated effluents. The sewage stabilization ponds were resequenced to create a four-cell series, quaternary ponds C1 and C2, and a five-cell series, a quintenary pond Q2 (Fig. 4.1, P = primary; S = secondary; T = tertiary; C = quaternary; and Q = quintenary pond; Fig. 4.2). These ponds were shallow, 1 m deep, batch-fed ponds that received only sufficient water to compensate for seepage and

evaporation losses. All other ponds were conventional continuous-flow ponds. Aerial BOD$_5$ loading rates were set between 250 and 350 kg/ha/day, which means that the early ponds in the series were operated in the facultative mode. Mean values of aerial soluble BOD$_5$ loadings for the various ponds used for aquaculture were: T1, 18.0; T2, 6.7; C1, 2.5; C2, 3.9; and Q2, 0.9 kg/ha/day. Fish were stocked in ponds T1, C1, T2, C2, and Q2, while prawns were stocked only in ponds C2 and Q2.
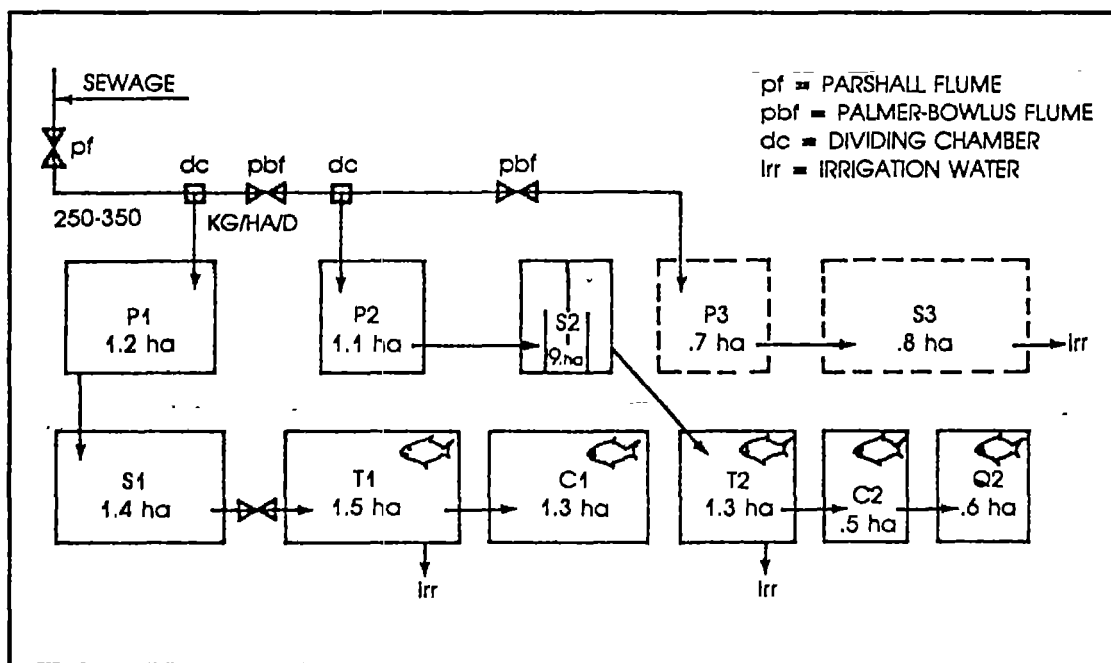
Figure 4.1 Pond arrangement at the San Juan de Miraflores sewage stabilization ponds in Lima, Peru, during the aquaculture studies *(Source: Bartone 1985)*

Figure 4.2 Seining a polishing pond stocked with fish at the San Juan de Miraflores sewage-reuse project in Lima, Peru

The aquaculture study began in June 1983 and continued for 12 months. It included two rearing phases that corresponded to the cold and warm seasons. The first rearing phase, to assess survival and growth of fish and prawns, took place in winter, from June to September, with the mean water temperature about 22°C. Tilapia were stocked in T2, C1 and C2, and freshwater prawns were stocked in Q2. Tilapia were stocked at relatively low densities of 0.16 in T1, 0.21 in C1, and 0.53 fish/m^2 in C2. Survival was high, ranging from 83 percent to 97 percent, and fish growth was good: the initial mean weights were 7.7, 2.4, and 8.2 g, and final mean weights were 106.0, 147.2, and 89.0 g in T1, C1, and C2, respectively. Freshwater prawns exhibited growth rates in Q2 equal to those held in 50 m^2 concrete tanks in clean water and fed poultry rations. Unfortunately, only 10 percent of stocked prawns were harvested because of a thick layer of sludge in the pond and difficulty in draining the pond. The prawns were subjected to poor water quality during harvest. The pond had been used for secondary sewage treatment with high loadings and had not been desludged prior to the trial.

The second aquaculture phase took place from October 1983 to April 1984, during the summer, and pond temperatures averaged about 27°C. Tilapia of 96.3 g meanweight were stocked at a density of 0.2 fish/m^2 in monoculture in Q2 in September 1983 and 140.3 g mean weight at a density of 0.1 fish/m^2 in T2 in October 1983. They grew well to mean weights of 355 g and 368 g in Q2 and T2, respectively, by the time they were harvested in April 1984. Unfortunately, in February 1984 there was a shock loading of secondary effluent into T2, and a less severe down gradient in C2 and Q2, caused by farmers tampering with pond inlet sluice gates to tap wastewater for irrigation. Soluble BOD$_5$ concentrations in T2 shot up to 44.9 mg/l (compared to the average 18.7 mg/l). Surface loadings of soluble BOD$_5$ in T2 increased to 20 kg/ha/day compared to the mean of 6.7 kg/ha/day. Only about 40 percent of the tilapia survived in T2, compared to

88 percent in Q2. No prawns stocked in monoculture in C2 survived, probably because of poor water quality before the shock loading. The prawns did not grow and remained so small that they passed through the mesh of the sampling net. A group of freshwater prawns were held in a net cage at the same time, but they did not grow at all in 1.5 months and suffered progressive mortality. Poor performance of prawns was attributed to high concentrations of un-ionized ammonia with a mean of 0.60 mg/l in C2. The 96-hour LC50 concentration of un-ionized ammonia (NH_3-N) ranged from 0.40-2.31 mg/l for crustaceans (Colt and Armstrong 1981). A polyculture was established in C1 with freshwater prawns, tilapia of 0.6 g mean weight at a density of 0.2 fish/m^2, mirror carp of 19.2 g mean weight at a density of 0.08 fish/m^2, and big-belly carp of 4.8 g mean weight at a density of 0.14 fish/m^2. The fish grew well and attained mean weights of 240 g for tilapia, 512 g for mirror carp and 168 g for big-belly carp. The big-belly strain of common carp was selected because of its tolerance to low dissolved oxygen even though it is supposed to grow less well than mirror carp. Mirror carp did grow better than big-belly carp, but part of the difference may have been due to the stocking density of the former species being only about half that of the latter. It was reported that tilapia grew much better in polyculture in C1 than in monoculture in T2 and Q2, but it is not possible to reach such a conclusion because of the large differences in initial stocking weight. Comparisons of tilapia growth rates in T2 and Q2 were similarly affected by differences in weights of stocked fish. Unlike tilapia, common carp continued to grow when the water temperature fell from 26°C to 21°C.

Acceptable conditions for fish culture were attained only in the batch-operated polishing ponds (C1, C2, and Q2), and only marginal water quality for fish was obtained in the tertiary ponds. Low nighttime dissolved oxygen levels were not considered a problem for fish at the loading rates used, but the prawns may have been stressed by persistently low benthic dissolved oxygen concentrations. Total ammonia nitrogen levels below 2 mg/l were recommended in order to avoid toxic effects on fish, but that was not possible in the tertiary ponds where mean concentrations ranged from 8 to 12 mg/l; fish were apparently stressed and grew poorly relative to fish in the batch-fed ponds. However, short-term ammonia toxicity problems may have arisen in the batch-fed ponds on sunny days when intense photosynthesis raised the pH above 10, a level at which most of the ammonia is the toxic, un-ionized form.

4.3.3 United States

The major reason for interest in the United States in fish cultivation in sewage stabilization ponds is that, while phytoplankton are efficient in nutrient removal, they are difficult to remove from effluents in an economically viable way. Advanced wastewater treatment standards are beginning to be imposed, and attention is being directed to biological wastewater-treatment systems because of the high cost and limited effectiveness of physicochemical methods (Reid 1976, Ryther 1980, Henderson 1982). Aquaculture involving filter-feeding fish has been considered an alternative method to remove suspended solids in the form of phytoplankton because sewage stabilization ponds fail to meet secondary treatment standards for suspended solids (Henderson and Wert 1976, Reid 1976). It is expected that the major reuse of wastewater in aquaculture will be preceeded by conventional secondary treatment with emphasis on nutrient removal and polishing treated

effluents (Duffer 1982). However, Tchobanoglous et al. (1979) emphasized that the primary purpose of cultivating animals and plants in sewage treatment systems is the treatment of wastewater, and not the production of energy, feed, or other products.

Despite considerable research in the United States on fish culture in sewage stabilization ponds, there are now major doubts that fish are effective at removing suspended solids (see Section 5.2.4). Duffer and Moyer (1978) reviewed the developmental status of the reuse of wastewater and concluded that preliminary studies have demonstrated a potential for wastewater reuse in aquaculture, although at the time there were insufficient data to design operational systems to treat wastewater in aquaculture. Another obstacle to the acceptance of fish culture as an alternative wastewater treatment strategy is the current lack of assurance that it can meet water-quality standards continuously (Henderson and Wert 1976). Attention has shifted gradually in the last decade towards the cultivation of macroscopic plants to treat wastewater (Ryther 1980), possibly due in part to the fact that aquatic animals in general are more sensitive than aquatic plants to wastewater (Tchobanoglous et al. 1979). Sewage treatment systems involving fish seem to be less efficient at waste treatment, require more land area, and are more difficult to control than systems based on aquatic macrophytes (Reed et al. 1979).

Despite the current decline in interest in the United States on fish cultivation in sewage stabilization ponds, the research conducted in the country is reviewed below. Myers (1948) suggested that the effluent of waste stabilization ponds could be used for fish farming, and thus stabilization ponds could contribute to biological conservation. According to Meron et al. (1965), waste stabilization-pond effluents were sometimes used to supplement the water in ponds through a 1:5 dilution with fresh water.

The feasibility of developing a sports fishery in tertiary treated wastewater to meet increasing recreational demands was investigated near Tucson, Arizona (Hallock and Ziebell 1970). Channel catfish (*Ictalurus punctatus*), Malacca tilapia hybrids (*Oreochromis hornorum* x *O. mossambicus*) and rainbow trout (*Salmo gairdnerii*) were selected because they do not reproduce in lakes and grow rapidly to attain acceptable size fish for a recreational fishery. Effluents from an activated-sludge plant flowed over spreading experimental sand and gravel filters and were pumped from filter sumps to ponds. Channel catfish were stocked for year-round fishing, but rainbow trout and tilapia hybrids were stocked to provide additional winter and summer fishing, respectively. Survival of rainbow trout did not exceed 1 percent, but channel catfish and tilapia survived and grew well. Total fish yields of 0.8 ton/ha/yr were obtained, an outstanding figure compared to fish production in natural waters. It was concluded that wastewater could be used for sports fisheries near urban areas. The production of fathead minnow (*Pimephales promelas*), a popular bait fish, was described in experimental polishing ponds receiving the effluent of a trickling-filter treatment plant in Iowa (Konefes and Bachmann 1970). Growth of fish in the ponds was comparable to that in conventional hatchery ponds.

The high cost of water in the United States Virgin Islands prompted a study in wastewater reuse (Buros 1977). Most of the water was reported to be provided by desalination, used once, and after primary treatment discharged by ocean outfall. The

effluent from an experimental activated sludge plant was used to grow phytoplankton to feed clams and fish. Phytoplankton were produced in mass culture in chemostats as feed for the freshwater clam, *Rangia cuneata*, and the latter were ground up as a protein supplement for poultry. Blue tilapia (*Oreochromis aureus*) were also grown in cages in small ponds in which algae were cultivated, and it was hoped that the fish could be used as human food.

Monosex hybrid tilapia (*Oreochromis mossambicus* x *O. hornorum*) were stocked in floating cages at a density of 53 fish/m^3 in the Oak Ridge National Laboratory sewage stabilization ponds equipped with aerators (Suffern et al. 1978). Production rates of 206 tons/ha/yr were calculated, and it was considered reasonable to expect production of about 50 tons/ha/yr from a waste-heat, waste-nutrient aquaculture system based on cage culture of tilapia.

Freshwater clams have been assessed for their potential in sewage treatment. Preliminary research in small outdoor pools showed that the oriental clam (*Corbicula fluminea*) could clarify phytoplankton-laden water and that it could survive eutrophic conditions if provided with a constant water circulation and temperatures below 30°C (Greer and Ziebell 1972). However, no data on the potential growth rate or yield of the clam were given, and its potential as a candidate for excreta reuse systems cannot be evaluated. The main mechanism involved in the clarification of water by clams is the formation of pseudofeces. Silt and detritus which accumulate on the mantle of the clam are bound by mucus into pseudofeces, which are ejected periodically and quickly settle to form a dense sediment. Clams readily remove phytoplankton, colloidal material and fecal coliforms from the water. Clam beds rise as the sediment layer increases and decomposition of organic matter creates eutrophic conditions in the lower part of the clam bed. The clams are tolerant of polluted water as long as there is sufficient water flow to provide oxygen and disperse excretory products, but mass mortality of clams may occur if there is an interruption of water flow. Clams could be grown in stacked shellfish trays in properly baffled flumes for clarification of wastewater; perhaps with supplemental aeration and the sediment trapped in sumps and subsequently removed by pumping (Dinges 1982). However, such a system would be expensive to set up and to operate.

Two major projects on the cultivation of fish in sewage stabilization pond systems at Quail Creek, Oklahoma, and Benton, Arkansas, are presented in detail below.

4.3.3.1 Quail Creek

The Oklahoma State Department of Health began preliminary studies on the removal of phytoplankton from sewage stabilization pond effluents in 1970 (Coleman et al. 1974, Carpenter et al. 1976, Carpenter 1978, Henderson 1982). The aim was to meet the Environmental Protection Agency (EPA) effluent standard for secondary treatment of 30 mg/l suspended solids, most of which are in the form of phytoplankton. Although advanced physical-chemical treatment systems capable of producing an effluent of high quality exist, they are costly and produce a waste product requiring further disposal. It was reasoned that biological removal by filter-feeding herbivorous fish would be cheaper and would produce a product with commercial value rather than a by-product requiring further

disposal. Various alternatives were suggested for use of the fish, for instance, animal feed, live fish for bait, restocking, or forage. The Quail Creek study may have been the first attempt to cultivate fish in a full-scale sewage stabilization pond system (Henderson 1982).

The Quail Creek sewage stabilization pond system near Oklahoma City was made up of six ponds of mean size 2.6 ha, total area 15.8 ha. It served a residential area of about 10,000 persons who produced about 1 million gallons (3,802 m³) sewage per day (Fig. 4.3). The ponds were arranged in series, the first two aerated by a conventional Hinde Air-Aqua System in which diffused air was introduced through subsurface air lines. The following four ponds operated in series at a depth of 0.9 to 1.5 m. There was an engineering flaw that caused a short circuit in pond number 4.
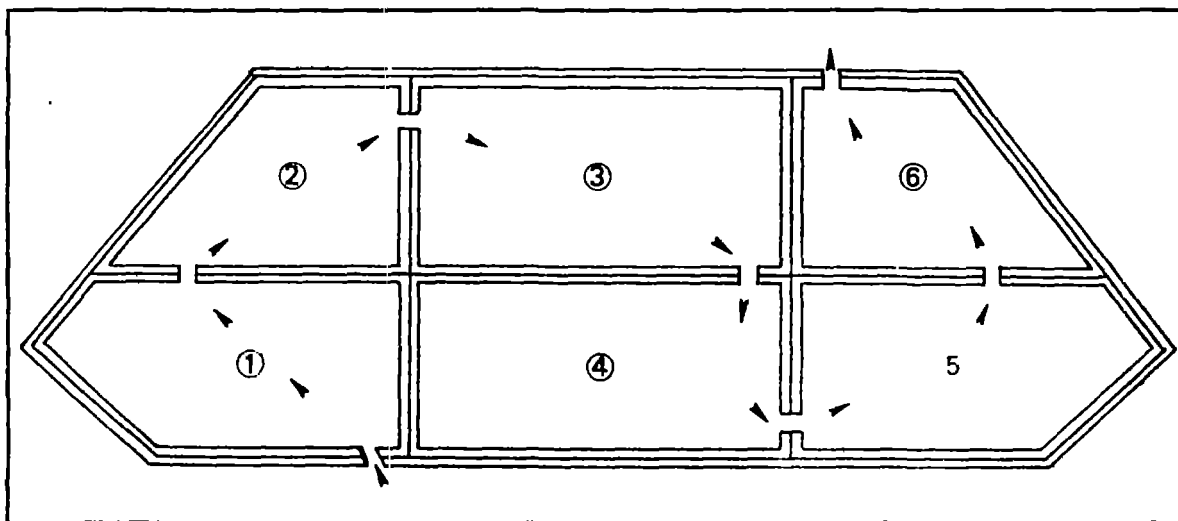
Figure 4.3 Schematic representation of Quail Creek lagoon system
(*Source:* Coleman et al. 1974)

Various fish species were initially cultured in the laboratory in aquaria containing wastewater at various levels of treatment which was changed weekly. Species successfully cultivated included black bullhead, bluegill, carp, channel catfish, fathead minnow, golden shiner, goldfish, green sunfish, largemouth bass, mosquito fish, and *Tilapia nilotica* (probably *Oreochromis aureus*).

Studies began in 1971 on the cultivation of fish in the sewage stabilization ponds. Initially the system included two serially operated ponds with the Hinde Air-Aqua System and received about 750,000 gallons (2,852 m³) of raw domestic sewage per day. Approximately 200 individuals of promising species, including bluegill, channel catfish, and largemouth bass, were reared in cages anchored to a cable stretched across the width of the pond between two air lines near the effluent end of the second cell to verify the bench-scale viability studies.

After the lagoon facility was completed, fish were stocked in May 1973 in the four nonaerated ponds, which were run in conjunction with the existing aerated system to

form the six-cell, serially operated system. At that time the system received about one million gallons per day (3,802 m³) of raw domestic sewage. Channel catfish (*Ictalurus punctatus*) (25,000 5-10 cm fingerlings) were stocked in ponds number 3 and 4, and 15.9 kg of adult golden shiner (*Notemigonus crysoleucas*) were stocked in ponds number 5 and 6 in May 1973; 175 *Tilapia nilotica* (7.5 cm) and 2.3 kg of fathead minnows (*Pimephales promelas*) were stocked in pond number 3 in July 1973. Golden shiner, fathead minnow, and tilapia are primarily plankton feeders, although the first two species usually do not produce high yields even under ideal pond conditions. Channel catfish is omnivorous but depend on larger organisms as food (Henderson 1982). However, wild fish, including black bullhead (*Ictalurus melas*), green sunfish (*Lepomis cyanellus*) and mosquito fish (*Gambusa affinis*) contaminated the test ponds. Estimates of fish biomass were made by seining a closed known area of each cell.

Fathead minnows, golden shiners, and tilapia were found to consume phytoplankton and, to a lesser extent, microcrustacea and insect larvae. Channel catfish used microcrustacea and insect larvae as principal foods. The total biomass of tilapia was not determined due to "procedural difficulties" coupled with a sudden drop in temperature that caused a large fish mortality. There was a tremendous rate of increase in weight of tilapia before mortality caused by low water temperatures in November, but because of the cold kill, an accurate assessment of productivity was not possible. Tilapia biomass increased from the initial 1.8 kg (175 fish) stocked in July to 74.1 kg (2,339 fish, up to 25 cm long) in October, based on tilapia removed. It was likely that a significantly greater amount of tilapia was not recovered.

The biomass of channel catfish increased by a factor of about seven from the initial 273 kg to an estimated 2,000 kg, the majority of the biomass gained in the six-week period from late May to mid-July after stocking, but growth ceased as their food habit changed to that of the adults. The slow growth following the initial rapid gain may have been due to limited food supply because of the inability of the fish to continue to remove significant amounts of plankton from the water, and also because of disease. Total production of both golden shiner and fathead minnow was disappointing, although the biomass increased by a factor of six over the initial stocked weight. Only an estimated 243 kg of golden shiner and fathead minnows were harvested from the initial stocking of 39 kg, a smaller amount than expected, probably due to bullhead catfish predation. The choice of species was clearly less than ideal.

The secondary treatment standards for BOD_5 of 30 mg/l were met in the effluent from the second cell, and for suspended solids of 30 mg/l and fecal coliforms of 200 per 100 ml in the effluent of the fifth cell. Mean values for BOD_5, suspended solids, and fecal coliforms per 100 ml in the effluent from the sixth cell were 6, 12, and 20, respectively, compared with 184 mg/l, 197 mg/l, and 3.05×10^6/100 ml in raw sewage, respectively (Table 4.2).

The study was repeated without fish in the summer and autumn of 1974 to assess the effectiveness of the stabilization pond system without fish. Mean effluent data from a preliminary analysis indicated BOD_5 of 13 mg/l, suspended solids of 39 mg/l, and

Table 4.2

Mean Values (mg/l except as noted) of Weekly Analyses of Raw Sewage and Water Samples of the Effluents from Each Pond from the Quail Creek Lagoon System

Parameters	Raw sewage	1	2	3	4	5	6
Biochemical oxygen demand (5 day)	184	47	24	17	14	9	6
Suspended solids	197	79	71	52	54	26	12
Volatile suspended solids	131	54	45	34	27	13	6
Total nitrogen (as N)	18.94	10.50	7.04	6.65	3.97	3.13	2.74
Nitrite nitrogen (as N)	0.07	4.54	0.96	0.86	0.34	0.34	0.16
Nitrate nitrogen (as N)	0.20	1.00	2.31	1.79	0.79	0.31	0.29
Ammonia nitrogen (as N)	12.67	0.91	0.40	0.31	0.28	0.10	0.12
Organic nitrogen (as N)	6.10	4.05	3.37	2.69	2.56	2.28	2.17
Total phosphorous (as P)	9.01	9.87	7.97	5.80	3.66	3.01	2.11
Fecal coliform/100 ml	3.05 x 10^6	1.09 x 10^4	1.38 x 10^3	3.22 x 10^2	15	15	20
Turbidity	55	15	23	25	42	17	9
pH	7.3	7.8	8.2	8.6	8.9	8.4	8.3

Source: Coleman et al. (1974)
Samples collected June 6–October 3, 1973

fecal coliforms of less than 200 per 100 ml, that is, BOD_5 and fecal coliform criteria for secondary effluents were met, but criteria for suspended solids were not. A significantly higher-quality effluent was obtained in the previous year with fish in the system. According to Henderson (1982), water quality was improved, partly due to the ability of new ponds to absorb the nutrient loads but "undoubtedly in part to the presence of fish." However, it is difficult to conclude anything concerning the influence of the fish on water quality because of the weakness in the experimental design.

4.3.3.2 Benton

The Arkansas Game and Fish Commission, funded by the United States EPA, stocked Chinese carps in a sewage stabilization pond system at the Benton Services Center at Benton, Arkansas, to evaluate further the effect of fish on water-quality improvement in sewage stabilization ponds (Henderson 1979, 1982). The project was inspired by the results of Quail Creek and also by a conceptual model of fish culture in sewage stabilization

ponds by Lin (Henderson 1982). Lin (1974) had proposed a pilot project to assess the role of fish culture in sewage stabilization ponds.

Raw sewage, 1,711 m³ per day, was passed through a bar screen, grinder, and clarifier to remove larger solids before introduction to the 10.2 ha total surface area, six-pond system. Individual ponds were similar in size (1.55-1.80 ha) with a retentiontime of about 12 days per pond, or a total residence time for the system of approximately 70 days. The mean organic load was 444 kg BOD_5/day with 209 kg total suspended solids per day, and the mean influent BOD_5 and total suspended solids concentrations were 260 and 140 mg/l, respectively.

In a preliminary experiment in 1975, the six-celled pond series was run with two parallel series of three ponds in each series which received equal volumes of the same wastewater (260 mg BOD_5/l; 140 mg SS/l) by dividing the total influent load into two equal streams by a division weir. The ponds in one series were stocked with bighead carp (*Aristichthys nobilis*), grass carp, (*Ctenopharyngodon idella*), and silver carp (*Hypophthalmichthys molitrix*). The other series was operated without fish and was run for a full annual cycle (Fig. 4.4, a). The pond series with fish (the "a" ponds) were stocked as follows: Pond 1A, 1.76 ha, 280 bighead carp, 450 grass carp, 1,275 silver carp (1,139 fish/ha); Pond 2A, 1.55 ha, 380 bighead carp, 400 grass carp, 5,250 silver carp (3,890 fish/ha); and Pond 3A, 1.56 ha, 400 bighead carp, and 20,000 silver carp (13,077 fish/ha). No fish survived the low levels of dissolved oxygen in Pond 1A longer than four weeks. Dissolved oxygen levels in Pond 2A fluctuated widely diurnally and oxygen-related fish kills occurred. Oxygen levels were well within limits for fish in Pond 3A, and no problems occurred. According to Henderson (1979), the average BOD_5 of the effluent from the series without fish was 37.6 percent higher than in the series with fish. Reed et al. (1979) reanalyzed the data and concluded that the two systems performed similarly, but the system with fish consistently performed slightly better than the system without fish. Effluent BOD_5 values for the system with fish ranged from about 7 mg/l to 45 mg/l with concentrations < 15 mg/l more than 50 percent of the time, compared to corresponding concentrations of 12 mg/l to 52 mg/l and <23 mg/l for the system without fish. Effluent suspended solids were similar in both systems except in July, when readings were recorded of about 60 mg/l and 110 mg/l for the systems with and without fish, respectively. Pond 3A with fish was never dominated by blue-green algae but by green algae, and no phytoplankton die-offs were observed. In Pond 3B, without fish, dense blue-green blooms, periodic die-offs, and odors were frequent throughout the summer. The stable and healthy community of green algae was attributed to grazing by fish, which decreased BOD_5 levels. A total of 6.546 tons of fish/ha were harvested from August 1975 to December 1976, one full growing season, although (presumably) the fish grew well only during the 235 day growing season of central Arkansas. However, the net annual yield cannot be determined from the data presented because the weight of stocked fish, which ranged in size from 5 cm to 13 cm, was not given.
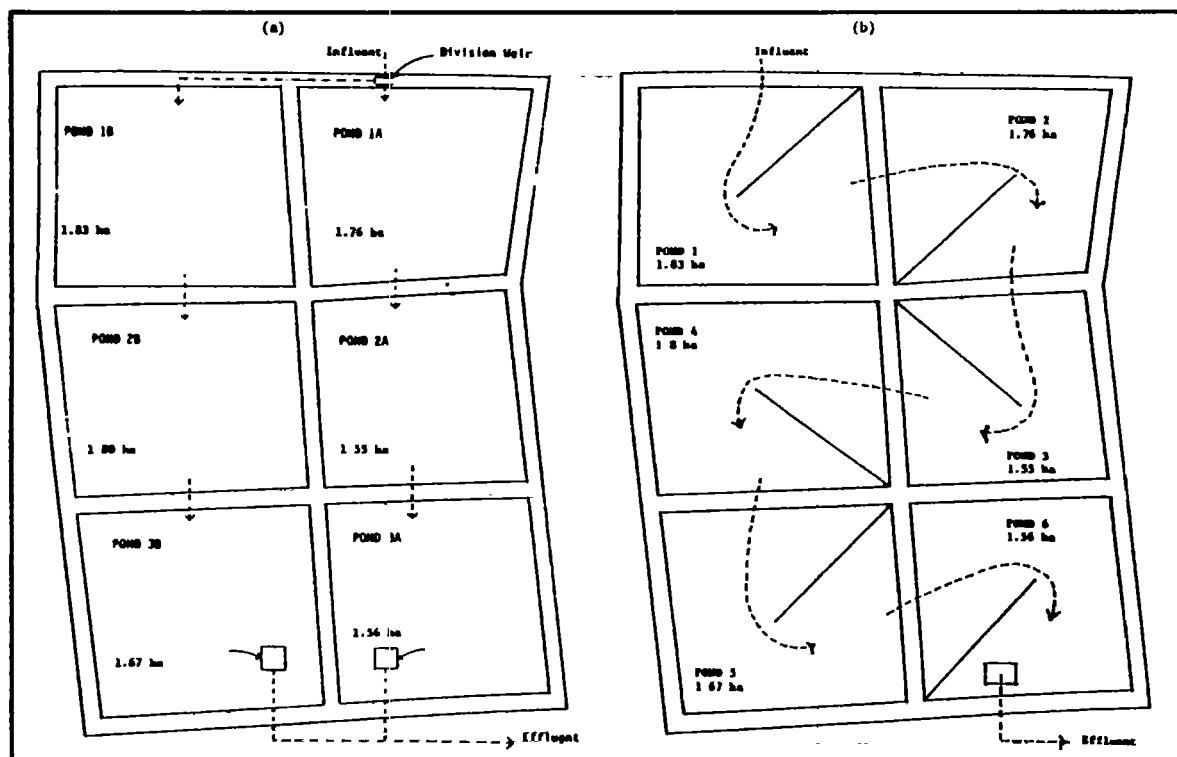
Figure 4.4 The Benton State Hospital Sewage Lagoons [Ponds stocked with fish ("a") and controls ("b"); second phase, six ponds in series with ponds 4-6 stocked with fish. *Source:* Henderson 1979]

In a second phase of the study, 1977-80, the six cells were connected in series with a baffle in each pond to reduce short-circuiting (Fig. 4.4b). The ponds were drained, desludged, and regraded to their original contour with minor (unspecified) changes to facilitate fish harvest. Pond depth averaged 1.2-1.3 m with the bottom graded to the deepest point at 2 m. The first two ponds served only as stabilization units with plankton production, and the remaining four were stocked with fish. Bighead silver carp were stocked in ponds 3 to 6, and buffalo fish, channel catfish, and grass carp were added in pond 6.

The four ponds were stocked as follows: Pond 3, bighead and silver carp with a total of 15,700 fish/ha; Pond 4, bighead and silver carp with a total of 7,900 fish/ha; Pond 5, bighead and silver carp with a total of 8,500 fish/ha; and Pond 6 with grass carp, buffalo fish and channel catfish in addition to bighead and silver carp at a total of 6,000 fish/ha. Water quality data for the six ponds in the second phase of the study are presented in Table 4.3.

BOD$_5$ and suspended solids removal for the first eight months of the study averaged 96 percent and 88 percent, respectively, and the effluent corresponded to criteria for secondary treatment (Henderson 1979). After almost two years of operation with fish,

Table 4.3
Water Quality in the Second Phase of the Study of the Sewage Stabilization Ponds, Benton, Arkansas

Parameters	Raw sewage	1	2	3	4	5	6
BOD_5	260	66.7	28.1	22.2	15.5	10.9	9.4
Suspended solids	140	65.1	38.0	30.0	18.7	16.7	17.1
NH_3	—	6.42	5.06	4.78	4.02	2.03	1.99
NO_2-N	—	0.01	0.02	0.04	0.25	0.09	0.11
NO_3-N	—	0.01	0.01	0.04	0.15	0.61	0.50
Total P	—	3.61	3.02	2.87	2.68	2.51	2.50

NOTE: Figures are averages (milligrams per liter) of weekly samples of pond effluents, December 1978-July 1979 during first eight months of the study. Fish were cultivated in ponds 3-6.

the plant consistently met the discharge requirements for secondary treatment. The presence of fish, which continually grazed phytoplankton, appeared to reduce total inorganic nitrogen and total phosphorus (Henderson 1982). Reed et al. (1979), however, questioned the role of fish in improving effluent quality. Although the BOD_5 removal for the entire system averaged 96 percent, about 89 percent of the removal occurred in the first two conventional stabilization ponds. Furthermore, 73 percent of the removal of suspended solids occurred in the first two cells, compared to 88 percent in the whole system. It was not clear whether fish, or the additional detention time, or both, caused the additional 7 percent BOD_5 removal in the final four cells with fish (Reed et al. 1979). Reed et al. (1979) pointed out that the final average effluent of 9 mg BOD_5/l is typical for a six-pond series of stabilization ponds of comparable detention time. Fish also probably contributed significantly by filtration of phytoplankton to the low final average effluent concentration of 17 mg suspended solids per liter, two to three times lower than for stabilization ponds without fish.

Based on monthly samples of fish and an assumed survival rate of 85 percent of the initial fish stock, there was an estimated standing crop of fish in excess of 22,777 kg in the four ponds with fish, or an average net yield of 3,036 kg/ha with about three months remaining in the growing season. (Henderson 1979). This corresponds to an extrapolated annual net yield of 4.0 tons/ha/yr. Henderson (1982) later wrote that the system was capable of producing about 5 tons fish/ha in the 235 day growing season of central Arkansas.

4.3.3.3 Simplified food chains: Texas and California

Studies have been conducted in the United States on the establishment of simplified food chains composed of sequential stages of monocultures or limited numbers of plants and animals. The rationale is that discrete populations or communities of organisms in sequence accomplish specific treatment objectives, and such studies may lead to the development of efficient and potentially economically viable systems for upgrading stabilization pond effluents.

Dinges (1976) set up what he referred to as an integrated biological wastewater-treatment system. The idea for the system developed from preliminary studies with *Daphnia* and water hyacinth. The biological waste-treatment system was designed with separate biological waste-treatment steps in series, each providing its own improvement in water quality. The animal and plant biomass was to be harvested to remove nutrients. A filter was designed to retain a high concentration of suspended solids with rapid flow-through. Aerobic conditions were to be maintained in the filter by recirculation of water from the second pond, and carbon dioxide from respiration of microorganisms on the filter was to reduced the pH to levels suitable for zooplankton. The pond was approximately 84 m long and 9 m wide, divided into 4 segments separated by stacked rock barriers (Fig. 4.5). Water hyacinth was to be grown in the first pond to take up nutrients and suppress phytoplankton growth. It was proposed that duckweed (*Lemna*) replace water hyacinth during the winter when the latter is dormant in temperate climates. Scuds (*Hyalella*), snails (*Physa*) and midge larvae (*Chironomus*) should be present in large numbers.
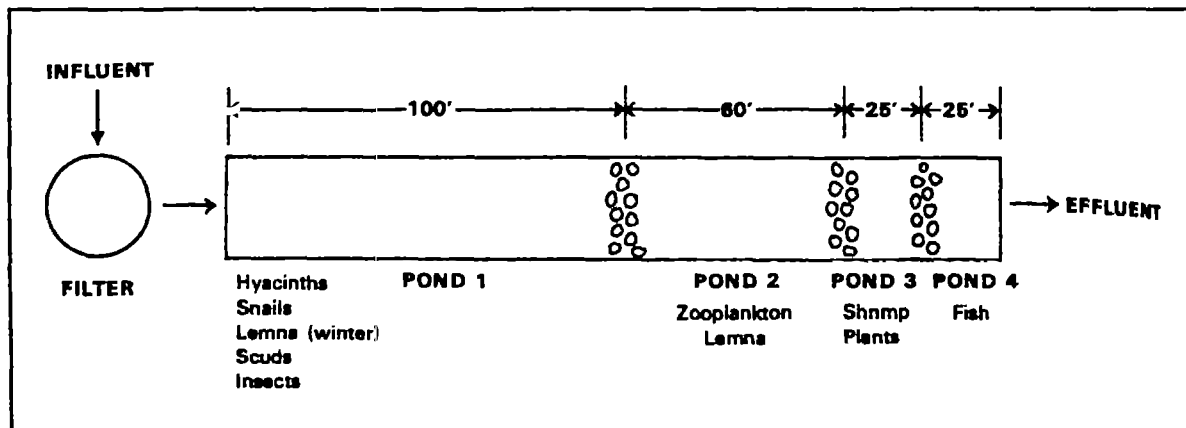
Figure 4.5 A five-step biological treatment system (*Source:* Dinges 1976)

The second pond unit was to be devoted to the cultivation of zooplankton for water clarification. An 84-m^2 area in the center of the pond was to be 2.4 m deep compared to 0.6 m deep for the rest of the pond cultivation system. The deep area was to be mixed by an aerator (airlift pump) to retard pH fluctuations. Duckweed was to cover most of the water surface to inhibit phytoplankton growth. The third and fourth ponds were mainly to convert biomass to larger forms that could be harvested. Glass shrimp (*Palaemonetes*),

which are predators on small invertebrates, possibly giant freshwater prawn (*Macrobrachium rosenbergii*), and an attached submersed aquatic macrophyte (*Ludwigia repens*) to provide cover for crustacea, were proposed for the third pond. Fish were proposed for the fourth pond: golden shiner minnow (*Notomigonus crysoleucas*) and fathead minnow (*Pimephales promelas*), which may be used as bait fish, and goldfish (*Carassius auratus*) to feed on plant detritus that may enter the unit. Preliminary data obtained on the system from June to November 1975 indicated that the biological treatment system functioned as expected.

A multidisciplinary research program at the University of California at Los Angeles (UCLA) studied food chains composed of sequential monocultures of phytoplankton, zooplankton, and fish in the laboratory based on secondarily treated domestic sewage (Gordon 1977, Kawasaki et al. 1982, Tarifeno-Silva et al. 1982ab, Gordon et al. 1982). The unicellular green alga *Scenedesmus*, cladocerans *Daphnia magna* and *D. pulex*, and fish, golden shiner (*Notemigonus crysoleucas*), fathead minnow (*Pimephales promelas*), and red shiner (*Notropis lutrensis*) were components of the "artificial" food chains.

Unmodified secondarily treated domestic effluent was deficient in iron and lacked buffering capacity for optimal algal growth. The addition of 1 mg/l ferrous iron and 5 percent carbon dioxide were required to produce phytoplankton cultures suitable for feeding cladocerans. The food conversion coefficients of phytoplankton to cladocerans were 12-40 percent dry weight. Most nutrient removal (nitrates and phosphates) occurred in the first phytoplankton stage of the food chain but subsequent cladoceran and fish stages added nutrients, mainly ammonia and phosphates, back into the effluent. A final stage involving the filamentous green algae *Ulothrix* and *Cladophora* was needed to remove nutrients regenerated by cladocerans and fish. Large matted masses of filamentous green algae were reported to be easy to harvest.

Although the authors considered the system technically feasible on a laboratory sale, they refrained from making extrapolations to larger volumes and biomass. The food chains were described as "simple," but the numerous problems that arose revealed that even simplified food chains in monocultures of successive trophic levels are complex. The continuous-flow, chemostat-like cultures of phytoplankton and cladoceran cultures were unreliable both mechanically and biologically, at least without control of pH, and it was necessary to use temporarily staggered batch cultures of phytoplankton. There was a problem in phytoplankton species succession from green algae to blue-green algae. This was usually more rapid in periods of high temperature in late spring and summer in temperate California. Temperature could be a major constraint if attempts were made to develop such a system in the tropics. Cladocerans could not be used to filter unbuffered phytoplankton cultures because of toxic elevated pH of 10.5 and higher, and the development of filamentous blue-green algae such as *Phormidium*, which cladocerans were unable to harvest. The addition of carbon dioxide inhibited species succession, probably by maintaining neutral pH (blue-green algae favor high pH). Another problem was the occasional uncontrollable heavy grazing of phytoplankton by rotifers which developed from eggs that remained viable in secondary effluent, even after chlorination and dechlorination. It was thus necessary to maintain backup stock cultures of phytoplankton to permit rapid

replacement of damaged cultures. Attempts to grow the phytophagous silver carp (*Hypophthalmichthys molitrix*) in a two-stage buffered phytoplankton and fish food-chain failed, possibly due to ammonia toxicity to fish. The system was described by the authors as a low-technology approach because the apparatus and procedures were kept as simple as possible. However, it would require relatively sophisticated monitoring equipment, skilled supervision, and environmental control equipment to keep such a system functioning smoothly.

The study of "simplified" food chains may be a valuable academic exercise in attempting to understand how complex waste-fed ecosystems function, but they do not appear to be feasible for commercial practice because of the many problems encountered in their operation. In a later publication, Dinges (1982) wrote that off-stream units subsidiary to the main treatment system would be better suited to cultivate delicate organisms than his initial concept of units arranged in a straight line, with the entire wastewater flow passing from one unit to the next. Some stabilization-pond effluent could be used to grow fish-food organisms, or a unit receiving part of the effluent from a water-hyacinth culture pond could be used for fish culture, or some of the pond water might be diverted into a tertiary unit to produce submersed aquatic macrophytes for herbivorous fish. Dinges (1982) concluded that a number of options may be used to treat wastewater and reuse the nutrients, but none has yet been demonstrated to work on the scale required for a commercially viable system.

4.4 Sewage stabilization ponds: Asia

Most of the research on sewage-fed aquaculture in Asia has been carried out in India, which has well-developed commercial sewage fisheries. Hong Kong and Israel each report one research project on sewage-fed aquaculture. In Hong Kong, the reuse of sewage effluents in aquaculture was considered as a possible solution to the shortage of water, since most ponds are rainfed (Sin and Chiu 1987a). Water shortage in arid Israel is also a major motivating factor for research in the reuse of sewage in aquaculture. It was not feasible to separate research on sewage-fed aquaculture from commercial operations in China because most experimentation there involved large-scale production trials associated with commercial aquaculture (see Section 2.6.2).

4.4.1 Hong Kong

Sin and Chiu (1987a,b) cultivated fish in the secondary effluents of a pilot sewage treatment plant at Shek Wu Hui, Hong Kong. The plant was located in a rural town and was designed to serve a population of 12,500. Crude sewage was treated by primary sedimentation followed by high-rate biological filters or by activated sludge, and the effluents were further treated in polishing ponds. The plant was designed to produce a final effluent with 20 mg/l BOD_5 and 30 mg/l suspended solids. The two U-shaped stabilization ponds were each 0.4 ha in area with a water depth of 1.25 m. Pond 1 received only secondary effluents from the activated sludge plant, but Pond 2 received a mixture of secondary effluents from both activated sludge and high-rate biological filter systems.

Effluents were initially discharged continuously but were later recirculated and discharged at intervals.

Mozambique tilapia (*Oreochromis mossambicus*) were cultivated for 190 days, March-October 1975, when water temperatures stayed above 20°C (Sin and Chiu 1987b). Manually selected males were stocked at 2,000 fish/ha in Pond 1 and 1,000 fish/ha in Pond 2. Stocking densities of only 15-20 percent of those normally used in commercial aquaculture were used because of sudden changes in effluent quality, particularly in Pond 2. Fish that died in the initial trial period were replaced with fresh stock. Growth rates were determined from monthly samples obtained by seining, and all fish were harvested by draining the ponds at the end of the trial. Mean weights of fish in Ponds 1 and 2 increased from initial weights of 56 g and 41 g to 276 g and 299 g at harvest, respectively. Survival of stocked fish was 79 percent and 83 percent in Ponds 1 and 2, respectively. Manual sexing of tilapia was unreliable because spawning occurred. Extrapolated net yields were 1.5 tons/ha/yr and 2.1 tons/ha/yr in Ponds 1 and 2, respectively. Small fish comprised 59 percent and 81 percent of the harvest in Ponds 1 and 2, respectively.

No bacteria were detected in the liver, heart and spleen of harvested fish, but bacteria (mainly *Aeromonas* and *E. coli*) were detected in the gills, mucus, and intestine of tilapia from Pond 1. *Aeromonas* and *Micrococci* spp. were found in the spleen, gill, intestine and mucus of tilapia early in the trial in Pond 2, and *Alcaligenes* and *Achromobacter* were found in tilapia at harvest. No microbiological analyses of muscle tissue were reported.

Ammonia concentrations were high, ranging from 0.5 mg/l to 26.5 mg/l, with a mean of 10.0 mg/l in Pond 1, and 1.0 mg/l to 23.5 mg/l, with a mean of 10.4 mg/l in Pond 2. Phytoplankton biomass peaked at 60 mg/l, but concentrations were usually less than 30 mg/l.

The effluents from Ponds 1 and 2, in which Mozambique tilapia were cultured, were fed into two ponds of the same dimension, Ponds 3 and 4. Four species of Chinese carp (bighead carp, *Aristichthys nobilis*; common carp, *Cyprinus carpio*; grass carp, *Ctenopharyngodon idella*; and silver carp, *Hypophthalmichthys molitrix*) were cultured in these two ponds from May 1975 to March 1976, a period covering one warm and one cold season (Sin and Chiu 1987b). The fish were stocked at a density of 3,000 fish/ha in a proportion of 5:6:6:7 for bighead, common, grass, and silver carp, respectively. It was considered necessary to use a lower stocking density than in commercial ponds because of abrupt changes in effluent quality. No supplementary feed was given. The Chinese carp grew well in the system but there were mass mortalities in October and January in Pond 4.

The quality of the effluent from the biological filter system decreased during the latter half of the growth trial, as indicated by increases in BOD_5, suspended solids, and ammonia, and a decrease in the dissolved oxygen concentration. It was not possible to determine the cause of fish mortality because dissolved oxygen measurements were not made at dawn. However, ammonia concentrations were high in Ponds 3 and 4, ranging from 2 mg/l to 40 mg/l, with a mean of 9.9 mg/l, and 5 mg/l to 36 mg/l, with a mean of

15 mg/l, respectively. Phytoplankton biomass was consistently higher in Pond 4 than in Pond 3. The maximum recorded was 48 mg/l, but concentrations were usually less than 30 mg/l.

The bighead, common, and silver carp grew at rates comparable to or even higher than those in commercial ponds. Their high growth was attributed to abundant natural food and low fish-stocking densities. The mean initial and final weights at harvest of bighead, common and silver carp were 7.7 g and 1,125.5 g, 25.0 g and 246.7 g, and 6.4 g and 988.7 g, respectively. Growth of grass carp was poor compared with that in commercial ponds due to a lack of sufficient macrophytes. Higher growth of grass carp was observed in the first two months in Pond 3 when there was an abundance of duckweed, but growth declined after the duckweed was consumed. The extrapolated net yield for the approximately 300 day trial was 2.0 tons/ha/yr. The yield might have been higher if a higher stocking density had been used, and had the trial not included a winter period when the growth rate of the fish was very low.

4.4.2 India

Research in sewage-fed aquaculture in India has been conducted in four parts of the country, in Madras, Nagpur, Raipur, and in particular in West Bengal, where the Calcutta sewage fisheries are located.

4.4.2.1 Madras

The first research project was apparently carried out in Madras. A plan was described for a proposed sewage fish farm in Madras to utilize the effluents of the sewage-irrigated agricultural farm belonging to the Madurai Municipality (Ganapati and Chacko 1950). Experiments were carried out in which *Etroplus suratensis*, *Barbus sarana*, *Labeo fimbriatus*, *Cirrhina reba*, and *Osphromenus goramy* were stocked in a section of the effluent channel. The fish flourished for more than six months before they escaped through an opening in the screens used to partition the channel. Gourami increased in length two to three times, and the carps doubled in size.

The growth of common carp (*Cyprinus carpio*) was studied in a 650 m^2 pond which received 272 m^3/day of effluent from a sewage stabilization pond on the campus of the College of Engineering, Guindy, Madras (Muthuswamy et al. 1974). The detention time was only two days. The fish were stocked at a density of 0.8 fish/m^2. The mean weight of stocked fingerlings was 0.3 g, and they attained a maximum weight of 0.62 kg in about 6 months with no mortality. The extrapolated fish yield was about 7.7 tons/ha/yr. In a further study with the effluent of the sewage stabilization pond at the College of Engineering, Guindy, Madras, a polyculture of common carp (*Cyprinus carpio*), mrigal (*Cirrhina mrigala*), rohu (*Labeo rohita*), and *Labeo fimbriatus* was stocked in the last two ponds of a series of three 650 m^2 ponds connected in series which received the effluent (Muthuswamy et al. 1978).

Good fish growth rates were reported for Ponds 2 and 3 with detention times of about three days, in which fish were grown for 206 days. The extrapolated fish yield was reported to be 11.5 tons/ha/yr from the two ponds combined, and in addition, about 1.3 tons/ha/yr of tilapia were harvested, although they were not included in the study. However, the authors made a computational error in calculating extrapolated yields by assuming that the total fish yield was derived from only one of the two 650 m^2 ponds. The extrapolated net yield of Indian major carps recalculated from their data was 5.7 tons/ha/yr, about half the yield reported. Blue-green algae predominated in the ponds, especially *Microcystis*.

4.4.2.2 Nagpur

Common carp (*Cyprinus carpio*) and rohu (*Labeo rohita*) were grown in 90-m^2 experimental tanks fed with the effluent from a sewage stabilization pond diluted to different degrees with water at Nagpur (Krishnamoorthi et al. 1975, Krishnamoorthi and Abdulappa 1979). Common carp had a much higher growth rate than rohu and grew from less than 10 g to a mean weight of 350 g in 6.5 months in the best treatment. Growth of rohu leveled off at about 75 g after four months. In a second experiment with only common carp, the ponds were connected in series and were fed undiluted effluent. Fish growth increased as the effluent passed through the ponds in series; fish in the fifth pond in the series attained a weight of 800 g compared to 350 g in the third pond after 4 months. This was followed by a sudden heavy mortality attributed to the depletion of dissolved oxygen in the predawn hours. There were also occasional mortalities of fish in the first experiment in the predawn hours, and some of the dead fish showed chokage of gills with *Microcystis*, the predominant phytoplankton.

Walking catfish (*Clarias batrachus*) were subsequently grown in the experimental ponds fed with the undiluted effluent of a sewage stabilization pond at Nagpur in an attempt to overcome the adverse effects of nocturnal depletion of dissolved oxygen and high ammonia levels (Krishnamoorthi et al. 1976, Krishnamoorthi and Abdulappa 1979). One hundred fingerlings of a mean size of 20 g were stocked in the 91-m^2 ponds and reached a mean size of 0.55 kg in two years. The ponds contained blooms of phytoplankton, mainly the blue-green algae *Microcystis* and *Agmanellum* and the green algae *Scenedesmus* and *Chlamydomonas*, and also zooplankton and benthos upon which the fish were reported to feed. The growth rate of walking catfish was reported to be 2.5 times less than that of common carp, but it was able to tolerate low dissolved oxygen and high ammonia, the latter reaching as high as 30 mg/l.

4.4.2.3 Raipur

The Indian major carps catla (*Catla catla*) and rohu (*Labeo rohita*) were cultured in domestic sewage stabilization ponds at Bhilai, Raipur (Chatterjee et al. 1967). The ponds, which had a total water area of about 1.6 ha, received dilute raw sewage without pretreatment. Catla and rohu grew from initial mean weights of 6 g and 19 g to 0.9 kg and 1.4 kg, respectively, in the first year. Restocked catla and rohu of mean initial weights of 70 g and 24 g grew to mean weights of 1.9 kg and 0.7 kg, respectively, in the second year.

The disparty in the growth of the two species was attributed to widely varying stocking ratios, with catla making up 97 percent and 50 percent of the stocked fish in years one and two, respectively.

4.4.2.4 West Bengal

Scientists from the Central Inland Fisheries Research Institute studied a 0.67-ha pond on a private sewage-fed fish farm which received effluents from the Titagarh Sewage Treatment Plant at Khardah (Anon. 1973b; Ghosh et al. 1973, 1974). The pond was located next to the main sewage feeder canal and received effluent already subjected to primary sedimentation. Silver carp (*Hypophthalmichthys molitrix*) were stocked in the pond in addition to the usual Indian major carps (catla, mrigal, rohu). The pond was initially fed with 2,140 m^3 of sewage following sedimentation, and a total of 1,000 m^3 at periodic intervals thereafter. Silver carp grew from a mean weight of 8 g to 996 g in five months, a much more rapid growth rate than the Indian major carps catla, mrigal and rohu, which grew from initial mean weights of 1 g to 155 g, 143 g, and 188 g, respectively, during the same period. However, the low growth rate of Indian major carps might have been due to a much higher total stocking density of 5/m^2 compared to only 0.01 silver carp/m^2. Total fish production was estimated to be about 7.7 tons/ha in 7 months, or 13.2 tons/ha/yr. Analyses of the gut contents revealed that the silver carp fed mainly on phytoplankton, particularly the blue-green alga *Oscillatoria*. The study indicated the feasibility of cultivating silver carp in sewage-fed ponds along with Indian major carps.

Nile tilapia (*Oreochromis niloticus*) were also raised in a 0.076-ha pond fed with domestic sewage effluent from the Titagarh Sewage Treatment Plant. The fish, stocked initially at 1.7 fish per m^2, spawned frequently, and periodic harvesting led to an estimated total production of 9.4 tons/ha/yr (Anon. 1976).

The feasibility of culturing walking catfish (*Clarias batrachus*) in sewage-fed ponds was studied by Ghosh et al. (1976). A 0.076-ha pond was fed with domestic sewage from the Titagarh Sewage Treatment Plant with a BOD_5 of 139-275 mg/l (probably subjected to only primary sedimentation) at periodic intervals. BOD_5 of pond water ranged from 11.0 mg/l to 13.5 mg/l. The catfish were stocked at a density of 0.3 per m^2 in combination with *Oreochromis niloticus* at 2.9 per m^2. The catfish showed remarkable mean growth of 196 g in 100 days, and tilapia increased from 40 g to 215 g, indicating the possibility of culturing the species together. The food of the catfish in the sewage-fed pond, determined by an examination of the gut contents, comprised about two thirds insect larvae, mainly chironomids, and one third organic detritus.

An experiment was reported on the use of semitreated sewage effluent from the Titagarh Sewage Treatment Plant involving a polyculture of native Indian major carps and introduced Chinese carps (Dehadrai and Ghosh 1977). A 0.170-ha pond was initially fertilized with 4.68 x 10^5 liters sewage/ha and then diluted in the ratio of 1:2 (sewage:fresh water) prior to stocking fish. The pond was stocked with Indian major carps (catla, mrigal, rohu) and introduced carps (common carp, silver carp) at 2.4 fish per m^2 and the pond fertilized at periodic intervals with 3.94 x 10^5 liters sewage/ha, depending on the water

quality. Net fish production was 971 kg, an extrapolated yield of 5.7 tons/ha within nine months, or 7.6 tons/ha/yr.

Fish production was reported in four 130 m^2 experimental ponds fed with the effluent from a two-stage series of sewage stabilization ponds (Kutty 1979, cited by Jhingran 1982). One pond, which received effluent directly, had an extrapolated yield of 8.4 tons/ha/yr, but a second, which also received the effluent directly, had a yield of only 4.3 tons/ha/yr, attributed to few silver carp in the composition ratio and the absence of catla. The two other ponds, which received the effluent from the above two ponds, had extrapolated yields of 3.3 tons/ha/yr and 3.5 tons/ha/yr. Milkfish were also a constituent species but had poor growth and survival.

Based on a decade of experiments on sewage-fed fish culture at the Rahara Research Centre of the Central Inland Fisheries Rsearch Institute in West Bengal, an extension manual has been published on carp culture using domestic sewage (Ghosh et al. 1985).

4.4.3 Israel

Blue tilapia (*Oreochromis aureus*), common carp (*Cyprinus carpio*) and silver carp (*Hypophthalmichthys molitrix*) were raised in a series of four 400-m^2 experimental ponds in Israel. The ponds were filled with and also received extended aeration effluent during the growing season. The ponds were arranged in series to give a range of water qualities so that the tolerance of the different species of fish to various effluent concentrations could be determined (Buras et al. 1987). All silver carp died within a very short time in Ponds 1-3, and the survival rates for common carp and blue tilapia were 9 percent and 16 percent, respectively. The limiting concentrations of ammonia for tilapia were 8 mg NH_4^+-N/l and 0.3-0.6 mg NH_3-N/l, and for common carp and silver carp were 4 mg NH_4^+-N/l and 0.2-0.4 mg NH_3-N/l.

4.4.4 China

Considerable research on sewage-fed aquaculture has been reported from China. However, it is included in Chapter 2 on past and extant excreta reuse systems because research in China is intimately associated with commercial production of fish.

4.5 Sewage stabilization ponds: Australasia

Only one reference was found in the literature relating to the experimental culture of fish in sewage stabilization ponds, from New Zealand.

4.5.1 New Zealand

Fish culture in sewage stabilization ponds has never been practised in New Zealand, although large carp and eel have frequently been found in stabilization ponds. An experimental study on the culture of fish was conducted in a 150-m^2, 1.8-m deep subsidiary

pond adjacent to the main sewage stabilization pond near Blenheim, Marlborough (Slack 1974, Teoh 1974). The subsidiary pond was filled from near the inflow of the main stabilization pond, which received raw sewage, and was topped up regularly to compensate for losses by evaporation and seepage with a dilution of approximately 1:5 (sewage:pond water). Weight gains of up to 20-fold for rainbow trout (*Salmo gairdneri*) in six months and 30-fold for goldfish (*Carassius auratus*) in ten months were obtained. Common smelt (*Retropinna retropinna*) had a poorer survival and growth rate. The results indicated that clean, highly oxygenated water is not essential for the culture of rainbow trout, as was commonly believed. Dissolved oxygen in the experimental pond ranged from 4 mg/l to 14 mg/l, as determined by diurnal observations, a suitable range for fish. However, the oxygen regime in the main stabilization pond was anaerobic at night on two occasions (attributed to phytoplankton blooms) and it was not considered suitable for fish culture. The temperature in the experimental pond ranged from 5°C to 22°C, a suitable range for rainbow trout for 10 months a year and for goldfish for nine months a year.

The good growth of the fish was attributed to large populations of zooplankton in the experimental pond. The three species of fish raised in the experimental pond were also not considered suitable for rearing in the main sewage stabilization pond because zooplankton populations fluctuated in the latter. Zooplankton usually had a lower biomass in the main pond than in the experimental pond and were negligible for several months. It was considered that herbivorous fish could probably be reared successfully in the main pond because of the high phytoplankton biomass. It was not envisioned that fish raised in sewage effluents would be accepted as suitable for human consumption in New Zealand, but the possibility of rearing rainbow trout cheaply for stocking public waters for recreational use was noted. The possibility of rearing salmon fry in stabilization ponds, where they might reach migrating age before migrating to the sea, was also noted. It was suggested that sewage effluents, even in developed countries, should be regarded as a highly valuable resource for aquaculture.

4.6 Sewage stabilization ponds: Europe

Sewage fish culture was developed in Germany during the first two decades of this century. Research culminated in the construction of the Munich sewage-fed pond system, which has continued operation essentially unchanged since it was constructed more than 50 years ago. Research in sewage-fed aquaculture seems to have ceased until recently, with the exception of a report from Russia. Reports in the literature are from France, Hungary, Poland, and the United Kingdom.

4.6.1 France

Experiments were conducted in Montpellier on the use of sewage stabilization pond effluents for aquaculture (Bailly 1978, 1979). Sewage was treated in three stabilization ponds in series and then reused in aquaculture. Fish were cultivated in ten 100-m² ponds

lined with black polyethylene and fed with clean irrigation water mixed with either 30 percent or 50 percent sewage stabilization pond effluent. Feeding of water was discontinuous, with 10 m³ of the approximately 60 m³ of water in each pond changed weekly. The growth of four species of carp and tilapia was monitored: bighead carp (*Aristichthys nobilis*), common carp (*Cyprinus carpio*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), and Nile tilapia (*Oreochromis niloticus*). Mortality of common carp occurred in spring and was attributed to ammonia toxicity because of symptoms characteristic of ammonia poisoning: mucus, ulcers, necroses with pathogenic bacteria. Concentrations of un-ionized ammonia reached sublethal (> 0.1 mg NH_3-N/l) and sometimes lethal (> 0.5 mg NH_3-N/l) levels because pH rose as high as 9 to 10 at the end of the day. Ammonia toxicity apparently did not affect Chinese carp. Mass mortalities of fish in two ponds were caused by oxygen depletion after the collapse of an algal bloom. Impressive growth of bighead carp and silver carp, plankton feeders, was obtained in the system, and common carp and grass carp also grew well. Tilapia were tested for a short time and performed well.

4.6.2 Hungary

Sewage reuse in ponds in Hungary was first investigated in 1914, but no significant results were obtained at that time (Kovacs and Olah 1984). No fisheries were established specifically for sewage treatment in Hungary, but effluent from the Balation Foldvan sewage treatment plant (good mechanical but only partial biological purification) was pumped into commercial fish ponds and small natural lakes where decomposition of the wastewater was completed without detrimental effects (Donaszy 1974). Studies of the system were conducted, but no experimental data on the optimal amount of wastewater per unit area of pond were reported (Donaszy 1974). A call for large-scale experiments in sewage-fed aquaculture culminated in perhaps the most comprehensive study on the use of domestic sewage in aquaculture. This was conducted over a five-year period from 1974 to 1978 in Szemes, near Lake Balaton (Kovacs and Olah 1982, 1984).

Raw sewage was subjected to physical treatment before introduction to specially constructed ponds (Figs. 4.6, 4.7). A wire net was used for primary filtering followed by a sand trap to remove finer particles, and a sedimentation tank. The clarified sewage effluent was pumped under high pressure to four to six sprinklers (Germenc-T type) in each pond. Spraying of sewage effluent was generally carried out daily, in the morning. The sprinklers were also used for aeration, and pond water was pumped into the sprinklers to solve the problem of early-morning oxygen depletion in the ponds.

The total area of the 12 ponds was 10.7 ha, six ponds of 1.65 ha and six of 0.18 ha. The mean depth of the ponds was 1.0-1.3 m. The fan-shaped layout of the ponds was designed to locate the monitoring system in a central position. The small ponds were incorporated to increase the flexibility of the experimental system and the most critical parameters were tested initially in them. Fish were harvested from a pit along the longitudinal axis of the ponds. Two-year-old bighead carp, common carp, grass carp, and silver carp of 300-350 g individual weight were used in the experiments.

Untreated ponds were used in 1974, the first year of the project, with a stocking density of 0.13-0.14 fish per m². The spraying unit was put into operation in 1975. Extreme dosages of sewage were used in 1975, with a standard fish stocking density. A loading of 5 m³/ha/day did not significantly change the water quality and fish yield from the control, whereas a loading of 250 m³/ha/day caused mass mortality of fish because of early-morning depletion of dissolved oxygen in the ponds. The best result in 1975 was a yield of 1.2 tons fish/ha, with a dosage of 50 m³/ha/day.

Sewage was sprayed at 50 m³/ha/day in 1976, using a stocking density of 0.3-0.5 fish per m². The feeding habits of the fish species and the types and quantities of natural food in the sewage-fed ponds were studied. Common carp could not be stocked at more than 10 percent of the total fish stocking density to yield market-size fish and properly purified water. Grass carp were reported to control macrophytes at 5-7 percent of the total fish stocking density. The greatest problem was the selection of the optimal stocking density of bighead carp, the most aggressive species. The highest yield and best degree of water purification were achieved by stocking silver carp at 50-65 percent. Fish yield ranged from 1.3 tons/ha to 1.6 tons/ha depending on the fish stocking structure.
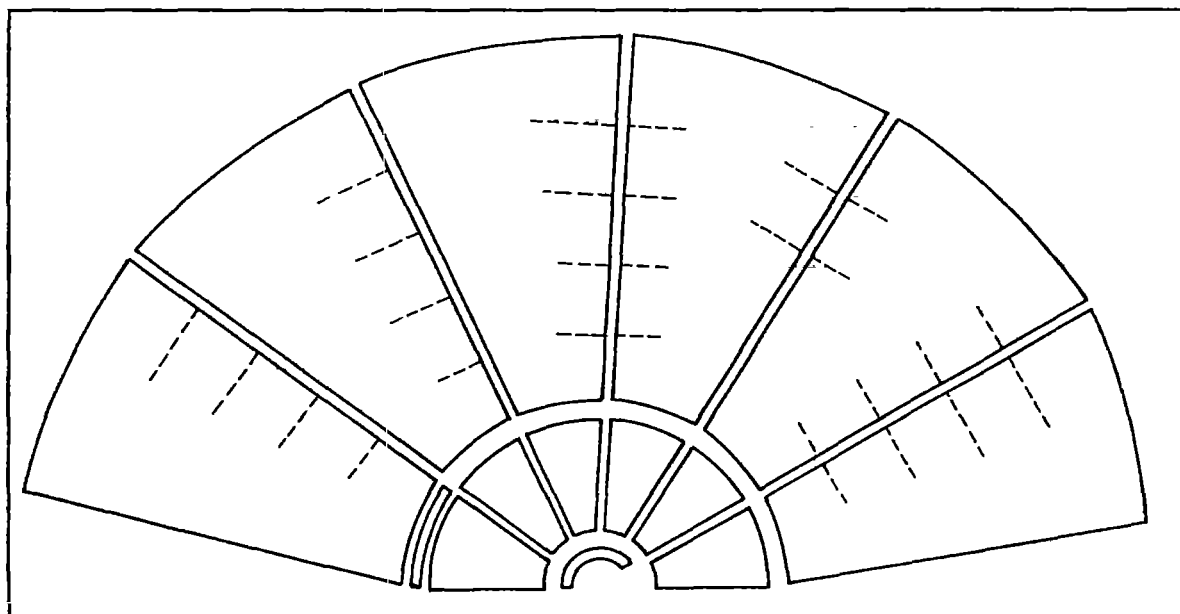
Figure 4.6 Layout of experimental sewage-fed fish ponds in Fonyod, Hungary (Dotted lines represent sprinklers.)

The best stocking rate of fish in 1976, 0.35 fish per m², was used in 1977 at sewage loading rates of 75, 100, 150, and 200 m³/ha/day to determine the optimal dosage. The best yield in 1977, 1.8-2.0 tons/ha, was obtained with 100 m³ sewage/ha/day. In the last year of the project, 1978, a sewage loading rate of 100 m³/ha/day was used with a stocking density of 0.35 fish/m². The results of the 5-year research project are summarized in Figure 4.8.
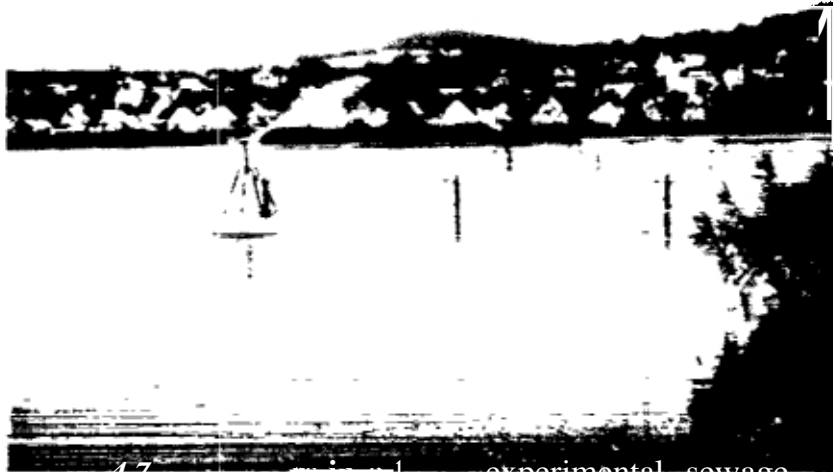
Figure 4.7 Sprinklers in a large, experimental, sewage-fed fish pond at Fonyod, Hungary

The optimal sewage dosage was 100 m³/ha/day, equivalent to a domestic sewage production of 800-1,200 persons/day, which introduced 400-500 kg nitrogen and 80-120 kg phosphorus into the pond system during the 120 day culture period. The BOD_5 of the settled sewage was 110-120 mg/l (Olah, personal communication) which gave an organic loading of 11-12 kg BOD_5/ha/day with the optimal sewage dosage of 100 m3/ha/day.

The optimal fish stocking structure was:

Common carp	5-10 percent	150-300 fish/ha
Silver carp	50-65 percent	1,500-1,650 fish/ha
Bighead carp	22-30 percent	750-900 fish/ha
Grass carp	8-10 percent	240-300 fish/ha
Total	**100 percent**	**2,640-3,150 fish/ha**

A stocking density of 2,640-3,150 300-350 g fish/ha gives an initial stocking weight of 0.8-1.1 tons/ha. Net yield was reported to be 1.8-2.0 tons fish/ha/120 day growing season, equivalent to an net yield of 5.5-6.1 tons/ha/yr.

Olah et al. (1986) reported a simple two-species polyculture of silver carp and common carp in apparently the same system of sewage-fed ponds as reported by Kovacs and Olah (1984). The optimum daily loading of sewage in terms of both fish growth and water purification was reported to be 150 m³/ha/day from an experiment with sewage loadings of 50, 100, 150, 200 and 250 m³/ha/day, as opposed to 100 m³/ha/day reported earlier by Kovacs and Olah (1984). The ponds were stocked in April with 2,500 200-g

fingerlings of silver carp and 1,500 190-g fingerlings of common carp/ha to give an initial stocking weight of 785 kg/ha. The fish were reared until October without other fertilizer or supplementary feed, a growing period of 120 days. Fish production was reported to be 12 kg/ha/day, or an equivalent yield of 4.4 tons/ha/yr, assuming a year-long growing season.
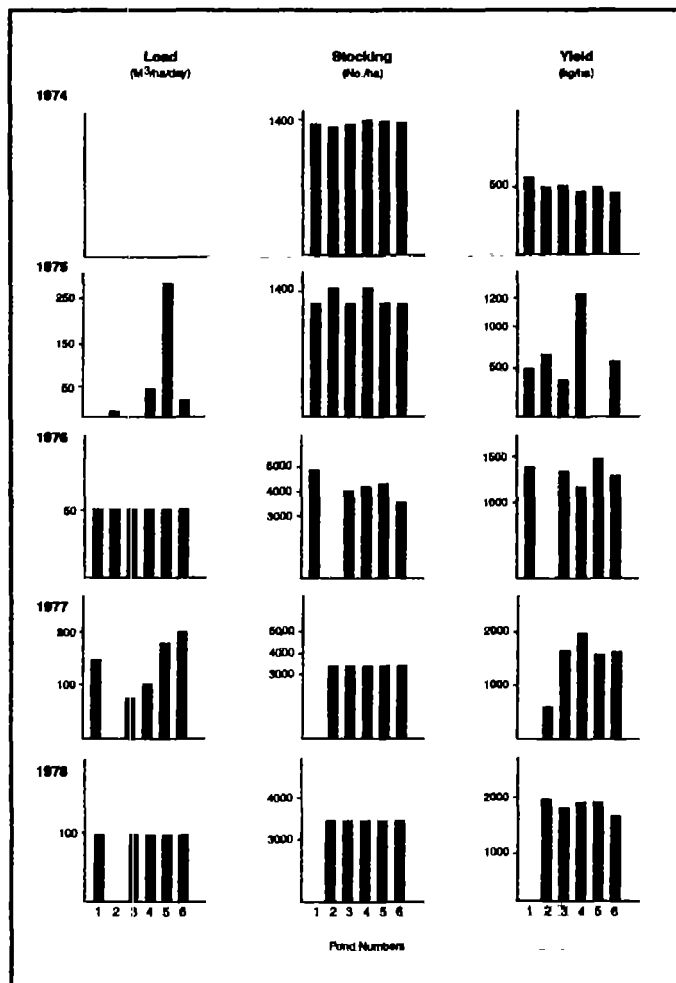
Figure 4.8 Results of the five-year research project on domestic sewage oxidation technology
(*Source:* Kovacs and Olah 1984)

Additional data were obtained from Fish Culture Research Institute (1979), a summary report of recommended practice for sewage-fed fish culture in Hungary. The ponds were filled with water in February or March, and fish were stocked 30 days later. There was no effluent from the ponds during the 120-day fish culture period. A minimum fish-culture cycle was considered to be 30 days because the ponds should be drained after a minimum of 30 days after the last application of sewage. A slightly different optimum stocking density was given to that reported by Kovacs and Olah (1984): 3,000-

4,000 yearlings/ha with a recommended composition of 60-70 percent silver carp, 10-15 percent bighead carp, 10-15 percent common carp, and 5 percent tench; the above percentages should be reduced if grass carp are required to allow the fish to be stocked at 3-8 percent of the total. However, it was pointed out that silver carp is the main consumer of phytoplankton and its stocking proportion could be increased to 80 percent of the total.

The mean water depth was 1-1.5 m. Water depths of less than 0.5 m or more than 2 m were not recommended because submerged macrophytes grow in shallow ponds and release nutrients absorbed by the sediments, and an anaerobic zone develops in deep ponds. The oxygen regime in the ponds has to be considered when loading sewage, with dawn dissolved oxygen in mid-August the most critical time of the year in the temperate climate of Hungary. The maximum organic loading in the ponds without supplementary aeration was 20 kg BOD_5/ha/day, above which fish kills occur. The normal loading was 10-12 kg BOD_5/ha/day with the maximal BOD_5 loading used only when dissolved oxygen is measured regularly between 3 A.M. and 6 A.M. An average chlorophyll concentration of 200 mg/l, equivalent to 13.4 mg phytoplankton biomass/l, was reached when the nitrogen and phosphorus loads to the ponds exceeded 4 kg and 0.5 kg/ha/day, respectively.

4.6.3 Poland

Investigations were conducted by Wolny on the use of sewage for fish culture from 1958-1961 at the sewage treatment plant at Kielce, Poland (Wolny 1964, 1966; Thorslund 1971). Crucian carp (*Carassius carassius*) were cultivated year-round in five 321-1,800 m^2 experimental ponds in undiluted effluent from an activated sludge treatment plant, to give a maximum yield of 1,318 kg/ha. Fish were cultivated in both stagnant and flow-through ponds, and water quality was compared with control ponds not stocked with fish. The fish not only hindered or eliminated rooted submersed aquatic macrophytes by mechanically loosening sediments and pulling out plants when feeding, but they also stimulated the development of phytoplankton with relatively short life cycles, such as *Chlorella* and *Scenedesmus*. Fish enhanced photosynthesis and improved oxygen conditions in the water, as indicated by both the night and day percentage oxygen saturation of water almost twice as high in stocked as in unstocked ponds. Dissolved oxygen concentrations never fell below 3 mg/l, the concentration at which crucian carp stopped feeding. Thus, fish accelerated the cycling of nutrients in the pond and therefore had a positive benefit on sewage purification. Furthermore, the fish raised on sewage effluent had a lower fat and a higher protein content than fish fed ground barley on a farm. There was no tainting of the flesh in the sewage-raised fish.

Satisfactory growth of common carp (*Cyprinus carpio*), grass carp (*Ctenopharyngodon idella*), and silver carp (*Hypophthalmychthys molitrix*) was reported in two experimental ponds fed with the effluent from an activated sludge plant receiving municipal and industrial sewage at Pruszkow, near Warsaw (Klekot 1978). Pond 1, 1,600 m^2 in area, had a continuous summer flow of 6 m^3/hour. Pond 2, with a surface area of 2,800 m^2, was stagnant, with effluent added periodically to maintain the water level. The common carp raised in the two sewage-fed ponds had a higher flesh protein content

and lower flesh fat content than common carp raised on a fish farm with supplementary feed.

4.6.4 Russia

Fish were cultured in a cascading series of six ponds fed with undiluted sewage at Luberetz sewage farm, Moscow (Mayenne 1933, cited by Mortimer and Hickling 1954, and by Hepher and Schroeder 1977). Carp could be kept only in the last three ponds in summer. There was abundant plankton in the earlier ponds in the series, but fish could not be cultured in them because of the depletion of dissolved oxygen.

4.6.5 United Kingdom

The Rye Meads Sewage Purification Works in England treated domestic and industrial sewage by a conventional diffused-air plant and subjected the effluent to tertiary treatment in a series of lagoons (Williams et al. 1973, Noble 1975). Studies of fish that had been stocked in the lagoons indicated relatively high standing crops of fish with rapid growth rates. An experiment was conducted to examine the feasibility of fish culture in the lagoons. A small lagoon of 0.2 ha was emptied and subdivided into four equal sections of 500 m^2 by 0.6 cm plastic netting. The lagoon was refilled to a depth of 1.5 m and left for two weeks, a sufficient time for a dense biomass of zooplankton to develop. The sections were then stocked with carp (*Cyprinus carpio*) at densities of 0.4, 1.4, 2.2 and 3.2-3.5 g/m^2. The common carp grew well, but there was considerable mortality over the two-year experimental period, particularly at the highest stocking densities. The two most heavily stocked sections suffered heavy fish mortality by a disease provisionally identified as carp pox. Fish hardly grew at all from when they were stocked in late October to late April, presumably due to low temperature. The highest mean weight of fish, 519 g after two years, occurred in a section with a final density of 0.2 fish/m^2.

Edwards and Densem (1980) discussed the feasibility of using macroinvertebrates (psychodid flies and enchytraeid and lumbricid worms) produced in trickling-filter beds as fish feed. Total annual production of macroinvertebrates may be about 12.5 kg dry matter/m^2 of filter surface, although more studies on macrofaunal populations were recommended before conclusions concerning their exploitation could be drawn. Furthermore, much of the macroinvertebrate productivity would not be exploitable without changes in management procedures. The possibility was also considered of incorporating a fish culture unit before final effluent settlement, although the ammonia and dissolved oxygen concentrations may not be suitable for fish culture. Edwards and Densem (1980) pointed out a further constraint to the economic viability of the use of macrofauna from trickling filters as fish feed. More than 90 percent of trickling filters in United Kingdom sewage treatment works serve populations of fewer than 104 people. Less than 4 tons of fish could be grown annually, assuming maximum exploitation of macrofauna as fish feed, much less than the 50 ton fish culture unit regarded as an economically suitable size in the United Kingdom.

4.7 Sewage sludge

Following the current trend to assess the feasibility of converting wastes of various kinds into protein, there have been studies on the reuse of sewage sludges in fish culture. Studies have been conducted on the reuse value of primary sewage sludge and on activated sludge, both as a fertilizer to stimulate the production of natural feed and as an ingredient in compound feed formulated with other feedstuff ingredients.

Anaerobically digested primary sewage sludge was added to concrete tanks stocked with fingerlings of common carp (*Cyprinus carpio*) and catla (*Catla catla*) in India (Natarajan and Varghese 1978, 1980). The good fish growth was attributed to the fertilization effect of the sludge. The feed value of primary sewage sludge from the primary settling tank of the East Lansing, Michigan, wastewater treatment plant was assessed for goldfish (*Carassius auratus*) fingerlings (Lu and Kevern 1975). A 30 percent sewage sludge diet was prepared by combining three parts of sun-dried sludge and seven parts of salmon feed. Fish fed a 30 percent sewage sludge diet grew as well as or better than controls.

More research has involved the reuse of activated sludge. Activated sludge added as small flakes to cement tanks containing fingerlings of common carp (*Cyprinus carpio*), catla (*Catla catla*), and mrigal (*Cirrhina mrigala*) stimulated their growth by a fertilizing effect leading to the production of plankton, although the addition of large amounts of sludge to the tanks caused fish mortality (Gopalakrishnan and Srinath 1963). Saigal (1972) mentioned that activated sludge had a positive effect on the growth of fingerlings of common carp (*Cyprinus carpio*), catla (*Catla catla*) and mrigal (*Cirrhina mrigala*) when used as a fertilizer in India. Experiments were also reported in which common carp (*Cyprinus carpio*) were fed with suspensions of unicellular algae cultured in extracts of sewage sludge (probably activated sewage sludge) (Wong and Tam 1984).

The rationale for the incorporation of activated sludge in fish diets is that the former contains large quantities of bacterial and protozoal cell protein as well as appreciable quantities of vitamin B_{12} (Tacon and Ferns 1976, 1978/79; Tacon 1978/79). Processed activated sludge is a stable, dark-brown material with a nutritive value similar to brewers yeast or protein-rich cereal. Up to 20 percent activated sludge by weight was successfully incorporated in pelleted trout rations to replace pure white fish meal and wheat middlings on an isonitrogenous and isocalorific basis, with no apparent loss in the growth response or gross efficiency of food conversion of the fish (Tacon and Ferns 1976). Up to 33 percent activated sludge by weight was again successfully incorporated in pelleted trout rations to replace soybean meal and wheat middlings on an isonitrogenous and isocalorific basis and, again, there was no apparent loss in either growth reponse or gross efficiency of food conversion of the fish in short-term feeding trials (Tacon 1979). Activated sewage sludge was also incorporated in diets of common carp (*Cyprinus carpio*) as a replacement for a wheat bran-cottonseed meal commonly used in Egypt, at levels of 40, 70 and 100 percent (Anwar et al. 1982). Activated sewage sludge increased fish growth relative

to the control (no incorporation of the sludge) at levels of 40 percent and 70 percent incorporation, although growth was decreased slightly at 100 percent relative to the control.

The rationale behind attempts to reuse sludges in aquaculture is the large quantities that are available, at least in developed countries. About 1.4 million tons of dry sewage solids are disposed of annually in the United Kingdom, and the cost is considerable. About 1.0 million tons are primary sludge containing 16 percent available protein, and 0.4 million tons are secondary sludge from biological treatment containing some 40 percent available protein. The total sewage sludge could yield 0.4 million tons of protein annually. The nominal value as animal feedstuff was estimated at £70 million (Fish 1978). However, there are several constraints to the reuse of sewage sludges in aquaculture. Sewage sludges are likely to be readily available only in developed countries where activated sludge and trickling-filter treatment plants are common. Natarajan and Varghese (1978) pointed out the restricted availability of sewage sludges to cities with sewage treatment plants. The low moisture of dried sewage sludge and digested sewage-sludge cake was considered to be an advantage in terms of easy storage and reduced transportation costs (Saigal 1972; Natarajan and Varghese 1980), although the high cost of harvesting activated sludge from treated sewage was considered to be a major constraint by Tacon (1979).

A major disadvantage in the use of sewage sludges as a fertilizer in ponds is the accumulation of organic matter on the pond bottom (Saigal 1972, Natarajan and Varghese 1980). Primary sedimentation or anaerobic ponds are recommended in sewage-fed ponds to reduce the undesirable buildup of sludge on the pond bottom (see Section 5.5.4), and it would be counterproductive to use sewage sludge as a pond fertilizer.

According to Fish (1978), sewage sludges are unsuitable for incorporation in animal feeds because of their content of heavy metals, detergent residues and persistent organic chemicals. The limited data then available on the accumulation of heavy metals by fish fed diets containing activated sludge suggest that heavy metal accumulation might not be a major concern (see also Section 5.4.5). There was some accumulation of copper, iron, and aluminum in rainbow trout fed on a diet containing 20 percent sewage sludge for 35 days (Tacon and Ferns 1976). Singh and Ferns (1978) ran an experiment of longer duration than the one above, 10 weeks, with rainbow trout fed a nutritionally balanced diet containing 30 percent by weight activated sewage sludge. Fish fed on the diet containing sewage sludge had significantly elevated levels of chromium, iron, nickle and lead, though the concentrations were within the range reported for uncontaminated fish. However, the fish accumulated only a small portion of the heavy metals ingested within the experimental period, and manganese showed no accumulation at all. Chromium and lead both showed a significant reduction in concentration towards the end of the experiment, suggesting some regulatory ability by the fish. However, zinc and nickel concentrations were still rising at the end of the experiment.

According to Tacon (discussed in Fish 1978), activated sludge contains about 0.4 percent phytic acid, derived from cereals, which binds some metals such as copper, iron and manganese. Sewage sludge also has a high fiber content which acts as roughage,

decreasing the transit time of the food in the gut, so that any metals present do not get absorbed by the fish because of the rapid passage of the food through the gut.

Although there is potential for activated sludge to be a relatively cheap feed ingredient compared to conventional sources, it is illogical to use it as an ingredient in pelleted feed for the high market-value fish usually cultured on pelleted feed. Concerns over the quality of fish raised on feed containing activated sludge, irrespective of whether they are real or imaginary, could jepardize their acceptance by consumers of high socioeconomic status who can afford fish fed with pelleted rations.

4.8 High-rate sewage stabilization ponds

High-rate sewage stabilization ponds, often refered to as high-rate algae ponds (HRAP), are shallow stabilization ponds which are operated at short retention periods to maximize algal productivity. Researchers at the University of California introduced the concept of the mass production of algae to treat water and produce algae as a potential source of high-protein animal feed in the 1950s (Gotaas et al. 1954, Oswald and Gotaas 1957, Oswald 1963), but studies on sewage-fed HRAPs have also been carried out in Thailand (McGarry 1971, McGarry and Tongkasame 1971, McGarry et al. 1974), in Israel (Shelef et al. 1973, 1978, Azov and Shelef 1982), in the Philippines (Oswald et al. 1978), and in South Africa (Viviers et al. 1980, Pretorius and Hensman 1984). There is voluminous literature on the HRAP: for more recent reviews, see IDRC 1980, Shelef and Soeder 1980, and Richmond 1986.

Influent sewage is subjected to primary treatment to remove settleable solids, and the clarified effluent is continuously added to the HRAP (Fig. 4.9). The HRAP is extremely shallow, only 30-40 cm deep, and the contents are either intermitently or continously mixed to prevent the phytoplankton from settling. The most economic mixing device is usually a paddle wheel. The retention time is only three to six days to maximize algal productivity. HRAPs can be loaded with as much as 350 kg BOD_5/ha/day and produce a filtered effluent of 25 mg/l after removal of the algae, although there is a relatively low removal efficiency of excreted pathogens (Mara and Pearson 1986, see Chapter 7). Rates of biomass production have attained 40 g dry matter/m^2/day (146 tons/ha/yr), but typical average yields are closer to 30 g dry matter/m^2/day (110 tons/ha/yr), of which approximately 50 percent is protein (McGarry 1982). The term "albazod" has been introduced to indicate that the particulate matter recovered from HRAPs consists not only of algae but also of bacteria, zooplankton, and detritus (Soeder 1984).

Since HRAPs are designed for maximum algal-biomass production, an efficient and cost-effective method is required to harvest the biomass. The latter is present as a dilute suspension of only 200-500 mg dry weight/l (parts/million). Various methods are available to harvest microalgae: centrifugation, electroflotation, chemical flocculation followed by sedimentation or air flotation, continuous-belt filtration, vibrating and stationary screens, sand-bed filtration, and auto-flocculation. However, only a few have potential as
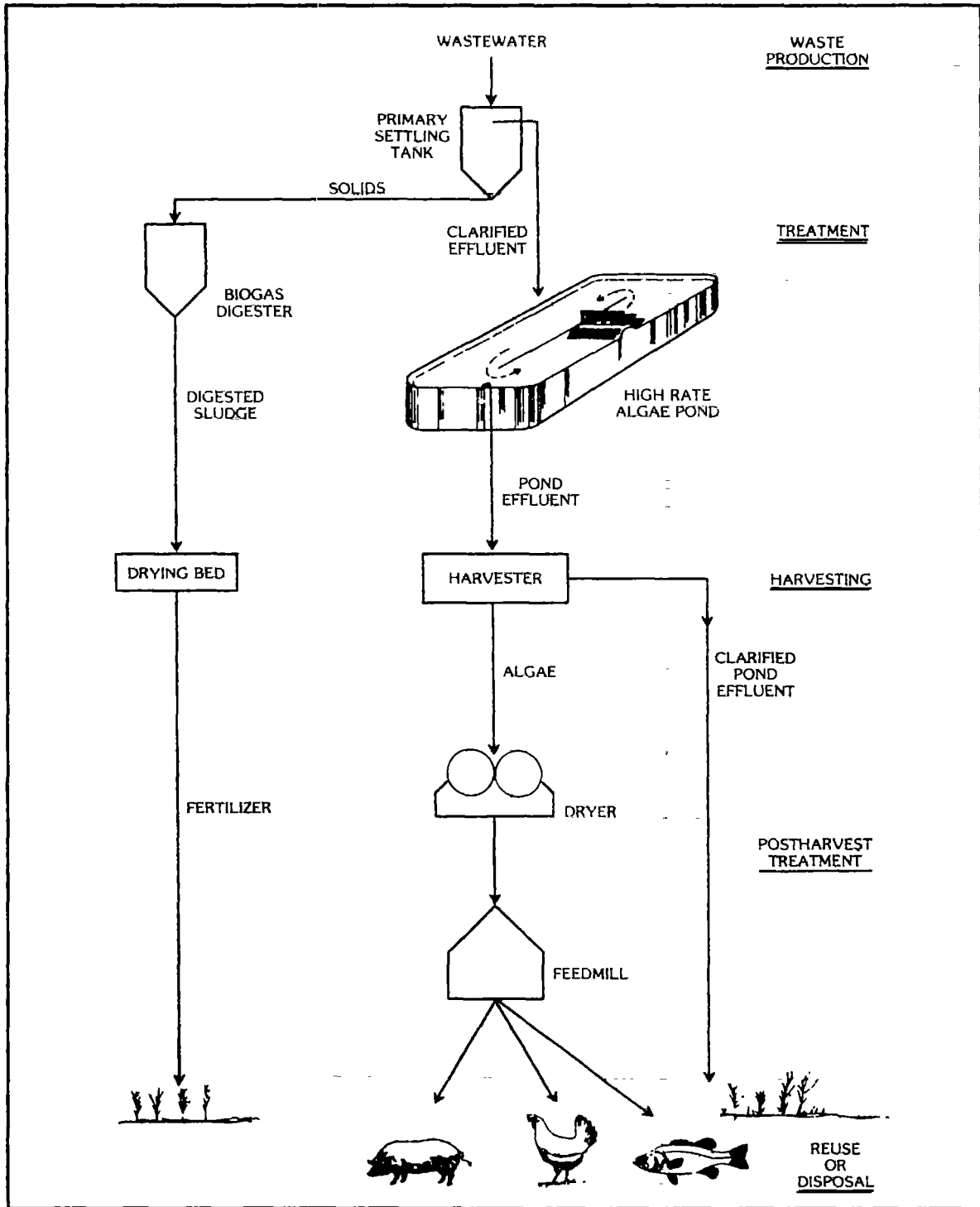
Figure 4.9 Scheme for wastewater treatment and resource recovery through algae production in a high-rate pond (*Source:* IDRC 1980)

efficient, low-cost methods. Filamentous or colony-forming microalgae can be separated by screens or sieves, but species control in sewage-fed HRAPs has proved to be elusive. Polyester fabrics are now available for the fabrication of microstrainers with nominal ratings down to 1 μm, which permit harvest of small phytoplankton, although at a slow filtration rate. The phytoplankton sometimes spontaneously separate from the growth medium to form visible flocs that sediment or float, a process called autoflocculation. Conditions that impede algal growth often promote autoflocculation, but it has not been possible to induce the process consistently. Flocculation may be induced artifically by the addition of chemicals, for example, aluminum sulfate (alum) at a dose of 150 mg/l at pH 6.5. Disadvantages of chemical separation of algae are the cost of the chemicals and their presence in the separated biomass. Alum has been shown to interfere with phosphate in bone development in chickens and caused a rickets-like condition. Chitosan, a natural carbohydrate obtained by acetylation of the chitinous exoskeleton of shrimp is a nontoxic flocculant which may be used to avoid possible toxic effects of chemical flocculants. Dehydration of the harvested algal biomass is another costly process, that is, by surface drying on a rotation steam-heated drum. The cells are heated for a few seconds to 120°C; heating opens the green algal cell wall and greatly increases the digestibility of the powdered product. Drying is not required where wet algae are used as feed.

The most reliable and cost-effective methods to harvest the phytoplankton biomass are chemical flocculation with lime or alum, followed by separation of the flocs from the growth medium by either sedimentation or dissolved-air flotation. However, these methods are still quite expensive, with estimated costs of about $100/10^6$ liters (Richmond 1986). The dewatered algal biomass is then usually dried by drum drying in which the algae are retained for a few seconds on heated steam rollers.

Ryther (1971) proposed that herbivores, which could be subsequently used as food for animals or humans, be evaluated for their cost-effectiveness in harvesting algae from HRAP effluents. Ryther and coworkers later coined the concept of "controlled eutrophication" which included physical separation and compartmentalization of the producer and consumer levels in sewage-reuse systems (Ryther et al. 1972). McGarry and Durrani (1972) conducted a preliminary experiment on the use of tilapia, a filter-feeding fish fed with phytoplankton-laden HRAP effluent (reported as *Tilapia mossambica* but probably *Oreochromis niloticus*) and obtained good fish growth rates. The ability of the filter-feeding Nile tilapia (*Oreochromis niloticus*) to harvest the biomass from the effluent of a sewage-fed HRAP was evaluated in detail in a series of experiments (Edwards and Sinchumpasak 1981, Edwards et al. 1981ab). A linear relationship was established between fish yield and phytoplankton biomass in the water in tanks fed with different flow rates of HRAP effluent. Although high fish yields were obtained, the removal of phytoplankton biomass from the water by the fish was inefficient, and there were large losses of phytoplankton biomass in the fish-tank effluent. The production of phytoplankton in a HRAP and its subsequent utilization by herbivorous fish could not be optimized simultaneously because the fish did not harvest phytoplankton as efficiently as they were produced in the HRAP. It was concluded that it is not efficient to use fish to harvest phytoplankton from HRAP effluents.

The yields of protein-rich phytoplankton in sewage-fed HRAPs were reported to be more than ten times greater than those for soybean, the most prolific agricultural plant-protein producer (Oswald 1962). The yearly yield of protein from a sewage-fed HRAP in tropical Bangkok was estimated to be even higher, 37 times better than maximum protein yields of soybeans in the United States (McGarry 1982). Such high phytoplankton yields have caused great optimism over the future of the sewage-fed HRAP. Oswald (1980) entitled a paper on the potential of sewage reuse in HRAPs "The coming industry of controlled phytosynthesis." Later he prophesied about "the Age of Microalgae" in which the potential of phytoplankton to aid in the elimination of poverty and malnutrition will be realized (Oswald 1980). Borgstrom (1978) believed it most likely that sewage will be fed into huge algal factories to produce animal feed in the future.

Most data on HRAPs have come from small experimental systems, and only a few full-scale systems have been built after more than 20 years of research. HRAPs are still experimental and cannot be considered an established technique with standard operational criteria (Richmond 1986). While phytoplankton can efficiently treat sewage and produce high yields of biomass, they cannot yet be economically harvested and dried. The cost of production of algae in HRAPs in the small industrial plants in operation today is about ten times that of current prices of soybean, a high-protein plant commonly used in animal feeds (Richmond 1986). However, sewage-fed HRAPs for simultaneous wastewater treatment and animal feed production may be able to compete with conventional terrestrial crops for land and capital in the future. Experience has repeatedly shown that productivity increases and the cost of production decreases by an order of magnitude or more with time in the development of new agricultural and industrial processes. Commercial production of microalgae is still in early development, and every phase of this biotechnology, particularly harvesting and drying techniques, could be greatly improved (Richmond 1986). Mass culture of algae on sewage in HRAPs may soon become a viable, high technology industry (Mara and Pearson 1986), but it is not an appropriate technology for excreta reuse today.

4.9 Mass culture of zooplankton

Studies have been conducted on the feasibility of the mass cultivation of zooplankton for the clarification of sewage stabilization pond effluents containing high concentrations of phytoplankton (Ehrlich 1966; Dinges 1974, 1982). It was noticed that sewage stabilization ponds with high concentrations of the zooplankton *Daphnia* had clear effluents because *Daphnia* are able to filter bacteria, protozoa, phytoplankton and detritus particles from the water. As a *Daphnia* population becomes established in a wastewater stabilization pond, the euphotic zone and the phytoplankton turnover rate increase (Dinges 1982). The water becomes clearer due to a reduction in phytoplankton biomass, but mineralization of organic matter is rapid with an excess of nutrients available for the small standing crop of phytoplankton, as indicated by the presence of nitrate. Potential maximum sustained yields of wastewater-grown *Daphnia* under controlled conditions have not been determined, but there is a report of the harvest of *Daphnia* from a wastewater stabilization

pond of 3.36 tons wet weight/ha/month (Dinges 1982). However, since fish are effective predators of *Daphnia*, fish production and the mass cultivation of *Daphnia* are not possible in the same unit (Dinges 1982). Dinges (1974) studied the efficacy of *Daphnia* for both water quality improvement and as an aquarium fish feed. He believed the market for the latter to be quite limited and would soon be flooded were *Daphnia* production to become commonplace. However, he also considered that *Daphnia* may have potential as a protein source in commercial pelleted fish feed.

An attempt was made from 1970 to 1973 to locate sewage stabilization ponds in Texas with *Daphnia* populations. *Daphnia* were found to be uncommon and were present in only 29 of 470 sewage stabilization pond systems (6 percent) in Texas (Dinges 1974). Field studies were also made to evaluate the environmental factors affecting *Daphnia* with the objective of establishing a continuous culture for effluent improvement. *Daphnia* occurred seasonally from early winter to late spring before a large biomass of phytoplankton developed (Dinges 1974). All the ponds which supported *Daphnia* had certain characteristics that moderated pH to less than 8.5: a greater depth than normal (1.5-4.6 m), recirculated water, diffused aeration, a suspension of colloidal clay particles which restricted phytoplankton growth, or a complete cover of duckweed which shaded out phytoplankton (Dinges 1982). It was believed that high pH caused by intense photosynthesis produced ammonia levels toxic to *Daphnia* (Dinges 1974).

Moina were present in 56 installations, or about 12 percent of the pond systems. Fourteen ponds with *Daphnia* also had *Moina* populations, indicating a similarity in environmental requirements, although *Moina* may be more suited for mass cultivation in the tropics than *Daphnia* (Dinges 1982).

Dinges constructed a pilot scale pond at Giddings, Texas, to serve as a *Daphnia* culture unit. The unit was fed by effluent from the final pond in the sewage treatment plant consisting of an Imhoff tank and three stabilization ponds in series (Dinges 1974, 1982). It was proposed to harvest *Daphnia* by pumping culture-unit water through a screen so that small zooplankton and food material would be returned to the unit to aid in sustaining production. A light-weight, movable, perforated boom supported by floats could serve as a collector for the pump. Since *Daphnia* tend to swarm and form dense localized concentrations, the boom was made moveable.

An attempt was made to reduce pH by lowering phytoplankton productivity by shading the experimental *Daphnia* culture unit with black plastic panels. Ehrlich (1966) reduced the concentration of the green alga *Chlorella* in his experiments by shading with a cover of the duckweed *Lemna*. Evaluations of pH control by addition of chemicals and sulfide reduction through mixing of pond waters by diffused air were also made. The black polyethylene panels were unable to suppress algal growth, and the water in the *Daphnia* culture unit was greener than the stabilization pond effluent used to feed the unit. The panels were converted to rafts, but motile algae were able to move to the uncovered areas even though 85-90 percent of the surface was covered. *Daphnia* became established and the unit performed fairly well for almost three months, but they died suddenly as the water temperature and pH increased with the season and the bottom water became anaerobic.

In a final phase of the study, pH was maintained near 7.5 using commercial grade hydrochloric acid (HCl). Aeration was also required for successful operation.

Since chemical control of pH using carbon dioxide or mineral acids is not economically feasible, complete shading by plastic netting, which excludes more than 90 percent of incident light but allows the passage of rainwater, may be the best approach to pH control (Dinges 1982). Stabilization pond effluent laden with phytoplankton would need to be retained in a small covered basin to reduce pH prior to feeding the effluent to the *Daphnia* cultivation unit. Deep basins of 3-5 m could be used to reduce the area required, since depth is not critical, but air-lift pumps mounted in sumps would be needed to mix water in the unit to prevent stratification and sulfide formation (Dinges 1982).

Dinges (1982) discussed the limitations of large-scale mass culture of *Daphnia*. A very low outflow velocity of the flow-through culture units is needed to prevent washout of the population. *Daphnia* cultivation in wastewater effluent requires pH control within a range of 7.0-7.5 because ammonia is toxic to *Daphnia* and the percentage of un-ionized ammonia increases with pH. A gentle aeration-mixing of the water is required to suppress soluble sulfides (which occur in lower layers of ponds due to stratification) to concentrations below 0.4 mg S_2-/l. *Daphnia* are also susceptible to both low dissolved oxygen at night due to phytoplankton respiration and to oxygen supersaturation due to photosynthesis. The latter floats *Daphnia* to the surface when a gas bubble accumulates beneath the carapace (Ehrlich 1966).

According to Mara and Pearson (1986), the commercial production of *Daphnia* has been successful in an experimental pond complex at Meze, in Southern France. High concentrations of *Daphnia* were reported to be produced and could easily be harvested by microstraining, packaged frozen, and sold as fish feed, although details were not given.

The various problems discussed above suggest that the culture of *Daphnia* may be difficult, particularly on a large scale, and would require relatively sophisticated control and monitoring systems for success.

4.10 Septage

Research on the reuse of excreta in aquaculture has been carried out for more than a decade at the Asian Institute of Technology (Edwards 1980a,c). An initial study involved an assessment of Nile tilapia (*Oreochromis niloticus*) to harvest phytoplankton cultured in a sewage-fed, high-rate stabilization pond (see Section 4.7). More recent research has been concerned with the reuse of "dry" wastes such as septage, which are more prevalent in most situations in developing countries (Polprasert et al. 1982, Edwards et al. 1984, 1987; Edwards 1987).

The research at AIT emphasized the production of tilapia as high-protein animal feed for high market-value carnivorous fish in Thailand such as walking catfish (*Clarias*

spp.) and snakehead (*Channa striata*) because of possible public health and social acceptability constraints to the direct consumption of excreta-raised tilapia as human food. The system involved the concept of lengthening the food chain (see Chapter 1) with "resource recovery" separated from "utilization" involving the production of fish as human food (Fig. 4.10).
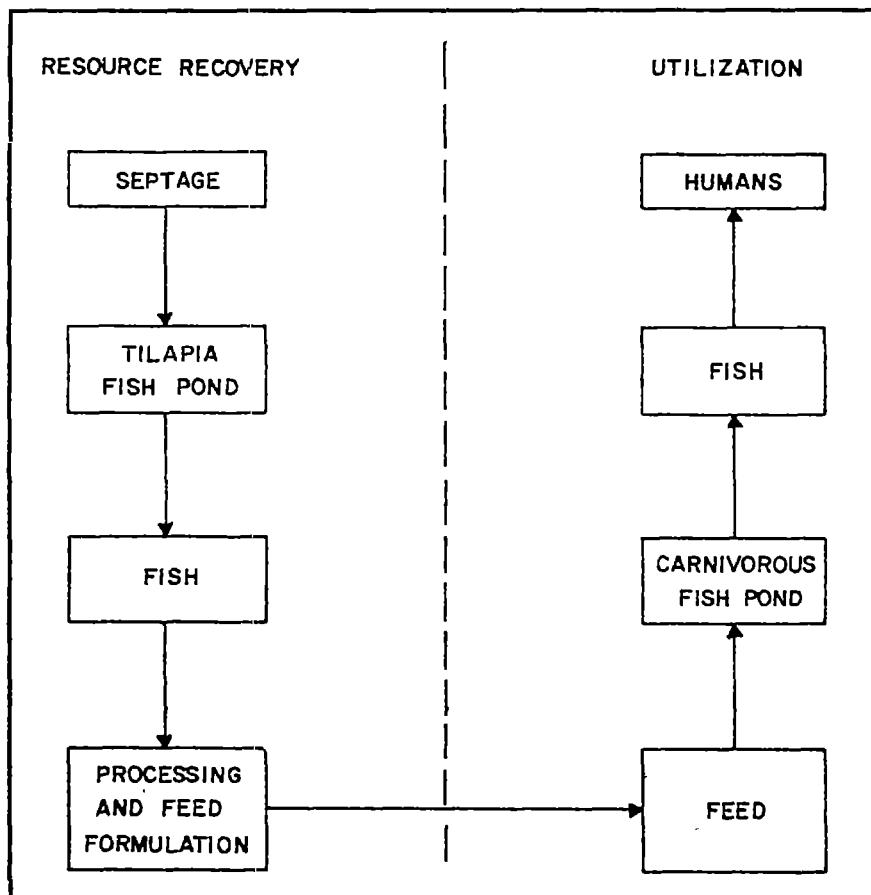
Figure 4.10 Schema of the proposed urban septage-reuse system (*Source:* Edwards et al. 1987)

The earlier AIT work on the culture of tilapia in the phytoplankton-rich effluent of the high-rate stabilization pond suggested the possibility of obtaining high yields of relatively small tilapia suitable for processing into high-protein feed. Although the mean size of harvested fish was inversely related to fish stocking density, the yield was directly related to stocking density. Extrapolated net fish yields of almost 20 tons/ha/yr were obtained in a 3 month growth period at a high stocking density of 10 fish/m² in a series of 4 m³ concrete tanks through which phytoplankton-rich effluent was pumped. The feasibility of attaining such high fish yields was also suggested by Bardach et al. 1972), who believed that maximum yields of small tilapia may be as high as 18 tons/ha/yr. Tapiador (1973) also considered it conceivable to obtain a total production of 50 tons/ha/yr

of 20-40 g fish if several crops of fish were raised each year. Suffern et al. (1978) reported extrapolated production rates of 206 tons/ha/yr of monosex tilapia in small floating cages in sewage stabilization ponds equipped with aerators; they considered it reasonable to expect a yield of about 50 tons/ha/yr from a scaled-up system based on cage culture.

The AIT septage-reuse system was conceived as a single pond for both treatment of septage and culture of tilapia. The pond was loaded to provide adequate natural food for the fish from fertilization of the pond with septage, with the maintenance of aerobic conditions for the well-being of the fish. The addition of septage to the pond did not produce an effluent because of its high solids content, and water needed to be added to maintain the water level in the pond in the dry season. It was believed that the absence of a continuous flow through the system would lead to an efficient reuse of the nutrients contained in the waste.

Experiments at AIT were conducted in a series of sixteen 200 m2 septage-fed earth ponds stocked with small fingerlings of Nile tilapia (Polprasert et al. 1982, Edwards et al. 1984, Edwards 1987). Preliminary experiments on the culture of Nile tilapia in septage-fed 4 m^2 concrete tanks 1 m deep were also reported by Polprasert et al. (1984) and Sharma et al. (1987). Five experiments were run in the earth ponds. Two experiments were run with a constant fish stocking density of 1 fish/m^2, with a range of organic loadings of septage from 0 to 300 kg COD/ha/day. Two experiments were run with a constant organic loading of septage of 150 kg COD/ha/day, with a range of fish stocking densities from 1 to 20 fish/m^2. Ponds were loaded twice a week at three times the daily organic loading rate to give an equivalent loading of septage of six days per week. Five to 10 percent of the initial stocked fish were weighed at monthly intervals, and all fish (stocked fish and progeny) were counted and weighed on draining the ponds at the end of each experiment. The fifth experiment was a study of the relative contribution of stocked fish and recruits to total biomass. All ponds were stocked at 1 fish/m^2 and loaded with septage at 150 kg COD/ha/day. Different treatments were harvested by draining ponds at successive monthly intervals.

The rate of increase in weight and final weight of individual fish both increased with an increase in rate of organic loading, although the growth rate of stocked fish slowed considerably after three to four months, even at the higher organic loading rates. The final mean weight of stocked fish was usually 120-180 g. Extrapolated net fish yield also increased linearly with an increase in organic loading. There were highly significant correlations between extrapolated net fish yield and both total Kjeldahl nitrogen loading rate and mean phytoplankton biomass. Although higher fish yields were obtained at higher organic loading rates, it was considered prudent to select a lower organic loading rate of 150 kg COD/ha/day as the optimal loading rate to minimize the risk of overloading with a possible reduction in fish growth and an increase in fish mortality. Equivalent total Kjeldahl nitrogen and dry matter loading rates at an organic loading rate of 150 kg COD/ha/day ranged from approximately 5 to 8 and from 100 to 125 kg/ha/day, respectively.

There was little variation in fish yield with initial stocking density despite a strong inverse relationship observed between mean fish weight and initial stocking density. The maximum extrapolated net fish yields from the series of five experiments ranged from 4.8 to 6.5 tons/ha/yr, with a mean maximum yield of only 5.7 tons/ha/yr, less than one third of the suggested attainable yield based on the earlier study with the effluent of the high-rate pond. The maximum extrapolated standing stocks of fish determined on draining the ponds at the end of the experiments, which ran for less than one year, ranged from 2.3 to 3.8 tons/ha, with a mean of only 2.8 tons/ha.

The relatively low fish yield in the septage-fed ponds may have been due to insufficient natural food. A linear relationship was established between pond phytoplankton concentration and tilapia yield up to the maximum mean pond phytoplankton concentration of about 70 mg/l in tanks fed with the effluent of the high rate stabilization pond (Edwards et al. 1981a). Fish growth would probably not have continued to increase at higher concentrations of phytoplankton because dissolved oxygen concentrations at dawn were frequently zero at the upper phytoplankton concentrations. Mean maximum phytoplankton concentrations in the septage-fed ponds were usually only about 25-30 mg/l, less than half the concentration in the tanks fed with the high-rate stabilization pond effluent. Phytoplankton in the septage-fed ponds was produced in situ in a 1 m deep static-water pond, whereas the phytoplankton available to the fish in the tanks was the effluent from a sewage-fed, high-rate stabilization pond pumped through the tanks (Edwards and Sinchumpasak 1981).

The relative contributions of stocked fish and recruits to total pond bimass were assessed in Experiment 5. Breeding was first observed at the end of the second month. The recruits were 33 percent of the total fish biomass after 5 months, when the experiment was terminated. Bhattarai et al. (1986) attempted to develop dynamic and empirical models of a septage-fed pond, but they ignored the reproduction and growth of tilapia progeny which made up a significant percentage of the fish biomass in the system.

On completion of the five experiments in the septage-fed 200 m^2 ponds, a septage-fed tilapia pond system was set up with experimental ponds an order of magnitude larger to approximate those of commercial size (Edwards et al. 1987). It was hypothesized that intermediate harvesting of a precociously breeding population of tilapia in a pond fed with septage at 150 kg COD/ha/day may produce cumulative harvests of perhaps 9-10 tons fish/ha/yr by harvesting relatively small fish with a high specific growth rate but allowing the newest recruits to pass through the net for further growth (Edwards et al. 1984). An attempt was made to improve tilapia yields in septage-fed ponds by intermediate harvesting a freely breeding, mixed-aged population in three 1,740 m^2 ponds. The same stocking and loading rates were used as in the 200 m^2 ponds. However, fish were seined at two- to four-week intervals, starting about three months after tilapia were stocked and were breeding prolifically, over a period of 15 to 18 months. Sustainable extrapolated net tilapia yields of 6.2-7.3 tons/ha/yr, with a mean of 6.8 tons/ha/yr, were obtained by intermediate harvesting of the three large ponds.

Tilapia yields were about 20-30 percent lower than the 9-10 tons/ha/yr predicted by intermediate harvesting of a freely breeding population of tilapia. Constraints to higher yields were identified from an analysis of the population structure on draining the ponds at the end of the experiment. The two largest-size classes (20-25 cm and 25-30 cm) which contained relatively large slow-growing fish made up a mean of 33 percent of the standing stock. The use of more efficient seining techniques, possibly involving electricity, was recommended to ensure that the population consists only of relatively small, rapidly growing fish. Another constraint was the relatively small number of fish in the smallest-size class (under 10 cm) which represented the recruits, a mean of only 4 percent at the end of the experiment. Further studies were recommended on the management of the tilapia population in septage-fed ponds to achieve higher yields.

Although it was believed that no significant accumulation of sludge would occur because the ponds were loaded to maintain aerobic conditions (Edwards 1980c), rapid sludge accumulation in septage-fed ponds has proven to be a major constraint. However, the mean depth of the sludge in the three large ponds was 24 cm after draining. Sludge build-up impeded seining of fish and may have reduced the potential fish yield because of a reduction in the depth of the water column at the end of the experiment. Sludge build-up would also lead to the development of an anaerobic zone in the lower water layers which could adversely affect fish growth. Sludge removal at the end of the experiment was time consuming and adversely affected the economic viability of the scheme. Sludge was pumped on to the tops of the pond dikes but sludge disposal could pose a major problem for the proposed system. Research was suggested on methods to reduce the build-up of sludge in septage-fed ponds, perhaps by loading the septage into an anaerobic pond, the effluent of which would feed the fish pond (Edwards et al. 1987).

4.11 Biogas

The anaerobic digestion of organic matter, including excreta, leads to the production of a mixture of methane and carbon dioxide known as biogas, which can be used as a fuel. The slurry has potential as a fertilizer and can be used as a fish pond input. Biogas production has a long history, particularly in Europe, and the anaerobic digestion of sludges at municipal sewage treatment plants in developed countries is a common practice (Van Brakel 1980).

More recently, there has been interest in small-scale anaerobic digesters in developing countries because of concern over the cost and availability of fuel (Barnett et al. 1978, ESCAP 1980). However, there are major technological, sociological and economic constraints to the dissemination of biogas technology. A biogas plant for a family in a rural area in a developing country may cost more to build than the family house (McGarry 1977). Another major constraint to the reuse of excreta in a biogas digester for a rural family is the per capita biogas consumption for cooking is four to five times greater than the biogas production from one person's night soil (Subramanian 1978). If a farmer possesses adequate livestock and their manure can be easily collected and fed into the

digester to supplement night soil, small-scale biogas technology may be viable (Polprasert et al. 1986). However, there do not appear to be many successful small-scale rural biogas plants in developing countries, with the exception of certain areas in China.

The main benefits from a biogas plant are the production of gas and the effluent slurry and the use of both may be necessary before the benefits outweigh the construction and operating costs (McGarry 1977). While the literature on biogas is voluminous, there has been little attention to the reuse of the slurry in aquaculture. Chan (1972, 1974) proposed that excreta from humans and farm animals be channeled into small biogas digesters to prevent pollution of the fragile lagoon ecosystems of the islands of the South Pacific. He suggested that biogas slurry could be allowed to flow into a narrow excavated pond lined with butyl rubber or fiberglass-reinforced plastic sheet to produce phytoplankton, which could be harvested (method not specified) as a high protein and vitamin supplement for chicken and pig feed. The purified effluent from the algae pond could be fed into ponds to raise phytophagous fish for human food and the overflow from the fish pond could be used to irrigate vegetables.

Biogas slurry from experimental small-scale digesters fed a mixture of night soil, water hyacinth and rice straw was loaded at different rates into small fish ponds stocked with Nile tilapia (*Oreochromis niloticus*). There was a linear relationship between net fish yield and slurry loading rate, with maximum extrapolated net yields of 3.7 tons/ha/yr. It was concluded that biogas slurry is a useful fish pond fertilizer but that constraints to the dissemination of integrated biogas technology are most likely to be associated with the digester itself rather than with the reuse of the slurry (Edwards et al. 1988a).

4.12 Compost

Thermophilic composting is a relatively low-cost technology for the treatment of night soil that produces a pathogen-free product because of the rise in temperature in the compost pile (Gray et al. 1971a,b, 1973). Night soil is mixed with a carbon source such as refuse or plant matter to achieve an optimal C:N ratio of approximately 20-30:1. The moisture of the compost pile is regulated at an optimal content of 50-60 percent. The simplest methods to maintain aerobic conditions in the pile are to place ventilation tubes in the pile and to turn the pile at intervals.

Compost is usually regarded as an agricultural fertilizer or soil conditioner. However, there is a report of the use of compost produced from night soil and water hyacinth by the Chinese method of aerobic composting as a fish pond input. Extrapolated yields of Nile tilapia (*Oreochromis niloticus*) were a maximum of 5.6 tons/ha/yr (Edwards et al. 1983b, Polprasert 1984). The mean conversion ratio of compost (computed with a 12 percent moisture content, close to that of grain) to fish was 7.4, only slightly higher than the food conversion ratio of 4-6 reported for cereals. The fish were observed to consume compost to some extent, but the compost probably functioned mainly as a pond

fertilizer. Compost does have potential as a pond input but a major constraint in the technology resides with the reluctance of people in most societies to handle night soil to prepare compost.

4.13 Macrophytes

Much of the experimental work on the use of excreta to cultivate aquatic macrophytes is carried out in the United States and is based on the ability of macrophytes to remove nutrients from wastewaters. Macrophyte biomass must be periodically harvested for such systems to function efficiently, but it has little to no commercial value in developed countries. The role of macrophytes in sewage treatment is reviewed briefly because of the potential for macrophytes in excreta reuse in developing countries.

Emergent macrophytes rooted in the pond bottom, with their photosynthetic parts projecting into the air (*Phragmites, Scirpes, Typha*), or floating macrophytes (*Eichhornia Lemna, Salvinia, Spirodela, Wolffia*), which are usually rooted with the roots hanging into the water, are used to treat wastewater. Such systems are designed to "shade out" the phytoplankton in the water column and ultimately in the effluent by forming a canopy of leaves on or close to the pond surface to reduce light in the water column (Mara and Pearson 1986). Submersed aquatic macrophytes do not grow in sewage stabilization ponds in warm climates because the large phytoplankton biomass reduces light on the pond bottom to levels that are insufficient for macrophyte growth. Sewage stabilization ponds in temperate areas with low organic loadings, and the zooplankton *Daphnia* which remove phytoplankton, do support submersed aquatic macrophytes (Dinges 1982).

Some species of submersed aquatic macrophytes are reported to grow in highly eutrophic water, for instance, *Ceratophyllum demersum, Elodea canadensis*, and *Potamogeton foliosus* (Dinges 1982). Plankton-feeding fish would need to be absent from such systems, because they would crop the zooplankton and cause the development of phytoplankton which would eliminate the submersed macrophytes through reduced light penetration (see Section 5.2.4).

One of the few reports of the development of aquatic macrophytes in fertilized pond systems is the Michigan State University Water Quality Management Project (Bahr et al. 1977). Secondary effluent from a conventional activated-sludge treatment plant was pumped through a series of four lakes with a total water surface area of 16 ha. The mean depth of the lakes was made 1.8 m to keep the bottom within the euphotic zone and encourage growth of submersed aquatic macrophytes. All lakes except the first were planted with several species of submersed aquatic macrophytes (*Elodea canadensis, Myriophyllum spicatum, Najas flexilis*, and *Potamogeton foliosus*) shortly after the lakes were first filled in 1973. Phytoplankton densities were considerably lower in these than commonly found in wastewater systems. The major objective of the project, removal of nutrients from the wastewater, was achieved with phosphorus and nitrogen removals greater than 90 percent and 99 percent, respectively. However, it was necessary to harvest the

aquatic macrophyte biomass, otherwise it would eventually decompose and recycle nutrients back into the water column. The harvest of vegetation was of paramount importance in achieving the main objective of high water quality, although reuse of the plant biomass was considered to have potential as a secondary benefit of the system, assuming that it could be achieved economically. The filamentous green alga *Cladophora* invaded the lakes and formed a floating mat on the surface which winds generally drove to the shore. The floating algae were harvested by skimming, using a small powered barge equipped with a movable fork attachment. A commercial aquatic weed harvester was used to cut submerged macrophytes which were then moved to the shore and lifted onto the bank with a rake attachment. A potential use of the harvested vegetation was reported to be as an ingredient in livestock or fish diets. Promising results of feeding trials with steelhead trout were reported in which a test diet incorporating about one third filamentous green algae by weight resulted in the same growth as fish fed a control diet, but at much lower cost.

An experimental wastewater reuse system was set up in Florida in which secondary sewage effluent was passed through ponds stocked with macroscopic freshwater algae or aquatic macrophytes. The concentrations and flow rates permitted the vegetation to remove inorganic nutrients (Ryther et al. 1976a, 1977). The new growth of vegetation was harvested and fed to an aquatic herbivore in a separate pond system. The macroscopic alga *Chara* was fed to grass carp (*Ctenopharyngodon idella*) but freshwater shrimp (*Macrobrachium*) were also stocked later to make use of wastes from inefficient feeding of grass carp on macrophytes. The major problem was the development of dense blooms of phytoplankton in the *Chara* culture which defeated the objective of tertiary treatment and probably reduced the growth of *Chara*. It was suggested that the problem of phytoplankton could be overcome by reducing the retention time in the pond or by also stocking a filter-feeding herbivore such as freshwater clams or mussels, the zooplankton *Daphnia*, or finfish such as silver carp. However, it is doubtful that the cultivation of submersed aquatic macrophytes in fertilized water has potential because of the propensity of phytoplankton to grow and shade them out in such systems.

The water hyacinth (*Eichhornia crassipes*) is the most widely used plant for wastewater treatment in tropical and subtropical areas (Ryther 1980). There are several water hyacinth-based advanced wastewater treatment systems under evaluation in the southern United States, and design criteria for water-hyacinth systems have been published (EPA 1988). Since an economically attractive method of using water hyacinth has not been found, the use of water hyacinth in waste-fed aquaculture is omitted from this review.

Duckweeds have also been used in sewage treatment in the United States and, in contrast to water hyacinth, they can be grown throughout the year in the southern part of the country because they are more tolerant of cold than water hyacinth. Duckweed was reported from a two-cell sewage stabilization pond system in North Biloxi, Mississippi, in which the effluent quality was better than secondary effluent standard (Reed et al. 1979, Wolverton 1979). Duckweed developed naturally on the surface of the second pond but it was not harvested regularly. When it was first harvested after four years, the duckweed was an average of 2 cm thick. Duckweed was also used in the Marsh Pond System at the Brookhaven National Laboratory, New York (Reed et al. 1979). The Solar Aquacell

Treatment System installed by the city of Hercules, California, a controlled-environment aquaculture wastewater treatment process also used duckweed as well as water hyacinth to shade out growth of phytoplankton and remove nutrients (Stewart and Serfling 1979).

More recently, a new, patented treatment process using duckweeds has been approved by the United States Environmental Protection Agency as an innovative alternative technology (Ngo 1987, Ngo and Poole 1987). The "Lemna Technology" can reduce BOD_5 and total suspended solids to comply with stringent discharge requirements, and it can eliminate algae and odors and reduce nutrients and heavy metals; it is equivalent to advanced secondary or tertiary treatment. The system includes a floating barrier system to prevent the duckweeds from being blown around by wind. A more or less complete duckweed cover can be maintained, an essential element for the system to operate. A specially designed aquatic harvester collects duckweed by skimming the pond surface. The system was successfully tested in two pilot projects under different climatic conditions: in cold, temperate Devil's Lake, North Dakota, and in warm, temperate De Ridder, Louisiana (Buddhavarapu and Hancock 1989).

Based on a review of the development of wastewater treatment in aquaculture, it was concluded from available technology and the potential for early payoff that current research and development should be concentrated on aquatic macrophytes and wetlands rather than on fish (Duffer 1982). However, current information suggests that macrophyte ponds are less efficient than conventional sewage stabilization ponds in terms of pathogen attenuation, and that sludge accumulation is more rapid (Mara and Pearson 1986). From an operational point of view, macrophytes should be cultivated only on the final maturation or polishing pond because phytoplankton are an essential component of sewage treatment in ponds (Mara and Pearson 1986).

A constraint to wastewater-fed aquaculture systems is that, while they may remove nitrogen to a concentration that meets most advanced wastewater-treatment standards, their removal of phosphorus normally does not meet such standards. The ratio of nitrogen to phosphorus in sewage is usually about 3:1 by weight, much less than the mean ratio of 5:1 in living organisms. Excess phosphorus would have to be removed by another method (Ryther 1980). It may be feasible to add inorganic nitrogen in such a nitrogen-limited system at a rate that would permit uptake of excess phosphorus.

Another major constraint is the disposal or reuse of the plant biomass, particularly water hyacinth. Water hyacinth has a moisture content similar to that of primary sludge, and the dry weight of plant biomass produced is about four times greater than the sludge produced from an activated sludge plant. Anaerobic digestion to produce methane, composting, and processing for animal feed are all technically feasible, but the economics of these reuse operations do not appear favorable. It is unlikely that disposal costs of solids can be recovered by plant harvesting and reuse (Reed et al. 1979).

Although the benefits of the cultivation of aquatic macrophytes in sewage stabilization ponds for waste treatment are controversial, the reuse of excreta in the cultivation of duckweeds (*Lemna, Spirodela, Wolffia*) for animal feed as a primary objective

has more obvious potential. A commercial excreta-reuse system in Taiwan uses duckweed (see Section 2.7.2), and there is ample literature on duckweeds which indicates their potential value (see Culley et al. 1981, and Gaigher and Short 1986, for recent reviews). The reported crude protein content of various species of duckweed varies from a low of 7 percent to a high of 43 percent, with the higher protein levels associated with nutrient-rich water (Edwards 1980b). Duckweed yields are reported to range up to 15 g dry matter/m²/day (55 tons/ha/yr), although reasonable yields in well-managed systems are about 8 g dry matter/m²/day (29 tons/ha/yr) (Gaigher and Short 1986). Duckweed yields from secondary sewage-treatment systems are also reported to reach 15 g dry matter/m²/day (Oron et al. 1984, 1986). Such high yields may characterize short-term yields from small-scale experimental units rather than indicate potential average long-term yields from commercial systems. A yield of *Spirodela* of about 9 tons dry matter/ha/yr was obtained in a long-term experiment in septage-fed, 200 m² ponds (Edwards et al. 1984). A yield of *Wolffia arrhiza* of 8.4 tons dry matter/ha/yr was reported in 180 m² cement cisterns fertilized with primary-treated sewage effluent in India (Naskar et al. 1986).

Low feed-conversion ratios of duckweed to fish (indicating high feeding efficiency) have been reported (Edwards 1987). Feed conversion ratios of 3.1 and 5.9 were obtained with septage-raised *Spirodela* fed to Nile tilapia (*Oreochromis niloticus*) at 2.5 percent and 5.0 percent of fish body weight/day, respectively, and 2.2 percent and 3.7 percent for *Lemna* fed at the same rates (Hassan 1986). A feed conversion ratio of 6 was obtained in feeding *Wolffia* to a polyculture of Indian and Chinese carps fertilized with primary-treated sewage effluent (Naskar et al. 1986).

The feasibility of excreta reuse in the cultivation of duckweed was assessed in Thai villages (Edwards et al. 1987). Ten family-level reuse systems were built and monitored. Each consisted of a pour-flush latrine with a water-sealed pit. Effluent overflowed from the toilet pit into a small duckweed pond. Duckweed was harvested periodically and used to feed Nile tilapia in an adjacent pond. Duckweed yields in most ponds were low, probably because of insufficient nutrients, and fish yields were reduced by the entry of wild carnivorous fish. It was suggested that an excreta-reuse duckweed-tilapia system may function better as part of an urban reuse system in which nutrients would not limit duckweed growth.

4.14 Summary

Most experimental studies on the reuse of excreta in aquaculture have involved sewage and fish. Despite the considerable amount of work devoted to the subject, understanding of such systems remains fragmentary. The majority of studies lack an adequate experimental design, probably because their scope is restricted by being conducted in, or in close association with, existing sewage treatment systems. Many studies had only a single experimental treatment, and most lacked replication. The majority of data are more anecdotal than facts determined by rigorous scientific experimentation. A notable exception is the research conducted in temperate Hungary (Fish Culture Research Institute

1979, Kovacs and Olah 1984, Olah et al. 1986) but the research report has not been translated from Hungarian. Nevertheless, the data in the literature have been used to suggest design criteria for sewage-fed fish ponds (Chapter 5).

Impressive yields of phytoplankton have been obtained in sewage-fed, high-rate stabilization ponds, but an efficient, low-cost method to harvest and dry the relatively dilute algal suspension has not been developed. The mass cultivation of zooplankton using sewage effluents faces several technical constraints.

Promising results on the reuse of septage in fish ponds suggest that commercial systems to reuse septage may be feasible. The establishment of septage reuse systems would have a major impact on tropical developing countries where "solid" forms of excreta are more prevalent than sewage. Research has demonstrated that both biogas slurry and compost are useful inputs, but neither sanitation technology is likely to become widespread.

Most research on macrophytes has involved an assessment of their role in sewage treatment, but the benefits of their cultivation in sewage stabilization ponds remains controversial. However, the reuse of excreta in duckweed cultivation for animal feed shows potential because of high yields and high protein content when grown in eutrophic water.

Most studies on excreta reuse have involved the culture of fish as a potential source of human food. Studies have also been carried out on both tilapia and duckweed production in septage-fed ponds for the production of animal feed. Such indirect-reuse systems may have potential in societies in which direct excreta reuse is unacceptable.

Many authors have pointed out the need for research on changing waste disposal systems into waste reuse systems (Allen 1972, Donaszy 1974, Tsai 1975, Alsten 1980, Chesnin 1982). An important conclusion of this chapter is that further research is warranted before excreta reuse systems can be adequately designed for the tropics. However, the ideological gap between the disciplines of aquaculture and sanitary engineering must be bridged by the creation of multidisciplinary research teams to develop design criteria for aquacultural excreta-reuse systems (Reid 1976, Edwards 1980a).

5. Design Considerations for Excreta Reuse Systems

5.1 Introduction

In theory, all sanitation options except chemical toilets may be linked with aquaculture reuse because of the organic nature of excreta: it can serve as fertilizer or feed for aquatic culture systems (see Chapter 3 for discussion of aquaculture in relation to sanitation technology options). Past and current systems of excreta reuse in aquaculture are described in Chapter 2, and experimental work on the subject is discussed in Chapter 4. This chapter brings together information relevant to the design of excreta reuse systems which include aquaculture. The most feasible systems for excreta reuse in aquaculture make use of night soil, septage, and existing or specially designed sewage stabilization-pond systems. Stabilization ponds are considered the most appropriate sewage reuse option for developing countries. Activated sludge and trickling filters should be considered for sewage treatment in developing countries only where land is limited, since linkage to land-intensive aquaculture is effectively precluded.

A case has been made in Chapter 1 for the promotion of excreta reuse in aquaculture. Excreta reuse already takes place, unintentionally and intentionally, in fecally polluted surface waters. Excreta reuse should be promoted as a well-defined system with a recognizable boundary so that it can be managed and controlled, from both production and public-health points of view, without harming the environment. Nutrients contained in excreta should be transformed to useful biomass within defined systems, either in a combined treatment-reuse system or in a reuse subsystem closely associated with a preceding waste treatment subsystem.

A good example of an excreta reuse system that lacks a well-defined boundary is the culture of common carp (*Cyprinus carpio*) in cages in fecally polluted streams in Java, Indonesia (Vaas and Sachlan 1956). The production of natural food for the fish, benthic invertebrates, takes place in fecally polluted streams. The food is carried by the water to cages placed in the stream where it supports the growth of the stocked fish. The system depends on poor sanitation. The fish in the cages remove only a fraction of the benthic invertebrates as the stream flows through the cages. A more efficient reuse system could improve sanitation and eliminate indiscriminate discharge of fecal matter into the environment.

From a biological point of view, there is little difference in the reuse of various types of excreta (night soil, septage, sewage) in aquaculture. "Dry" forms of excreta such as night soil and septage are much more concentrated than sewage in terms of organic matter and nutrients, so they need to be loaded into a pond on a much lower weight or volume basis. A second important difference is that ponds fed with "dry" forms of excreta,

with a much lower water content than sewage, need added water to compensate for water lost due to evaporation and seepage. The reuse of "dry" forms of excreta should be more efficient than the reuse of sewage in aquaculture because of the absence of an effluent in the former.

Most data in the literature relevant to waste-fed aquaculture relate to sewage and sewage stabilization ponds. Discussions are presented of sewage stabilization ponds, culture of fish in relation to sewage, constraints to fish culture in existing sewage stabilization-pond systems, and designs for optimal sewage treatment or reuse. Most sewage fish-culture systems involve ponds, but the feasibility of cage culture is reviewed, and night soil-fed ponds are also reviewed. The dynamics of waste-fed ponds are presented, followed by a discussion of various design criteria for excreta reuse systems.

5.2 Sanitary engineering and aquaculture

A major constraint to the development of bioengineering design criteria for excreta reuse systems involving aquaculture is that two widely separate disciplines are involved. The biological processes involved in waste treatment and aquaculture are similar; naturally occurring microorganisms in the former are used to stabilize organic matter, while in the latter the fertilization of a fishpond with organic wastes involves the stimulation of the growth of pond biota, especially microorganisms, as fish food. A major difference is that fish culture requires a continuous supply of dissolved oxygen. The extent to which oxygen is maintained throughout the waste treatment process to provide a suitable environment for fish depends on the importance attached to excreta reuse.

The theoretical basis of adding organic wastes to water has been developed for waste treatment by sanitary engineers. It has little relevance for the design of excreta reuse systems because the major cause of dissolved oxygen depletion in a fertilized pond is the respiration of pond biota, not the oxygen demand of wastes added to the pond. Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are used to measure the oxygen required to oxidize organic wastes.

Biochemical oxygen demand is usually measured over 5 days at $20\,^{\circ}C$ (BOD_5), but this measurement has limited value for aquaculture, particularly in the tropics. A more appropriate test for aquaculture is overnight BOD of pond water ($BOD_{0.5}$) at ambient pond temperature: the most critical factor in waste-loaded ponds containing fish is the decrease of dissolved oxygen in the pond water during the night. However, there is still the need to measure biochemical oxygen demand in excreta reuse systems to assess if such systems conform to waste treatment criteria, usually expressed in part in terms of BOD_5.

The organic loading, the rate at which biodegradable organic matter is added to a pond, is measured in kg BOD_5 or COD/ha/day. High organic loadings are employed in waste treatment because an objective of waste treatment is to utilize the minimum amount of land possible to reduce costs. However, lower organic loadings must be used if fish are

to be cultured in excreta reuse systems, at least in the pond. The principle of a waste-loaded pond is to add sufficient organic matter as a fertilizer to stimulate the development of pond biota as food for the fish, but not so much organic matter that it causes depletion of dissolved oxygen at night by the respiration of pond biota.

5.3 Sewage

5.3.1 Sewage stabilization ponds

As a basis for an appreciation of how excreta treatment and reuse might be combined, a brief description of a sewage stabilization pond system is given. Furthermore, although sewage stabilization ponds may represent the cheapest wastewater treatment option in warm or tropical climates where land is available, they still represent a significant cost for pond construction and maintenance. It is essential that wastewater treatment be linked to reuse in order to defray the costs of pond systems (Mara and Pearson 1986). It is widely acknowledged that fish should be cultured in such systems to reduce overall treatment costs (Ryther 1980, McGarry 1982, Nupen 1983). Commercial sewage fish culture is not widespread outside West Bengal, India, and China. Arthur (1983) visited 30 sewage stabilization pond systems in different parts of the world, but none were conducting aquaculture on a commercial basis, although many systems contained fish which local residents caught for domestic consumption or sale.

Wastewater treatment and aquaculture are not mutually exclusive, and both can be done within the same system (Allen 1972, Ryther 1980, Arthur 1983). But wastewater treatment and fish culture cannot both be optimized, either technically or economically, in a single, combined system (Donaszy 1974, Reed et al. 1979, King 1979). Waste treatment ponds are designed to optimize sewage treatment to achieve a desired level of wastewater treatment using a minimum area of land since there is usually no financial revenue from the system. Optimal conditions for sewage reuse in aquaculture require a large area of land: to maintain aerobic conditions for fish cultivation, the overall organic loading of sewage needs to be lower than for waste treatment (Edwards 1980b).

Aquaculture in sewage stabilization ponds must not impair the pond system in treating waste water (King 1979). Because existing designs of sewage stabilization pond systems are not optimal for aquaculture, an economic assessment is required to determine if the additional construction costs for drainage, fish collection basins, etc., are justified (Meadows 1983). Despite research on fish culture in sewage stabilization ponds (see Chapter 4 for a discussion of experimental excreta reuse), there are still insufficient data to justify routine culture of fish in sewage treatment systems. Specific removal rates for BOD_5 and suspended solids, fish growth rates, and operation and maintenance needs under different environmental and sewage conditions must be defined (Reed et al. 1979).

Sewage stabilization ponds are a low-cost, simple-technology system: they rely on solar-driven natural processes unaided by mechanical devices, they have simple

maintenance requirements, and they achieve a higher degree of excreted-pathogen attenuation than any other form of treatment (Mara 1976, Arthur 1983, Mara and Pearson 1986). Waste stabilization ponds are essentially an extension of the natural environment (Ferrara and Harleman 1980). They consist of a series of shallow earth ponds into which waste water flows continuously and from which a treated effluent is discharged. Stabilization ponds can also be fed with night soil and septage besides sewage. There are three main types of ponds which are usually arranged in sequence to treat waste water to any desired water quality standard:

1. **Anaerobic ponds** are 2-5 m deep, with a short hydraulic retention time of one to five days. They function essentially as open septic tanks and require desludging every three to five years. They receive raw waste water and are best used with strong wastes with a BOD_5 greater than 300 mg/l and a high solids content. The solids settle to the bottom where they are digested anaerobically, and the partially clarified supernatant flows into a facultative pond for further treatment. The BOD_5 loading is so high that the pond is usually completely devoid of dissolved oxygen at all times.

2. **Facultative ponds** are shallower, 1-2 m deep, and have longer hydraulic retention times, 10-40 days. They receive either raw sewage (primary facultative ponds) or settled waste water (secondary facultative ponds). Secondary facultative ponds do not have a sludge layer because they receive settled waste water from which most of the settleable solids have been removed. Facultative ponds have a lower anaerobic zone and an upper zone which is aerobic in the day due to the intense photosynthesis of phytoplankton but anaerobic at night due to respiratory oxygen demand. The oxygen for bacterial metabolism is provided by photosynthesis of the phytoplankton.

3. **Maturation ponds** are also shallow, 1-2 m deep, with hydraulic retention times of five to ten days. They receive facultative-pond effluent and are designed principally to reduce the number of excreted pathogens and nutrients, although there is some additional removal of BOD. Maturation ponds are aerobic at all times. Polishing ponds, equivalent in operation to maturation ponds of stabilization pond sytems, are used to produce a tertiary-quality effluent from conventional secondary treatment plants such as activated sludge and trickling filters.

Anaerobic and facultative ponds are designed to remove biochemical oxygen demand, whereas maturation ponds are designed to destroy excreted pathogens. Fish can be cultured only in maturation ponds that are aerobic at all times.

The microbiology of waste stabilization ponds is complex. The size of the total heterotrophic bacterial community decreases through a series of waste stabilization ponds as the quantities of organic substrates decline, with BOD_5 removal synonymous with organic carbon removal in general sanitary engineering terms (Mara and Pearson 1986).

Bacteriological activity occurs in the anaerobic pond, where the degradation of organic solids to methane is the most important process. Phytoplankton are absent from the anaerobic pond because of the toxicity of undissociated ammonia and sulfide in high concentrations (Azov and Goldman 1982, Mara and Pearson 1986). A symbiotic relationship between bacteria and phytoplankton takes place in the facultative pond and, to a lesser extent, in the maturation pond (Myers 1948, Mara and Pearson 1986). Heterotrophic bacteria oxidize the organic matter, the degradation of which releases inorganic nutrients that are taken up by phytoplankton to sustain their productivity; phytoplankton photosynthesis releases dissolved oxygen which is required by aerobic bacteria (Fig. 5.1).
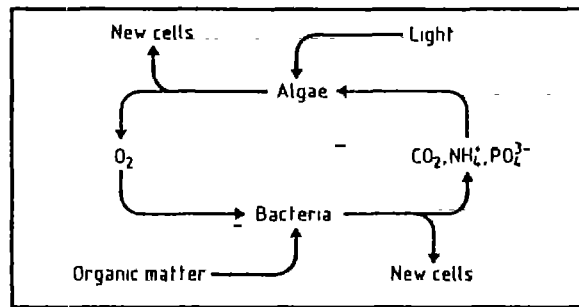
Figure 5.1 Symbiotic relationship between heterotrophic bacteria and phytoplankton in facultative and maturation ponds (*Source:* Mara and Pearson 1986)

The dominant genera of phytoplankton in sewage stabilization ponds are likely to be green algae and euglenoid algae in temperate latitudes. However, in the summer in warm-temperate latitudes, blue-green algae may dominate. In the tropics blue-green algae may form more or less persistent blooms (Colman and Edwards 1987). The phytoplankton biomass in facultative ponds is usually 1,000-3,000 μg chlorophyll a/l (67-201 mg phytoplankton biomass/l) or even higher, depending on the BOD_5 surface loading (Fig. 5.2) (Mara and Pearson 1986). Mara and Pearson (1986) extrapolated their curve at lower BOD_5 surface loading rates to indicate a further increase in phytoplankton biomass. However, the latter is more likely to decrease through a series of maturation ponds because of the decrease in the organic loading and nutrient input required for phytoplankton growth. In fact, if the BOD_5 loading of the maturation pond does not substantially exceed 50 g/m^3/day (50 kg/ha/day), there may be a large biomass of filter-feeding zooplankton with phytoplankton largely absent to give a "clear water state" (Uhlmann 1980). The predominance of zooplankton occurs only in the absence of fish, which otherwise consume them with the development of phytoplankton. Pronounced diurnal fluctuation in dissolved oxygen in facultative stabilization ponds due to intense photosynthesis, from zero or near zero at night to double or triple supersaturation in the day, is a well known phenomenon (Bartsch and Allum 1957, Caldwell 1946, Williford and Middlebrooks 1967). Fish can usually be cultured only in maturation ponds in which phytoplankton biomass and the magnitude of the corresponding diurnal fluctuation in dissolved oxygen are lower.
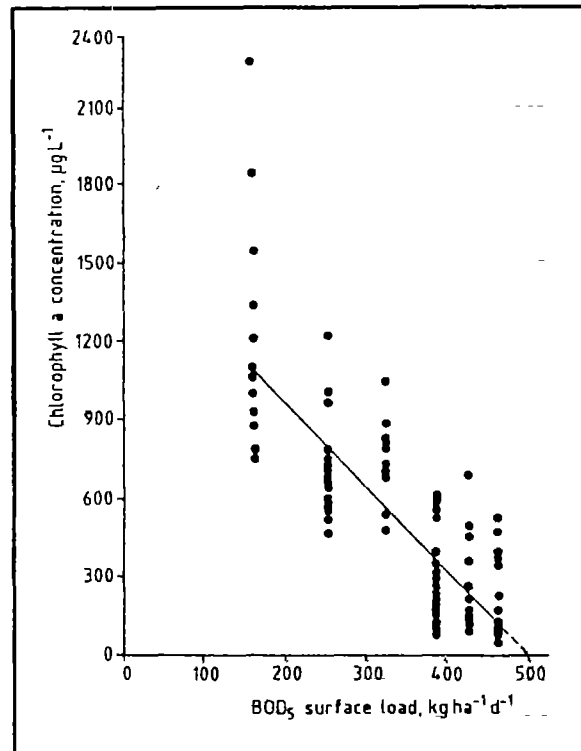
Figure 5.2 Chlorophyll-a concentrations at different organic surface loadings in facultative ponds receiving raw domestic wastewater in northeast Brazil (Adapted from Mara and Pearson 1986)

Nitrogen is of major significance for the productivity of phytoplankton and indirectly as a nutritional source for fish in waste-fed ponds, although certain forms of nitrogen, particularly un-ionized ammonia, are toxic to fish. Nitrogen removal from wastewater treatment in stabilization ponds may reach 80 percent or more, but there is scant agreement about the mechanisms involved. It appears that nitrite and nitrate concentrations are low, even though maturation ponds and the surface layers of facultative ponds are aerobic, and rates of nitrification and denitrification in stabilization ponds are minimal (Mara and Pearson 1986). Most of the possible nitrogen transformation routes in stabilization ponds appear to be short-circuited because of very limited nitrification and denitrification. Most nitrogen is cycled in a continuous flux between ammonia and the organic fraction. According to Ferrara and Avci (1982), the primary mechanism for nitrogen removal in waste stabilization ponds is through sedimentation of organic matter rather than ammonia volatilization. Phytoplankton take up some ammonia originally present in the influent waste water or ammonia released during bacterial degradation of organic matter. Some phytoplankton biomass eventually settles to the bottom sediment layer, where some cells die and nitrogen is removed from the pond water-column and effluent (Fig. 5.3: thickness of arrows shows relative quantitative importance of pathway; broken arrows show mechanisms of net nitrogen removal). Ammonia volatilization induced by high pH (from

intense phytoplankton photosynthesis) and sedimentation of organic nitrogen in phytoplankton biomass appear to be the two major mechanisms for nitrogen removal.
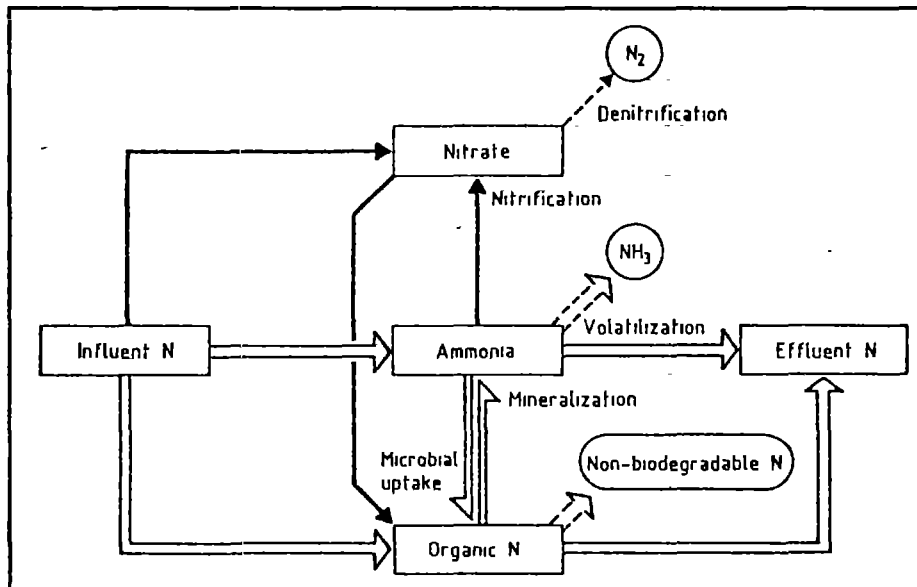
Figure 5.3 Nitrogen transformation and losses in a facultative waste stabilization pond (*Source:* Mara and Pearson 1986)

5.3.2 Fish culture with sewage

Fish cannot be cultured directly in sewage: its high BOD must be reduced before it can be used as a pond input. Hepher and Schroeder (1977) presented a three-category classification scheme for BOD reduction related to aquaculture:

1. Sufficient pretreatment of waste water so that it does not endager fish.

2. Dilution of waste water with water before introduction to the pond.

3. Dilution of waste water with the water in the pond. There is little danger to the fish if fresh sewage is discharged into a sufficient volume of pond water with a high dissolved oxygen concentration (Fowler 1944).

The scheme was subsequently modified to include four categories: pretreatment of waste water and dilution of waste water, corresponding to categories (1) and (2) above; a third category, pretreatment combined with dilution of waste water; and a fourth category, no treatment of waste water, corresponding to category (3) of the initial scheme (Allen and Hepher 1979). Both schemes of classification are somewhat arbitrary since all sewage reuse systems involve at least some pretreatment, even if only unintentional primary sedimentation of sewage in the feeder canals. Furthermore, dilution of sewage in pond water occurs whether or not it is mixed with water prior to addition to the pond.

The various methods of fish culture involving sewage may more usefully be characterized by a more detailed schematic representation (Fig. 5.4). A primary distinction is made between systems in which fish are cultured using raw sewage (or sewage which has received primary treatment only) and systems in which fish are cultured in sewage that has received secondary treatment. Most of the fish cultured in excreta reuse systems fall into the direct-reuse category, and fish culture is the major objective. In most excreta reuse systems in which fish are cultured with secondarily treated sewage, sewage treatment is the major concern. The culture of fish is incorporated into an existing sewage treatment system. Most examples in the second category are either experimental or small-scale units. Primary sedimentation is employed in the direct reuse of sewage in aquaculture, either intentionally by conventional sanitation technology (Munich sewage-fed ponds; Hungary), or unintentionally (India) in the sewage feeder canals leading to the ponds.
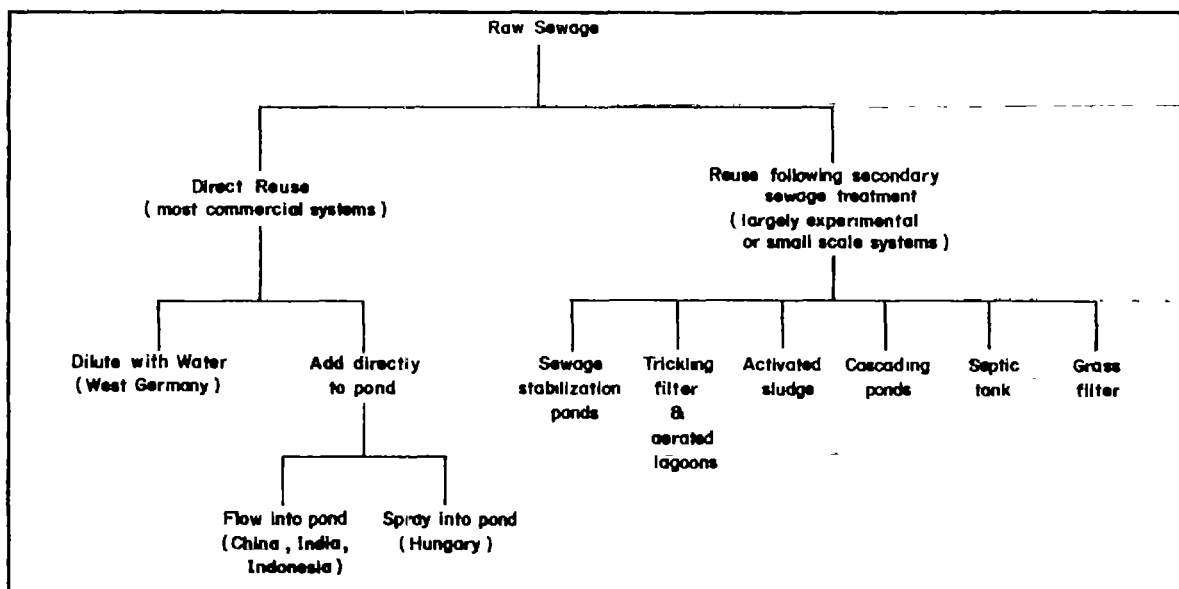
Figure 5.4   Various sytems of sewage reuse in aquaculture

In the Munich sewage-fed ponds, raw sewage is subjected to primary sedimentation and then diluted with river water at a ratio of 1:3 in early summer and autumn, to 1:6 in summer, before it is introduced into the pond by sprinklers. There is a relatively short detention time of 42 hours, with a minimum of 20-30 hours. Occasional fish mortality has been reported because of overloading with sewage (Liebmann 1960). The Munich sewage-fed pond system is a unique type of excreta-reuse system which was developed to suit the method of fish culture in Germany when it was developed over 50 years ago, essentially a monoculture of bottom-feeding common carp. It does not appear to have been replicated elsewhere (with the possible exception of East Europe), nor is it a system to be recommended for future implementation. The bottom-feeding common carp were cultured mainly in Germany and elsewhere in continental Europe in monoculture because there are no cultured fish of European origin which possess the ability to filter phytoplankton from the water. However, the introduction of filter-feeding Chinese carps,

silver carp and bighead carp has led to large increases in fish yield because the large biomass of phytoplankton that develops in fertilized ponds can be utilized (Colman and Edwards 1987). The Munich sewage-fed ponds have a rather short detention time for a fertilized pond system, less than two days, an insufficient time for the efficient production of phytoplankton and their use by filter-feeding fish. Benthic invertebrates, the major type of natural food of common carp, are less likely to be washed out of the system than plankton because they inhabit the mud. However, the system is an inefficient way to reuse excreta in aquaculture because plankton are not cropped effectively. This is reflected by an extrapolated net fish yield of only 0.5 ton/ha/yr.

Most sewage fish culture involves the direct reuse of raw, or at least partially sedimented, sewage in ponds in which the pond water itself is the diluent. There are systems in China, India, and, to a much lesser extent, Indonesia, in which sewage is allowed to flow into ponds in regulated amounts. An even distribution of sewage is desirable, particularly if diluent water is not used (Donaszy 1974).

Two types of wastewater flow systems were reported to be in use in Changsha, China: a continuous-flow system for more stable wastewater flow in larger ponds, and an intermittent-flow system for unstable wastewater flow in smaller ponds (Kuo 1980). Fertilization of sewage-fed ponds in China involves primary fertilization before fish are stocked, usually when the pond is dry, followed by supplementary fertilization (Anon. 1973a). The amount of sewage used for primary fertilization is 10-20 percent of the volume of the pond, with supplementary fertilization at an organic loading of about 30 kg BOD_5/ha/day, with loading from once or twice per day up to once every two days, depending on the color of the water and the growth and activity of the fish. An amount of sewage equal to about 10 percent of the total volume of the pond can be added in winter before fish are stocked (primary fertilization), but only 1-2 percent during the fish growth cycle (secondary fertilization). A weekly discharge of sewage into ponds does not adversely affect fish growth (Institute of Hydrobiology 1976).

A similar system of primary and secondary fertilization also appears to be used in the Calcutta sewage fisheries in India (Nair 1944b, Basu 1948). The ponds are dewatered at the end of the dry season in late March or early April, filled with raw sewage (considerable sedimentation of solids takes place in canals leading to the ponds) to a depth of 1 m, and left for 15-20 days to allow the development of phytoplankton. Sewage is subsequently added slowly, about once per month over a four- to five-day period to give a ratio of sewage:pond water of approximately 1:4. Sewage is fed into the ponds once a month during the cool and hot seasons, but water is let out of the ponds in the monsoon season to prevent flooding. According to Olah et al. (1986), the ponds are fed with sewage seven days per month for three hours during the morning at a rate of 130 m³ sewage/ha/day. This corresponds to a total of about 9 percent of the pond volume of sewage added per month, assuming a mean water depth of 1 m, and a more likely ratio of sewage:pond water of about 1:11 rather than 1:4 reported above.

The second type of system in which primarily sedimented sewage is directly added to the pond, with pond water itself acting as the diluent, is a large-scale experimental

system developed in Hungary (Kovacs and Olah 1984). It was suggested 60 years ago that it might be possible to spray undiluted sewage into ponds at some distance from the shore, with provision made to spray fresh water into the pond to alleviate depletion of dissolved oxygen in hot weather (Demoll 1926, cited by Mortimer and Hickling 1954). Such a system has been successfully implemented in Hungary. Optimal sewage application rates were reported to be 100 m^3/ha/day (Kovacs and Olah 1984) and 150 m^3/ha/day (Olah et al. 1986), with no effluent from the ponds. The detention time corresponded to the fish culture season with a recommendation that pond water should be drained only after at least 30 days following the last application of sewage.

The second major category of fish culture associated with sewage treatment is the culture of fish in waste-treatment systems involving secondary treatment. Most reports of fish culture are in maturation ponds of sewage stabilization pond systems (see Chapter 2 for operating systems and Chapter 4 for experimental systems) but there are also reports of fish cultivation in ponds which received the effluents of activated sludge and trickling filter plants.

There are relatively few reports of fish culture in existing sewage stabilization pond systems (Arthur 1983). There are reports of the intentional culture of fish in sewage stabilization pond systems in Malawi (Cross 1985, Balarin 1987). Waste water is used to maintain the water level in the ponds and counteract losses due to seepage and evaporation in Israel; sewage at least partially treated in stabilization ponds for a minimum of five days is used to top off ponds. The sewage input contributes only partially to fish production because the ponds receive other types of fertilizer and supplementary feed.

There are reports of the experimental culture of fish in ponds receiving trickling filter effluent (Hey 1955, Konefes and Bachmann 1970, Clarke and Frazer 1983, Gaigher and Toerien 1985, Sin and Chiu 1987ab) but no commercial systems are reported.

There are several reports of the experimental culture of fish in ponds receiving the effluents of activated sludge plants (Wolny 1964, Hallock and Ziebell 1970, Williams et al. 1973, Coleman et al. 1974, Buros 1977, Klekot 1978, Buras et al. 1987, Sin and Chiu 1987 ab). However, there is only one report of commercial fish culture using activated-sludge plant effluents. A pond on the estate of the Government Rifle Factory at Ishapore, near Calcutta, was fed with the effluent of an activated sludge plant Nair (1944b).

There is a report from Russia of fish culture in the last three ponds of a cascading series of six ponds fed with raw sewage (Mayenne 1933, cited by Mortimer and Hickling 1954; M. Prein, personal communication). The system was introduced at the sewage-field site of Luberzi near Moscow in 1927 to treat sewage and grow common carp without any dilution water. Ninety percent of the suspended matter of the raw sewage was removed in a pretreatment tank from which it was fed to the first pond. Fish culture was possible only in the last three ponds, about one third to one half of the total pond area, because extreme diurnal fluctuations in dissolved oxygen led to fish mortality in the upper ponds of the series. Fish productivity was reported to be 300-400 kg/ha/year.

There is also a report from Indonesia of fish culture in a pond that received the effluent of a septic tank mixed with river water in a 1:3 ratio (Vaas 1948). Finally, there is a report from Poland of fish culture in ponds fed with effluent from grass fields over which raw sewage was spread (Thorslund 1971).

5.3.3 Sewage purification

Data concerning the efficiency of fish for sewage treatment are lacking in the literature. Experimental studies in the United States on the use of fish stocked in sewage stabilization pond systems to improve sewage treatment were inconclusive (see Section 4.3.3). However, there are data from Hungary and China on the efficiency of waste treatment in sewage-fed ponds.

Sewage which received only mechanical pretreatment was sprayed into ponds which were drained after 120 days, at the end of the fish growing season in Hungary (Kovacs and Olah 1982, 1984; see Section 4.6.2 for details of the system). With 100 m³/ha/day of sewage sprayed into the pond, 400-500 kg nitrogen and 80-120 kg phosphorus were introduced into the pond system during the fish culture period. Eighty to 90 percent of the nitrogen and phosphorus load was eliminated.

Treated water on draining the ponds at the end of the fish growing season was reported to have the following characteristics:

BOD$_5$	4-5 mg/l
COD	60-70 mg/l
pH	8.1-8.3
Total N	2-3 mg/l
Total P	0.7-1 mg/l
ANA (anion active detergents)	0.2-0.3 mg/l

Additional data were reported in a summary report of recommended practices for sewage-fed fish culture in Hungary (Fish Culture Research Institute 1979). The sewage-fed ponds retained 70-80 percent of the total nitrogen load, with 20-30 percent in the effluent when the ponds were drained at the end of the season. The efficiency of water purification increased with an increase in the nitrogen load up to 2-3 kg N/ha/day, after which nitrogen removal efficiency decreased. Phosphorus retention efficiency was about 80-90 percent with an increase in the phosphorus content of the effluent above a loading of 0.3 kg P/ha/day. The efficiency of the ponds in the removal of total dissolved solids was only 20-40 percent, and above a loading of 30 kg total dissolved matter/ha/day the concentration in the effluent on draining the ponds increased considerably. Ninety to 95 percent of the anionic detergents were broken down in the ponds; with a loading of 0.3-0.4 kg ANA/ha/day, the concentration in the effluent never exceeded 0.15 mg/l, an acceptable level.

There was no effect of the fish on the reduction in BOD_5 because the fish did not play an important role in breaking down organic matter. However, the fish had an effect on the removal of plant nutrients, mainly phosphorus; there was only a 50-60 percent retention of phosphorus in the pond without fish but it increased to 85-90 percent with fish stocked in the pond. Six percent of the phosphorus was removed in fish biomass. It was also pointed out that it is necessary to retain the phosphorus-binding capacity of the sediments by periodic draining of the pond and drying of the sediments. Oxidation and liming the pond bottom facilitates good nutrient retention in the ponds.

Typical removal efficiencies for sewage-fed ponds in Changsha, China, were reported by Wang (1987) (see Section 2.6.2 for details of the system). With a hydraulic wastewater loading rate of 400-500 m^3/ha/day, a BOD_5 loading rate of 20-30 kg/ha/day, and a pond water temperature of 15-25°C, the following typical removal efficiencies were reported from waste water: suspended solids, 74-83 percent; BOD_5, 75-91 percent; total nitrogen, about 70 percent; and phenol, cyanide and heavy metals such as arsenic, cadmium, lead and mercury, above 90 percent.

5.3.4 Constraints to fish culture in existing systems

The fact that existing wastewater treatment plants were not designed for the cultivation of fish imposes constraints on excreta reuse (Henderson and Wert 1976, Tortell 1979). There are problems in pond management, particularly with regard to harvesting fish and maintaining adequate water quality for fish survival and growth. Harvesting fish from sewage stabilization ponds presents physical difficulties (Williams et al. 1973). The accumulation of sediment from effluents with a high suspended matter content, and the promotion of plant growth or "moss" such as filamentous algae because of the nutrient-rich water, both impede the use of nets.

There were heavy sludge deposits in some ponds in the San Juan sewage stabilization ponds in Lima. These were not removed prior to experimental fish culture trials (Moscoso and Nava 1984, Bartone et al. 1985). They constituted a significant oxygen sink which may have affected fish growth, and they were probably an important factor in the high mortality of freshwater prawns. Sludge deposits were of particular significance during harvesting, both in impeding the movement of seine nets and on water quality as the water level was drawn down. Gaigher and Krause (1983) and Henderson and Wert (1976) also pointed out that sewage stabilization ponds are usually very difficult to seine. Sewage stabilization ponds often have inadequate provision for the rapid draining necessary for efficient harvesting (Gaigher and Krause 1983, Bartone et al. 1985). Furthermore, some pond systems may be too deep for easy management (Henderson and Wert 1976).

It may be difficult to control the quality of sewage effluents at all times in stabilization pond systems, and shock loading may impair water quality and cause fish mortality. A shock loading in the Lima sewage stabilization pond system caused high mortality of Nile tilapia (Oreochromis niloticus) in a tertiary pond in which they had been growing well (Moscoso and Nava 1984, Bartone, et al. 1985). Mozambique tilapia (Oreochromis mossambicus) initially grew well in cages in polishing ponds fed with the

effluent of a trickling filter in South Africa, but high mortality occurred after raw sewage was fed directly into the ponds when problems occurred with the trickling filters (Gaigher and Toerien 1985).

Although fish can be cultured in maturation ponds in existing sewage stabilization pond systems, the management of such systems may be more difficult than in properly designed ponds. It has been suggested that fish could be cultured in cages suspended in ponds to facilitate fish harvest (Gaigher and Krause 1983), but this is unlikely to be economically feasible (see Section 5.2.6). New sewage treatment systems should be designed with a view to their use for fish culture if sewage-fed aquaculture is to become viable in a given area.

5.3.5 Role of fish in sewage treatment

There are various references in the literature related to the ability of filter-feeding fish stocked in sewage stabilization ponds to improve waste treatment by removing phytoplankton (Lin 1974, Hepher and Schroeder 1974, Schroeder 1975, Allen and Hepher 1979, Schroeder and Hepher 1979, Henderson 1982). According to Mara and Pearson (1986), it has been suggested that ponds can be considered useful tertiary treatment systems for sewage effluents because they reduce the concentrations of BOD, suspended solids, nitrogen, and phosphorus. However, few data support such beliefs. In fact, more studies indicate that stocking filter-feeding fish may have an opposite effect and lead to an increase in phytoplankton biomass because they reduce the biomass of zooplankton that also consume phytoplankton (Colman and Edwards 1987). Relevant studies in sewage stabilization ponds and eutrophic ponds and lakes are discussed below.

Ponds stocked with fish and fed with the effluent of an activated sludge plant in Poland had both night and day oxygen concentrations almost twice those of control ponds without fish (Wolny 1964, 1966; Thorslund 1971). Fish were believed to accelerate the cycling of nutrients in the pond and aid in sewage purification by stimulating the development of phytosynthesis. However, it cannot be deduced from the data whether phytoplankton biomass increased or decreased in response to stocking fish (see Section 5.5.3).

The effect of manipulating fish populations on phytoplankton and zooplankton was studied to determine the effect of fish on the final effluent of stabilization ponds (Williams et al. 1973). Great variations in phytoplankton standing crops were observed in different lagoons in the Rye Meads Sewage Purification Works in England. Some lagoons appeared consistently to support blooms, whereas others usually had clear water with small biomass of phytoplankton. Evidence was obtained that a large biomass of fish may exert considerable influence on the stabilization pond ecosystem by leading to high phytoplankton biomass. The fish (chub, *Leuciscus cephalus*; common carp, *Cyprinus carpio*; perch, *Perca fluviatilis*; and roach, *Rutilis rutilis*) removed large quantities of *Daphnia* and *Diatomus*, the major zooplankton herbivores. The fish affected not only the biomass of *Daphnia* but also the mean size of individuals because they selectively cropped the large species *D. magna* and the larger individuals of *D. longispina*. In contrast to the

herbivorous zooplankton, raptorial copepods (*Cyclops*) were more abundant in ponds with higher fish biomass because the fish did not appear to consume *Cyclops* to any great degree. The ability of *Cyclops* to increase as their prey (*Daphnia* and *Diatomus*) decreased due to fish predation was noted as puzzling. Rotifers also decreased in biomass with an increase in fish biomass, probably because of the increase in *Cyclops*, which feeds also on rotifers. However, the overall effect of stocking fish was to increase phytoplankton biomass because the fish reduced herbivorous zooplankton (Fig. 5.5: Arrows pass from predator to prey; dimensions of arrows and boxes are not to scale). A second mechanism postulated to explain the increase in phytoplankton biomass with the presence of fish was the release of nutrients into the water column by the bottom-feeding common carp disturbing the sediments.
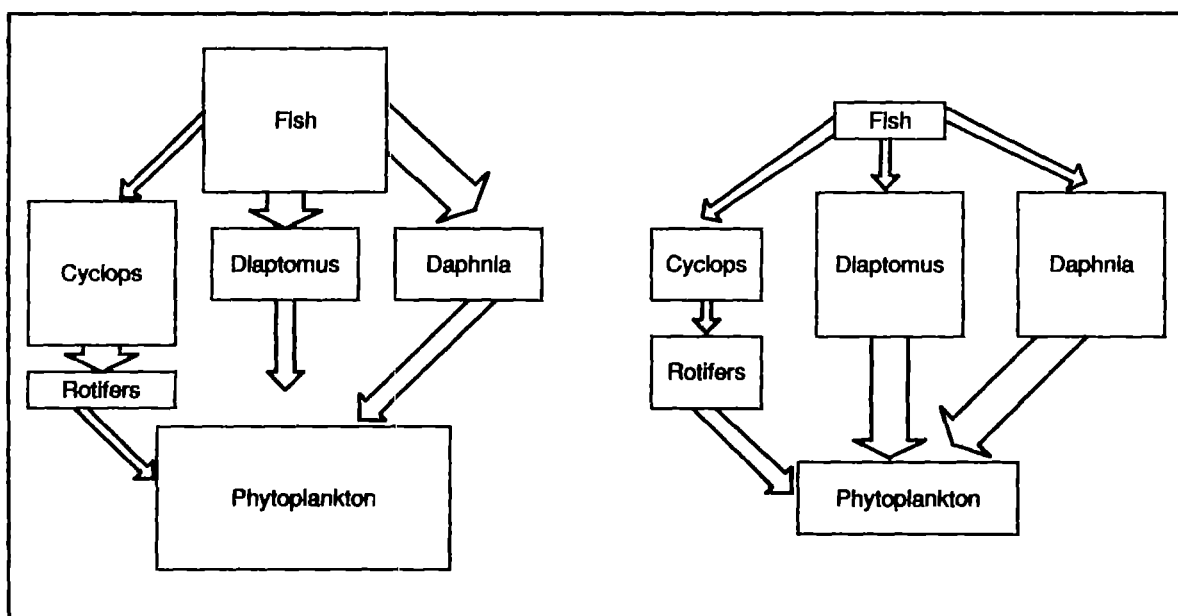
Figure 5.5   Relationships between fish and plankton in Rye Mead lagoons
(*Source:* Williams et al. 1973)

An attempt was made to assess the efficiency of fish in improving the effluents of sewage stabilization ponds at Quail Creek, Oklahoma (see Section 4.2.3), but it is difficult to reach conclusions concerning the role of fish in waste treatment because of a weakness in the experimental design. Fish were included in the system during the first year of operation of the new pond system but were excluded the following year for comparison. A higher quality effluent was demonstrated with fish, but the design did not permit the assessment of possible differences due to different years. Furthermore, it was suggested that the pond system, when stocked with fish in the first year, may have been better able to absorb nutrients than when not stocked with fish in the second year because the ponds were new in the first year. New ponds are better able to absorb nutrients than established ponds, and the observed differences in waste treatment between the two years may have been caused by variation in pond age rather than the presence or absence of fish.

The effect of Chinese carps stocked in a series of six sewage stabilization ponds fed with sewage that had undergone primary sedimentation was studied in Benton, Arkansas (see Section 4.2.3.2). The six-celled pond series was run initially with two parallel series containing three ponds in each series, one series stocked with fish and the other run without fish as a control. The average BOD_5 of the effluent from the series without fish was 38 percent higher than in the series with fish according to Henderson (1979), but Reed et al. (1979) concluded, after reanalyzing the data, that the two systems performed similarly; the one with fish consistently performed slightly better than the one without. Effluent suspended solids were similar in both systems. However, the third pond in the series with fish was dominated by green algae with no phytoplankton die-offs, compared to the third pond in the series without fish which had blue-green algal blooms, periodic phytoplankton die-offs, and odors. A stable, healthy community of green algae was attributed to fish grazing.

The six ponds were run in a single series with fish stocked in the last four ponds in a second phase. The system with fish consistently met secondary effluent standards for almost two years of operation, according to Henderson (1979). However, Reed et al. (1979) again questioned the role of fish in attaining the effluent standards because it was not clear whether fish, or the long detention time, or both, were responsible. The final mean effluent of 9 mg BOD_5/l is typical for a six-pond series of stabilization ponds of comparable detention time, although fish may have been responsible for the average of 17 mg suspended solids per liter in the final effluent, a figure two to three times lower than stabilization ponds not stocked with fish (Reed et al. 1979).

If the BOD_5 load of the maturation pond does not substantially exceed 5 g/m^3/day (approximately 50 kg/ha/day), there is a high probability that a large biomass of filter-feeding zooplankton (*Brachionus, Daphnia, Moina*) will occur to give a "clear-water state" with phytoplankton largely absent (Uhlmann 1980). The predominance of zooplankton occurs only in the absence of fish, which otherwise consume the zooplankton with the development of phytoplankton. A dense stock of fish which feeds on zooplankton may substantially increase the stability of the phytoplankton bloom.

There are numerous studies in ponds and eutrophic lakes that indicate that fish may actually cause phytoplankton biomass to increase. In Sweden, dense fish populations in experimental enclosures in eutrophic lakes led to low biomass of large filter-feeding cladocerans and blooms of blue-green algae, whereas similar enclosures without fish had a higher abundance of large cladocerans and lower phytoplankton biomass (Andersson et al. 1978). Leah et al. (1980) reported an experiment in which a shallow constructed lake was divided into two basins. In the basin to which fish had access from the river, phytoplankton biomass remained high, but in the basin with low fish biomass, zooplankton grazing reduced phytoplankton growth sufficiently to allow the development of aquatic macrophytes because of increased light penetration into the water column.

The activities of planktivorous and benthivorous fish in European lakes may have contributed to their eutrophication (Tatrai and Istvanovics 1986). The increase in silver carp biomass in Lake Kinneret, Israel, may have reduced the zooplankton biomass

with a concomitant increase in nannoplankton biomass (Spataru and Gophen 1985). Opuszynski (1978) formulated a theory of fish eutrophication (ichthyoeutrophication) to account for dense stocks of silver carp causing increases in phytoplankton biomass and primary productivity. An increase in phytoplankton in a lake food-web structure due to the addition of planktivorous fish was represented diagrammatically by Hessen and Nilssen (1986). (Fig. 5.6: Upper diagram without fish; lower diagram after introduction of planktivorous or detritivorous roach. Thickness of line represents relative significance of energy path; size of box represents biomass of each component.)
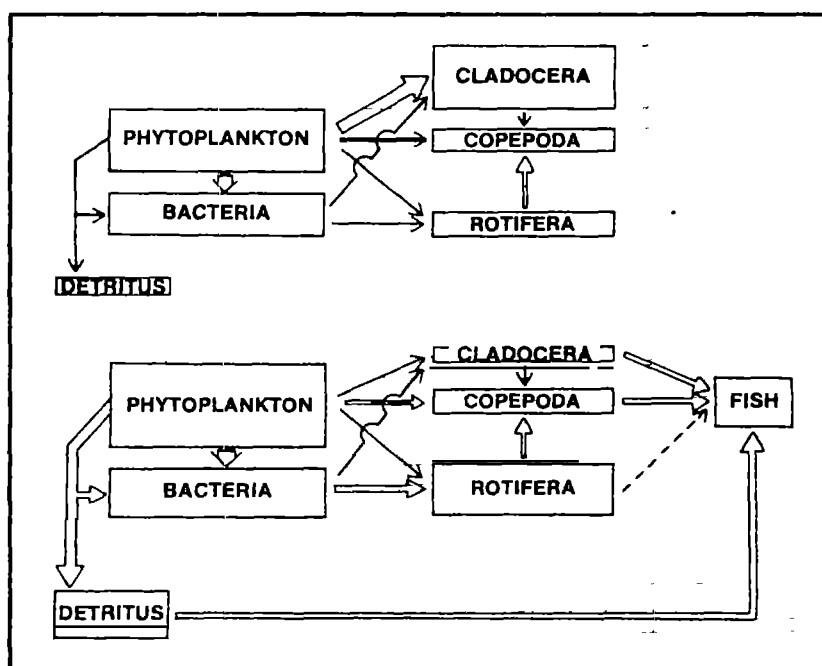
Figure 5.6   Change in eutrophic lake food web after addition of fish (Adapted from Hessen and Nilssen 1986)

It is most commonly assumed that bottom-feeding common carp stimulate phytoplankton growth by stirring up sediments and causing an increase in the nutrient content of the water column. However, the digestive activities of the fish also release nutrients that stimulate phytoplankton growth (Lamarra 1975).

The role of fish in waste treatment is still unclear, despite several references indicating that fish cause an increase in phytoplankton biomass. According to Prowse (1969), silver carp can prevent the formation of dense blooms of phytoplankton and retard the natural succession from green algae to blue-green algae that accompanies eutrophication. Henderson (1979, 1982) reported that Chinese carps in sewage stabilization ponds prevented the development of blue-green algae which were subjected to periodic die-offs. The carps promoted the formation of stable green algal communities.

The ability of filter-feeding fish to reduce phytoplankton biomass may be related to the biomass of fish stocked. A decrease in the dominance of blue-green algae and decreases in both phytoplankton and zooplankton biomass with fish present compared to controls without fish were reported in a study on the influence of fish in 6 m² enclosures in a eutrophic lake (Kajak et al. 1975). It was believed that the ability of fish to reduce rather than increase phytoplankton biomass (as reported by most other workers) was due to the high stocking density, 1-3 fish/m³, used in the study. High stocking densities of Nile tilapia similarly decreased blue-green algal biomass in experimental tanks at the Asian Institute of Technology (Colman and Edwards, unpublished data).

Fish stocked in excreta-fed ponds may be able to reduce phytoplankton biomass only at very high stocking densities. However, fish appear able to prevent the development of relatively slow-growing blue-green algae by favoring competition from more rapidly growing green algae (Colman and Edwards 1987). It can be calculated that nitrogen and phosphorus removed by the harvest of fish from maturation ponds represents only a small percentage of the nutrients in sewage introduced in the pond system during the fish growth cycle (Dinges 1982). The hypothesis that fish stocked in stabilization ponds are able to reduce phytoplankton biomass significantly does not appear to be generally valid.

5.3.6 Designs for optimal treatment or reuse

It is a useful theoretical exercise to attempt to compare a sewage stabilization pond system designed for optimal waste treatment with fish cultivation in the maturation ponds, and a sewage-fed pond system designed for optimal fish production irrespective of the area of land required for ponds.

A typical design figure for oxygen demand of sewage for an urban area of a developing country would be 40-50 g BOD_5/capita/day, with a wastewater contribution of 100 l/capita/day (Arthur 1983). Based on a contribution of 40 g BOD_5/capita/day, approximate probable BOD_5 loadings and sewage volumes from communities of various sizes are given in Table 5.1.

Assuming sewers are well constructed with infiltration of groundwater of only about 15 percent of wastewater flow (Arthur 1983), daily contributions of 40 g BOD_5 and 100 l of waste water/capita/day give a raw sewage with a BOD_5 of 350 mg/l (Arthur 1983). Using a city with a population of 100,000 as an example, there are 8,500 m³/day of raw sewage with a BOD_5 of 350 mg/l. The hypothetical design for optimal waste treatment is a conventional series of ponds made up of anaerobic, facultative and maturation ponds, with fish culture in the final maturation ponds in the series.

Anaerobic ponds are extremely efficient in the tropics and may remove approximately 80 percent of BOD (Mara and Silva 1979). However, the efficiency of anaerobic ponds is normally 40-60 percent and, while efficiency may be higher in hot climates, a 60 percent removal efficiency is recommended for design to allow for seasonal variation and poor operation (C. Bartone, personal communication). Following treatment in anaerobic ponds, the 8,500 m³ of raw sewage has a strength of 140 mg BOD_5/l.

Table 5.1
BOD₅ Loading and Sewage Volumes from
Typical Urban Areas in Developing Countries

Population equivalent	BOD₅ (kg/day)	Sewage (m³/day)
10,000	400	1,000
25,000	1,000	2,500
50,000	2,000	5,000
100,000	4,000	10,000
250,000	10,000	25,000

To estimate the area required for facultative ponds, the empirical formula given by Arthur (1983) is used:

$$\lambda = 20\ T - 60$$

where λ = surface loading rate (kg BOD_5/ha/day)

T = minimum mean monthly temperature (°C), 24°C for Bangkok as an example for the tropics

$$= (20 \times 24) - 60$$

$$= 420\ \text{kg}\ BOD_5/\text{ha/day}$$

The area required to load 8,500 m³/day of anaerobic pond effluent of 140 mg BOD_5/l (BOD_5 load of 2,083 kg/day) is 2.8 ha.

Two maturation ponds in series, each with a retention time of 7 days, produce a high quality effluent with a BOD_5 less than 25 mg/l (Mara 1976).

$$\text{Retention time (days)} = \frac{\text{Volume (m}^3\text{)}}{\text{flow rate (m}^3/\text{day)}}$$

Assume the maturation pond is 1.5 m deep. Area of the maturation pond is:

$$\text{Volume} = 14 \times 8,500\ \text{m}^3$$

$$= 119,000\ \text{m}^3$$

$$\text{Area} = \frac{\text{Volume}}{\text{depth}}$$

$$= \frac{119.000 \text{ m}^3}{1.5 \text{ m}^2} = 79,333 \text{ m}^2 = 7.9 \text{ ha}$$

Fish could still not be cultured in the two maturation ponds because dissolved oxygen and ammonia concentrations could be critical, as determined in the second and third ponds in series at San Juan in Lima (C. Bartone, personal communication). While the effluent from this pond system would be only about 20-30 mg/l of soluble BOD, the total BOD (which includes plankton biomass) would be about 60-120 mg/l. This effluent is suitable for fish culture in additional ponds to be fertilized with the treated effluent.

Assuming the same organic loading for the ponds as in the hypothetical case for optimal fish culture of 25 kg BOD_5/ha/day, the area required for 8,500 m³ of effluent with a total BOD of 60-120 mg/l is 20-40 ha of ponds. The total area required for optimal waste treatment is 2.8 ha of facultative ponds, 7.9 ha of maturation ponds, and 20-40 ha of maturation/fish ponds, a total area of 30.7-50.7 ha.

Two hypothetical designs are given for optimal sewage reuse in aquaculture. The first is based on a loading of clarified effluent of 150 m³/ha/day, as suggested by Hungarian experimental work (see section 4.5.2). Efficiently designed and operated primary sedimentation tanks should reduce the BOD_5 by 25-40 percent (Metcalf and Eddy 1979). A 30 percent reduction is assumed as a reasonable average efficiency, so following primary sedimentation the 8,500 m³/day of clarified sewage effluent has a strength of 245 mg BOD_5/l. Reuse of the 8,500 m³/day of clarified effluent at a loading rate of 100 m³/ha/day needs 85 ha with a corresponding organic loading to the ponds of about 25 kg BOD_5/ha/day. Such an organic loading may be suitable for the culture of tilapia, but it is approximately double the organic loading for Chinese carp recommended in Hungary. The raw sewage BOD of 350 mg/l used in the example for a developing country is higher than that in Europe, which is probably about 150-250 mg/l (C. Bartone, personal communication).

In the second hypothetical design for optimal sewage reuse in aquaculture, an anaerobic pond is included instead of primary sedimentation tanks because the latter are not normally a part of pond systems. The same 60 percent BOD_5 removal efficiency is assumed as in the optimal waste treatment design, which reduces the strength of the raw sewage to 140 mg BOD_5/l. It is assumed that the 8,500 m³/day of effluent are loaded into ponds at the same organic loading rates used for fish culture in the preceding examples, 25 kg BOD_5/ha/day. This gives a pond area requirement of 47.6 ha.

Table 5.2 shows the areas required for the various hypothetical designs and compares their fish production potentials. The pond areas in which fish can be cultured

and the corresponding total fish production are greater in the optimal reuse options than in the design example for optimal waste treatment. This is simply because more organic matter is removed in optimal waste treatment than in optimal reuse before sewage is loaded into the ponds. Lower fish production in design 2 than in design 1 of optimal reuse reflects the greater efficiency of anaerobic ponds than primary sedimentation tanks in BOD_5 removal. Fish culture in fully treated sewage stabilization pond effluents is about 25-50 percent as efficient in terms of fish production as the system which uses only clarified sewage effluents. The range of fish production in optimal waste treatment is based on the variation in total BOD_5 in maturation pond effluents. Fish production would more likely be correlated with mean total BOD_5 concentrations and would be correspondingly lower. In fact, there may be insufficient nutrients in fully treated sewage to sustain high levels of fish production.

Table 5.2
Comparison of Optimal Waste Treatment and Optimal Reuse for a Hypothetical Urban Area in a Developing Country with Population of 100,000

| | Optimal waste treatment | —— Optimal reuse —— | |
		Design 1	Design 2
Anaerobic pond	+	-	+
Primary sedimentation tanks	-	+	-
Area of facultative ponds (ha)	2.8	-	-
Area of maturation ponds (ha)	7.9	-	-
Area of maturation/fish ponds (ha)	20-40	85	47.6
Total area (ha)	30.7-50.7	85	47.6
Population equivalent/ha	3,257-1,972	1,176	2,100
Fish production (tons/year)	100-200	425	238
Fish production/population equivalent (kg)	1.0-2.0	4.3	2.4

The (relatively) small areas required for anaerobic ponds and primary sedimentation tanks have been omitted.

It is clear from the examples above that the greater the degree of sewage treatment prior to its reuse in fish culture, the lower the total production of fish from the system. However, there are insufficient data available on sewage-fed systems to support dependable predictions concerning their fish production potential.

The production of about 4.3 kg fish/capita from design 1 of optimal reuse is a significant amount of fish. It represents almost 20 percent of the 22.9 kg/capita/yr annual consumption of fish in Thailand, where fish provide 55 percent of the animal protein supply of the country (Josupeit 1981). The reuse of excreta in aquaculture clearly has potential to alleviate malnutrition in developing countries.

5.3.7 Sewage-fed fish culture in cages

The only reported commercial cultivation of fish in cages in association with excreta reuse is from Java, Indonesia (Vaas and Sachlan 1956) (see Section 2.5.1). However, there are reports in the literature of the experimental culture of fish in cages in systems associated with sewage treatment in sewage-fed ponds in the United Kingdom (Williams et al. 1973, Noble 1975), and in Kenya (Meadows 1983). Gaigher and Krause (1983) and Gaigher and Toerien (1985) cultured Mozambique tilapia (*Oreochromis mossambicus*) in cages in a sewage stabilization pond in South Africa to overcome the difficulty of harvesting fish from such a system and to prevent predation by catfish. Fish have also been cultured in cages in sewage stabilization ponds equipped with aerators in the United States (Suffern et al. 1978).

Fish harvest is made easier by stocking fish in cages within a pond system, but culture of fish in a pond associated with sewage treatment is likely to yield a higher economic return if the pond itself is used to confine the fish, rather than cages. They are an additional fish culture system, and the extra cost of cages may not be necessary and can diminish the economic viability of the fish culture operation.

5.4 Night-soil-fed ponds

Night soil is used as a fish-pond input in several Asian countries (see Chapter 2). It is also considered feasible to treat night soil in waste stabilization ponds (Stander and Meiring 1965). Night-soil ponds may be considered primary facultative ponds that receive batch loads of night soil transported to the pond by cartage rather than a continuous inflow of waste water (Mara and Pearson 1986), although a pond loaded as a primary facultative pond is not a suitable environment for fish. Night soil is a most useful pond input, but it should never be used fresh as a pond fertilizer; for public health reasons, it should be stored for at least two weeks before use (see Chapter 7).

The treatment of night soil was studied in an experimental waste-stabilization pond (Shaw 1962). An essential difference between the treatment of night soil and raw sewage in pond systems is the low water content of night soil relative to the organic matter content. There was no effluent from the night-soil-fed pond, and water had to be added to the pond to compensate for losses due to seepage and evaporation. There was also a slow buildup of potassium and sodium ions, but the rate of increase of dissolved solids was not considered likely to cause trouble over a period of years. It was suggested that it may eventually be necessary to pump out the pond contents and replace them with fresh water. Such an operation would be routine in a night-soil-fed pond with the periodic draining of the pond, and the accumulation of dissolved solids should not be a constraint in a waste-fed fish pond.

Volumes of excreta produced by different communities depend on diet, health, and climate (Feachem et al. 1983). Individual wet fecal weight can vary from less than

20 g to 1.5 kg/day. Based on national or regional averages, Europeans and North Americans produce 100-200 g/day compared to mean wet fecal weights of 130-520 g/day in developing countries. With a total daily volume of excreta and anal cleansing material of 1.5 l/adult, the strength of adult night soil in developing countries may be calculated to be 21,700 mg BOD$_5$/l.

An attempt was made to determine the rate of organic loading of night-soil-fed fish ponds based on data in the literature (Table 5.3). The daily weights of night soil added to ponds were calculated from data presented in the literature and the organic loading rates in terms of kg BOD$_5$/ha/day were estimated assuming a production rate of night soil of 1.5 l/person/day with an oxygen demand of 21,700 mg BOD$_5$/l. The amount of night soil added to ponds was reported to vary widely, due no doubt to its availability and relative importance to other pond fertilizer and feed inputs, rather than to maximal loadings commensurate with fish production. Loading rates of night soil ranged from 1.5 kg to 16.3 kg BOD$_5$/ha/day. There is little indication in the literature of the optimal loading of night soil for fish culture. However, the dissolved oxygen in some night-soil-fed ponds with overhung latrines in Java, Indonesia, was low during the day, indicating overloading (Djajadiredja et al. 1979). The estimated maximum loading rate reported for Java is 16 kg BOD$_5$/ha/day, which may approximate the optimal loading rate of night soil into ponds. The same upper loading rate was reported for Taiwan (Lin 1968). The highest estimated loading rate, 24 kg BOD$_5$/ha/day from Malaysia, was into a pond with a continuous supply of running water (Seow et al. 1979).

The reuse of night soil in both agriculture and aquaculture has declined in some countries in which its use has been traditional. Reuse of excreta was traditional in Japan, but the practice declined rapidly after World War II because of rapid industrialization and rising labor costs (Takahashi 1978). The use of night soil in aquaculture is now rare in Taiwan and Hong Kong because the intensification of livestock agriculture frequently integrates farming systems with fish culture. Livestock manure can be conveniently disposed of in the ponds, and the need to purchase, transport and spread bulky night soil is eliminated. There has been a parallel decline in the use of organic fertilizers in agriculture in both countries because of an increasing shortage of farm labor due to industrialization. The reuse of bulky organic manures has become expensive, and the ready availability and relatively low price of chemical fertilizers further discourage night-soil reuse.

The fertilization of ponds with night soil was reported to be decreasing in Malaysia because the traditional bucket system was being replaced by sewerage. Municipalities did not issue permits for delivery of night soil because of concern for public health, and most fish farms were integrated with livestock to provide pond fertilizer (Seow et al. 1979).

A decline in the reuse of night soil in China may be taking place because Chinese freshwater aquaculture is becoming more intensive, and organic fertilizers are being replaced by inorganic fertilizers and supplementary feed (Li 1987). A recent report states that Shanghai has a night soil disposal problem because farmers are losing interest in

Table 5.3
Night-soil Loading Rates of Fish Ponds

Country	Quantity of night soil added	Loading rate (kg BOD₅/ha/day)	Citation
Hong Kong	6.1 tons/ha/month, or 0.2 ton/ha/day	4.3	Hickling (1947) cited by Mortimer and Hickling (1954)
Indonesia	10-20 persons used overhung latrine on 400 m² pond, or 250-500 persons/ha/day	8.1-16.2	Djajadiredja et al. (1979)
Malaysia	3.6-4.5 m³/month, or 0.12-0.15 ton/ha/day	2.6-3.3	Seow et al. (1979)
	7.9 m³/week, or 1.1 tons/ha/day	23.9	Seow et al. (1979)
Taiwan	Up to 205 tons/ha/yr, or 0.75 ton/ha/day assuming 9-month fish-growing season	16.3	Lin (1968)
Taiwan	38 tons/ha/yr, or 0.14 tons/ha/day assuming 9-month fish-growing season	3.0	Tang (1970)
Taiwan	4.5 tons/ha, 4-6 times in 9-month growing season, or 0.07-0.10 ton/ha/day	1.5-2.2	Lo (1979)

night-soil reuse (China Daily 1987). The rapidly developing chemical fertilizer industry supplies farmers with relatively cheap fertilizers that are easier to transport than night soil. Farmers in Jiangsu and Zheijing provinces have stopped transporting night soil from Shanghai, and farmers in rural Shanghai are using less night soil. Rural industrialization means that there are fewer people on the farm to reuse night soil.

However, reuse of night soil in aquaculture will no doubt continue in those countries where it is traditional and large segments of the population have a relatively low economic status. Djajadiredja et al. (1979) suggested that the reuse of night soil in fish ponds in Java should be continued because the system provided badly needed protein, but he suggested modifications to the system to improve sanitation. The storage of night soil prior to discharge to the pond, perhaps by the use of a Chinese three-tank system that allows for excreta to be stored prior to discharge to the pond, was suggested as a possible way to upgrade the system (McGarry and Wing 1986). Furthermore, the reuse of night soil in ponds in China has been improved recently by storage of excreta in a sealed tank for a few weeks prior to reuse (FAO 1977, 1979, 1983). An improved system for overhung latrines has been designed with a small sedimentation pond linked to the fish pond in Vietnam. Water is prevented from flowing directly from the fish pond into the river by the installation of a pipe fitted with a trap door that allows water to enter the pond from the river at high water but prevents escape of pond water to the river at low water (D. C. Van Ginhoven, personal communication).

5.5 Dynamics of waste-fed ponds

5.5.1 Biota

The objective in fertilizing a pond with excreta is to produce natural food for fish. The reuse of raw sewage or fresh night soil in ponds should be avoided because several species of fish feed on fecal solids (Fowler 1944). Hoffmann (1934) reported that feces dropped directly into ponds in China were consumed directly by fish. Common carp (*Cyprinus carpio*) raised in cages in fecally polluted streams in West Java fed voraciously on human feces, and the gut contents of sampled fish contained mainly human feces (Vaas and Sachlan 1956). Human feces were reported to be a most effective fattening diet for silver-striped catfish (*Pangasius pangasius*) raised in wooden cages in Thailand (Thiemmedh 1961). Sewage should be sedimented and night soil stored prior to use as pond fertilizers to minimize consumption of fecal solids by fish.

Food chains in an excreta-fed pond are complex. They involve ultimate decomposers or bacteria, phytoplankton, zooplankton, and invertebrate detritivores (Fig. 5.7). Excreta are a form of detritus or particulate organic matter which are decomposed by bacteria. Nutrients released by the bacterial degradation of excreta are taken up by phytoplankton. Zooplankton graze phytoplankton and small detritus particles coated with bacteria. The latter also serve as food for benthic invertebrate detritivores. The major sources of natural food in an excreta-fed pond are plankton (bacterio-, zoo-, and especially phytoplankton). Benthic invertebrates, mainly chironomids, also serve as fish food but are quantitatively less important than plankton. It follows that to optimize fish production in an excreta-fed pond, most of the fish should be filter feeders that can exploit the plankton. A major reason for low fish yields in the Munich sewage-fed ponds is that the ponds are stocked only with common carp, a carnivorous or detrital benthic-feeding fish (Fig. 5.7: solid lines represent flows of particulate matter; broken lines, flows of

dissolved nutrients; heavy lines, major components and pathways). Much higher yields have been reported from experimental sewage-fed ponds in Hungary (a similar, temperate climate) stocked with filter-feeding fish.
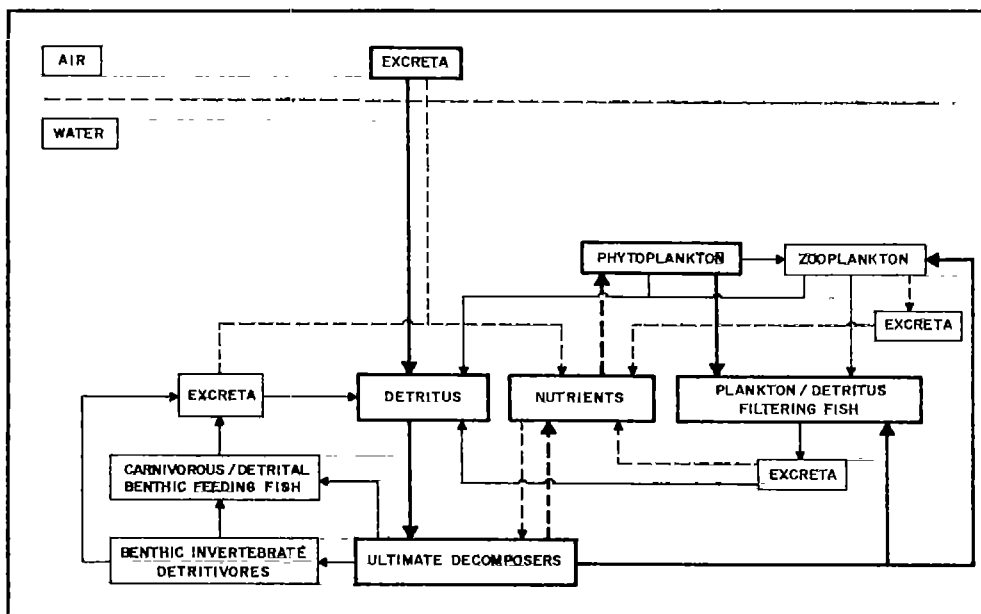
Figure 5.7 Food chains in an excreta-fed aquaculture system
(*Source:* Edwards et al. 1988b)

There is disagreement in the literature concerning the relative importance of the various food-chain pathways in excreta-fed ponds. The topic was reviewed recently, and it was concluded that phytoplankton are the major source of natural food for plankton or detritus-filtering fish (Colman and Edwards 1987). The mean phytoplankton biomass in sewage-fed ponds in Hungary used to raise Chinese carps was about 13 mg/l (Fish Culture Research Institute 1979). A peak phytoplankton biomass of 60 mg/l was reported from Hong Kong, but concentrations were usually less than 30 mg/l in polishing ponds used to raise Mozambique tilapia (*Oreochromis mossambicus*) (Sin and Chiu 1987a). Mean phytoplankton biomass concentrations in septage-fed ponds used to raise Nile tilapia (*Oreochromis niloticus*) were about 25-35 mg/l (Edwards et al. 1984, 1987). Tilapia are more sensitive to low dissolved oxygen concentrations than Chinese carps, and the former can probably be cultured in ponds with higher concentrations of phytoplankton biomass than the latter, as implied by the data above.

It is desirable to determine not only the biomass or standing crop of the various kinds of natural food in excreta-fed ponds, but also their rates of production or productivities. Productivities are more important than biomass in assessing the potential relative contributions of various types of natural food to fish nutrition, but there are major methodological difficulties in measuring phyto-, zoo-, and bacterioplankton productivities. The maximum sustained rate of photosynthesis in a tropical fish pond may be about 4 g C/m²/day, about 8 g phytoplankton biomass/m²/day, or about 30 tons dry weight/ha/yr

(Colman and Edwards 1987). A highly efficient feed-conversion ratio of phytoplankton to fish of 2:1 (dry phytoplankton to wet fish) has been reported, and the maximum theoretical fish yield from an excreta-fed pond may be about 15 tons/ha/yr.

Zooplankton are an important natural food for filter-feeding fish, but there appears to be a lack of data on zooplankton productivity in fertilized tropical fish ponds. The highest zooplankton productivity rates for eutrophic waters in temperate regions are only 0.5-1.3 tons dry matter/ha/yr (Edwards and Densem 1980). Zooplankton biomass in septage-fed ponds was almost an order of magnitude lower than that of phytoplankton (Edwards et al. 1984, 1987). Zooplankton productivity should be much lower than that of phytoplankton because the generation time of the former is much longer than that of the latter.

The importance of benthic chironomids as feed for benthic-feeding fish such as common carp is well known (Hepher and Schroeder 1977, Edwards and Densem 1980). An inverse relationship was found between chironomid and fish biomass in ponds fed by effluent from an activated sludge treatment plant (Hallock and Ziebell 1970). Benthic biomass tended to be higher in winter when cool temperatures slowed fish feeding, and in ponds without fish. Total benthic productivity was estimated at 14.2 tons wet weight/ha/yr or 1.6 tons dry weight/ha/yr. Zoobenthos may be more productive than zooplankton; most estimates of zoobenthos productivity are below 0.7 tons dry weight/ha/yr, but productivities of up to 2.5 tons dry weight/ha/yr have been recorded (Edwards and Densem 1980).

The predominant color of a well-managed, excreta-fed fish pond is green due to the predominance of green and blue-green phytoplankton in the water column. The color of the pond water is an important criterion of pond fertility and was reported to be an important guide to loading excreta into the ponds in both China and Malaysia (Institute of Hydrobiology 1976, Seow et al. 1979). According to the Chinese study, brown or green reflects the color of dominant phytoplankton, but black-colored water indicates too high a loading, and sewage discharge should be reduced. Secchi-disc visibility can also be used as a guide to loading sewage, with the addition of more sewage if the visibility exceeds 20-30 cm. The growth and behavior of the fish are also important criteria. Fish never swim near the surface in infertile ponds but swim continuously near the surface throughout the day when a pond is overloaded. A correct balance between phytoplankton biomass and dissolved oxygen concentration is indicated by fish floating with their heads inclined towards the water surface to breath air only in the early morning (Institute of Hydrobiology 1976).

It has been suggested that insects from sewage stabilization ponds could be used as high-protein animal feed for livestock (Schurr 1972, 1976). A floating mass of plant growth consisting of filamentous algae and aquatic macrophytes provided cover for large numbers of invertebrates in a secondary sewage stabilization pond, and protein levels of the combined plant and animal biomass ranged from 15 percent to 25 percent. It was suggested that the same machinery used to produce alfalfa meal could be used to dry and chop the biomass for use as a nutritional supplement for animals. However, such biomass is unlikely to be used commercially. Floating vegetation is not a feature of well-managed sewage

stabilization ponds, and the supply of biomass would be unreliable. Furthermore, it is unlikely that it would be economically feasible to dry aquatic macrophyte biomass because of its high moisture content.

5.5.2 Fish species

The wide variety of fish species that have been raised in excreta-fed systems reflects, to a large extent, the culture of local species in different countries rather than fish optimally suited to such environments (Chapters 2 and 4). Common carp (*Cyprinus carpio*) is the major cultured species in the Munich sewage-fed ponds, with tench (*Tinca tinca*) as a secondary species. Common carp are also raised in Indonesia, most notably in cages in fecally polluted streams. Most night-soil-fed ponds in Java have a polyculture of at least five of the following six species: common carp, kissing gouramy (*Helostoma temmincki*), silver barb (*Puntius gonionotus*), nilem carp (*Osteochilus hasseltii*), giant gourami (*Osphronemus goramy*) and tilapia (*Oreochromis* spp.) (Djajadiredja et al. 1979). Chinese carps and Indian major carps are the major species raised in excreta-fed systems in China and India, respectively.

More than 70-80 percent of the biomass of fish stocked in sewage-fed ponds in China are filter-feeding silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*), with bottom-feeding fish making up the remainder (Kuo 1980). Grass carp (*Ctenopharyngodon idella*) grew well only during the initial period in a sewage-fed pond in Hong Kong when duckweed was abundant, but its growth was poor once the duckweed was consumed (Sin and Chiu 1987b). The appropriate combination of silver carp and bighead carp depends on the composition of the plankton, with bighead carp making up less than 15 percent of the stocked fish if phytoplankton predominate. For example, yields of less than 7.5 tons/ha/yr, 5.8 tons/ha/yr, and 4.2 tons/ha/yr were reported from sewage-fed lakes in China, with bighead carp stocked at 15 percent, 25 percent, and 37 percent of the stocked fish, respectively (Institute of Hydrobiology 1976). However, the proportion of filter-feeding fish such as bighead carp, crucian carp (*Carassius auratus*), and silver carp is decreasing in China as fish culture becomes more intensive with increasing use of supplementary feed (Li 1987).

Traditional freshwater fish culture in Europe is a monoculture of common carp, which does not utilize phytoplankton. There is a lack of native European fishes which can filter phytoplankton, but Opuszynski (1964) drew attention to the feasibility of using the Chinese silver carp to consume natural food not eaten by common carp. Chinese carps were used in an experimental sewage-fed fish project in Hungary, where they constituted 90-95 percent of both the initially stocked fish and the yield (Kovacs and Olah 1984), but the optimal stocking structure in sewage-fed ponds in Hungary was reported to contain 50-65 percent silver carp (Kovacs and Olah 1984). In another paper from Hungary it was reported that the optimal stocking structure of silver carp should be 60-70 percent, or even 80 percent, of the total because the fish is the main consumer of phytoplankton, with 10-15 percent bighead carp, 10-15 percent common carp, 5 percent tench, and 3-8 percent grass carp (Fish Culture Research Institute 1979).

While sewage-fed fish culture in India relies to a large extent on native Indian major carps, a trial was conducted in which a private, sewage-fed pond was stocked with both Indian major carps (catla, *Catla catla*; mrigal, *Cirrhina mrigala*; rohu, *Labeo rohita*) and Chinese silver carp (FAO 1973, Ghosh et al. 1973, 1974). Silver carp grew much faster than the Indian major carps, but the former were stocked at a density of only 0.01 fish/m^2 compared to the latter at 5 fish/m^2.

Tilapia are cultured to a much lesser extent in excreta-fed systems than Chinese carps and Indian major carps because the carps are traditional fish in both China and India, countries with considerable excreta reuse. Tilapia culture is constrained in China because of the temperate climate, although it is the main species in polyculture with Chinese carps in water bodies enriched with sewage in southern China (Anon. 1980). According to Wang (1987), tilapia (*Oreochromis mossambicus*) are raised in sewage-fed ponds in Changsha. Tilapia have not been widely promoted in India, although Mozambique tilapia (*Oreochromis mossambicus*) are cultured to some extent in the Calcutta sewage-fed fisheries (A. Ghosh, personal communication). However, tilapia may be a more suitable fish for excreta-reuse systems than carp because tilapia are better able to tolerate the adverse environmental conditions in such systems. The promotion of tilapia culture in excreta-reuse systems is being furthered by major research programs raising the species in sewage stabilization pond effluents in Peru and in septage-fed systems in Thailand.

There are reports of the culture of less suitable species than Chinese carps, Indian major carps, and tilapia in excreta-fed systems. The temperate rainbow trout (*Salmo gairdneri*) grew well in the Munich sewage-fed ponds, and fry attained at least 250 g in one season. However, trout swim close to the surface, and high mortality was caused by fish-eating birds. Harvest was difficult because trout were sensitive to the poor water quality in the harvesting pit. However, survival of rainbow trout stocked in polishing ponds fed with effluents from an activated-sludge plant that had been treated further by sand and gravel filters did not exceed 1 percent in the United States (Hallock and Ziebell 1970).

It was recommended that milkfish (*Chanos Chanos*) be introduced into fecally polluted Beira Lake, Sri Lanka, to utilize lake phytoplankton (Mendis 1964). Sreenivasan (1967) reported "good fish yields" of over 1 ton/ha/yr of milkfish as well as the usual Indian major carps (catla, mrigal, and rohu) in fecally polluted fort moats in India. It was also reported that milkfish were raised in Indonesia in ponds fed with "dilute sewage," presumably fecally polluted surface water, and yields were high (Huet 1972). However, the species was reported to have poor growth and survival compared to Indian major carps and Chinese carps in ponds fed with the effluent of sewage stabilization ponds in India (Kutty 1979, cited by Jhingran 1982).

Good growth of walking catfish (*Clarias batrachus*) was reported in a sewage-fed pond in West Bengal, although its growth rate in tanks fed with sewage stabilization pond effluent was 2.5 times less than that of common carp (Ghosh et al. 1976). Catfish (*Pangasius larnardi*) are raised in ponds with overhung latrines in Vietnam (D. C. Van Ginhoven, personal communication 1986) and silver-striped catfish (*Pangasius pangasius*) were fed human feces in Thailand (Thiemmedh 1961). Channel catfish

(*Ictalurus punctatus*) raised in sewage stabilization ponds in Oklahoma grew well only when young, possibly because the adults feed on larger organisms that were not readily available (Coleman et al. 1974).

A study was undertaken in India with the freshwater prawn *Macrobrachium lanchesteri* in various dilutions of domestic sewage. Concentrations of 25 percent, 50 percent, 75 percent, and 100 percent sewage were lethal, and the survival time of the prawns decreased with increasing concentrations of sewage. The prawns exhibited a marked surfacing activity within ten minutes of exposure to 25 percent sewage. Backward darting and loss of balance occurred within 30 minutes, and the prawns became translucent with 50 percent mortality. All prawns died within 40 minutes of exposure. The prawns exhibited similar behavior in other concentrations, with 100 percent mortality occurring within 20 minutes, 17 minutes and less than 10 minutes in concentrations of 50 percent, 75 percent, and 100 percent, respectively. In sublethal sewage concentrations of 0 percent, 1 percent and 4 percent, prawn behavior was normal, and they remained on the bottom of the aquarium with normal pleopod movements. In 7 percent and 10 percent sewage concentrations, occasional surfacing and darting movements indicated stress. However, prawns demonstrated considerable growth on continued exposure to sublethal concentrations of 0-10 percent sewage when fed *ad libitum* with *Tubifex tubifex* worms (Ponnuchamy et al. 1980). However, studies in Peru demonstrated that *Macrobrachium rosenbergii* are not suitable to cultivate in sewage-fed ponds (see Section 4.2.2).

There is great confusion in the literature concerning fish feeding on natural food, particularly concerning filter-feeding fish (Colman and Edwards 1987). Fish are generally divided into different types according to their natural nutritional habits, that is, fish that feed on phytoplankton, or zooplankton, or benthic animals, to list the main types of natural food in excreta-fed systems. However, it appears that Nile tilapia and silver carp (fish which are usually regarded as phytoplanktivorous) are not strict herbivores but feed on whatever particles are suspended in the water, including zooplankton and bacteria-coated detritus. The diet of common carp includes mainly zoobenthos, but the fish fed on the blue-green alga *Microcystis*, the dominant phytoplankton in experimental ponds fed with the effluent of a sewage stabilization pond (Krishnamoorthi et al. 1975). Common carp raised in an experimental pond fed with the effluent of a sewage stabilization pond were dissected and a wide variety of algae, including *Microcystis*, was found in the digestive tract (Muthuswamy et al. 1974).

There is pronounced uncertainty concerning the types of phytoplankton fed upon by filter-feeding fish (reviewed by Colman and Edwards 1987). It is commonly believed that certain species of phytoplankton, particularly blue-green algae, are indigestible to fish and therefore "undesirable." Tilapia have been shown to digest blue-green algae readily, and there is evidence that silver carp also digest blue-green algae. Ghosh et al. (1973) examined the gut contents of silver carp raised in a sewage-fed pond. The dominant phytoplankton in the digestive tract was the blue-green alga *Oscillatoria*, the photosynthetic pigments of which were completely absorbed in the posterior region of the gut.

5.5.3 Environmental factors

Two types of balances are of concern in excreta-fed aquaculture: (a) organismic balance, to produce an optimal supply of natural food in the pond for fish (see Section 5.4.1), and (b) chemical balance, to generate sufficient oxygen for the growth of fish and their natural food organisms while minimizing the buildup of toxic metabolic products (Colman and Edwards 1987). Chemical balance is usually regulated in excreta-fed ponds by adjusting pond organismic balance because the most important chemical transformations are biologically mediated.

The large diurnal fluctuations in chemical parameters in fertilized tropical ponds, particularly dissolved oxygen (DO), are well known (Chow 1958, Dunn 1967, Muthuswamy et al. 1978). It was believed that the chief source of dissolved oxygen in a manured pond was the atmosphere (Bhaskaran 1952) and that the rate of addition of organic matter to the pond could be determined from its BOD_5 (Bhaskaran 1952, Schroeder 1974, Schroeder and Hepher 1979). However, it is now appreciated that depletion of dissolved oxygen in fertilized ponds results primarily from the high nighttime rates of respiration of dense concentrations of phytoplankton (Romaire et al. 1978, Colman and Edwards 1987).

Biological activity in the pond accounts for the greatest variation in DO. The major source of DO in the water is the photosynthesis of phytoplankton during daylight, while the major cause of oxygen depletion is the respiration of pond biota. In a well-managed excreta-fed pond, the minimum DO in the early morning hours is only a few mg DO/l, but the pond is supersaturated with oxygen in the late afternoon.

The following equation shows the factors that influence DO at dawn, the critical period for low DO in an excreta-fed pond (Romaire et al. 1978):

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

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

Excreta-fed ponds are normally supersaturated with DO at dusk due to phytosynthetic oxygen production. It has been estimated that the net loss of oxygen by diffusion from a pond with double supersaturation in the late afternoon may exceed 4 mg DO/l, although there may be diffusion into the pond from the air during the early morning hours. Mud respiration probably lowers the DO in the water by less than 1 mg/l overnight. A fish population weighing 3,000 kg/ha would lower the DO in the water by only about 1 mg/l overnight. The most important factor in reducing the DO of the water overnight is the respiration of plankton (bacterio-, phyto-, and zooplankton). It has been estimated that plankton respiration can lower overnight DO by 8-10 mg/l, much more than

the other factors involved. The oxygen demand of organic waste is not included in the equation above because it is accounted for in the BOD of plankton and mud. However, it has been estimated that the BOD of excreta added to a pond is a minor factor in the nighttime consumption of oxygen, less than 0.5 mg/l. The oxygen demand of organic waste added to a pond is a major factor only in an anaerobic pond without phytoplankton, in which a high organic loading leads to depletion of oxygen by bacterial respiration. Thus, it is not the BOD of the excreta itself that causes the greatest reduction of dissolved oxygen in an excreta-fed pond, but the respiration of the phytoplankton that develops as a result of the nutrients contained in the excreta.

Phytoplankton are often considered undesirable in ponds in the West because dense blooms can deplete dissolved oxygen at night and cause fish mortality. In contrast, they provide feed for the greatest percentage of farmed fish in Asia. However, phytoplankton which exhibit positive net 24-hour primary productivity are net oxygen contributors to the pond (Colman and Edwards 1987). Maximum net primary productivity occurs at an algal standing crop that is less than the maximum, when there is the maximum rate of production of phytoplankton biomass for fish feed as well as maximum net generation of dissolved oxygen (Fig. 5.8). The objective in an excreta-fed pond should be to maintain the algal standing crop at the optimum for net primary productivity by balancing the production of phytoplankton biomass in response to fertilizing with excreta, with the grazing of phytoplankton biomass by filter-feeding fish.
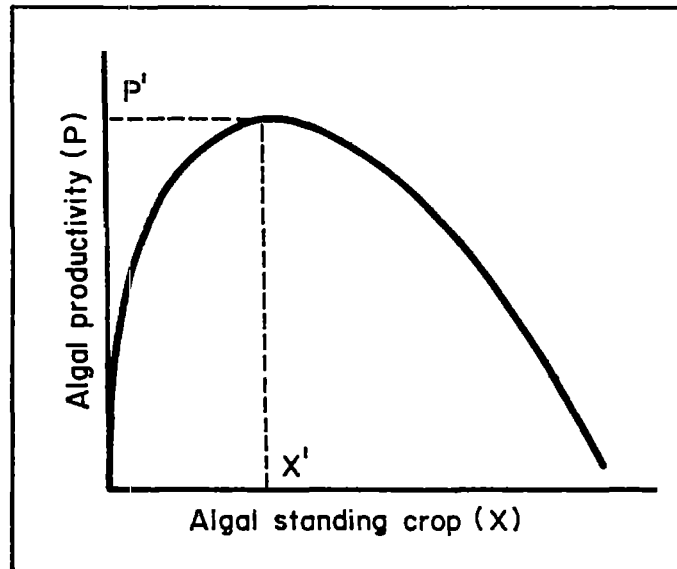
Figure 5.8 Generalized relationship between algal productivity and algal standing crop
(P' = maximum algal productivity;
X' = maximum algal standing crop;
Source: Colman and Edwards 1987)

Fish kills have been reported from overloaded excreta-reuse systems, but it is seldom possible to ascertain the cause because water quality was not appropriately monitored. There are at least three possible causes of death from overloading an excreta-reuse system. The first is depletion of dissolved oxygen from bacterial respiratory oxygen demand, in response to a sudden large increase in organic matter. Second is the nighttime depletion of dissolved oxygen from the respiratory demand of an excessive concentration of phytoplankton which grew in response to an increase in inorganic nutrients. Third is high concentration of ammonia in the excreta. Fish death was reported from the Calcutta sewage fisheries due to overloading with sewage and continuous cloudy weather without winds. Death was probably due to asphixiation because the fish gasped for air at the surface (Nair 1944a). Bhaskaran (1952) reported large-scale mortality of fish in the Hanakhali sewage fishery near Calcutta. He identified the cause as a sewage overload. Heavy of fish was reported in polishing ponds fed with the effluent of a biological filter in South Africa, attributed to nighttime dissolved oxygen depletion from phytoplankton blooms (Hey 1955). A sudden heavy die-off of common carp in experimental tanks fed with sewage stabilization pond effluent in India was attributed to depletion of dissolved oxygen in the predawn hours (Krishnamoorthi et al. 1975, Krishnamoorthi and Abdulappa 1979). The death of Chinese carps stocked in sewage stabilization ponds in Arkansas was attributed to low levels of dissolved oxygen (Henderson 1979, 1982). Mass die-off of Chinese carps in Hungary was attributed to early morning depletion of dissolved oxygen rather than to ammonia toxicity when 250 m^3/ha/day of clarified sewage (subjected to only primary treatment), equivalent to an organic loading of 27.5-30 kg BOD_5/ha/day, was sprayed into ponds (Kovacs and Olah 1984).

A major constraint in the design of excreta-reuse systems is that data on the tolerance of fish to low levels of dissolved oxygen are scarce. Most of the experimental data relate to fish response to constant DO regimes rather than to the diurnal fluctuation of concentrations characteristic of excreta-fed systems. Sensitivity to DO also varies with species, life stage (eggs, larvae, adults) and life process (feeding, growth, reproduction). A minimum constant value of 5 mg/l is satisfactory in most cases. However, minimum acceptable values, consistent with the mere presence of fish observed in polluted waters, are probably less than 1 mg/l (Alabaster and Lloyd 1980).

Fish cultured in excreta-fed systems do appear to be able to tolerate very low DO concentrations, at least for short periods. The lower limit is species-specific: airbreathing fish are the most tolerant, followed in decreasing order of tolerance by tilapia, carps, channel catfish, and rainbow trout. Airbreathing walking catfish (*Clarias batrachus*) were able to tolerate low concentrations of dissolved oxygen better than common carp (*Cyprinus carpio*) in concrete tanks fed with sewage stabilization pond effluent in India (Krishnamoorthi et al. 1975, Krishnamoorthi and Abdulappa 1979). Two fish kills were reported in sewage maturation ponds in Kenya of up to 50 percent of the stocked common carp (*Cprinus carpio*) but not tilapia (probably *Oreochromis* sp.) (Meadows 1983). The lowest DO levels for common carp for short and for longer periods were reported to be 0.5 mg/l and 2 mg/l, respectively (Demoll 1926, cited by Mortimer and Hickling 1954). However, Reichenbach-Klinke (1963) reported that, while common carp and tench (*Tinca tinca*) survive only on the surface and for a short time at 0.5 mg/l, even 3.0 mg/l is too

low for long term, and 4.0 mg/l is required as a standard minimum long-term DO concentration at maximum West German summer temperatures in shallow ponds, 25-30°C.

The resistance of common carp and Indian major carps to at least periodic (diurnal) low dissolved oxygen concentrations may be greater than commonly supposed. Good growth rates, without , were reported for common carp (*Cyprinus carpio*), mrigal (*Cirrhina mrigala*), rohu(*Labeo rohita*), and *Labeo fimbriatus* in two tanks fed with sewage stabilization pond effluent in Madras in which predawn dissolved oxygen concentrations were at or barely above zero (Muthuswamy et al. 1978) (Fig. 5.9. Upper left: DO cycle, Pond II; lower left: DO cycle, pond III. Upper right: growth of mrigal (*Cirrhina mrigala*); lower right: growth of common carp (*Cyprinus carpio*). The growth patterns of mrigal and common carp in the two tanks during the study are also shown.)
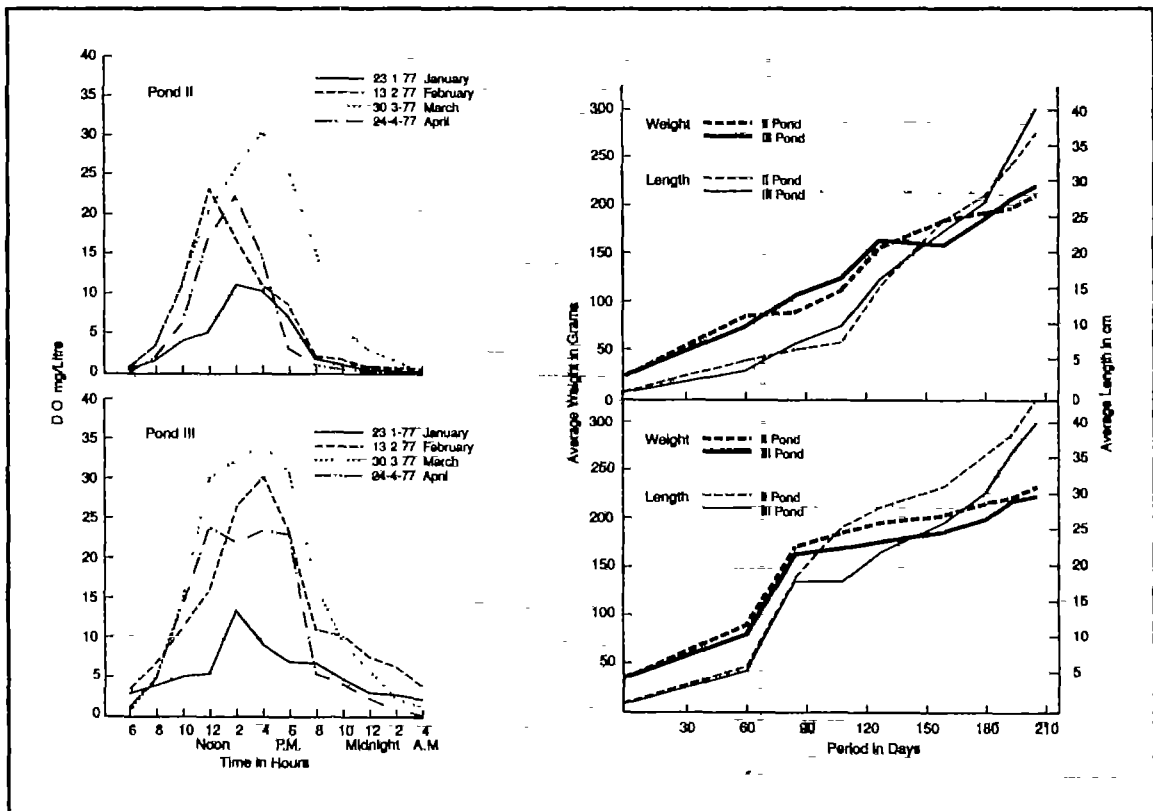
Figure 5.9 Dissolved oxygen cycles and fish growth (*Source:* Muthuswamy et al. 1978)

Chinese carp were reported to grow well at a dissolved oxygen concentration of 4-5 mg/l, fairly well at 2-3 mg/l, and survive for a time at a concentration less than 1 mg/l (Lin 1974). of channel catfish (*Ictalurus punctatus*) was reported in ponds fed with the effluent from an activated-sludge treatment plant when sunrise DO concentrations were less than 0.5 mg/l (Hallock and Ziebell 1970).

The lower short- and long-term dissolved oxygen concentrations for rainbow trout (*Salmo gairdneri*) were reported to be 1.5 mg/l and 3-4 mg/l in the Munich sewage-fed ponds, respectively (Demoll 1926, cited by Mortimer and Hickling 1954). A study in New Zealand of a pond fed with raw sewage to compensate for water loss due to evaporation and seepage confirmed that clean, highly oxygenated water is not essential for rainbow trout culture; good growth was obtained in diurnal fluctuations of dissolved oxygen from 4 mg/l to 14 mg/l (Slack 1974, Teoh 1974). However, Hallock and Ziebell (1970) found it difficult to account for of rainbow trout stocked in ponds fed with the effluent of an activated-sludge treatment plant and attributed it to a combination of factors. It was suggested that low dissolved oxygen (minimum 2.7 mg/l) and elevated ammonia (maximum 11 mg/l which may have caused direct) stressed the fish which grew slowly and became susceptible to disease.

Although many cultured species of fish are tolerant of low dissolved oxygen concentrations and can survive concentrations of 1 mg/l or less, feeding can be depressed in some species by concentrations as high as 6 mg/l, while growth and metabolism can be inhibited at concentrations around 3 mg/l (Payne 1984). The critical oxygen tension for Nile tilapia (*Oreochromis niloticus*) measured in a laboratory respirometer at 30°C was about 3.0 mg/l, below which the respiratory rate decreased rapidly (Ross and Ross 1983). It was suggested that it is advisable to maintain dissolved oxygen levels above 3.0 mg/l when culturing Nile tilapia. Dissolved oxygen levels in excreta-fed ponds containing more sensitive carps as well as tilapias do fall below 3.0 mg DO/l, at least for short periods of time before sunrise. It would be useful to know to what extent growth is affected by such adverse low DO concentrations in excreta-fed ponds. The phytoplankton biomass used by the fish as feed would need to be reduced to ensure a minimum DO concentration of 3.0 mg/l, which could well depress growth more than exposure to a few hours of low DO concentrations in the early morning hours.

A wastewater-reuse system designed for maximum fish production may occasionally require a standby mechanical oxygenation system to keep the fish alive during periods of extremely low dissolved oxygen levels (Carpenter 1978). Some highly loaded sewage-fed ponds were reported to be equipped with aerators in China, and aerators to increase the rate of oxygen transfer from the air or pumps to pump in fresh water were recommended to increase the dissolved oxygen concentration of the water if fish gulp at the surface (Zhou 1986). High-pressure sprinklers used to spray sewage into experimental sewage-fed ponds in Hungary were also used for aeration to solve the problem of early-morning dissolved-oxygen depletion by pumping pond water through the sprinkler system (Kovacs and Olah 1984). It was also suggested that water should be drained from ponds just above the mud where the water is the least oxygenated; the same author also suggested that aeration could be effected by gravity without pumping, if the ponds could be terraced to form cascades (Demoll 1926, cited by Mortimer and Hickling 1954). The provision of a standby mechanical aeration system would add to the cost of an excreta reuse system (Carpenter 1978), but it would not be necessary if ponds were well managed to avoid overloading. This applies especially to the culture of tilapia, which appear to be more resistant to low DO concentrations than most carps.

Ammonia toxicity to fish is a potential problem in excreta-fed ponds, although the extent of the problem is reduced by phytoplankton utilization of ammonia as a direct source of inorganic nitrogen. The un-ionized fraction (NH_3) is toxic to fish and the ionized fraction (NH_4^+) has little or no toxicity (Alabaster and Lloyd 1980). The un-ionized fraction and therefore the toxicity of ammonia increases with rises in both pH and temperature, which occur during the day in ponds with large concentrations of phytoplankton. Laboratory experiments of relatively short duration have shown that the acute lethal concentrations of ammonia for various species lie in the range of 0.2-2.0 mg NH_3/l, with trout being the most sensitive and common carp the most resistant species (Alabaster and Lloyd 1980). According to Colt and Armstrong (1981), the acute lethal concentration (96 h LC_{50} value) of un-ionized ammonia ranges from 0.4 to 3.1 mg NH_3-N/l for fish. Tilapia species can probably survive high concentrations of un-ionized ammonia because it was reported that blue tilapia (*Oreochromis aureus*) survived concentrations of un-ionized ammonia as high as 3.4 mg/l (Redner and Stickney 1979). However, there was a progressive reduction in the growth rate of common carp (*Cyprinus carpio*) beyond a concentration of un-ionized ammonia of 0.017 mg N/l, equivalent to total ammonia concentrations of 0.23 mg N/l at pH 8 and 0.075 mg N/l at pH 9 and 30°C (Payne 1984). Concentrations of ammonia in excreta-reuse systems far exceed these levels and thus constitute chronic toxicity. Sewage-fed ponds in both Hungary and India exerted a moderate and tolerable environmental stress for fish, with ranges of total ammonia nitrogen of 0.1-0.9 and 0.2-3.6 NH_4-N mg/l for the two countries, respectively (Olah et al. 1986).

The limited data in the literature on ammonia toxicity to fish in excreta-reuse systems suggest that the tolerance of different species of fish varies. Blue tilapia (*Oreochromis aureus*), common carp (*Cyprinus carpio*) and silver carp (*Hypophthalmichthys molitrix*) were cultured in Israel in four experimental ponds arranged in series and fed with extended-aeration effluent to assess the tolerance of the various species to different effluent concentrations. The silver carp died quickly in the first three ponds, and the survival rates for common carp and blue tilapia were 9 percent and 16 percent, respectively. Limiting concentrations of ammonia for tilapia were 8 mg NH_4^+-N/l and 0.3-0.6 mg NH_3-N/l and for common carp and silver carp were 4 mg NH_4^+- N/l and 0.2-0.4 mg NH_3-N/l (Buras et al. 1987). Fish were cultured in France in experimental ponds fed on a batch basis with various proportions of clean water and sewage stabilization pond effluent. Ammonia toxicity apparently did not affect Chinese carps (bighead, grass, and silver carp) but of common carp occurred in spring and was attributed to ammonia toxicity due to characteristic symptoms of poisoning. Concentrations of un-ionized ammonia reached sublethal concentrations of >0.1 mg NH_3-N/l and sometimes lethal concentrations of >0.5 mg NH_3-N/l at the end of the day due to pH of 9-10 (Bailly 1978 1979). However, very high ammonia concentrations were reported from polishing ponds fed with the effluent of an activated sludge plant and/or the effluent from a high-rate biological filter in Hong Kong (Sin and Chiu 1987a). Mozambique tilapia (*Oreochromis mossambicus*) showed good survival and growth rates but total ammonia concentrations ranged from 0.5 mg/l to 26.5 mg/l, with a mean of 10.0 mg/l in one pond, and ranged from 1.0 mg/l to 23.5 mg/l, with a mean of 10.4 mg/l in the other pond. The effluents from the tilapia ponds were fed into two ponds used to raise bighead carp (*Aristichthys nobilis*), common carp (*Cyprinus carpio*), and silver carp (*Hypophthalmichthys molitrix*) (Sin and Chiu 1987b). Growth rates

were comparable to, or even higher than, those on commercial fish farms, but mass occurred in one pond. The may have been due to low dissolved oxygen (although nighttime concentrations were not measured) or to high ammonia concentrations. Ammonia concentrations ranged from 2 mg/l to 40 mg/l, with a mean of 9.9 mg/l in the pond without, and from 5 mg/l to 36 mg/l, with a mean of 15 mg/l in the pond with mass mortalities of fish. However, phytoplankton biomass was consistently higher in the pond with , with a maximum of 48 mg/l but with concentrations usually below 30 mg/l, which could have led to nighttime depletion of dissolved oxygen.

Guidelines were suggested for average total and un-ionized ammonia concentrations based on a study in Lima, Peru (Bartone et al. 1985). Ammonia concentrations were measured in two continuous-flow tertiary sewage stabilization ponds (T_1, T_2) stocked with fish, and in three batch-operated ponds fed with the tertiary effluent. Daily total ammonia concentrations averaged 11.6 mg-N/l in T_1 and 8.3 mg-N/l in T_2 with corresponding un-ionized ammonia concentrations of 1.0 and 1.4 mg-N/l, respectively. Approximately 14 percent of the daily concentrations of un-ionized ammonia exceeded 2.0 mg-N/l, and many were in T_2, in which there was a fish kill due to overloading on one occasion. It was concluded that satisfactory growth and survival of tilapia are possible when average total ammonia is less than 2 mg-N/l and average un-ionized ammonia is less than 0.5 mg-N/l, with short-duration concentrations of un-ionized ammonia not exceeding 2 mg-N/l.

An additional environmental constraint in an excreta-fed pond may be the accumulation of decay products such as sulfides and methane in the pond sediments caused by anaerobic conditions brought about by the introduction of large quantities of organic matter (Ram et al. 1982). Fish growth was reported to be inhibited between 50 and 70 days after stocking in intensive ponds in Israel. Bottom-feeding common carp (*Cyprinus carpio*) ceased to feed on the pond bottom once anaerobic sediments developed, and there was a complete disappearance of macrozoobenthos.

5.5.4 Fish yields and population management

A wide range of fish yields has been reported from both actual (Table 5.4) and experimental (Table 4.1) excreta reuse systems. However, there are constraints in interpreting the data. The yield is often given without stating whether it is the gross yield (weight of harvested fish) or the net yield (weight of harvested fish minus the weight of stocked fish). The difference between gross and net yields is considerable if a high initial weight of fish is stocked. The length of the fish culture period is not always given, so it is difficult to compare yields from different systems. However, the extrapolation of yields to a standard year is more meaningful in the tropics where year-round culture is feasible, although one must consider the time required to turn ponds around between successive culture cycles. It is also necessary to use a standard area, 1 ha, to compare different systems: yield data extrapolated from a small-scale experimental unit are hardly likely to be representative of a large commercial operation. Variations in the operation of excreta-fed systems — different fish population management strategies, and nutritional sources in addition to excreta — also lead to differences in yields. There is the additional

problem of the reliability of the data. Phenomenal yields of fish have been claimed for sewage-fed ponds, but the data seem less impressive when critically analyzed (Prowse 1967). Many studies merely reported the yield without presenting either supporting data or an indication of how the yields were obtained. Despite the large amount of yield data from excreta-fed systems in the literature, there is still a need for more research to generate reliable data, including yields.

Yields from night-soil-fed ponds varied from low yields of 1.7 and 2.1 tons/ha/yr from Hong Kong and Java, respectively, to high yields of 6.5 and 8.8 tons/ha/yr from China and Taiwan, respectively (Table 5.4). The highest yield, an extrapolation from a gross yield of 7.3 tons/ha/10 month growing season reported from Taiwan, is from a pond in which night soil was 77 percent of the total organic fertilizer input; rice bran was a supplementary feed. Yields reported from ponds and lakes fed by fecally polluted surface water range from 2.3-2.5 tons/ha/yr from Beira Lake in Sri Lanka to 3.5-7.8 tons/ha/yr for ponds in Taiwan.

A range of yields has been reported from the Calcutta sewage fisheries, from a low of 1 ton/ha/yr to a high of 9 tons/ha/yr. High yields have also been reported from experiments in sewage-fed ponds in India. Silver carp and the usual Indian major carps were stocked in a sewage-fed pond, and total fish production was estimated to be about 7.7 tons/ha in seven months, equivalent to 13.2 tons/ha/yr (FAO 1973, Ghosh et al. 1973 1974). In seven years of experimentation in experimental sewage-fed ponds at Rahara, West Bengal, polycultures of Indian major carps and Chinese carps ranged from 5.4 to 8.6 tons/ha/yr, with an average of 7.0 tons/ha/yr (Ghosh et al. 1985). Muthuswamy et al. (1978) reported a yield extrapolated to 11.5 tons/ha/yr, but this high yield was due in part to the phytoplankton-rich effluent of a stabilization pond being fed to the pond with a low retention time, about 3 days, and partly due to a miscalculation of the data; the actual extrapolated yield was 5.8 tons/ha/yr. However, it is likely that fish yields would be lower in a more or less static water pond with the phytoplankton produced *in situ* in the pond.

Fish yields from sewage-fed ponds in Indonesia range from 2 to 6 tons/ha/yr. Yields from sewage-fed ponds in China range from 2.7 to 9.3 tons/ha/yr. Fish yields in the Munich sewage-fed ponds are low, with gross and net yields only about 0.5 and 0.3 tons/ha/7 month growing season, equivalent to gross and net extrapolated yields of 0.9 and 0.5 tons/ha/yr, respectively. Such low yields are no doubt due to the culture of bottom-feeding common carp only.

Impressive net fish yields were reported from experimental sewage-fed ponds in Hungary. Kovacs and Olah (1984) reported a net yield of a polyculture of Chinese carps of 1.8-2.0 tons/ha/120 day growing season, equivalent to a net yield of 5.5-6.1 tons/ha/yr. Olah et al. (1986) reported a net yield of a polyculture of common carp and silver carp of 12 kg/ha/day over an 120 day growing period, equivalent to a net yield of 4.4 tons/ha/yr.

Yields from sewage-fed ponds in Israel are not given here because the ponds are also given inorganic fertilizer and supplementary feed.

Table 5.4
Fish Yields in Actual Excreta Reuse Systems Reported in the Literature

Yield	Excreta reuse system	Fish species	Citation	Country	Comments
> 1 t/ha/yr	Unintentional reuse in fort moat	Milkfish[a],catla[b], mrigal[c],rohu[d]	Sreenivasan (1967)	India	
1.6 t/ha/yr	Unintentional reuse in fort moat		Sreenivasan (1964)	India	
1.3 t/ha/yr	Unintentional reuse in fort moat		Sreenivasan (1968)	India	
2.1 t/ha/yr	Overhung latrine	Common carp[e], kissing gouramy[f], silver barb[g], niles carp[h], giant gourami[i], tilapia	Djajadiredja et al. (1979)	Indonesia	Mean for Java; includes systems other than night-soil-fed ponds.
6.5 t/ha/yr	Night-soil-fed ponds		Anon (1973a)	China	
Gross yield 7.3 t/ha/10-mo season	Night-soil-fed pond	Bighead carp[j], Common carp[e], grass carp[k], grey mullet[l], sea perch[m], silver carp[n]	Tang (1970)	Taiwan	Night soil was 77 percent of total organic fertilizer input. Rice bran used as supplementary feed.
1.7 t/ha/yr	Night-soil-fed pond		Hickling (1947) cited by Mortimer and Hickling (1954)	Hong Kong	
5.1-7.6 t/ha/yr	Night-soil-fed ponds	Bighead carp[j], grass carp[k], mud carp[o], silver barb[g], common carp[e], marble goby[p]	Seow et al. (1979)	Malaysia	Bighead carp, grass carp were major species, the latter fed grass and cassava leaves.
4 t/ha/yr	Ponds fed with fecally polluted surface water		Ilan and Sarig (1952)	Indonesia	
2.3 t/ha/yr	Fecally polluted lake	Mozambique tilapia[q]	Mendis (1964)	Sri Lanka	
2.5 t/ha/yr	Fecally polluted lake	Mozambique tilapia[q]	Costa and Liyange (1978)	Sri Lanka	
3.5-7.8 t/ha/yr	Ponds fed with fecally polluted surface water	Mozambique tilapia[q] (?)	Huang (1968)	Taiwan	
13.5 t/ha/yr	Sewage-fed pond	Major Indian carps	Ghosh et al. (1974)	India	Yield 7.7 tons/ha/7-month growing season. Commercial farm in West Bengal, Titagarh.

Table 5.4
Continued

Yield	Excreta reuse system	Fish species	Citation	Country	Comments
7.8 t/ha/yr	Sewage-fed ponds	Catla[b], mrigal[c], rohu[d], Mozambique tilapia[e]	Olah et al. (1986)	India	Extrapolated to 1 year from a fish production of 21.3 kg/ha/day over 300-day growing period.
0.6 t/ha/yr	Sewage-fed ponds	Catla[b], mrigal[c], rohu[d], *Labeo bata, L. calbasu*	Basu (1948)	India	Calculated from the annual production and total area of Calcutta sewage fisheries
1.4 t/ha/yr	Sewage-fed ponds	Major Indian carps	Saha (1970)	India	Mean fish yield from Calcutta North Lakes calculated from annual productin and area of sewage fisheries.
1.0 t/ha/yr	Sewage-fed ponds	Major Indian carps	Saha (1970)	India	Mean fish yield from Calcutta South Lakes calculated from annual production and area of sewage fisheries.
1.4-2.1 t/ha/yr	Sewage-fed ponds	Catla[b], mrigal[c], rohu[d]	Saha (1970)	India	State fish farms near Calcutta.
3.2 t/ha/yr	Sewage-fed ponds	Catla[b], mrigal[c], rohu[d]	Saigal (1972)	India	Goverment fish farm, West Bengal.
4-9 t/ha/yr	Sewage-fed ponds		Ghosh (1983)	India	
6 t/ha/yr	Sewage-fed ponds	Chinese carps	Kuo (1980)	China	
2.7 t/ha/yr	Sewage-fed pond	Chinese carps	Zhou (1986)	China	
1.2 t/ha/yr	Sewage-fed lake	Chinese carps	Anon (1973a)	China	
2.7-9.3 t/ha/yr	Sewage fed ponds	Chinese carps	Institute of Hydrology (1976)	China	Hankou sewage fish farm.
2-5 t/ha/yr	Sewage-fed ponds	Common carp[e], kissing gouramy[f], tilapia	Vaas (1957)	Indonesia	
4-6 t/ha/yr	Sewage-fed ponds		Djajadiredja et al. (1979)	Indonesia	
4 t/ha/yr	Effluent of septic tank mixed 1:3 with river water and added to pond.	Common carp[e], silver barb[g], snakeskin gourami[f], kissing gourami[f]	Vaas (1948)	Indonesia	

Table 5.4
Fish Yields in Actual Excreta Reuse Systems Reported in the Literature (continued)

Yield	Excreta reuse system	Fish species	Citation	Country	Comments
3 t/ha/yr	Sewage-fed ponds	Common carp[*], silver barb[g]	Vaas (1948)	Indonesia	
0.5-0.7 t/ha	Raw sewage spread over grass fields and drained into ponds		Thorslund (1971)	Poland	Growth period not specified.
0.5 t/ha/yr	Raw sewage subjected to primary sedimentation, diluted with river water and sprayed into ponds with a 2-day detention time	Common carp[*], tench[k]	Liebmann (1960)	Germany	Extrapolated net yield.
4 t/ha	Sewage stabilization ponds	Oreochromis shiranus and Tilapia rendalli	Balarin (1987)	Malawi	Growth period not specified.
4-5 t/ha/ 240 days	Sewage stabilization ponds	Oreochromis shiranus	Cross (1985)	Malawi	
0.8-1.2 t/ha/yr	Maturation ponds of sewage treatment works	Tilapia rendalli and Mozambique tilapia[q]	Mackenzie and Livingstone (1968)	South Africa	

[*]Chanos chanos, [b]Catla catla, [c]Cirrhina mrigala, [d]Labeo rohita, [e]Cyprinus carpio, [f]Helostoma temmincki, [g]Puntius gonionotus, [h]Osteochilus hasseltii, [i]Osphronemus goramy, [j]Aristichthys nobilis, [k]Ctenopharyngodon idella, [l]Mugil cephalus, [m]Lateolabrax japonicus, [n]Hypophthalmichthys molitrix, [o]Cirrhina molitorella, [p]Oxyeleotris marmoratus, [q]Oreochromis mossambicus, [r]Trichogaster pectoralis, [s]Tinca tinca

Extremely high extrapolated yields of 20 tons/ha/yr were predicted by Edwards (1980a,c; Edwards et al. 1981a) from experimental tanks fed with the effluent of a high-rate stabilization pond. Even higher extrapolated yields of 206 tons/ha/yr were reported by Suffern et al. (1978) based on cage culture of fish in stabilization ponds equipped with aerators; they considered it reasonable to expect a yield of about 50 tons/ha/yr from a scaled-up system based on cage culture. However, in both experimental systems the phytoplankton were produced outside the fish culture system; such high fish yields are not likely from a pond in which phytoplankton are grown in situ.

Most excreta reuse systems use common, Chinese and Indian major carps. However, there are commerical excreta reuse systems which use tilapia: fecally polluted Beira Lake in Sri Lanka, small-scale excreta reuse systems in Indonesia, and a few sewage-stabilization pond systems in Africa. Tilapia are also raised as the main species in polyculture with Chinese carps in water bodies fertilized with sewage in southern China (FAO 1980). Tilapia yields for excreta-reuse systems reported in the literature range from

0.8-1.2 to 6.1-7.6 tons/ha/yr. Research in both Peru and Thailand has demonstrated the potential of tilapia in excreta-fed systems.

It is necessary to manage a fish population well to obtain a high fish yield from an excreta-fed system. The increase in weight of small fingerlings stocked in a pond follows a sigmoid curve (Fig. 5.10a). The first phase of growth is slow because the individual weights of fingerlings are small. The second phase of growth is more rapid because the fish are larger, and the third phase slows again as the carrying capacity of the pond is reached. A higher weight of fish should be stocked initially to speed growth in phase 1 and better utilize the spatial and nutritional resources of the pond. This can be achieved by stocking larger fish with a higher initial weight to start the fish growth cycle in the pond. Fish at least one year old were reported to be stocked in West Germany, China, and Hungary.

Fish are stocked at a very low density, 0.05 fish/m^2, in the Munich sewage-fed ponds, although the fish are fairly large, 150-250 g one-year fish, which are marketed at 1.5 kg when two to three years old. Kuo (1980) recommended stocking fish larger than 17 cm at a density of about 1 fish/m^2 in China. Fish yield is positively correlated with the size of the stocked fish at a given stocking density. Fish yields in Machine Marsh Lake fed with sewage, Wuhan, China, were 5.1, 6.1, and 9.3 tons/ha/yr with sizes of stocked fingerlings of 5, 10, and 17 cm, respectively (Institute of Hydrobiology 1976). Kovacs and Olah (1984) recommended stocking Chinese carp yearlings of 300-350 g individual weight at a density of 0.26-0.32/m^2 to give an initial stocking weight of 0.8-1.2 tons/ha. There are conflicting data concerning the stocking of Indian major carps in the Calcutta sewage fisheries. According to Nair (1944b), the carps were stocked at an individual weight of 50 g at a low density of 0.1 fish/m^2 to give an initial stocked weight of only 50 kg. However, Olah et al. (1986) reported that Indian carps were stocked at an individual weight of 20-30 g but at a much higher density of 3.5 fish/m^2 to give an initial stocked weight of 869 kg/ha. Saigal (1972) reported an initial stocked weight of 500 kg/ha of the three Indian major carps in the government sewage-fed fish farm in West Bengal.

Tilapia are usually stocked when fairly small but at a relatively high density of 2-3 fish/m^3. A total weight of 20-28 g tilapia of 0.3-0.4 ton/ha was stocked initially in ponds fed with fecally polluted surface water in Taiwan (Huang 1968). In southern China, tilapia are stocked once a year at rates of either 30 g fish at 0.15/m^2 or 1.3 g fish at 2.3-3.0/m^2 (FAO 1980).

An increase in the weight or biomass of the fish in the pond leads initially to an increase in the yield or production, but there is a reduction in the growth rate of individual fish because of the limitation in natural food production in the system (Brocksen et al. 1970) (Fig. 5.11). Therefore, the stocking density of fish should not be so high that the fish fail to attain a minimum marketable size because of the decrease in their growth rate. Although yield increases with an increase in initial biomass, higher stocking densities lead eventually to decreased yields or production because of the decrease in fish growth rate (Institute of Hydrobiology 1976). Higher fish stocking densities of Chinese carp in
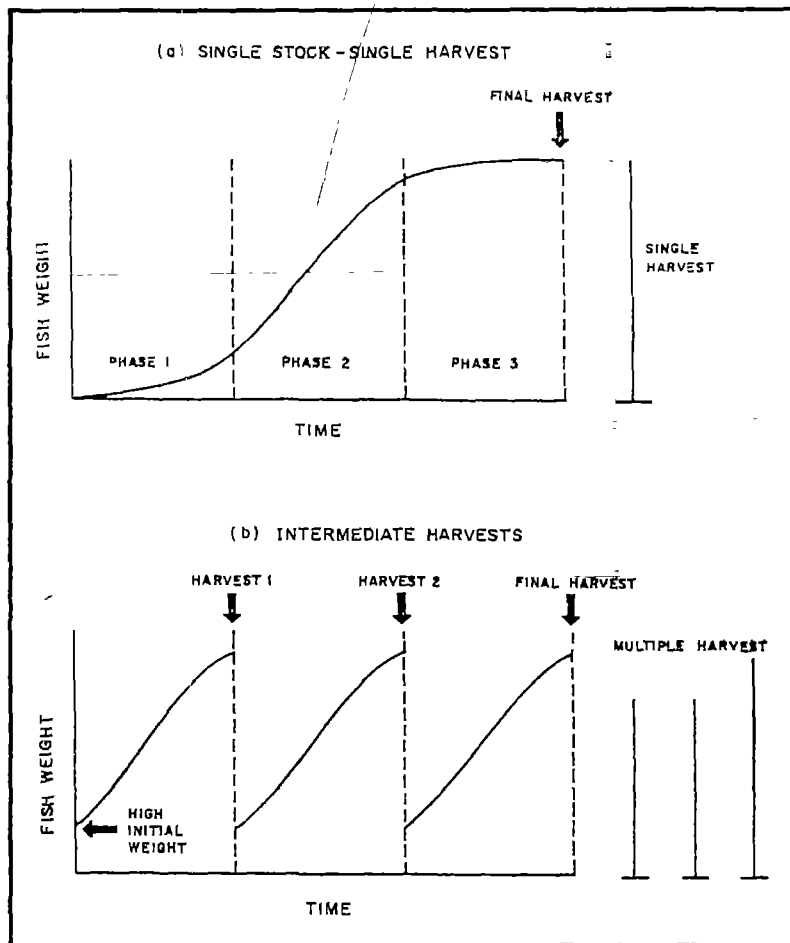
Figure 5.10   Fish stock management to increase fish yields   (*Source:*   Edwards et al. 1988b)

sewage-fed Machine Marsh Lake in China led to a decrease in fish yield; yields were 5.8, 2.1, and 3.2 tons/ha with fish stocking densities of 1.5, 3.0 and 3.4 fish/m^2, respectively.

The third phase of slow growth is because the total weight of fish in the pond is approaching the carrying capacity, the biomass of fish in the pond that can be supported by the nutritional resources and water quality (Fig. 5.10a). Intermediate harvests carried out when rapid growth ceases at the end of phase 2 should lead to significant increases in total yield (Fig. 5.10b). Intermediate harvesting of fish is reported for excreta-fed ponds. Fish harvest was reported to begin in the Calcutta sewage fisheries 5-6 months after fish were stocked in September, and continue at intervals until February when the ponds were drained (Nair 1944b). According to Olah et al. (1986), intermediate harvesting of fish in the Calcutta sewage-fed fisheries started 120 days after stocking fish. Fingerlings were stocked three to four times per year and harvested four or five times per year in sewage-fed ponds in China (Kuo 1980). Tilapia raised in ponds fed with fecally polluted surface water in Taiwan were seined eight to nine times during the growing season to remove
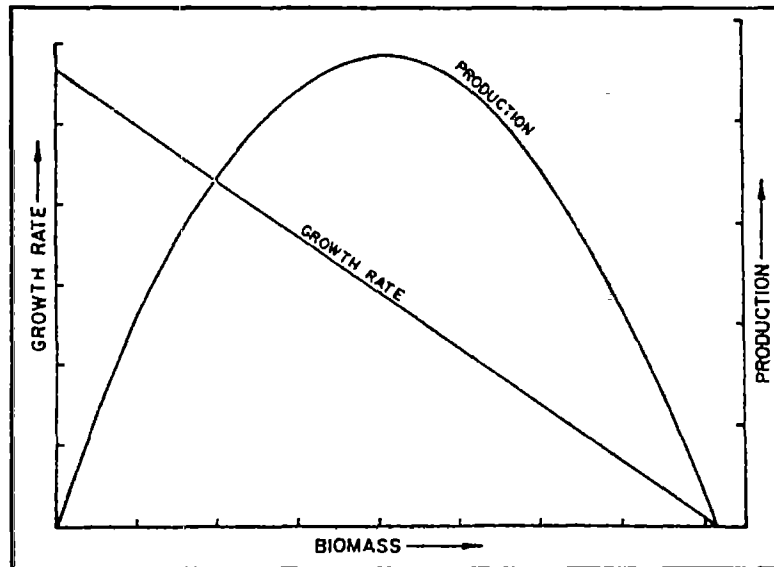
Figure 5.11 Theoretical relationship of growth rate and production to biomass (Production [yield] derived as product of growth rate and biomass; *Source:* Brocksen et al. 1970)

market-size fish (Huang 1968). High yields of tilapia in southern China in sewage-fed systems are produced by high stocking density and frequent harvesting (FAO 1980). The fish are usually harvested in three distinct phases according to rates of breeding and growth. Stocked fish are harvested at a size of 100 g at two-week intervals, with their harvest accounting for 20 percent of the annual output. The second phase of harvesting occurs in the third and fourth quarters of the year when the fish are breeding rapidly. Seining is carried out every four days with removal of large fish and restocking of small fish, with the harvest producing 50 percent of the annual output. The third phase is carried out with the approach of winter, when the pond is cleared and fingerlings are kept for the following year. The third harvest makes up 30 percent of the annual output.

The key to achieving high yields in an excreta-fed pond is to determine the carrying capacity of the pond, or the maximum standing stock of fish. This should be determined by varying the excreta load to determine the maximum production of natural food in the pond commensurate with adequate, sustainable water quality for the fish through a fish culture cycle.

The fish stocking density is related to the carrying capacity according to the desired weight of individual fish at harvest:

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

Marketable weights of fish vary with species and with consumer preference but, in general, desirable marketable sizes of tilapia range from 0.15-0.6 kg; Indian major carps, 0.5-1.5 kg (mrigal 0.5, rohu 1.0, catla 1.5 kg); and Chinese carps, perhaps 1-2 kg. The carrying capacities of excreta-fed ponds stocked with different species of fish remain to be determined, but assuming that they are similar, stocking densities of different species are inversely related to their marketable size, that is, Chinese carps should be stocked at lower densities than tilapia, with Indian major carps stocked at an intermediate density.

The length of the culture cycle or the frequency of intermediate harvesting depends on the time it takes stocked fish to reach marketable size. Small fingerlings should not be stocked in grow-out ponds to produce market-size fish. They should be cultured at high density in nursery ponds until they are large enough to grow rapidly, and then moved to grow-out ponds.

There is a well-known but largely unquantified relationship between fish stocking density and fish yield and the level of pond nutrition (Fig. 5.12). Only a certain fish yield is attainable from a manure or excreta-fed pond. The addition of energy-rich supplementary feed such as cereals or cereal brans will lead to an increase in fish yield, while nutritionally complete pelleted feed may be necesary to produce maximum yields in ponds. The highest yields are achieved only with a sufficiently high fish stocking density to benefit from the improvement in pond nutrition. Commercial fish culture in ponds which receive untreated or treated excreta and sewage may receive considerable amounts of other organic fertilizers and supplementary feeds as, for instance, in Israel and China. Treated sewage effluents are used only to maintain the water level in ponds in Israel. In countries where excreta-fed aquaculture is practiced or is feasible, the use of supplementary feeds in such ponds may lead to economically attractive increased yields of fish. The addition of sewage to ponds in Israel led not only to an increase in fish yield, but also to an increase in the efficiency of utilization of supplementary feed by the fish (Hepher and Schroeder 1977). Fish yields were 70 percent higher, and 40 percent less supplementary feed was required per kilogram of fish in sewage-fed ponds compared to ponds which received no wastewater.

The individual size of fish at harvest is of prime importance in the culture of table fish for human food. However, it is relatively unimportant for fish raised as high-protein feed for carnivorous fish or livestock. It has been suggested that large yields of small fish suitable for processing as animal feed should be possible from excreta-fed systems. An estimate of a potential yield of 20 tons/ha/yr was made based on extrapolated yields of Nile tilapia raised in small concrete tanks fed with the phytoplankton-rich effluent of a high-rate stabilization pond (Edwards 1980ac, Edwards et al. 1981ab). However, sustainable extrapolated net fish yields of only 6.2-7.3 tons/ha/yr, with a mean of 6.8 tons/ha/yr, were obtained by intermediate harvesting of a free-breeding population of Nile tilapia in septage-fed ponds (Edwards 1987, Edwards et al. 1987). Similar maximum yields of 6.5-7.8 tons/ha/yr of tilapia (probably *Oreochromis mossambicus*) were reported from Taiwan from ponds fed with fecally polluted surface water with eight or nine intermediate harvests of 20-80 g fish during the nine-month growing season (Huang 1968). It is now appreciated that much lower fish yields, even made up of high densities of small
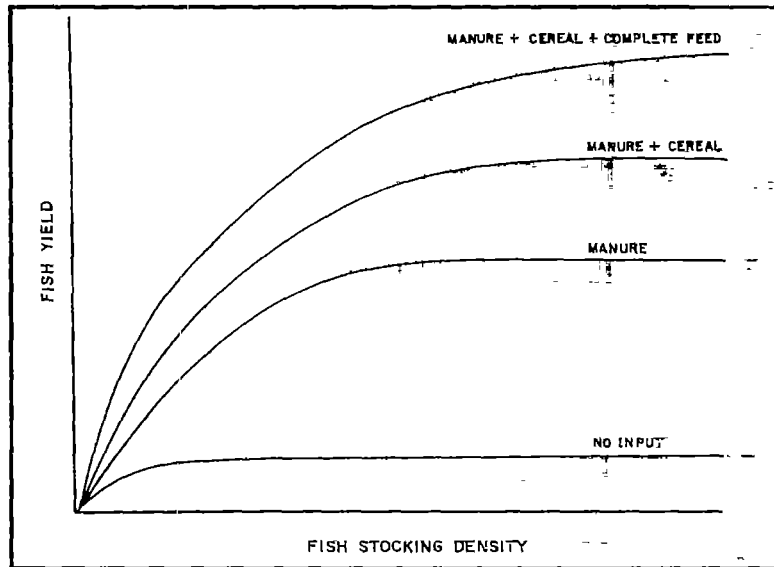
Figure 5.12 Relationship between fish stocking density and fish yield as a function of various types of pond nutritional inputs (Modified after Van der Lingen 1959)

fish with a high specific growth rate, are attainable from excreta-fed ponds in which the phytoplankton are produced *in situ* in the pond (Edwards 1987).

A large number of small individual fish should yield more than a population of the same initial weight but fewer, larger fish because the specific growth rate of fish is inversely proportional to size. The maximum theoretical fish yield from an excreta-fed pond may be about 15 tons/ha/yr based on phytoplankton productivity and the conversion ratio of phytoplankton biomass to fish (see Section 5.4.1). In practice, the maximum attainable yield is likely to be lower, perhaps 10-12 tons/ha/yr (Edwards 1987, Edwards et al. 1987).

5.5.5 Toxic substances

The possibility of the contamination of excreta-reuse systems with toxic substances such as heavy metals and industrial organic chemicals warrants attention. Such chemicals are unlikely to be of concern in the reuse of night soil and septage, which are essentially only toilet waste. However, domestic sewage may contain various toxic substances, particularly if it contains significant amounts of industrial effluents. While pollutants can cause of fish and their natural food organisms, sublethal effects are more likely in which growth is reduced (Mitrovic 1972). Of major concern is the hazard to consumers from fish which may contain toxic substances in the flesh. Furthermore, some organic chemicals impart an unpleasant taste to fish, even when present in very low concentrations.

All heavy metals are potentially harmful to most organisms at some level of exposure and absorption. Some heavy metals (cobalt, copper, iron, manganese, and zinc) are essential in trace concentrations to many organisms for enzyme function and are less toxic than nonessential heavy metals (cadmium, lead, mercury) which are toxic at the lowest concentrations (Miettinen 1975). Copper, chromium, zinc and nickel are associated with electroplating and other heavy-metal industries which tend to discharge wastes into municipal sewerage systems. Mercury is used in the production of a wide variety of industrial and consumer products: electrical apparatus, chlorine, caustic soda, industrial control instruments, paint, cosmetics, paper, pulp, and fungicides. Pesticides used in agriculture are unlikely to be of major concern in sewage, but domestic pesticides and detergents may be present in significant concentrations. A number of industrial chemicals may be present in sewage: polychlorinated biphenyls (PCBs) and phenols, for instance. Phenolic wastes arise from the distillation of coal and wood, from oil refineries, and chemical plants. They are toxic to fish and produce undesirable flavors in fish muscle tissue. Chlorophenols taint fish flesh at very low concentrations (Alabaster and Lloyd 1980).

The adverse effects of toxic wastes in domestic sewage on sewage-fed ponds have long been understood (Demoll 1926, cited by Mortimer and Hickling 1954). With the industrialization of developing countries, there is an increased possibility of discharge of industrial effluents into domestic sewage (Fowler 1944). Sewage in Changsha, China, had little industrial contamination in the 1960s, but an increase in industrial sewage has reduced fish quality and caused fish kills (Zhou 1986). It is impossible to avoid toxic residues in fish when sewage is used for fish culture. It has been suggested that the degree of contamination of sewage with toxic substances should be assessed before it enters the food chain, and that only wastewater of acceptable quality should be used for fish culture (Wissmath and Klein 1980). The Xiang Lake Fish Farm in Changsha, China, refused to accept raw sewage from some factories, by leading it along an additional ditch and not into the farm (Zhou 1986). Depuration of fish grown in wastewater improved taste, but the long time required to reduce mercury and PCB levels may make it uneconomic (Wissmath and Klein 1980).

If wastewater aquaculture treatment systems become more widely used, it will become critical to prevent the entry of toxic heavy metals, pesticides, and PCBs into municipal wastewater disposal systems. Water treatment using aquaculture will require greater control over what enters sewerage systems, although the adoption of such controls may lead to better water quality at lower overall cost (Henderson and Wert 1976). Changsha, China, was reported to be strengthening industrial wastewater control because the industrial wastewater was harmful to irrigation and aquaculture (Kuo 1980). Wastewater containing high concentrations of heavy metals should be pretreated in anaerobic ponds where a significant percentage will tend to be concentrated in sludge (Mara and Pearson 1986), before addition to ponds.

Analyses of fish raised in sewage stabilization ponds indicate some accumulation of heavy metals, but usually the levels are within acceptable limits. Common carp (*Cyprinus carpio*) raised in maturation ponds at the Rye Meads sewage purification works

in England had low mercury levels, 0.02-0.04 ppm dry weight, possibly because there was little industrial effluent in the sewage (Noble 1975). Heavy metal concentrations in the muscle tissue of tilapia (*Oreochromis mossambicus*) raised in secondary-treated effluents of a pilot sewage treatment plant in Hong Kong were 0.83 mg copper, 0.22 mg lead, 0.08 mg cadmium, and 3.83 mg zinc/kg wet weight of fish, within limits set by WHO for human consumption; mercury and chromium were not detected (Sin and Chiu 1987a). Levels of heavy metals in muscle tissue of bighead, common, grass, and silver carp from the same site were at acceptable levels, with the exception of mercury at 0.94 mg/kg wet weight of fish, which exceeded the maximum permissible level of 0.5 ppm set by the Hong Kong Public Health and Urban Services Ordinance (Sin and Chiu 1987b). A national survey of sewage-fed aquaculture in China made by the Yangtze River Fishery Research Institute revealed that out of eleven toxic substances analyzed in fish flesh (As, Cd, Cl, Cr, Cu, Hg, Pb, Zn, DDT and phenols), only 1.3 percent Hg, 2.5 percent DDT and 8 percent of phenol samples out of 666 tests exceeded their respective reference standard limits (Kuo 1980). Heavy metal levels in tilapia raised in cages in a sewage stabilization pond were extremely low compared to levels in sludge from the bottom of the pond and from other biota (Suffern et al. 1981).

Copper and mercury were found in the flesh of fish raised in sewage stabilization ponds near Benton, Arkansas, with 3 of 11 fish samples containing higher than acceptable levels of mercury in the edible portion. Considerable biological magnification of heavy metals occurred because the average level of mercury in fish from the ponds, 0.35 ppm, was 70 times higher than the average concentration of mercury in the pond water, 0.005 ppm. Similarly, the average concentration of copper of 3.58 ppm in fish flesh was much greater than the less than 0.01 ppm in pond water (Hejkal et al. 1983). However, no contaminant was found in the flesh of fish raised at Benton that exceeded FDA guidelines for human consumption (Henderson 1982). Common carp (*Cyprinus carpio*) were fed the green alga *Chlorella pyrenoidosa* cultivated on aqueous extracts of sewage sludge. Although the sludge-grown algae accumulated a substantial amount of various heavy metals, the contents in fish flesh were low, indicating that the fish did not concentrate metals in edible tissue (Wong and Tam 1984).

An analysis of fish grown in Xiang Lake Sewage Fish Farm, Changsha, China, by the Yangtze River Fishery Institute showed that, out of seven toxic substances tested, only phenol and mercury were present at higher levels than the permitted standard. Further analyses of fish grown in sewage-fed ponds in Changsha in 1982 and 1983 showed that the fish had higher levels than fish raised in normal ponds, although higher levels were also found in fish from one fish farm, probably because of feed contamination. Only five samples for copper and arsenic and three samples for DDT were over allowable levels from 250 samples from five fish farms (Zhou 1986). A homogenized composite sample of all muscle tissue from a single sample of six Nile tilapia (*Oreochromis niloticus*) obtained from a pond batch-fed with treated domestic sewage from slum areas at the San Juan sewage stabilization ponds in Lima was analyzed for the heavy metals, mercury, lead, chromium and cadmium and for organochlorine and organophosphorus pesticides. There was no indication of accumulation of toxics in tilapia grown in the treated domestic sewage; however, the conclusion was based on fish collected on only one occasion (Bartone et al.

1985). Shrimp (*Penaeus vannamei*) were cultured in seawater ponds fed with secondary sewage effluent from an activated sludge plant (Landau and Pierce 1986). Although elevated mercury levels occurred in the sediments, shrimp from the sewage-fed ponds did not have higher mercury concentrations in edible tissues than shrimp collected from natural environments.

Phytoplankton rapidly accumulate heavy metals (and halogenated hydrocarbons) from water (Ketchum 1975) but the contaminants do not appear to be readily accumulated by fish that feed on the algae. Concentrations of heavy metals were monitored in successive stages of sequential monocultures of a green alga (*Scenedesmus*), a herbivorous crustacean (*Daphnia*) and two fish (*Notomigonus crysoleucas* and *Pimephales promelas*) grown in secondary-treated sewage. Bioaccumulation of heavy metals occurred mainly in the phytoplankton, with lower concentrations in zooplankton and fish (Tarifeno-Silva et al. 1982b). The limited heavy metal accumulation by fish raised in sewage-fed systems is also supported by a preliminary survey of heavy metals in freshwater fish from a nonindustrialized and a heavily industrialized area in Canada (Uthe and Bligh 1971). In most cases, heavy metal concentrations from the industrialized area did not differ significantly from those of the nonindustrialized area.

The performance of sewage stabilization ponds is relatively unaffected by heavy metals, which are efficiently removed by a combination of chelation and precipitation, although some are taken up by phytoplankton (Mara and Pearson 1986). Although heavy metal ions were toxic to the green alga *Chlorella*, high concentrations of heavy metals did not affect waste stabilization pond performance, probably because high pH caused the metal ions to precipitate in the form of hydroxides (Moshe et al. 1972). The removal of metals from domestic sewage was studied in a waste stabilization pond system in New Zealand (Smillie and Loutit 1982). Concentration of Zn, Cu, Fe, and Pb were reduced in the treated effluent compared with raw sewage due to deposition of particulate-associated metal into the pond sediments and uptake of soluble metal by bacteria and phytoplankton; however, Mn and Cr were not removed. Certain species of green and blue-green algae may be able to release organic compounds which can form complexes with heavy metals and reduce the free ion concentration (Jardim and Pearson 1984, Kaplan et al. 1987). Furthermore, only a small fraction of the dissolved heavy metals in sewage stabilization ponds may be in a labile free form (Kaplan et al. 1987).

There are various reasons why fish raised in sewage stabilization ponds do not accumulate high concentrations of heavy metals. The concentrations of heavy metals may be accumulated at slower rates than new tissues develop in rapidly growing fish such as tilapia raised in sewage-fed ponds (Suffern et al. 1981). Heavy metal concentrations in muscle tissue of eels (*Anguilla anguilla*) were reported to decrease at higher temperature, possibly due to metal accumulation occurring at a slower rate than tissue growth (Romeril and Davis 1976). A decrease in the rate of heavy metal accumulation by freshwater prawns (*Macrobrachium hainanense*) fed with green algae fertilized with sewage sludge was related to an increase in size of prawns. This observation suggested that new tissue was being formed faster than heavy metal accumulation (Wong and Cheung 1985).

The position of a fish in the food chain is an important factor determining its mercury content: carnivorous fish accumulate more mercury than herbivores (Ratkowsky et al. 1975). In a study of mercury levels in freshwater lake fish in the United States, the highest mercury concentrations occurred in predatory game fish (Walter et al. 1973). The highest concentrations of mercury in Japan tended to occur in carnivorous fish and larger (and, presumably, older) fish (Doi and Ui 1975). Mercury levels may therefore be greater in carnivorous fish than in the herbivorous fish (D'Itri 1972) cultured in excreta-reuse systems.

Fish apparently have the ability to regulate the heavy metal content of their tissues, except for mercury (Chernoff and Dooley 1979). Concentrations of the essential metals Mn, Fe, Cu, and Zn, which are required metabolically, either remained constant or decreased in muscles of two species of marine fish with an increase in size, although concentrations of mercury increased significantly with size, an indication that mercury cannot be regulated (Cross et al. 1973). Studies with radioactively labeled feed for rainbow trout showed that most of the ^{109}Cd was rapidly eliminated, but labeled mercury compounds indicated that methyl mercury had the slowest rate of elimination (Miettinen 1975). Freshwater prawns (*Macrobrachium hainanense*) fed green algae fertilized with sewage sludge accumulated heavy metals from their food, but moulted exoskeletons had significantly higher heavy metal concentrations than the exoskeletons of harvested prawns; this indicated that the prawns eliminated heavy metals by periodic moulting of the exoskeleton (Wong and Cheung 1985). It has been reported that fish viscera contain significantly higher heavy metal concentrations than the edible (muscle) tissue (Doi and Ui 1975, Chernoff and Dooley 1979). Heavy metals accumulated in the liver to a much greater extent than in the muscle tissue in tilapia raised in cages in a sewage stabilization pond (Suffern et al. 1981).

There are few data on toxic substances other than heavy metals for fish raised in excreta-reuse systems. Sewage effluent from a trickling filter treatment plant in Israel contained hard detergents (ABS) at concentrations of 10-18 mg/l and caused fish in experimental ponds (Hepher and Schroeder 1974 1977). The lethal dose determined from bioassay was 10 mg/l. Sublethal concentrations reduced fish growth. A natural rate of degradation of 1 mg/l/week was observed in ponds, so the toxicity problem was solved by aging wastewater in ponds prior to stocking fish and then replacing daily losses due to evaporation and seepage by adding 100 m^3 effluent/ha/day. The concentrations of hard detergents (ABS) found in batch-fed polishing ponds at the San Juan sewage stabilization ponds in Lima did not appear to affect fish survival adversely (Bartone et al. 1985). There were slight reductions in detergent concentration through the pond series, probably due to removal by foaming at pond outlets. The mean concentrations of detergents in the ponds ranged from 0.85 to 1.13 mg-MBAS/l, much lower than the median lethal dose for ABS of 10 mg/l, although it was considered that sublethal concentrations could reduce fish growth.

In Czestochowa, Poland, there was an unsuccessful attempt to grow fish in domestic sewage mixed with 65 percent waste from a metal factory due to a high phenol content (Thorslund 1971). Hankou Sewage Fish Farm, Wuhan, China, stopped raising

table fish using sewage in 1984 because of increasing contamination of domestic sewage with industrial wastes, although the farm continued raising fingerlings. The farm had difficulty marketing fish because the flesh was unpalatable and smelled of phenols. Nile tilapia (*Oreochromis niloticus*) cultured in cages in secondary facultative sewage stabilization ponds in Kenya contained DDT and metabolites DDE and DDD, with concentrations of DDT in fish ranging from 0.06 to 0.3 mg/l (Meadows 1983). Negative results were reported for the qualitative analysis of organophosphorus and organochlorinated pesticides from fish raised in treated sewage effluents in Lima (Bartone et al. 1985).

Weis et al., (1989) reported the effects of treated municipal wastewater on the sensitive early life stages of three species of fish. Batch variability in the chemistry of the effluent was reflected in its biological impact, but moderately toxic batches caused cardiovascular and skeletal defects, depression of heart rate, and poor hatchling, larval and juvenile growth rates. The wastewater had a substantial industrial input. Analysis indicated relatively low levels of heavy metals, and adverse effects were attributed to unidentified organic fractions.

The operation of sewage stabilization ponds may be adversely affected by industrial wastes. In Kenya, ponds which received effluents from tanneries and textile mills suffered adverse effects due to sulfides and dyes, respectively (Meadows 1983). In one case, a nontoxic dye inhibited photosynthesis in the water column by over 70 percent because of reduced light penetration even though the dye waste was less than 5 percent of the total flow.

5.6   Design of excreta reuse systems

5.6.1   Organic loading

Nutrient loading is the most important factor in the performance of an excreta-fed pond (see Section 5.5.3). Nevertheless, it is useful also to know the loading to the ponds in terms of biochemical oxygen demand (kg BOD_5/ha/day) because this parameter is used in the design of waste treatment systems. However, there are complications in the use of organic loading in ponds because ponds may receive raw sewage or fresh night soil directly, or excreta treated in various ways and to different degrees. The conventional BOD_5 test does not distinguish between organic matter in raw excreta, which has a high oxygen demand, and the phytoplankton biomass in partially treated effluents from stabilization ponds, which generates oxygen (Caldwell 1946, Abbott 1948, Mara and Pearson 1986). Furthermore, the BOD5:nutrient ratio will be totally different in raw excreta and partially digested excreta such as septage. Organic loading rates are seldom given in the literature on excreta-fed aquaculture, but they can sometimes be calculated from data given.

The mean organic loading to the 200 ha of ponds used for grow-out in Munich varied from 7 tons to 18 tons BOD_5/day from 1965-1975 (Bavarian State Ministry for Land

Development and Environmental Protection 1980), equivalent to a mean areal organic loading of 35-90 kg BOD_5/ha/day. This is relatively high compared to most excreta reuse systems. However, the Munich sewage-fed ponds are fed highly oxygenated water produced by mixing clarified sewage effluent with river water which cascades into the ponds. They have a short detention time of two days (see Section 2.6.5).

The Quail Creek sewage lagoon system in Oklahoma included six ponds of mean size 2.6 ha which received about 1 million gallons (3,802 m^3) of domestic sewage per day. The first two of the serially arranged ponds were aerated lagoons, and fish were stocked in the last four ponds (see Section 4.2.3.1). The organic loadings to the four ponds containing fish were 35, 25, 20, and 13 kg BOD_5/ha/day.

The Benton sewage stabilization pond system in Arkansas was made up of six ponds, 1.55-1.80 ha in area, which received 0.45 million gallons (1,711 m^3) of clarified sewage effluent per day (see Section 4.2.3.2). Organic loadings cannot be calculated for the first phase of the study because pond effluent data were not given. Effluent data were given for a second phase in which fish were cultured in the last four of the six ponds arranged in series. The organic loadings to the four ponds stocked with fish were 31, 21, 16, and 12 kg BOD_5/ha/day. Corresponding total nitrogen loading rates were 7.8, 6.3, 4.1 and 3.4 kg N/ha/day.

Ponds in Israel are topped up with the effluents of sewage stabilization ponds to replace losses from seepage and evaporation (Hepher and Schroeder 1977). The resulting dilution of wastewater within the pond was about 100- to 150-fold because the addition of sewage effluents compensated for a daily water loss of 1-1.5 cm in 1.5 m deep ponds. The wastewater added was about 250-300 mg BOD_5/l which gave an organic loading of about 25-45 kg BOD_5/ha/day. The ponds were considered able to receive even higher loadings because of phtosynthetic oxygen production.

The reduction of the organic load of domestic sewage for use in sewage-fed ponds in India was discussed by Dehadrai and Ghosh (1977). Raw domestic sewage generally had a BOD_5 of 150-600 mg/l; primary treatment by sedimentation reduced that level by about two thirds, that is, more than by conventional primary sedimentation. The primary-treated sewage, with a BOD_5 of 50-200 mg/l, was introduced into the pond before fish were stocked, and the dilution ratio of sewage effluent and fresh water in the pond was adjusted so that the BOD_5 of pond water was about 50 mg/l. The development of phytoplankton increased the dissolved oxygen content of the water and helped lower the BOD_5 of the pond water to 20-25 mg/l or less when the fish were stocked. Primary-treated sewage was introduced into the pond after stocking fish to maintain surface dissolved oxygen at 2 mg/l or higher. These relationships are represented diagramatically in Fig. 5.13.

Sewage was loaded into ponds on the State Sewage Fish Farm near Calcutta when needed, a total of 13,650 m^3 sewage/ha/yr (Saha 1970). The length of the fish culture cycle was not specified, but a likely growth period of nine months would give a daily sewage loading of 50 m^3/ha. Using the figure of 50-200 mg BOD_5/l for

primary-treated sewage of Dehadrai and Ghosh (1977) above, the organic loading rate for 50 m^3 sewage/ha/day is 2.5-10 kg BOD$_5$/ha/day. In a more recent study, nutrient concentrations, net primary productivity and diurnal dissolved oxygen concentrations were studied in sewage-fed ponds at Rahara, West Bengal, at BOD$_5$ levels of less than 10, 10-20, and 20-30 mg/l (Chattopadhyay et al. 1988); the optimal range for fish culture was reported to be 10-20 mg BOD$_5$/l.

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┌─────────────────────────────────────────┐
│              Raw Sewage                   │
│        ( BOD₅ 150 - 600 mg/l )            │
│                   │                       │
│                   ▼                       │
│  Primary Treatment by Sedimentation       │
│           ( 2/3 Reduction )               │
│                   │                       │
│                   ▼                       │
│             Effluent Sewage               │
│        ( BOD₅ 50 - 200  mg/l )            │
│                   │                       │
│                   ▼                       │
│        Dilution in Pond Water             │
│           ( BOD₅ 50 mg/l )                │
│                   │                       │
│                   ▼                       │
│            Two Week Period                │
│                   │                       │
│                   ▼                       │
│              Pond Water                   │
│           ( BOD₅ 20 mg/l )                │
│                   │                       │
│                   ▼                       │
│              Stock Fish                   │
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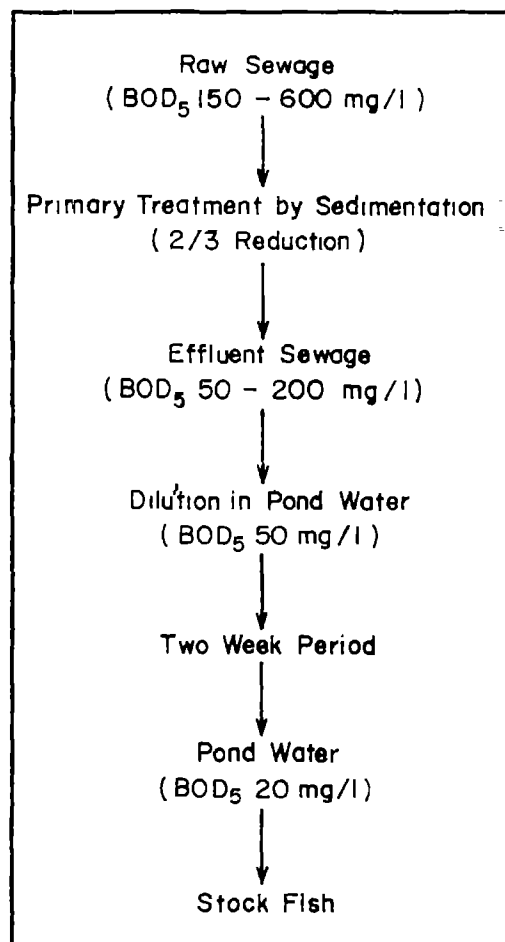
Figure 5.13 Reduction in BOD$_5$ of sewage in fish culture in India (Based on data of Dehedrai and Ghosh 1977)

Perhaps the most reliable data on the organic loading of sewage in ponds are from the Hungarian experimental system (see Section 4.5.2). A range of organic loadings of raw sewage subjected to primary treatment only was sprayed into a series of experimental sewage-fed ponds used to raise Chinese carps (Kovacs and Olah 1984). Sewage was sprayed at 5, 50, 75, 100, 150, 200, and 250 m^3/ha/day into the ponds. A loading of 5 m^3/ha/day did not significantly change the water quality and fish yield from

the control, but 250 m³/ha/day caused mass of fish due to early-morning depletion of dissolved oxygen. With a BOD₅ of clarified sewage effluent of 110-120 mg/l, organic loadings corresponding to volumes of 5, 50, 75, 100, 150, 200, and 250 m³/ha/day are 0.55-0.6, 5.5-6, 8.3-9, 11-12, 16.5-18, 22-24, and 27.5-30 kg BOD₅/ha/day, respectively. The optimal sewage dosage was 100 m³/ha/day, corresponding to an organic loading of 11-12 kg BOD₅/ha/day of settled sewage, with a mean BOD₅ of 110-120 mg/l. The equivalent nitrogen and phosphorus loading rates were 400-500 kg nitrogen/ha/120 day growing season or 3.3-4.2 kg nitrogen/ha/day. However, Olah et al. (1986) reported an optimum sewage loading rate of 150 m³ of clarified sewage/ha/day for the cultivation of a polyculture of only common carp and silver carp, equivalent to an organic loading rate of 16.5-18 kg BOD₅/ha/day, assuming the same strength of settled sewage reported by Kovacs and Olah (1984).

Wang (1987) reported BOD₅ loading rates of 20-30 kg/ha/day for sewage-fed ponds in Changsha, China, at water temperatures of 15-25°C. Hydraulic wastewater loading rates were 400-500 m³/ha/day.

The optimal organic matter loading rate of septage-fed ponds was considered to be 150 kg COD/ha/day (Edwards 1987). This corresponds to a BOD₅ loading rate of 15 kg BOD₅/ha/day, assuming a COD:BOD₅ ratio of 10:1 for septage. The more relevant total nitrogen loading rate was a corresponding 5-8 kg/ha/day.

5.6.2 Retention time

There is little information on retention times in ponds fertilised with sewage (Kalbermatten et al. 1982b). Nutrients may not be effectively utilized by a too-short retention time, but long retention times may be insufficient to provide optimal fish yields. They considered that the retention time should depend on the doubling time of phytoplankton in the pond and the grazing rate of fish, with a possible retention time of 1-5 days. However, the rate of flow of water should not be so great that large amounts of plankton are lost in the effluent (Demoll 1926, cited by Mortimer and Hickling 1954).

In an excreta-fed aquaculture system there is a need to consider the retention time with the organic loading. In conventional sewage stabilization pond systems, the retention time is inversely related to the organic loading, that is, as the retention time increases, the organic loading decreases. A relatively long retention time is required in an excreta-fed pond to ensure the production of adequate natural food and its efficient utilization by the fish. The cultivation of fish in excreta reuse systems essentially entails the use of relatively static water. However, the use of a relatively long retention time may correspond to such a low organic loading rate that the level of nutrients is inadequate to provide optimal production of natural food commensurate with good fish growth.

Good fish growth may be obtained in a fish culture system with a relatively short retention time if natural food for the fish is produced in an adjacent system and fed into the pond containing the fish, rather than being produced *in situ* in the fish culture system. High extrapolated fish yields were obtained in a series of concrete tanks fed with

the phytoplankton-rich effluent of a sewage-fed, high-rate stablization pond (Edwards et al. 1981a). Phytoplankton biomass and fish yield were inversely related to the retention time in the fish culture units, which varied from 2 to 40 days. The maximum fish yields were obtained at the shortest retention, two days, but about half of the phytoplankton biomass passed through the system without being used by the fish. The efficiency of phytoplankton use by the fish was directly related to the retention time. The highest efficiency of phytoplankton use by fish was at the longest retention time, 40 days, at which there was no effluent because the inflow just balanced water losses from evaporation and seepage. However, fish yields were low at the 40 day retention time because of low phytoplankton biomass. High extrapolated yields of fish of 7.7 and 11.5 tons/ha/yr were reported from India in experimental ponds with short retention times of two to three days and fed with the effluents of sewage stabilization ponds (Muthuswamy et al. 1974, 1978). High fish yields are feasible in excreta-fed systems with a short retention time if the natural food is produced outside the fish culture unit, but the efficiency of utilization of the natural food by the fish is low because of insufficient time for fish to filter it from the water. Clearly, raceways or running-water ponds with extremely short retention times are not suitable for excreta reuse in aquaculture, although they have been suggested (Middleton and Gromiec 1978).

It has been recommended as a rule of thumb that effluents from a system of waste stabilization ponds with an overall retention time of at least 20 days will provide an effluent that is safe in terms of public health for fish culture (Feachem et al. 1983, Mara and Pearson 1986, Pearson and Konig 1986). Arthur (1983) also suggested that tertiary and subsequent ponds in sewage stabilization pond series can be used for aquaculture. The concentration of plankton after such a long period of treatment may be insufficient for good fish yields. The use of a shorter overall retention time would provide adequate nutrients for aquaculture and would be safe from a public-health point of view because of the ability of excreta-fed ponds to attenuate enteric bacterial and viral indicator organisms (Chapter 7).

Ideally, an infinite retention time corresponding to the length of the fish culture cycle would provide maximum excreta reuse because of the absence of an effluent and loss of nutrients from the system. However, as discussed above, a very long retention time with a sewage-fed, flow-through system may provide insufficient nutrients for adequate fish yields because of the dilute nature of sewage. Sewage effluent subjected to only primary sedimentation was sprayed into ponds in Hungary; it produced impressive fish yields (Kovacs and Olah 1984, Olah et al. 1986). An infinite retention time could be used easily in a night-soil- or septage-fed reuse system with an optimal organic loading for fish culture because of the much lower water content compared to sewage. In fact, water would need to be added to balance losses due to evaporation and seepage and maintain the water level in the pond.

There are few data on retention times in sewage-fed ponds. The Munich sewage-fed ponds, with retention time of less than two days, were designed for the production of benthos for bottom-feeding common carp. Such a short retention time is unsatisfactory for optimum production of plankton and its use by filter-feeding fish. The retention times of ponds in China fed with sewage subjected to (at most) primary

sedimentation were reported to range from 10 to 40 days (Kuo 1980). Similarily, sewage-fed ponds in Hungary and China are fed with only primary-sedimented sewage. There is no effluent (thus, an infinite retention time) during the fish culture cycle, except during heavy rains in the monsoon season in India, when water may be released from the ponds.

5.6.3 Sludge accumulation

There are several reports in the literature concerning the need to avoid the use of raw sewage as a pond input to prevent sludge accumulation on the pond bottom. The first essential step in sewage reuse in ponds is the removal of most of the suspended solids in raw sewage, if considerable dilution (20:1 or more) with fresh water is not possible (Demoll 1926, cited by Mortimer and Hickling 1954). Otherwise, the ponds become filled with fermenting mud which causes problems and is costly to remove. The first large-scale reuse of sewage in ponds in Germany involved raw sewage without primary sedimentation, and there were problems of sludge accumulation. Mechanical methods of sedimentation can be used as long as the water is prevented from becoming foul by a too-long retention in the sedimentation chambers. Demoll also advised the removal of fat to avoid the danger of clogging fish gills. The Munich sewage-fed ponds use primary sedimentation, as recommended by Demoll. There has never been any sludge accumulation in the system after decades of use. However, a minimum dry period of three months in the winter is used to mineralize any sludge deposited (Liebmann 1960).

Several authors have pointed out that in India the use of raw sewage leads to the sedimentation of organic matter; this produces anaerobic conditions in the pond and raises the bottom of the pond (Saha 1970, Saigal 1972, Jhingran 1982). Fish farmers seldom allow raw sewage to settle, or they dilute it prior to introduction into ponds. Although by experience they have developed the skill of regulating the raw-sewage intake to avoid fish kills, the introduction of raw sewage causes the raising of the pond bottom by the accumulation of suspended solids in the form of silt (Saha et al. 1958). It was found that about 80 percent of the suspended solids settled within about 3 m and about 95 percent within about 12 m from the sewage inlet to the pond. Saigal (1972) believed the introduction of raw sewage into ponds should be discouraged because of the sedimentation of suspended solids, but Saha (1970) recommended periodic checking of the level of the pond bottom and removal of deposited solids as necesary. However, few ponds in Calcutta have been desludged since 1956, when the sewage fisheries were served with land acquisition notice, except for the construction of 2 m wide peripheral borrow pits in the ponds (Ghosh 1984). Not more than 0.5 m of sediments have been deposited on the bottom of the ponds because of the borrow pits. The latter act as silt traps and are excavated yearly to raise the pond dikes. An improved pond design incorporating peripheral borrow pits (Fig. 5.14) was presented by Ghosh (1984). However, the drainage of the ponds each year and the exposure of the bottom to the sun for a few months reduces pollution due to sludge (Nair 1944b, Basu 1948).

Pretreatment of sewage prior to reuse in ponds is considered essential in China, although the appropriate degree of pretreatment is debated because of the cost (Zhou 1986).
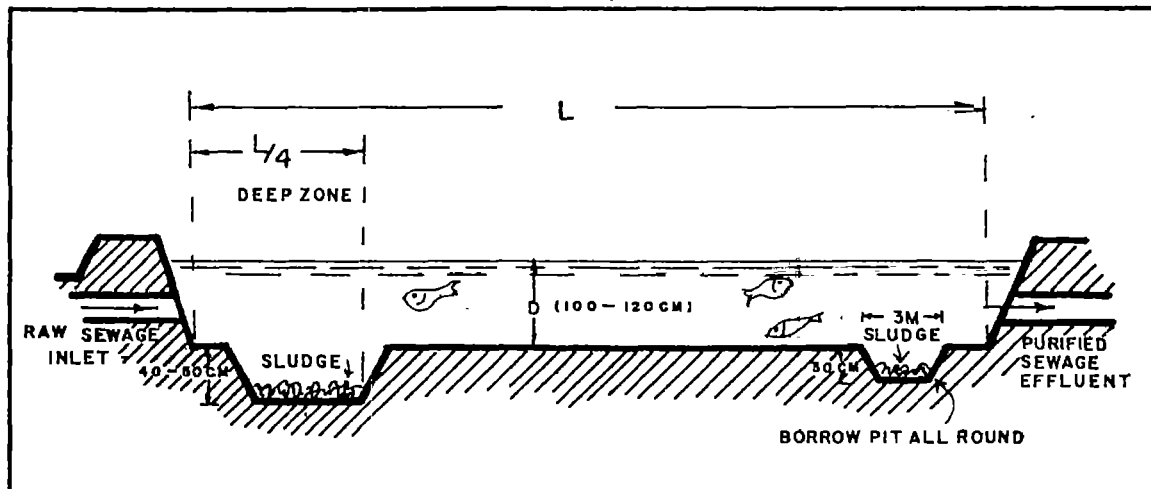
Figure 5.14 Cross-section of sewage-fed pond with a 3-meter wide pit for sludge deposition (*Source:* Ghosh 1984)

Screens remove oil and floating objects, and sedimentation ponds remove silt. An experimental sewage-fed pond at Changsha combined pretreatment of raw domestic sewage with fish culture in the same pond (Kuo 1980). The pond had three sections (primary sedimentation, purification, and reuse) which varied in extent according to wastewater flow and the weather. However, a design with a centralized primary sedimentation pond with clarified effluent distributed to separate ponds was being studied because of the problem of sludge accumulation in the former design. According to Kuo (1980), sewage-fed ponds in China are drained every two years, in winter, for desludging and liming.

It has been suggested that methods of mixing similar to those used in certain sewage treatment plants could be used to stir the bottom mud to resuspend sedimented sewage solids in the water column and facilitate their decomposition (Donaszy 1974). Sediment stirring could reduce sludge accumulation and increase fish yield by accelerating nutrient cycling in the water column. A balance would need to be established between increased nutrient availability, which could increase primary productivity, and higher turbidity from an increase in suspended particles, which would decrease primary productivity. However, it is unlikely that mechanical mixing of pond sediments would be economically viable.

A major constraint to the reuse of septage in ponds was the rapid accumulation of sludge, which probably created an anaerobic zone on the pond bottom, reduced the depth of the water column, impeded seining efficiency, and was costly to remove (Edwards et al. 1987). Further research on reducing sludge accumulation in septage-fed ponds is needed, perhaps through the incorporation of an anaerobic pond as a pretreatment stage. However, the hypothetical incorporation of an anaerobic pond in a system to treat the 20 m³ septage/day from a city of 100,000 led to a considerable reduction in the area of maturation ponds for fish culture because of an estimated 90 percent solids removal efficiency by the anaerobic pond (Liu 1986) (Fig. 5.15). It was pointed out 60 years ago that treated sewage can be used for aquaculture, but the fertilization effect is much less (Demoll 1926, cited by

Mortimer and Hickling 1954). Clearly, an intermediate solution is required in which the heavier solids are removed to reduce sludge accumulation, but without such complete removal of nutrients that too little is left to produce significant growth of fish.

5.6.4 Physical characteristics of pond

The size of ponds used for excreta reuse reported in the literature vary from about 400 m^2 for night-soil-fed ponds in Java to the Munich sewage-fed ponds which are up to 10 ha in area. Large ponds are cheaper to build than small ones in terms of construction cost per unit of water surface. Furthermore, greater water surface area can be achieved on a given amount of land by constructing large rather than small ponds since less land is required for dikes. However, very large ponds are difficult to manage if the fish are to be seined, and considerable time is required for draining and refilling. The most desirable pond size for a sewage-fed pond in China was reported to be 50-100 mu (3.3-6.7 ha); fertility was said to be uneven and harvest of fish difficult in larger ponds, and smaller ponds were sensitive to overloading, which often caused fish kills (Zhou 1986). Ponds in the tropics are usually smaller, and ponds of 0.2-0.5 ha may be optimal for successful management.

The pond should be deep enough to prevent the growth of submerged aquatic macrophytes but shallow enough to maintain algal growth and dissolved oxygen at all depths (Demoll 1926, cited by Mortimer and Hicking 1954; Fish Culture Research Institute 1979). There is disagreement about optimal pond depth because of a lack of research on the effect of varying depths on fish yields. Ponds traditionally are deep in China. Zhou (1986) recommended deep ponds of 2-3 m depth because such ponds have a high holding capacity of water and therefore also of fish. However, another Chinese study on sewage-fed ponds recommended a mean depth of 1-1.5 m because water depths greater than 2 m cause the development of anaerobic zones (Fish Culture Research Institute 1979). Ponds in the tropics are usually shallow, 1-1.5 m in depth.

Inlets and outlets to sewage-fed ponds should be built on opposite sides of the pond to avoid short-circuiting, and pond design should ensure that the entire area is fully utilized and that nowhere is there overloading (Demoll 1926, cited by Mortimer and Hicking 1954, Zhou 1986). Inlets and outlets should also be fitted with screens to prevent loss of fish, and gates are needed to control the water level (Zhou 1986). There should be provision to stop the flow of sewage into the pond when harvesting fish or drying and disinfecting the pond bottom (Donaszy 1974). Sewage diversion channels should also be built to divert sewage away from the pond as required to prevent overloading (Zhou 1986).

A periodic draining and drying schedule is needed for ponds to harvest all the fish, to control fish parasites and disease by using quicklime, to allow time for routine pond maintenance, to oxidize organic sediments by exposure to air, and to control the density of stocked fish (Liebmann 1960, Hickling 1971, Donaszy 1974).
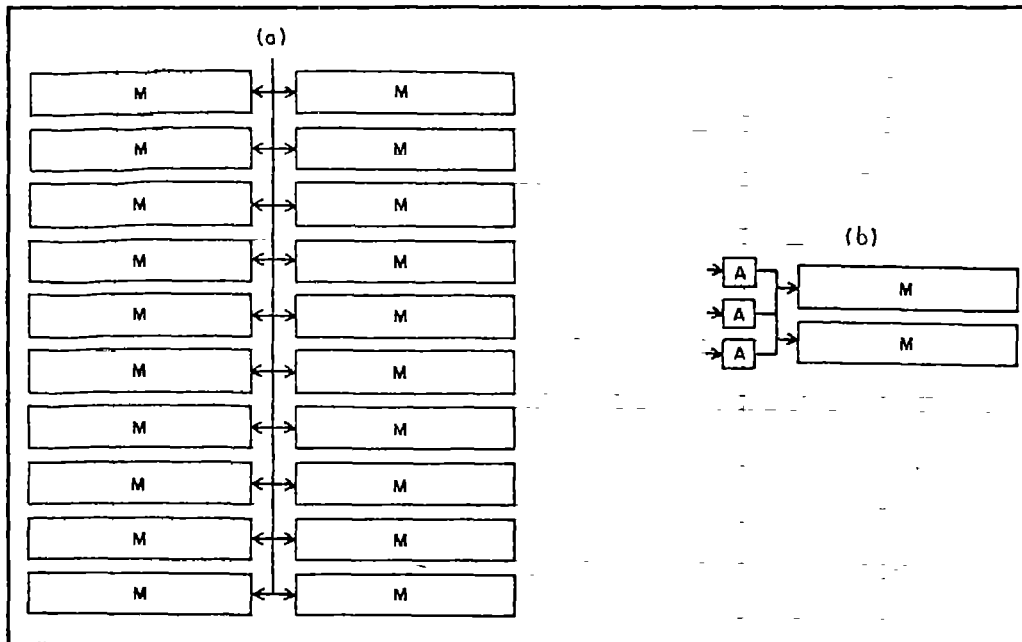
Figure 5.15 Septage reuse in aquaculture ([a] Septage added directly to the maturation pond. [b] Incorporation of anaerobic pond. A = anaerobic pond, M = maturation pond. Adapted from Edwards et al. 1987)

5.6.5 Climatic considerations

The species with the greatest potential in excreta reuse in aquaculture are warm-water fish, and these grow best in the high year-round temperatures found in the tropics. A large mortality of the tropical fish tilapia (probably *Oreochromis aureus*) occurred in a series of sewage stabilization ponds in temperate Oklahoma when temperatures fell in winter (Coleman et al. 1974). Common carp and Chinese carps are warm-water fish of temperate origin; they grow thorughout the year in the tropics and can survive year-round in climates with seasonally low temperatures. They may grow in temperate latitudes for only seven to eight months of the year when water temperatures are high enough. Fish are cultivated in sewage-fed ponds in Munich for only seven months per year because of the temperate climate. Attention has also been drawn to the seasonal nature of fish culture in experimental sewage stabilization ponds in China, Hungary, and the United States.

Aquaculture can be used to treat sewage in temperate latitudes only where there is a standby system; otherwise, an alternative treatment strategy is required (Henderson and Wert 1976). Where there is no alternative winter sewage disposal system, the use of aquaculture to treat sewage is limited by the short growing season for fish in temperate latitudes to cities with a significant summer peak of domestic sewage, such as Szemes, near Lake Balaton in Hungary (Olah et al. 1986). In theory, it should be possible to culture fish year-round in the tropics, where temperatures are relatively constant, although the

Calcutta sewage fishery seems to be seasonal, for reasons which are not readily apparent from the literature.

6. Excreta Reuse in Seawater

6.1 Introduction

The world's most productive marine fisheries are located in either upwelling or coastal areas (Ryther 1969). Natural processes in upwelling areas cause nutrient-rich deep water to be brought to the surface where light stimulates high phytoplankton productivity. Nutrients from terrestrial sources in coastal areas support the development of marine food chains.

Stimulation of marine productivity has been demonstrated experimentally by the use of inorganic fertilizers. The discharge of sewage into the sea can also benefit marine food chains through nutrient enrichment. There is a dilemma concerning conflicting uses of coastal zones because the choice is not simply between "clean" and "dirty" water but may also involve the choice between waters of low and high productivity, including food organisms for humans (Ryther 1971). However, adverse effects of sewage discharge on commercially important organisms in the marine environment have been reported.

Excreta reuse in mariculture is clearly in its infancy. There is only one commercial system reported in the literature, the fertilization of brackish milkfish ponds with night soil in Taiwan. However, there is great potential based on the list of marine organisms of commercial value that may be cultured in excreta-reuse systems (Table 6.1).

Two types of agar are extracted from certain genera of red algae: bacteriological agar obtained from the slow-growing, cold-water genera *Gelidium* and *Pterocladia*, and food-industry agar extracted mainly from *Gracilaria*. The latter, which is used as a gelling or stabilizing agent by the food industry, may have potential as a crop in marine excreta-reuse systems, and several species grow in warm water. The demand for agar is expected to continue to rise as the consumption of processed foods increases in both developed and developing countries. The price of high-quality *Gracilaria* has risen in the last 15 years from $500 to $1,400-1,500/ton dry weight (J. H. Ryther, personal communication). Most *Gracilaria* is obtained from wild populations, which are currently overharvested. Taiwan is the only place in the world where *Gracilaria* is cultivated (Shang 1976, Chiang 1984).

Bivalve molluscs, which feed on phytoplankton, include oysters, clams, mussels, and scallops. They have high economic value as luxury food items and can be grown in excreta-enriched culture systems.

Brine shrimp (*Artemia*) occur naturally in coastal and inland saline waters and are marketed as dried cysts. These readily hatch to produce live feed for larvae of

Table 6.1
Some Marine Organisms of Commercial Value That May Be Cultured in Excreta-Reuse Systems

Food source	Species grown	Commercial value
Dissolved nutrients: domestic wastes, food processing wastes, agricultural wastes, fertilizers	Phytoplankton, benthic algae, seaweeds	Agar, food stabilizers, fertilizers, human food
Phytoplankton	Filter-feeding molluscs: oysters, clams, mussels, scallops; brine shrimp	Human food

Tropical fish food |
Seaweeds	Abalone, lobsters	Human food
Benthic algae	Omnivorous fish, grey mullet, shrimp	Human food
Detritus, feces, pseudofeces	Small crustaceans: polychaete worms	Bait in sport fishing
Small crustaceans, worms, detritus	Carnivorous fish: flounder; lobster, shrimp	Human food

Source: Goldman and Ryther (1976)

commercially cultivated shrimps and marine and aquarium fishes. Brine shrimp have been raised experimentally on phytoplankton in excreta reuse systems.

There are also prospects for the culture of herbivorous fish such as grey mullet, tilapia, and milkfish in marine excreta-reuse systems. Additional candidates for such systems include omnivorous and detritivorous organisms such as high market-value penaeid shrimp and polychaete worms such as the clam worm (*Nereis virens*), which is commonly used as bait in sport fishing in the United States. Other polychaete worms such as *Capitella capitata* could be used as feed for omnivorous feeders such as flounder, lobsters, and shrimp in excreta-reuse systems.

Various experimental excreta-reuse mariculture systems described in the literature are outlined below, and a discussion of their prospects for commercial implementation follows.

6.2 Fertilization of the sea with inorganic fertilizers

The experimental fertilization of seawater with inorganic fertilizers increased the productivity of marine food chains. One of the earliest artificial fertilization experiments in a marine environment was a study of the addition of inorganic nitrogen and phosphorus to oyster polls in Norway (Gaarder 1932, cited by Mortimer and Hickling 1954). Fertilization resulted in an increase in phytoplankton biomass until light became a limiting factor.

A series of classic experiments on two sea lochs in Scotland demonstrated the feasibility of fertilizing seawater (Gross et al. 1944, 1946; Marshall 1947; Cooper and Steven 1948). It was hoped that fertilization of the sea lochs would lead to increased fish production and augment local supplies when the North Sea fisheries were interrupted during World War II. Large increases in phytoplankton biomass usually followed the addition of inorganic fertilizers, although phytoplankton were occasionally suppressed by zooplankton grazing. The benthic seaweeds also competed with the phytoplankton for nutrients. Both sea lochs contained rapidly growing fish compared to those in adjacent sea lochs (Weatherly 1972). Although fertilization led to marked increases in the lower links in the food chain, the effect on fish production was small because there was an insufficient initial fish biomass to utilize the increase in the trophic base (Hepher 1978).

Fertilization of a saltwater bay in Massachusetts with inorganic phosphate and nitrate increased the standing crop of the phytoplankton by several times (Pratt 1949). The collective effect of several fertilization experiments produced a significant increase in phytoplankton biomass which lasted throughout the second summer of the fertilization trials.

Fertilization of two small, partially enclosed marine bays on the coast of Yugoslavia with inorganic phosphate fertilizer had positive effects on the growth of commercial oyster and mussel beds (Buljan 1961). Fertilization caused a marked increase in phytoplankton concentrations, and benthic diatoms and blue-green algae also increased in density. The density of the fry of several species of fish increased and adult grey and red mullet fattened during the experiment. It was stressed that fertilization should be conducted with care to avoid harm to shellfish because the increased organic productivity in the fertilized area caused an oxygen deficiency in the bottom water layers. In some places there was a complete disappearance of oxygen from the water and production of H_2S.

6.3 Coastal discharge of sewage

The addition of sewage causes a general increase in the fertility of the sea and leads to greater primary and secondary productivity. It is feasible to use coastal areas that are slightly polluted with domestic sewage for aquaculture (Korringa 1976). It is well recognized that sewage-polluted seawater is highly beneficial for bivalve mollusc production, and there is little doubt that the high yields of shellfish from some estuarine waters is due in part to fertilization with human excreta (Ryther 1971, Ryther and Tenore 1976). The thousands of hectares of brackish ponds in the deltaic areas of West Bengal, India, in which mullets and prawns are cultured, are fertilized by the diluted sewage of Calcutta (Hickling 1971). The Lake of Tunis, Tunisia, a 30-km^2 lagoon with average depth less than 1 m, received sewage from about 300,000 inhabitants, mostly after treatment. The lake had rich phytoplankton and seaweed biomass throughout the year and provided the basis for mean fish catches of 147 kg/ha, close to the maximum yield for the Mediterranean (Stirn 1972). It is believed that the large-scale farming of the red seaweed nori (*Porphyra*) in the coastal waters of Japan is favored by slight eutrophication through domestic sewage pollution (Korringa 1976). The discharge of sewage into coastal waters is clearly beneficial because of the increased nutrient budget, provided there is good circulation of water. With high rates of mixing and dilution with seawater, there is complete oxidation of organic matter, and the oxygen content of the receiving water remains high. In fact, marine disposal of sewage by ocean outfalls is considered a viable wastewater management strategy for well-sited coastal cities (Gunnerson 1988).

Sewage is made up of a variety of subtances: oxidizable organic matter and nutrient salts, inert suspended solids or silt, pathogenic microorganisms, and conservative materials (O'Sullivan 1971). The discharge of large amounts of sewage into shallow coastal water embayments and estuaries with short circulation and long retention times can lead to anoxia and destruction of aquatic life. With increasing quantities of sewage, water with limited exchange or dilution may initially become anoxic at night due to the respiration of blooms of phytoplankton stimulated by sewage nutrients. With increasing eutrophication, the water may become continuously anaerobic through bacterial degradation of organic matter. Molluscan shellfish such as oysters, mussels, and clams will not survive in seawater with heavy influxes of domestic sewage in the absence of dissolved oxygen and the presence of hydrogen sulfide during part of the tidal cycle (Korringa 1976). The sedimentation of suspended solids in sewage can cover benthic organisms, including shellfish beds (O'Sullivan 1971). Pollution of shellfish beds with domestic sewage can lead to the accumulation of toxic heavy metals, radioactive isotopes and organic chemicals, or tainting which may render the product unsaleable (Korringa 1976, Ryther and Tenore 1976).

There are numerous references to the adverse effects of sewage effluents on commercially valuable organisms in coastal environments. Many oyster and clam beds in the United States have either disappeared or have been closed due to pollution in the last half century (De Falco 1967). The estuary, where approximately one third of the total population of the United States is located, has been called the septic tank of the megapolis. Oslofjord has been adversely affected by sewage effluent with the decline of fisheries and

the accumulation of toxins from dinoflagellate blooms by shellfish (O'Sullivan 1971). The shellfish in Manila Bay, Philippines, are declining because of increasing pollution of the bay, due in part to sewage discharge (Gunnerson 1988). Although the Lake of Tunis was reported to have one of the highest mean fish catches in the Mediterranean, attributed to the discharge of sewage effluents into the lake, there was a mass mortality of fish once a year (Stirn 1972). It has been predicted that coastal mariculture is likely to decline in Hong Kong because of increasing coastal pollution which includes screened raw sewage (Morton 1976).

6.4 Commercial excreta reuse

There appears to be only a single example of the commercial reuse of excreta in a mariculture system reported in the literature. Night soil was commonly used as fertilizer for brackish milkfish (*Chanos chanos*) ponds in Taiwan (Chen 1953, 1973; Tang and Chen 1957).

Brackish ponds were drained every December and, after dredging the pond bottom to repair the dike, about 14.5 tons night soil/ha were spread on the bottom four times between January and March (Lo 1979). No more night soil was added after the ponds were filled with water and stocked with fish in April. Kuhlthau (1979) also described the reuse of night soil in brackish-water milkfish culture. Night soil and bean cake were used as nutrients to stimulate the growth of benthic algae. Prior to flooding the ponds in March, night soil and bean cake were placed on the pond bottom. The ponds were initially filled with only 3 cm of water, and benthic algae soon developed. More night soil and bean cake were added as the water evaporated, and then more water was let in. When a substantial biomass of algae had developed after a month, the water level was raised to 25 cm and fish were stocked. Night soil and bean cake were applied in five or six doses throughout the season to stimulate growth of benthic algae and plankton. Five to six harvests of fish were made during the approximately seven-month rearing period until the end of November, when the ponds were drained.

The use of night soil in brackish milkfish ponds in Taiwan ceased a few years ago, probably due to the intensification of agriculture with the production of large amounts of by-products such as rice bran, which is currently the main fertilizer in milkfish ponds. The rising cost of labor no doubt also rendered the transporation of bulky excreta to, and its distribution in, the ponds increasingly uneconomic.

6.5 Experimental excreta-reuse mariculture systems

6.5.1 Woods Hole Oceanographic Institution, Harbor Branch Foundation Studies

Ryther and co-workers developed the concept of a tertiary sewage treatment-marine aquaculture system (Ryther et al. 1972, Douglas 1974). The culture of marine phytoplankton in sewage-seawater mixtures followed the work of Oswald and co-workers at the University of California at Berkeley on the use of freshwater phytoplankton to assimilate nutrients from sewage. The primary objective was to develop a biological tertiary sewage treatment system to remove all inorganic nitrogen from secondary sewage effluent. The second objective was to develop a mariculture system in which crops of commercially valuable marine organisms would pay for at least part of the cost of the tertiary sewage treatment process (Fig. 6.1). The concept was refered to as controlled eutrophication because the reuse of sewage to produce marine organisms was carried out under carefully controlled conditions. The discharge of nutrient-free water to the marine environment would reduce cultural eutrophication of natural waters caused by indescriminate sewage discharge.
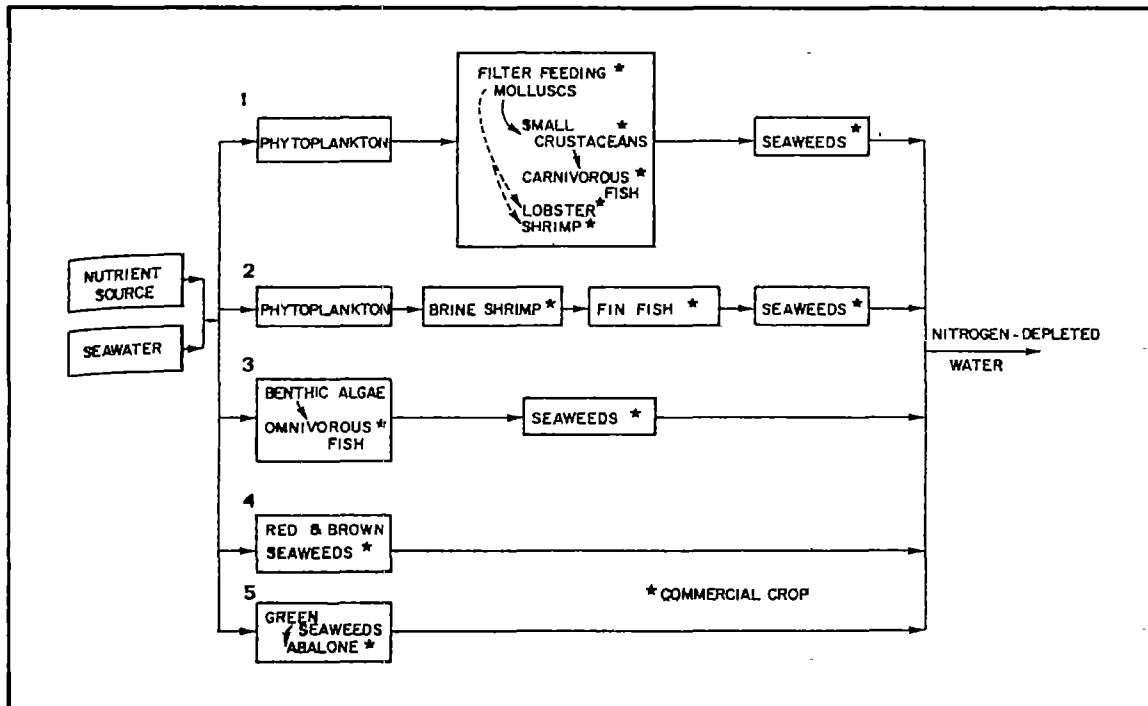
Figure 6.1 Flow schemes of potential integrated food chains for sewage reuse-mariculture systems (Source: Goldman and Ryther 1976)

Secondary sewage effluent was mixed with seawater as a source of nutrients to grow marine phytoplankton. Most subsequent studies involved feeding the marine phytoplankton to herbivorous shellfish such as oysters and clams. Such molluscs filtered algae from the water but excreted soluble and particulate products because of a relatively

low efficiency in converting ingested algae to their own biomass. Shellfish excretary products were subsequently used as food for additional links in a complex integrated marine food chain (Fig. 6.1). A final polishing step involving seaweeds was required to remove nutrients not assimilated by the phytoplankton, and those regenerated by excretion of the bivalves and decomposition of their solid wastes. Ultimately, research centered on a single-stage seaweed mariculture system for nutrient removal from secondary sewage.

Various components of the proposed tertiary sewage treatment-mariculture system were initially tested at Woods Hole on a small scale under controlled conditions in the laboratory, and later outdoors under natural light and temperature (Ryther et al. 1975, Goldman and Ryther 1976). Sufficient progress was made by the spring of 1973 to construct a complete physical model of the integrated system which was studied in continuous operation for 6 months from May through October of the same year. A pilot plant facility, the Environmental Systems Laboratory (ESL), went into operation in November 1973 at Woods Hole, and subsequent experiments were carried out. It was hoped that the concepts could be evaluated on a scale large enough to permit realistic extrapolation to commercial operation.

Experiments similar to those with the 1973 Woods Hole physical model were started in January 1974 at the Harbor Branch Foundation Laboratory in southeast Florida in a climate which permitted year-round operation of the system.

6.5.1.1 Laboratory experiments at Woods Hole

Laboratory experiments began at Woods Hole in 1970 on the growth of marine phytoplankton in seawater enriched with secondary sewage effluent (Dunstan and Menzel 1971, Ryther et al. 1972). Diluted sewage effluent was shown to be an excellent culture medium for marine phytoplankton, comparable to and perhaps even better than the artificially enriched seawater medium used for several years in the laboratory. In fact, the concept of an integrated tertiary sewage treatment-mariculture system was developed from the demonstration that secondary sewage effluent diluted with seawater was an adequate enrichment medium to grow marine phytoplankton (Ryther et al. 1975). Raw seawater enriched with secondary sewage effluent usually developed a community dominated by several species of diatoms which, in continuous culture, was soon reduced to a single dominant species (Dunstan and Menzel 1971).

6.5.1.2 Small-scale outdoor studies at Woods Hole

The phytoplankton cultures were then scaled up to 0.4 m^3 fiberglass tanks in naturally fluctuating conditions of light and temperature outdoors on the Woods Hole Oceanographic Institution docks (Dunstan and Tenore 1972). Phytoplankton removed inorganic nitrogen virtually completely, but only about 50 percent of the phosphorus was removed, as expected, because there was about twice as much phosphorus relative to nitrogen in sewage than is normally present in seawater and phytoplankton. However, the phytoplankton culture fulfilled the primary purpose of tertiary sewage treatment because

bioassay experiments showed that the phytoplankton-culture effluent was unable to support more growth of phytoplankton than seawater alone (Goldman et al. 1973).

A prototype made up of culture systems for marine phytoplankton, oysters and seaweed joined in series and fed with secondary sewage effluent diluted 1:4 with seawater was run for 11 weeks in the summer of 1972. Part of the phytoplankton cultures were harvested to feed juvenile oysters, clams, mussels and scallops held in trays in rectangular tanks (Ryther et al. 1972, Goldman et al. 1974ab, Goldman and Ryther 1976). Phytoplankton cultures were initially harvested in batches, but they were unstable and tended to collapse every one to two weeks. A change to continuous flow using 25 percent sewage effluent and 75 percent seawater with a two-day retention time led to a marked improvement in culture stability. Although the phytoplankton were effective in nitrogen removal, some nitrogen was returned to the system by shellfish excretion. A final polishing step using the seaweed Irish moss (*Chondrus crispus*) successfully assimilated regenerated nutrients to provide an overall 95-100 percent effectiveness of nitrogen removal.

A complete small-scale model of the entire system was constructed during the winter of 1972-73 (Fig. 6.2) and run continuously for six months (Goldman and Ryther 1975, 1976; Ryther et al. 1975). Secondary sewage effluent from a trickling-filter plant was collected daily and pumped from a 1-m^3 storage tank along with 1-m^3 filtered seawater to headboxes above two 2-m^3 circular phytoplankton growth tanks. Sewage effluent and seawater were blended into each pond at desired ratios and flow rates. The phytoplankton tanks were continuously mixed and aerated by motor-driven rotating arms and recirculated through pumping. Phytoplankton tank effluents flowed by gravity through the rest of the system because the tanks were elevated. The final effluent was discharged into Woods Hole Harbor. The effluents from both phytoplankton tanks were mixed and the combined effluent was passed through a high-speed homogenizer to separate clumped phytoplankton cells into single-cell food for the oysters.

The rest of the system, which included oysters, worms and seaweeds, was divided into two parallel systems. System A consisted of American oyster (*Crassostrea virginica*), the polychaete worm (*Capitella capitata*) and the red seaweed Irish moss (*Chondrus crispus*). The phytoplankton culture which flowed through the oyster tank was supplemented by 100 μm filtered seawater pumped in at varying rates. The seaweed growth tanks were mixed through recirculation. System B consisted of oysters, the polychaete clam worm (*Nereis virens*) and sea lettuce (*Ulva lactuca*), a green seaweed.

Attention was focused primarily on nutrient transformations in the phytoplankton cultures during the six months of continuous operation of the experimental model (Goldman and Ryther 1975). In short-term experiments in which the sewage effluent concentration and the retention time were varied, maximum phytoplankton yields were obtained with a 1:1 ratio of sewage effluent to seawater at a 1.3-day retention time (75 percent dilution rate/day). This combination removed only 50-60 percent of the nitrogen from the secondary effluent but the complete system, which included seaweeds, removed almost all the nitrogen present in the secondary effluent. Natural communities of phytoplankton were
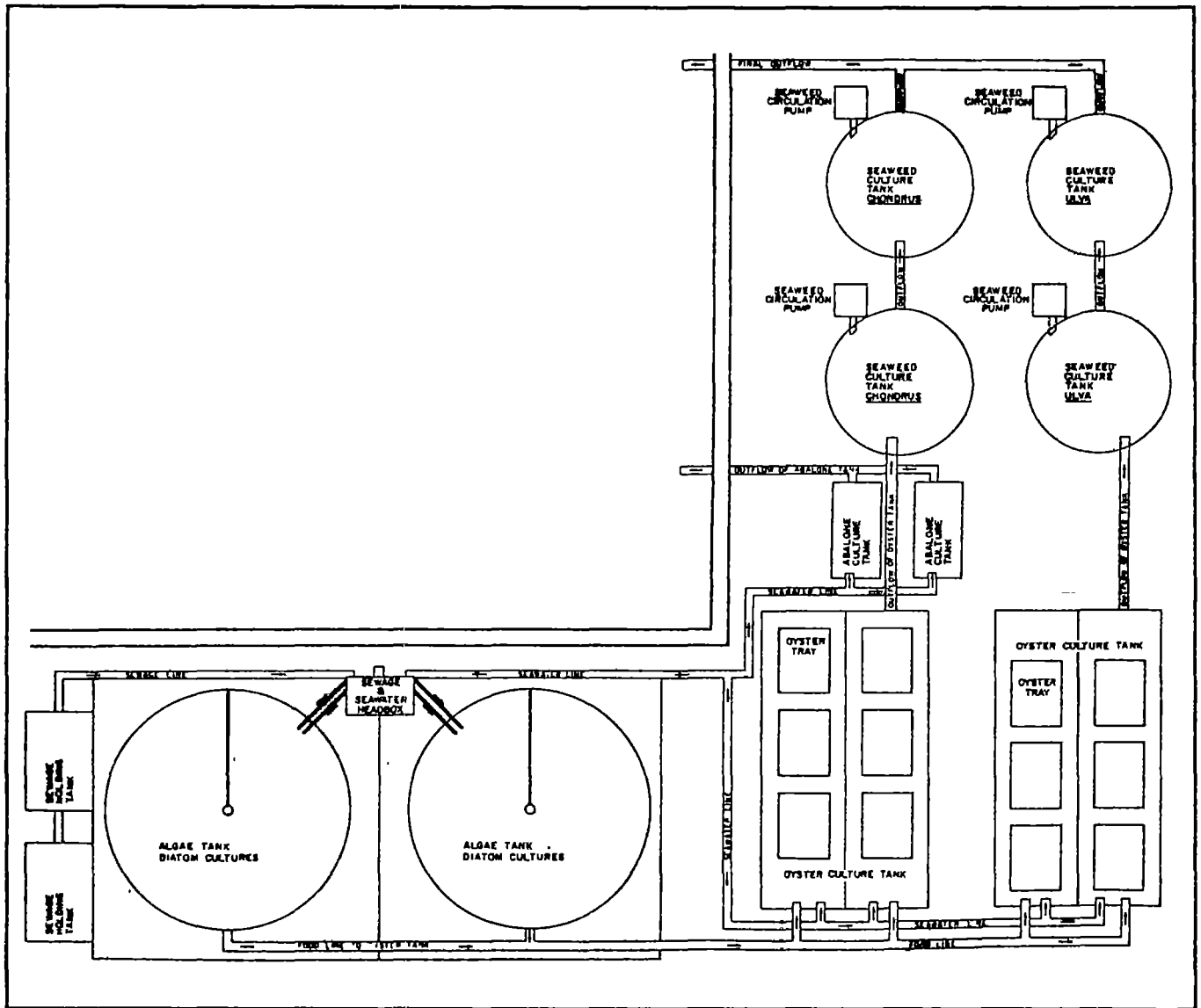
Figure 6.2 Flow diagram of nitrogen-stripping mariculture system (Source: Goldman and Ryther 1976)

allowed to develop and included a succession of marine pennate diatoms strongly correlated with pond temperatures.

Considerable time and effort were spent in collecting and stocking the animal and seaweed components and empirically achieving the proper balance between them; insufficient time remained in the six-month study to obtain meaningful growth and productivity data (Ryther et al. 1975). Oyster growth was poor, probably due to the species of phytoplankton which developed. *Phaeodactylum tricornutum* is not a good food source for bivalve molluscs, and other diatoms that developed tended to clump

into particles of 1 mm or more (despite the homogenizer) and were too large for shellfish assimilation. Studies on the detrital trophic level in the small-scale model demonstrated the feasibility of culturing polychaete worms (*Nereis virens, Capitella capitata*) and the amphipod *Corophium* sp. on the biodeposits of feces and pseudofeces of oysters (Tenore et al. 1974).

Sea lettuce (*Ulva lactuca*) cultured in the small-scale model was an adequate food source for three species of commercially important abalone (red abalone, *Haliotis rufescens*; green abalone, *H. fulgens*; Japanese abalone, *H. discus*). Sea lettuce was harvested and fed manually to abalone cultured in separate tanks with flowing filtered seawater. Although abalone usually prefer to eat brown seaweeds, it was concluded that abalone can be considered potential candidates for sewage-fed mariculture systems (Tenore 1976).

It was concluded from the results of the 1973 experiments with the complete small-scale model that the proposed system was a promising alternative to more conventional tertiary treatment methods (Ryther et al. 1975).

6.5.1.3 Environmental Systems Laboratory (ESL) at Woods Hole

The development, establishment, and preliminary experience of the Environmental Systems Laboratory (Fig. 6.3) were described by Huguenin and Ryther (1974), Huguenin (1975) and Ryther (1977). Daily deliveries of 30 m^3 of secondary sewage effluent from an activated sludge plant were trucked to the ESL and discharged into subterranean storage tanks. The effluent was pumped to a headbox and distributed to the phytoplankton culture ponds by gravity.

The six phytoplankton culture ponds were PVC lined, approximately 1 m deep, and 130 m^3 in volume. Phytoplankton were kept in suspension by recirculation of the water using pumps. Two ponds were capable of being heated and circulated by heat exchangers so that they could be operated at 15°C throughout the winter. The daily output of about 45 m^3 from each phytoplankton pond was fed into one of the cement raceways stocked with bivalve molluscs.

It was again not possible to control the species of phytoplankton that developed in the ponds despite inoculation of ponds filled with 1 μm filtered seawater with several hundred cultures of several species of phytoplankton. The species present varied with the season and was almost a monospecific culture. The diatom *Skeletonema costatum* was present at 0-9°C in winter. The diatom *Phaeodactylum tricornutum* was dominant during most of the rest of the year at 10-25°C, except for about one month in midsummer when an unidentified green flagellate was dominant at pond temperatures higher than 25°C (Ryther 1977 1979). The dominant species of phytoplankton probably did not affect tertiary treatment because it was unlikely that phytoplankton productivity and nutrient uptake varied with the species. However, phytoplankton species control was a major problem for rearing shellfish because the major dominant, *Phaeodactylum*, was a poor to indifferent food for the bivalves.
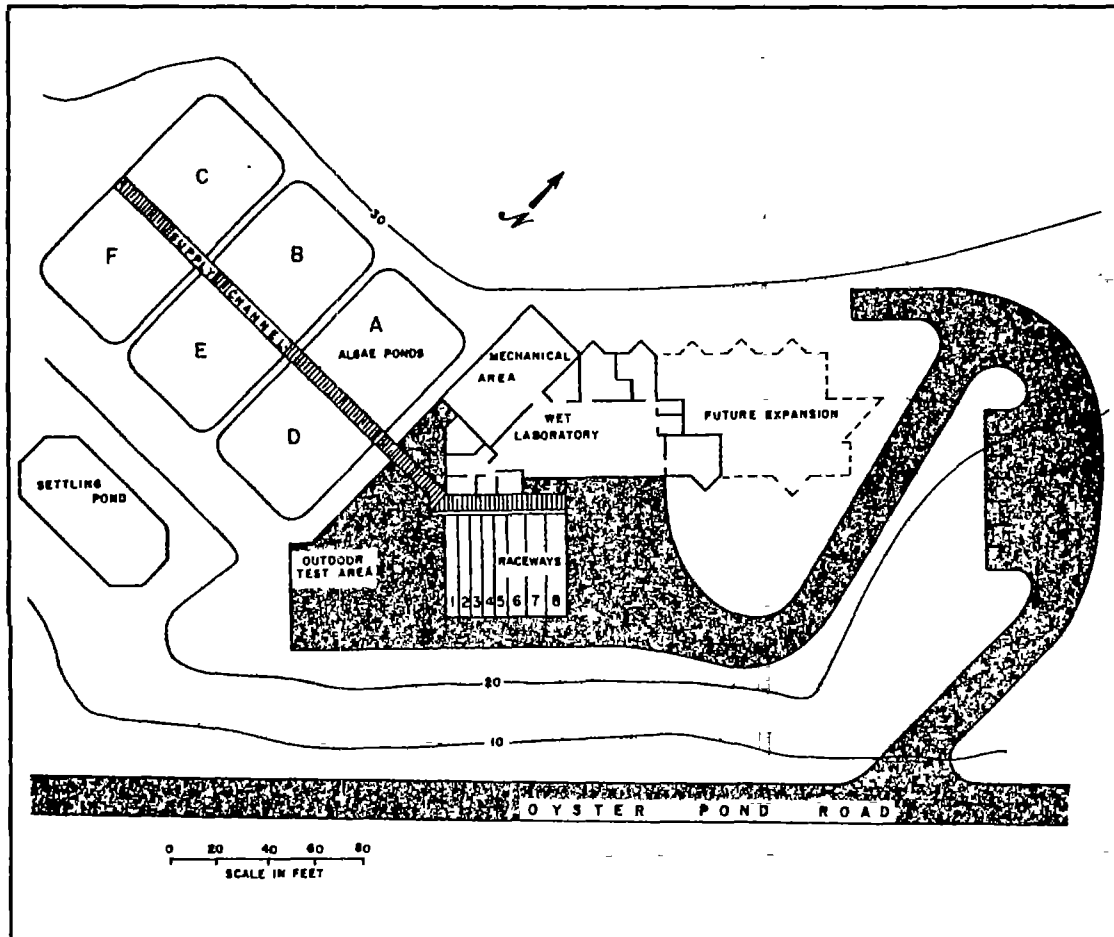
Figure 6.3 Environmental Systems Laboratory, Woods Hole Oceanographic Institution (Source: Ryther 1979)

The system depended on high-quality, completely oxidized, clear secondary effluent to produce marine phytoplankton. Phytoplankton productivity was inhibited by turbidity during approximately two months when the effluent contained large concentrations of undigested suspended solids (Ryther 1977, 1979).

Phytoplankton effluent was fed into a series of 12-m long x 1.2-m wide x 1.5-m deep cement raceways stocked with bivalve molluscs in wooden trays lined with plastic mesh. There was an air line along both sides of each raceway on the bottom to provide aeration and vertical mixing of the water. The shellfish were stocked at 1,500-3,000 animals/tray or 75,000-150,000 animals/raceway. The raceways were covered with plywood sheets to reduce heat loss and prevent fouling with filamentous algae.

The phytoplankton culture was diluted with coarse-filtered seawater (100 μm) at its point of entry to the raceway at ratios of 1:1 to 1:5, respectively. Dilution of

phytoplankton culture was carried out to dilute the suspension to 10^5 cells/ml, at which shellfish filter and assimilate the algae the most efficiently. Dilution also provided a more rapid flow of water through the raceway to enhance feeding and prevented build-up of shellfish metabolites, particularly ammonia.

Initial attempts at shellfish culture involved stocking seed of American oysters (*Crassostrea virginica*) and hard clams (*Mercenaria mercenaria*), but neither species grew, probably because the dominant phytoplankton for most of the year, *Phaeodactylum*, was unsuitable as food for the shellfish. Green phytoplankton are also known to be poor foods for larval and very young juvenile clams and oysters. The exotic shellfish Manila clam (*Tapes japonicus*), European oyster (*Ostrea edulis*) and Japanese oyster (*Crassostrea gigas*) were subsequently stocked and grown in the raceways. Thus, the problem of the inability to control phytoplankton species dominance to produce species suitable as food for indigenous clams and oysters was circumvented by culturing shellfish species which were able to utilize the phytoplankton that developed in the system.

The growth of six species of bivalve molluscs was subsequently compared in a single experiment at temperatures of 15-20°C from November to May and confirmed the earlier conclusion that bivalves indigenous to the United States grew less well than exotic nonindigenous species (Mann and Ryther 1977). *Crassostrea gigas, Tapes japonica* and *Ostrea gigas* grew well in raceways fed predominantly with *Phaeodactylum tricornutum* grown in large outdoor cultures enriched with secondary sewage effluent, but *Crassostrea virginica, Mercenaria mercenaria,* and *Mytilus edulis* grew poorly. However, the mussel *Mytilus edulis* grew well in the system when the experiment was repeated at a temperature of 14°C, due in part to the lower temperature; this species of mussel has difficulty in acclimating to water temperatures above 20°C (Mann 1978).

It was estimated from preliminary experiments that secondary treatment sewage from 10,000 persons could produce enough phytoplankton to grow 11 million, 8-10 cm, marketable-size oysters, equivalent to 183 tons oyster meat/yr (Ryther 1980, 1981).

Feces and pseudofeces produced by the shellfish and uneaten sedimented phytoplankton cells provided food for small invertebrate detritivores (amphipods, bryozoans, mussels, polychaetes, and tunicates) that probably entered the shellfish raceways as larvae in the coarse-filtered seawater used to dilute the phytoplankton pond effluent. The small invertebrates served to prevent the accumulation of solid wastes in the raceways but were also a source of food for carnivores or omnivores of potential commercial value. A raceway containing hard clams (*Mercenaria mercenaria*) was stocked with the clam worm *Nereis virens* to feed on clam biodeposits. The small polychaete worm *Capitella capitata* was inoculated in the bottom of one of the raceways stocked with oysters to feed on their feces and pseudofeces. Winter flounder (*Pseudopleuronectes americanus*) were subsequently stocked in the raceway to feed on the worms, which multiplied and grew well (Goldman and Ryther 1976). American lobsters (*Homarus americanus*) were also stocked in the shellfish raceways and attained in eight months a size that requires at least three years for wild lobsters in New England. However, a serious constraint to lobster cultivation was the need to keep them individually in separate containers to prevent cannibalism.

The seaweed raceways had the same dimensions as the shellfish raceways but were modified with a sloping plywood bottom. An air line along the bottom at the deep end of the raceway kept the seaweed in suspension and circulated the water so the plants were continually brought to the surface and exposed to light of high intensity (Fig. 6.4). Seaweed research was restricted to red algae with potential commercial value for agar or carrageenan: *Chondrus crispus, Gracilaria tikvahiae, Hypnea musciformis*, and *Neoagardhiella baileyi*.
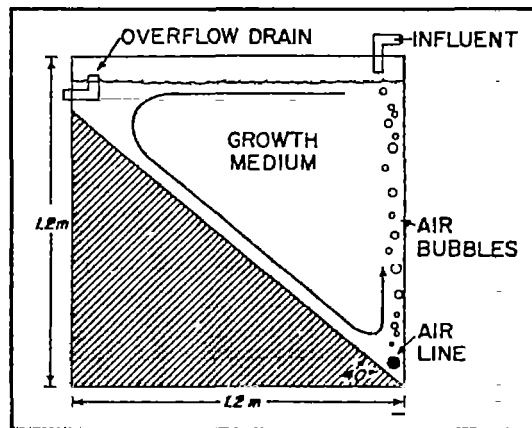
Figure 6.4 Cross-section of seaweed growth tanks (Source: Lapointe et al. 1976)

Yields for *Gracilaria tikvahiae* in temperate Woods Hole ranged from 5 g dry weight/m²/day in winter to 17 g dry weight/m²/day in summer, with maximum yields of 27 g dry weight/m²/day achieved for short periods in summer. The latter growth rate is equivalent to an annual yield of 99 tons dry weught/ha/yr. Fouling organisms, particularly the green alga *Enteromorpha*, occasionally grew epiphytically on the cultured seaweed. Cultures had to be discarded with severe infestations. Extrapolated annual yields of 63 tons and 33 tons dry weight/ha/yr were reported for *Neoagardhiella baileyi* and *Gracilaria foliifera (G. tikvahiae)*, respectively, but the raceways were artifically heated for approximately six months of the year (De Boer et al. 1977). It was predicted that even higher yields would be attainable in warmer climates.

A continuous mass culture of brine shrimp (*Artemia salina*) was established in a 130-m³ pond from nauplii hatched from eggs in the laboratory (Ryther et al. 1975, Goldman and Ryther 1976). The dense culture of adult *Artemia* actively produced live young and was fed the daily harvest of about 45 m³ of the diatom *Phaeodactylum tricornutum* at about 10⁶ cells/ml from a phytoplankton pond. *Artemia* completely removed the phytoplankton. The corresponding harvest of 45 m³/day from the *Artemia* pond, which contained both adult and larval brine shrimp, was fed into a raceway containing trout and other plankton-eating finfish. Although *Artemia* are normally associated with hypersaline water, preliminary laboratory experiments indicated that they would continue to grow and reproduce at the salinity of 15 percent used in the system with a 50 percent sewage effluent

enrichment of the seawater-fed ponds. However, it was recognized that the introduction of an additional link in the food chain would lead to a reduction of the final product by 80-90 percent from that of the herbivores.

Table 6.2
Mass Flow of Inorganic Nitrogen (Ammonia, Nitrite, and Nitrate) through the Phytoplankton-Oyster-Seaweed System

	Grams N/day	Total
Phytoplankton pond input		
Sewage effluent	84	
Seawater	1	85
Phytoplankton pond output		1.5
Shellfish raceway input		
Phytoplankton pond harvest	1.5	
Seawater	3.0	4.5
Shellfish raceway output (equals seaweed raceway input)		27
Seaweed raceway output (final effluent from system)		9.4
Total nitrogen removel efficiency (including seawater)		89.3 percent
Effluent nitrogen removal efficiency		93.6 percent

Source: Ryther (1979)

The nutrient-removal efficiency of the whole system is shown in Table 6.2. The data represent typical steady-state mass flow of nitrogen through the three-step system (phytoplankton-shellfish-seaweed) in late spring. More than 98 percent of the total inorganic nitrogen entering the system (84 g and 1 g N/day in secondary sewage effluent and seawater, respectively) was removed by the phytoplankton. The effluent from the phytoplankton pond with the remaining 1.5 g nitrogen and the phytoplankton were fed to the shellfish raceway where it was mixed with twice its volume of seawater. The seawater contained the same inorganic nitrogen concentration as the pond effluent to give a total of 4.5 g nitrogen. The shellfish raceway added 22.5 g inorganic nitrogen through excretion,

decomposition of solid wastes, and other sources, or about 25 percent of the amount that entered the raceway as phytoplankton. However, 18 g of the total output of 27 g nitrogen from the shellfish raceway were removed by seaweed, to leave a residual of 9 g nitrogen, which represents a total removal efficiency of the system as a whole of 90 percent (Ryther 1979).

It was recognized at the outset that a major constraint to bivalve mollusc cultivation on treated sewage effluents is their ability to concentrate pathogenic bacteria and viruses, toxic heavy metals and potentially toxic or unpalatable organic compounds (Ryther et al. 1972). Trace amounts of cadmium were added to isolated sections of the phytoplankton-bivalve food chain (Kerfoot and Redmann 1974, Kerfoot and Jacobs 1976). The phytoplankton were found to be the principal source of cadmium accumulation in the system and showed a rapid increase in metal concentration until an equilibrium was reached. Two species of shellfish, American oyster (*Crassostrea virginica*) and hard clam (*Mercenaria mercenaria*) exhibited a continual increase in cadmium when fed on the phytoplankton. Estimations were made of permissible levels of cadmium in the secondary effluent and in the dilution seawater as guidelines to prevent prolonged accumulation beyond permissible levels of cadmium in humans regularly consuming shellfish. However, long-term monitoring of heavy metals in the tertiary sewage treatment-mariculture system revealed no measurable increase in the cadmium content of bivalve tissue (Kerfoot and Jacobs 1974). This was attributed to the low cadmium content of both natural seawater and the domestic secondary sewage effluent used as culture media. Furthermore, the growth of the oysters led to a dilution of metals in their tissues. It was concluded that secondary effluent primarily from a domestic source was safe for reuse in the system.

There were no significant differences in the accumulation of seven heavy metals by three species of bivalves, lobster, and seaweed cultured in the pilot-scale, secondary sewage-fed mariculture system when compared to organisms raised in a contaminant-free, nutrient-enriched environment. The study was based on samples taken monthly over 18 months (Mann and Ryther 1979). Shellfish trace-metal concentrations were below the United States Food and Drug Administration's "alert" levels. The data suggested that heavy metals constituted a minimum public health problem in organisms cultured for human food in the system. However, there was accumulation above control organisms not reared in the system in a later study of heavy metals in bivalves, lobster, flounder and seaweed cultured in the system (Furr et al. 1981). It was recommended that heavy metal concentrations in both domestic and industrial wastewater be monitored prior to reuse.

A study was also made of bacteriophage survival patterns in laboratory-scale marine phytoplankton cultures grown on secondary sewage effluent. There was no significant virus removal, and phage survival seemed to be enhanced by the presence of algae, even at pH 8 or higher, which is inimical to virus survival (Vaughn and Ryther 1974). Molluscs raised in the system receiving phytoplankton-containing effluent would be exposed to viruses. It was suggested that perhaps the only acceptable solution would be to remove or deactivate viruses prior to reuse of effluent (Vaughn and Ryther 1974).

The pilot-scale experiments involved only 30 m³ of secondary treated effluent per day, 1,700 m² of phytoplankton ponds, and one million shellfish per crop. They were not run long enough to allow the collection of enough production data for an economic evaluation of the system because the project was adequately supported for only two years (Ryther 1980, 1981). An economic study of the system was conducted, but it identified only important relationships and interactions to obtain order-of-magnitude costs (Smith and Huguenin 1975). Heavy metals and organic trace contaminant concentrations were no higher than in shellfish from natural, unpolluted populations, and depuration for 10-14 days reduced the concentration of accumulated viruses to undetectable levels (Mann and Ryther 1979, Mann and Taylor 1980). However, it was concluded that bivalves grown in secondary treated sewage effluents, particularly oysters and clams since they are often eaten raw, would not be socially or legally acceptable for human consumption in the United States even if they were not contaminated above existing public health standards (Ryther 1980, 1981).

6.5.1.4 Harbor Branch Foundation Studies

The Harbor Branch Foundation Aquaculture Project was established in 1974 in Florida as an ancillary project to the larger original project at Woods Hole Oceanographic Institution in Massachusetts (Ryther et al. 1976b). Experiments were initiated in Fort Pierce to overcome the adverse effects of the low winter temperature of the temperate Woods Hole climate, which falls below 10°C. Heating water in temperate latitudes to permit biological activity to continue throughout the winter would be prohibitively expensive. It would be feasible to use the heated effluent from a coastal power plant, although the power and sewage treatment plants would need to be adjacent. It was also recognized that biological reuse systems could be used to advantage in coastal resort communities with sewage treatment peaks in summer (Ryther et al. 1972). However, biological reuse systems do have the greatest potential in warm climates in which organisms grow throughout the year at ambient water temperatures (Ryther et al. 1975, 1976b; Goldman and Ryther 1976). The outdoor studies at the Harbor Branch Foundation Laboratory were a continuation of similar studies at Woods Hole, but the major interest in Florida was on the efficiency of seaweeds in nutrient removal as the final step in the combined tertiary sewage treatment-mariculture system (Lapointe et al. 1976).

Phytoplankton were grown in continuous-flow cultures using a 1:1 mixture of secondary treated sewage effluent from an activated sludge plant and 1 m filtered seawater. The ponds were continuously well mixed by rotating arms and by pump recirculation. Phytoplankton were allowed to develop naturally because inoculation with specific cultures of algae was unsuccessful, as at Woods Hole. A severe fouling problem, particularly in summer, was infestation by the filamentous green alga *Enteromorpha* (Ryther et al. 1976b). The second-stage oyster culture was fed continuously with the effluent from the phytoplankton culture. The oyster culture effluent was discharged to the third-stage seaweed culture as the final nutrient removal step (Fig. 6.5). However, the culture of seaweeds was so successful that the culture of phytoplankton and shellfish was discontinued. Seaweeds were cultured alone in a single-stage tertiary sewage treatment system with the
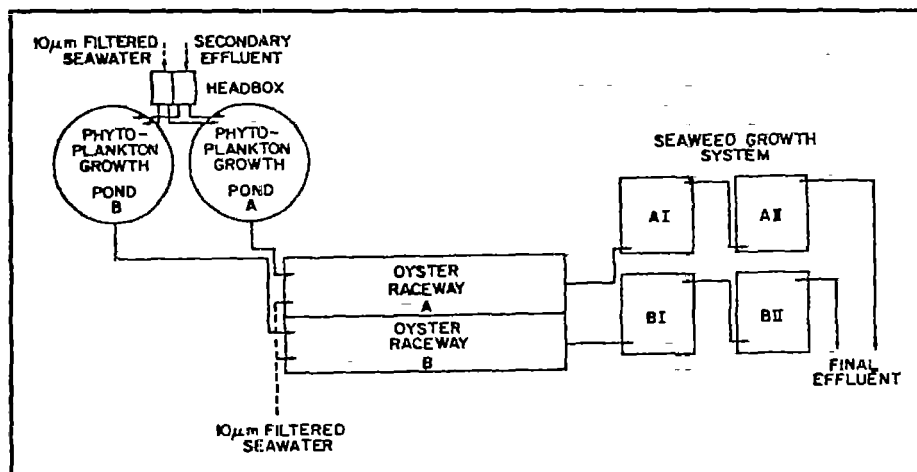
Figure 6.5 Schematic flow diagram of tertiary sewage treatment-mariculture system in Fort Pearce, Florida (Source: Lapointe et al. 1976)

production of potentially commercially valuable phycocolloids, and without the public health problem associated with bivalve molluscs (Ryther 1980, 1981).

The seaweeds were cultivated in new, specially designed tanks (Ryther et al. 1976a). The tanks had sloping sides and received compressed air at the base which provided the seaweeds with a rolling motion. This allowed dense seaweed cultures to stay in suspension and receive uniform light and nutrients (Fig. 6.6). The seaweeds remained in an indefinite asexual vegetative stage in the suspended culture system which permitted continuous, year-round cultivation (Ryther et al. 1976a).

Few data were recorded on seaweed yields in the initial studies because the primary interest was still on nutrient removal efficiency. *Hypnea musciformis* could not be grown in summer when temperatures reached 30°C but *Gracilaria* sp. (*G. tikvahiae*) grew throughout the year (Lapointe et al. 1976). Preliminary yields for both species were consistently between 12 g and 17 g dry weight/m^2/day, as high as those of mass cultures of microscopic marine algae or highly productive commercial terrestrial crops such as sugar and rice. An average yield of 15 g dry weight/m^2/day throughout the year is equivalent to an annual crop of more than 50 tons/ha/yr. The nitrogen content of *Gracilaria* was about 4 percent of its dry weight so it would remove 5.0 kg N/ha/day at the above yield. Although this is less than one third of the efficiency of phytoplankton, which are more productive and have a higher nitrogen content, seaweeds have considerable commercial value as a source of phycocolloids. It was estimated that the sewage from a city of 10,000 (1 mgd) would support the production of 1,000 tons *Gracilaria* dry weight/yr (Ryther et al. 1976a). The prospects for an economically viable system were believed to be promising because the price of agar containing seaweed was then about $500/ton dry seaweed and has since escalated (Ryther 1980).
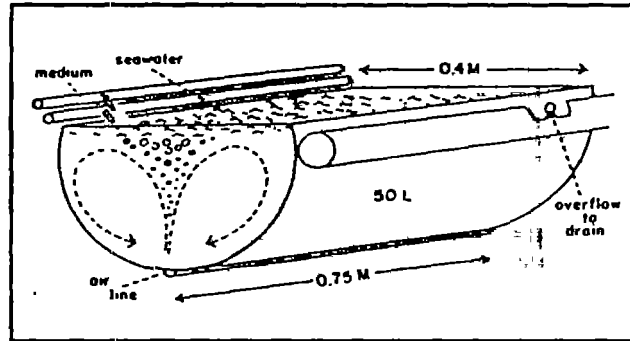
Figure 6.6 Diagram of seaweed culture system (Source: Lapointe and Ryther 1978)

A mean annual yield of *Gracilaria tikvahiae* of 34.8 g dry weight/m^2/day or 127 tons dry weight/ha/yr based on 12-month continuous operation was obtained at near optimal seaweed stocking density and flow rates of nonnutrient limited culture media using inorganic fertilizers (Lapointe and Ryther 1978). However, yields in large-scale culture may be only about half to one third of the small-scale yields, perhaps about 30 tons dry weight/ha/yr (J. H. Ryther, personal communication). *Gracilaria* was highly efficient at removing nutrients from secondary sewage effluent mixed with seawater, but high yields were achievable only with large inputs of energy in the form of pumped water and air. Economic analyses of the land-based intensive culture of seaweeds in tanks indicated it was not a cost-effective system (Huguenin 1976, DeBusk and Ryther 1984). Recent economic analysis revealed a production cost of about $2,000-3,000/ton dried *Gracilaria* for agar, approximately double the market price of the raw seaweed (J. H. Ryther, personal communication). It was suggested that the energy requirements of *Gracilaria* cultivation might be met to some extent by methane generated from the anaerobic digestion of the seaweed, either before or after agar was extracted (Hanisak 1981), although it is unlikely that this would significantly reduce the production cost.

Attempts are currently being made in Florida to develop methods of cultivating commercially valuable seaweeds on sewage that retain at least moderately high yields but involve decreased energy inputs (Ryther 1980). Such studies have been inspired by the commercial cultivation of *Gracilaria* in shallow earth ponds in Taiwan (Shang 1976, Chiang 1984). *Gracilaria* grows unattached on the bottom of ponds in which shrimps and crabs may also be cultivated to increase the economic efficiency of the pond. Milkfish and tilapia are usually stocked to browse on green and blue-green algae that tend to shade out *Gracilaria*, although the fish must be removed when contaminating algae are consumed, otherwise they will also consume the *Gracilaria*. The ponds are 1 ha or less in size and the water depth varies from 20-30 cm to 50-80 cm. Pond water is exchanged every two to three days by tidal action to provide nutrients for growth and maintain the salinity in the optimum range. The ponds are fertilized with about 3 kg urea/ha or 120-180 kg fermented pig or chicken manure/ha every two to three days at the time of introduction of new water. Annual yields were reported to range from 7 to 12 tons dry seaweed/ha/yr by Shang (1976), but Chiang (1984) more recently reported a lower range of 2.3-6.6 tons dry weight/ha/yr.

There was a preliminary experiment in Florida on growing *Gracilaria* on a shallow tidal flat in pens constructed with fishing net and pilings, with the net weighed at the bottom and buried in the sediment (J. H. Ryther, personal communication). Yields from a 5-m^2 pen over a six-month period ranged from 3 g to 11 g dry weight/m^2/day, extrapolated to 11-40 tons dry weight/ha/yr, considered to approximate those obtained from pond culture in Taiwan. Tidal exchange through the pen mesh provided current flow through the pen system, but the latter was adversely affected by storms.

The Harbor Branch Oceanographic Institution has also developed strains of *Gracilaria*, G-16 and G-16S, with both high growth rates and high-quality agar. A preliminary cost analysis of the pen system suggested rates of return similar to the pond culture system in Taiwan. It was suggested that the system may be ideal for the Caribbean, which has extensive areas of shallow tidal flats. However, there is the need to establish a fertilization technique, which would be unlikely to involve excreta reuse.

Artemia has high commercial value as feed for larval shrimps and marine fish and was assessed as a method to filter sewage-fed phytoplankton. Dense populations of *Artemia* were raised on diatoms produced in sewage-fed tanks, but they were unstable and did not maintain a high density or level of reproduction for more than a few weeks. One of the main reasons for the instability of *Artemia* was the gradual buildup of populations of a marine insect predator, *Halobates*. Another problem was the physical interference of *Artemia* by the green seaweed *Enteromorpha*, which grew in the system as a contaminant. Despite these problems, the culture of *Artemia* in a sewage-reuse aquaculture system was felt to have promise (Ryther et al. 1976b).

Tertiary treated sewage effluent mixed with seawater was also added to PVC-lined earthen ponds stocked with penaeid shrimp postlarvae, although penaeid shrimp are not filter feeders and feed on living and nonliving plant and animal organic matter on the pond bottom (Ryther et al. 1976b, Ryther 1981). Three species of penaeid shrimp (*Penaeus duorarum, P. aztecus, P. setiferus*) were cultivated in the 5-m^3 flow-through experimental ponds enriched with 14-40 percent treated sewage effluent, with residence times ranging from 6 to 20 days. Stocking densities varied from 2 to 400 postlarvae/m^2. Significant but incomplete phytoplankton removal by the community of animals living in the shrimp ponds occurred. The growth and survival of the postlarval shrimp varied with the species but appeared to be inversely proportional to stocking density, with larger shrimps demonstrating greater mortality. This suggested that food was limiting at the high stocking densities used. The postlarvae attained a size of 5.5 g in two months at the lower stocking densities. It was estimated that such a system could produce 50,000 5-g shrimp/ha/2 months at a stocking density of 10 postlarvae/m^2, to give an extrapolated yield, assuming year-round cultivation, of 1.5 tons/ha/yr.

Experiments on the feasibility of a benthic marine algae-grey mullet (*Mugil cephalus*) food chain as an alternative to the diatom-mollusc-seaweed system were reported to be under way (Ryther et al. 1975, Goldman and Ryther 1976), although data do not appear to have been published.

6.5.1.5 Summary

It was initially believed that it should be possible to design a controlled and balanced sewage-fed mariculture system made up of several commercially valuable organisms representing all the trophic levels (Goldman and Ryther 1976). However, this goal appears to have been elusive in practice. It was possible to achieve nutrient removal from secondary sewage effluents by phytoplankton, and filter-feeding bivalves were efficient at the removal of phytoplankton from tertiary treated effluent. Due to funding constraints, insufficient shellfish production data were collected to conduct a detailed economic analysis, but it was concluded that such shellfish would not be acceptable for human consumption in the United States even if they conformed to existing public health standards.

Attention was then focused on a single-stage tertiary sewage treatment system for the cultivation of seaweeds, particularly *Gracilaria*, to produce phycocolloids, which are potentially commercially valuable and would not be constrained by public-health considerations. While *Gracilaria* was efficient at removing nutrients from secondary sewage effluent and produced high yields, economic analysis revealed that the high-energy system's seaweed production cost was approximately double the market price of the raw seaweed.

6.5.2 Other phytoplankton-shellfish-seaweed reuse systems

Two other studies similar to the Woods Hole-Harbor Branch Foundation tertiary sewage treatment-mariculture system have been conducted. A pilot system at the Tallmans Island Pollution Control Plant in Queens, New York, involving phytoplankton, shellfish and seaweed culture stages similar to those at Woods Hole was reported briefly (Walrath and Natter 1976). However, the intention was to use the shellfish as livestock feed rather than as human food. Experiments with chickens indicated that sewage-grown shellfish were nutritionally superior to those grown with commercial feed.

A research program was started in 1975 in England to reuse sewage in mariculture, involving the use of reverse-osmosis membranes operating with tertiary treated sewage effluent. The reverse-osmosis technique involves the transfer of water through a membrane by applying greater pressure than the osmotic pressure of the system. The reverse-osmosis treatment of tertiary filtered sewage effluents produced a 60-75% permeate of water for potable or industrial use, and a 25-40% nutrient-rich concentrate which was used to enrich seawater to culture phytoplankton (Stead 1978). Preliminary experiments were carried out on feeding the marine phytoplankton *Dunaliella tertiolecta* to Japanese oyster (*Crassostrea gigas*) and European oyster (*Ostrea edulis*) and to brine shrimp (*Artemia salina*). Studies also indicated that the seaweeds *Chondrus crispus* and *Gracilaria verrucosa* were efficient in removal of nutrients, particularly nitrogen (Guiry 1978).

6.5.3 Humboldt Bay

The city of Arcata, California, constructed a 22-ha sewage stabilization pond in 1955 on the intertidal flats of the north arm of Humboldt Bay as a first step to protect

commercial oyster beds from contamination with human waste. Subsequently, a primary treatment plant, a facultative aeration pond, and a chlorination unit were built at the site (Allen and Dennis 1974). A preliminary study showed that undiluted sewage stabilization pond effluent was nontoxic during the winter months to juvenile king salmon (*Oncorhynchus tshawytscha*) in two-week static-water biossays (Allen and O'Brien 1967). However, the stabilization pond effluent became toxic to salmon fingerlings in June when the ratio of sewage to dilution water from infiltration into the sewerage system increased following cessation of winter rains. Nevertheless, it was felt that the preliminary laboratory experiments justified the construction of small experimental ponds adjacent to the Arcata sewage stabilization pond to evaluate the capacity of sea water fertilized with treated domestic sewage to produce food for juvenile salmon (Fig. 6.7) (Allen and Dennis 1974).

A series of experiments was run from July 1971 to December 1973 in two 0.15-ha experimental fishponds. The aim was to test the ability of brackish water and seawater fertilized with treated domestic sewage to produce food for juvenile salmon, and to raise them to migratory size (smolts). Fingerlings of coho salmon (*Oncorhynchus kisutch*) were raised in four short-term experiments during summer and late fall, and chinook salmon fry (*O. tshawytscha*) were raised in two experiments for three to four months in winter and spring.

Four substrates occurred in the ponds: a yellow sandy loam used for the dikes, river-run gravel, oyster shells to provide substrates for the production of food organisms, and mud which covered a majority of the pond bottoms. Nylon net pens 2 m^2 were constructed in each pond over a sample of each of the four substrates to rear known numbers of fish over each bottom type. The ponds were operated as static-water systems, with batch addition of stabilization-pond effluent and seawater. Floating net cages were also used to determine mortality of salmon. Aeration and mixing of water usually kept dissolved oxygen levels high. However, dissolved oxygen fell below 5 mg/l on a few occasions and caused salmon mortalities, particularly when water temperatures were high. During one experiment without water mixing and aeration, dissolved oxygen levels fluctuated widely diurnally because of the highly eutrophic conditions; salmon mortalities were high and were correlated with concentrations of 2-3 mg DO/l.

The fertilization of seawater with stabilization pond effluent led to high rates of photosynthesis as indicated by high pH, usually 8-9.5 but occasionally near 10. Dissolved oxygen concentrations declined rapidly when cloud cover was heavy or aeration systems were inoperative.

The benthos of the ponds comprised the polychaetes *Capitella* and *Polydora* and two species of gammarid amphipods (Sharp 1974). Total biomass of benthos was higher in ponds receiving sewage effluent, although there were no changes for some species. The major food item for the pond-reared salmon was the gammarid amphipod *Anisogammarus confervicolus* (Powers 1974). It was suggested that the pond should not be completely drained to harvest fish to allow the survival of enough amphipods as brood stock from one culture season to the next.
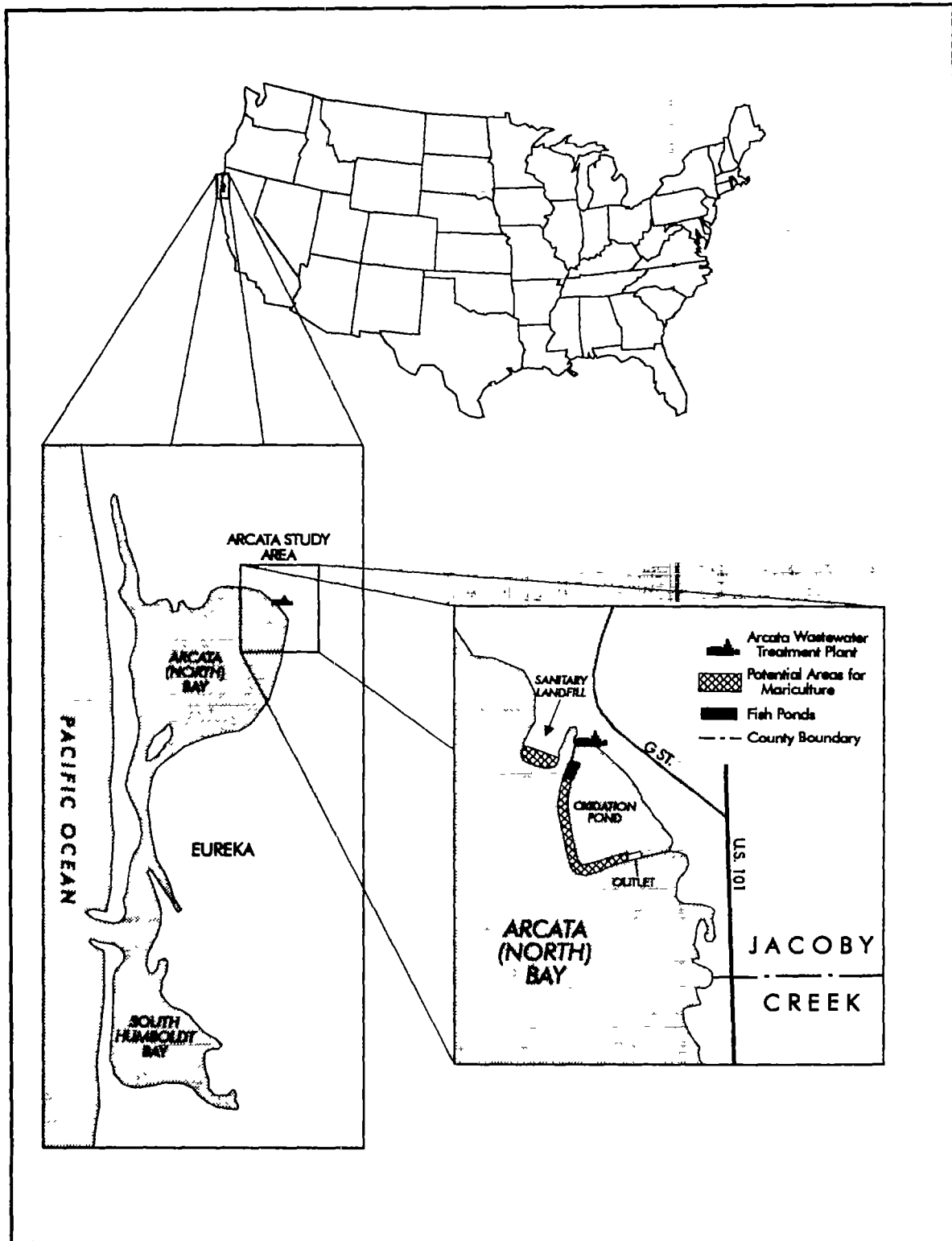
Figure 6.7 Location of Humboldt Bay experimental system

Fish were also raised in floating cages in the pond, and in the pond itself. The higher growth rate and survival of chinook fry in pens and cages placed in the ponds than in the open ponds, indicated that the full productive capacity of the system had not been reached. Better results in the former than the latter system may have been due to a higher ratio of surface area to water volume for the development of food organisms in the former than the latter. During the summer and fall of 1974, steelhead rainbow trout (*Salmo gairdneri*) and coastal cutthroat trout (*Salmo clarki*) were reared with coho salmon (Allen and Carpenter 1977).

It was stressed that reliable aeration systems are essential in wastewater mariculture systems because of the rapidity with which oxygen depletion can occur in eutrophic water, particularly under low light intensity caused by clouds or fog. Salmonids were also extremely sensitive to undissociated ammonia at high pH, and the pH occasionally approached 9.5-10.0. Conditions were marginal for chinook salmon when the pH approached 9.0. Water quality fluctuations led to low survival and productivity, although fish that survived demonstrated suitable growth.

Arcata sewage treatment plant has been redesigned and has integrated effluent disposal from the sewage stabilization pond system with wildlife enhancement in freshwater wetlands since 1986. It is also planned to use fresh water from the wildlife sanctuary to operate a smolt imprinting pond, and an adult salmon fishway, trap and holding pond. The proposed fishway would also permit a study of the reaction of migrating salmonids to residual free chlorine and chlorinated hydrocarbons produced in disinfected wastewater (G. H. Allen, personal communication).

6.5.4 North Carolina

The feasibility of the culture of white shrimp (*Penaeus setiferus*) in brackish ponds which received treated sewage effluent was investigated in North Carolina (Anon 1972, Rickards 1974). Shrimp survived and grew in control ponds that did not receive sewage effluent, but there was mortality in fertilized ponds. The mortality of shrimp in ponds fertilized with sewage effluent may have been caused by nighttime dissolved oxygen levels of zero. Aeration of the ponds by compressor and perforated air-line produced a consistent average minimum dissolved oxygen concentration of 3.4 mg/l, above the 3.0 mg/l considered the minimum desirable concentration. Penaeid shrimps survived and grew in the aerated ponds fed with treated sewage effluent at a similar rate to natural populations of penaeid shrimp in North Carolina, but detailed information on penaeid shrimp culture using sewage effluents was not recorded in this preliminary study.

6.5.5 Texas

Preliminary experiments were conducted in Texas on a controlled eutrophication system involving marine phytoplankton and the brine shrimp *Artemia* to remove the phytoplankton from the water (McShan et al. 1974, Songer et al. 1974, Trieff et al. 1976). Raw and secondary treated sewage effluents were used in small-scale laboratory and outdoor

systems to culture the alga *Tetraselmis* which was fed to *Artemia*, with some degree of treatment of wastewater.

Pilot-scale studies were conducted for several years on the culture of *Artemia* for clarification of industrial wastewater at the Dow Chemical Texas Division plant in Freeport, Texas (Dinges 1982). The influent to the experimental system, which included three 0.1-ha ponds 0.9 m deep was effluent from an aerated industrial waste stabilization basin with 55-70 g sodium chloride/l. About 10% of the input was raw seawater to provide trace nutrients for marine phytoplankton. The ponds received a total of 129 m³ influent/day and retention time varied from a minimum of 7 days in summer to a maximum of 28 days in winter. Phytoplankton dominance alternated between *Dunaliella* and *Chlorococcus*. About 10% of the effluent from the phytoplankton cultivation ponds was recirculated and 1.4 m³/day were introduced into the *Artemia* cultivation facility. The latter consisted of two tanks with a combined capacity of 18.9 m³, continuously aerated and heated in winter.

Artemia were dewatered in a liquids-solids separator and fed to brown shrimp (*Penaeus aztecus*) and to a fish (*Cyprinodon variegatus*). *Artemia* did not demonstrate a significant accumulation of industrial chemicals and there was no chronic toxicity to test species in long-term feeding trials. Total suspended solids reduction was 89% with an average effluent TSS of 20 mg/l. BOD₅ was reduced 89% on average. It was estimated that a full-scale marine phytoplankton-brine shrimp treatment system at the chemical plant would yield 1,430 tons dry weight of brine shrimp and over 3,100 tons dry weight of rotifers per year (Dinges 1982).

6.5.6 Natal, South Africa

An experimental pond system of ten 100 m² ponds was constructed on the coast of Natal, South Africa (Hemens and Turner 1980). Seawater and secondary treated sewage effluent from an activated sludge plant were added to the ponds daily, five days/week in mixture of about 1:3, effluent to seawater, respectively. An airlift water recirculation system was used during the addition of sewage effluent to prevent stratification because of the small pond surface area and the absence of mixing by wind. A number of sections of both polyethylene film and terylene mesh were suspended across the ponds below the surface to increase the surface area in the ponds. Organisms which feed at the base of the food chain were stocked to obtain maximum utilization of phytoplankton.

Attempts to use filter-feeding bivalve molluscs (brown mussels, *Perna perna*; oysters, *Crassostrea cucculata*, *C. gigas*) in floating racks were unsuccessful. Poor growth and high mortality indicated that the conditions in such highly fertile but static ponds were unsuitable for these bivalves.

The growth rate of mullet (*Liza macrolepis*) was slow, despite the fact that the fish were feeding, were active, and appeared to be in good physical condition. Examinations of gut contents showed them to be well-filled with sand particles containing remains of diatoms, zooplankton and the green seaweed *Enteromorpha*. The poor growth response may have been due to some adverse condition in the ponds.

Mozambique tilapia (*Oreochromis mossambicus*) stocked in the ponds grazed upon the green seaweed *Enteromorpha* which grew in abundance on surfaces. Tilapia no doubt also filtered blooms of phytoplankton dominated by diatoms. A hybrid of *O. aureus* male x *O. niloticus* female was later stocked to produce up to 100% male offspring to reduce unwanted reproduction. Assuming year-round growth, hybrid tilapia production was estimated to be 13.7 kg/ha/day, or 5.0 tons/ha/yr.

Preliminary laboratory tests showed that tiger prawn (*Penaeus monodon*) ate substantial quantities of *Enteromorpha*, but young prawns suitable for stocking the ponds were not available until late summer. The growth rate of stocked prawns declined after about 90 days due to decreasing water temperatures. However, a most promising growth rate of 16 kg/ha/day was attained at water temperatures above 22°C.

6.6 Prospects for excreta reuse in mariculture

It is surprising that with many of the world's largest cities located in coastal areas, there appears to be only a single documented case in the literature of excreta reuse in mariculture on a commercial scale. Night soil was used as a fertilizer in brackish milkfish ponds in Taiwan, although night soil has recently been totally replaced by rice bran as a fertilizer with an increase in socioeconomic conditions (see Section 6.4). There are conflicting uses of coastal zones, but there are numerous suitable sites with protected water suitable for excreta reuse in mariculture. It has been suggested that the reuse of organic wastes in the estuarine ponds of Southeast Asia should increase primary productivity by as much as an order of magnitude. If this were done under carefully controlled conditions, the yield of the cultured food species should also be increased (Goldman and Ryther 1976). Despite a considerable amount of research into a variety of technically feasible excreta reuse-mariculture systems (see Section 6.5), no system appears to be ready for commercial implementation.

Excreta reuse in seawater occurs unintentionally, as in fresh water, in fecally polluted surface waters with poor sanitation, or with sewage ocean outfalls (see Section 6.3). While sewage pollution of coastal waters stimulates the productivity of food chains in areas with adequate dilution and mixing, it may lead to a degradation of the environment in areas with restricted water circulation and exchange. Bivalve molluscs, which are often consumed raw, present a particular public health problem because of their ability to concentrate bacteria and viruses from the water (see Section 7.12.1).

There are obvious constraints to excreta reuse involving discharge into coastal waters. A major problem in the fertilization of open coastal waters is that most of the nutrients are washed away by the tide (Korringa 1976). It is feasible to develop excreta reuse systems in areas of the coast with an adequate geomorphological formation such as a bay, fjord, estuary, or lagoon which would permit relatively high levels of primary productivity compared to normal marine environments where sewage nutrients are rapidly flushed away (Stirn 1972). However, hypereutrophication would need to be controlled by the release of regulated amounts of treated sewage effluents. The treated effluents would

need to be of high quality, particularly in terms of pathogen content, if they were to be used to stimulate shellfish and crustacean productivity. A water quality standard of less than 10 fecal coliforms/100 ml is required in Europe if shellfish are to be cultured for human consumption, although this can be reliably met by waste stabilization ponds (Mara and Pearson 1986). Lower microbiological standards could probably be used to culture finfish for animal feed, or for direct human food if the fish were well cooked prior to consumption. This assumption is based on the rapid attenuation of fecal bacterial and viral indicators in septage-fed freshwater fishponds (see Section 7.7.4), although supportive data are currently lacking for excreta-fed seawater ponds.

Ideally, nutrients contained in excreta should be transformed into useful biomass in well-defined systems with a boundary, either in a combined excreta treatment-reuse system, or in a reuse subsystem closely associated with a prior excreta treatment subsystem (see Section 5.1). The reuse of excreta in a well-defined mariculture system which can be managed and controlled would permit the culture of the target organism to an acceptable public health standard, enable its productivity to be optimized, facilitate its harvest, and minimize eutrophication of natural waters.

The groups of potentially marketable organisms that have received the most attention in experimental studies on excreta reuse in mariculture are bivalve molluscs, seaweeds, penaeids, and finfish. Bivalve molluscs have been researched the most because of their high market value and their ability to filter phytoplankton from the water. A single oyster may filter all the phytoplankton from 10 liters of water in one hour, and a culture of one million oysters could remove the phytoplankton from 24 ha of ponds 1 m deep in one day (Ryther 1980). The initial forecasts of the potential of the Woods Hole studies on excreta-fed mariculture involving bivalves were most promising. It was initially estimated that a community of 50,000 persons would require 51 ha for a tertiary sewage treatment-marine aquaculture system, 50 ha for phytoplankton farms with an additional 1 ha to culture bivalves in raceways to remove phytoplankton from the tertiary treated effluent (Ryther et al. 1972). It was estimated that such a system would produce over 900 tons of oyster meat worth more than $5 million as a luxury table oyster or perhaps $1 million as a frozen product.

There are technical constraints to the culture of bivalves at high density. A continuous flow of water is required to stimulate their pumping and feeding rates, provide oxygen, and carry away feces (Ryther et al. 1972, Walne 1976). A flow of about 400 m^3/hr might be required for an aquaculture system supporting a biomass of 1 ton of bivalves to supply oxygen and to remove metabolic wastes (Ryther et al. 1972). A further important aspect of water flow is to reduce the concentration of phytoplankton to the optimal concentration for feeding of bivalves, particularly where phytoplankton are produced at cell concentrations as high as 10^6/ml, as in the ponds fertilized with secondary treated sewage effluent at Woods Hole. The pumping and filtering rate of oysters decreased at phytoplankton cell concentrations above about 10^5 cells/ml, and a large percentage of filtered cells were not consumed but became incorporated into pseudofeces that fell to the bottom (Ryther and Tenore 1976, Walne 1976).

Furthermore, phytoplankton cells consumed at high densities were assimilated with very low efficiency. In the cultivation of bivalves in the raceways at Woods Hole, the concentration of the phytoplankton in the culture medium made up of secondary treated sewage effluent and seawater had to be diluted with seawater as it was fed into the bivalve culture unit. Dilution with seawater reduced the concentration of phytoplankton to the optimal for filtration and assimilation by molluscs, and it also provided the flow of water and the oxygen supply required by the animals (Ryther and Tenore 1976).

The cultivation of bivalves in raceways at Woods Hole was not carried out long enough to generate sufficient production data to conduct an economic analysis. The high energy costs of pumping and mixing sewage effluent and seawater may have been prohibitive, but it was recognized that the tide could be used in certain localities for water flow (Ryther et al. 1972).

It has not been possible to raise shellfish in controlled, low-cost pond systems. Oysters had high mortality rates in brackish ponds fertilized with treated sewage effluents in North Carolina. The fertilized ponds were characterized by dense phytoplankton blooms and wide fluctuations in dissolved oxygen and pH (Chestnut 1973). Attempts to culture mussels and oysters in floating racks in ponds fed with secondary sewage effluent failed in highly fertile and static-water ponds in Natal (see Section 6.5.6).

Because bivalve molluscs are often eaten uncooked, they should not be considered for excreta-reuse mariculture systems because they concentrate pathogenic bacteria, viruses, heavy metals and organic contaminants in their tissues (see Section 7.12.1). Furthermore, eutrophic water containing high concentrations of phytoplankton may be dangerous if certain dinoflagellates are present, particularly certain species and strains of *Gonyaulax* and *Dinophysis*, which cause paralytic shellfish poisoning in humans. The toxins produced by dinoflagellates are not destroyed by boiling.

Seaweeds have been proposed as candidate organisms for excreta-reuse mariculture systems, with most of the work conducted by Ryther and his colleagues (see Section 6.5.1). However, there have been a few other studies which indicate that seaweeds respond to nutrient enrichment from excreta. A preliminary study was reported on the growth of the carrageenan-producing red seaweed *Hypnea musciformis* in experimental PVC tanks fed with 870-m deep sea water enriched with 4 percent primary treated sewage or with 35 percent secondary treated sewage on St. Croix, United States Virgin Islands (Haines 1975). Enrichment with 4 percent primary sewage led to only slightly better growth of the seaweed than deep water alone, but secondary sewage stimulated *Hypnea* growth about 22 percent more than that in deep water alone. Seaweeds have also been successfully cultured in seawater supplemented with secondary sewage effluent in Hong Kong (Chan et al. 1979, Wong and Lau 1979) and India (Dhargalkar 1986). The fertilization with primary settled sewage of a 63-m² experimental basin within a larger coastal lagoon in Yugoslavia showed a significantly lower phytoplankton biomass than a control basin. The daily input of sewage into the shallow lagoon led to prolific growth of benthic seaweeds which rapidly consumed most of the available nutrients (Fanuko 1984).

In the World War II experiments in which inorganic fertilizers were added to Scottish sea lochs, seaweeds competed with phytoplankton for nutrients (see Section 6.2).

Seaweeds were used initially at Woods Hole and Harbor Branch Foundation to "mop up" residual and regenerated nutrients from bivalve excretion, although research was later focused on a single-phase tertiary sewage treatment system in which agar-producing *Gracilaria* was used to remove nutrients from secondary sewage effluent. However, the energy-intensive system was shown to be uneconomic. *Gracilaria* is currently cultured in shallow brackish ponds in Taiwan using urea and fermented pig and chicken manure as fertilizers (Shang 1976, Chiang 1984). It may be possible to develop a similar pond culture system involving excreta reuse, although such a system remains to be investigated. Such a system would not be affected by public health considerations because the agar extraction process involves treatment with heat and strong alkali, but other possible technical constraints require study. Epiphytic growth of "weed" seaweeds on the target seaweed species is probably the single greatest problem in commercial seaweed cultivation in warm water (Ryther 1979).

Attention has also been directed towards the culture of penaeid shrimp in excreta-reuse systems involving mariculture because of their high market value and growing demand. Penaeid shrimp production increased some 200,000 tons in the last five years (Anon 1988). The increasing demand cannot be met by harvesting wild stocks, which are finite and heavily exploited, and aquaculture will be an increasingly significant supplier of warm-water shrimp. Shrimp have traditionally been cultured extensively in brackish ponds in Asia, either in monoculture or in polyculture with milkfish. However, there has been a recent trend to culture penaeid shrimps intensively in ponds with pelleted feed, mechanical aeration, and daily exchange of pond water.

Penaeid shrimp are omnivorous and eat seaweeds, small invertebrates, and detritus. Promising results on the culture of penaeid shrimp in excreta-fed systems were reported from the Harbor Branch Foundation in Florida (see Section 6.5.1.4) and in Natal, South Africa (see Section 6.5.6), but mortality was reported in ponds fertilized with treated sewage effluent in North Carolina (see Section 6.5.4). Mortality was attributed to low dissolved oxygen concentrations at night because penaeids generally require at least 2.0 mg/l, although shrimp grew at a similar rate to natural populations when the ponds were aerated.

Growth of phytoplankton in excreta-fed ponds would benefit shrimp, but only after the phytoplankton had been transformed along the food chain into benthic invertebrates or sedimented as detritus, because shrimp are not filter feeders. There would also be the need to aerate the pond to raise the low levels of dissolved oxygen characteristic of fertilized systems. It was concluded in a study of penaeid shrimp nutrition that fertilization may have enhanced shrimp growth through the production of phytoplankton, which eventually enriched the benthic food chain with detritus, but that supplementary feed had the greatest impact on growth, probably because of the large amounts given and its suitable nutritional composition (Rubright et al. 1981). The reuse of excreta in penaeid shrimp culture cannot be recommended because of the risk of mortality caused by low dissolved

oxygen. There would probably also be insurmountable problems in marketing high-value shrimp, which are largely exported to developed countries, if they are cultured in excreta-reuse systems (Ryther 1980).

The most likely candidates for mariculture excreta-reuse systems are probably certain species of finfish. Studies were conducted with salmon in ponds fertilized with sewage stabilization-pond effluent in Humboldt Bay, California (see Section 6.5.3), but culture of cold-water migratory salmonids has no potential in tropical developing countries where there is the greatest need for excreta reuse to produce food. There are conflicting reports concerning the culture of mullet in fertilized marine ponds. Mullet increased in growth in small, partially enclosed bays fertilized with inorganic fertilizers in Yugoslavia (see Section 6.2), but they grew slowly in excreta-fed ponds in Natal, South Africa, possibly due to adverse environmental conditions (see Section 6.5.6).

Filter-feeding tilapia, which can withstand the periodic low concentrations of dissolved oxygen characteristic of excreta-fed pond systems, may be the most promising species for marine excreta-reuse systems. Mozambique tilapia (*Oreochromis mossambicus*) were successfully cultured in brackish milkfish ponds in Indonesia in World War II, when the disruption of communications prevented stocking the ponds with milkfish fry (Hickling 1948). Mozambique tilapia used to be cultured mainly as a secondary crop to milkfish in brackish ponds in the Philippines (Guerrero 1981). Some milkfish farmers were reported to concentrate on tilapia culture with the increasing demand for tilapia in Metro Manila markets, although such a practice received no mention in a later publication on tilapia farming in the Philippines (Guerrero 1987), possibly because of the recent rapid increase in production of the more readily marketable Nile tilapia (*Oreochromis niloticus*). Tilapia are regarded as a pest in seaweed ponds in Taiwan because their biomass increases rapidly due to breeding in the pond (Chiang 1984).

There is a dearth of information on the fertilization of marine fish ponds in the tropics. Experiments on the use of night soil to fertilize milkfish pond water in Indonesia were reported to give unimpressive results because the content of zooplankton improved without the occurrence of a bloom of phytoplankton (Schuster 1952). This phenomenon can also occur in freshwater ponds (Section 5.2.4) but should not detract from the likelihood of a positive effect of fertilizing seawater ponds with excreta. This is supported by an estimated hybrid tilapia production rate of 13.7 kg/ha/day, equivalent to an extrapolated yield of 5.0 tons/ha/yr, in seawater ponds fertilized by secondary treated sewage effluent in Natal, South Africa (see Section 6.5.6).

Tilapia raised in excreta-fed seawater ponds could be used either directly for human food or for high-protein animal feed. Public health studies on tilapia cultured in seawater ponds have not yet been conducted, but a similar rapid attenuation of fecal bacterial and viral indicators to that reported for freshwater ponds is likely (see Section 7.7.4). A more attractive option for excreta reuse in mariculture may be the culture of tilapia as high-protein animal feed. The future of intensive livestock and fish farming, including penaeid shrimp, might well be govered by the availability of raw material for feed, particularly fish to make fish meal (Fish Farming International 1988).

A portion of the vast brackish milkfish ponds in Indonsia and the Philippines might be profitably turned to excreta reuse to culture tilapia as high-protein animal feed to serve these countries' burgeoning penaeid shrimp culture industries.

7. Public Health

7.1 Introduction

Potential threats to public health from excreta reuse in aquaculture must be reduced to acceptable levels, and aquaculture reuse systems which do not pose unacceptable risks to public health must be developed (Edwards 1985). Section 7.2 discusses pathogens associated with excreta, particularly those likely to be associated with reuse of excreta in aquaculture. Section 7.3 deals with the environmental classification of excreta-related infections and the categories that need to be considered potential sources of infection in excreta-fed aquaculture. Much of the basic information comes the definitive review by Feachem et al. (1983) on health aspects of excreta management and from shorter accounts by Bradley and Feachem (1979) and Feachem (1983).

The potential public health hazards associated with excreta reuse in ponds are the subject of Section 7.4. These hazards include the passive transfer of excreted bacteria and viruses, and the transmission of helminths, of which fish and other pond fauna are intermediate hosts in the life cycle. The potential of excreta-fed ponds as breeding sites for mosquitoes is also considered.

The use of indicator organisms for the assessment of enteric pathogenic viruses and bacteria is discussed in Section 7.5 because routine analysis of the latter is still not feasible. Section 7.6 contains a brief discussion of excreted pathogens in the environment and the role of waste stabilization ponds and thermophilic composting in excreta treatment, two processes which have relevance for linkage with aquaculture.

A detailed review of research on the potential infection of fish with excreted bacteria and viruses is presented in Section 7.7. Data collected during five major projects on excreta reuse in aquaculture are discussed, followed by a consideration of the human pathogenic bacterium *Salmonella*, the only pathogen for which there are substantial data. The efficacy of depuration in the removal of excreted microorganisms from fish raised in excreta-fed systems is dealt with in Section 7.8.

Public health aspects of macrophyte cultivation, high-rate sewage stabilization ponds, biogas slurry, and coastal aquaculture are the subjects of Sections 7.9, 7.10, 7.11, and 7.12, respectively.

A review of the development of standards for excreta reuse in aquaculture, with emphasis on freshwater ponds, is the subject of Section 7.13. Further improvements to standards to safeguard public health with various aquaculture-reuse strategies are proposed.

7.2 Pathogens in excreta

The disease-causing organisms or pathogens of excreta-related infections are transmitted from the excreta (most often feces, rarely urine) of an infected person, usually to the mouth of another by various routes. However, a few infections penetrate and infect the human body through the skin, for example, schistosomiasis.

There are the four major groups of pathogenic organisms: viruses, bacteria, protozoans and parasitic worms. There are more than 50 infections, excluding different numbered types of viruses and serotypes of enteric bacteria, caused by lack of sanitation, although not all are transmitted by improperly designed and managed aquaculture waste-reuse systems. For a detailed account of health aspects associated with excreta, see Feachem et al. (1983).

7.2.1 Viruses

More than 100 different viruses are known to be present in human feces (Melnick et al. 1978, Melnick and Gerba 1980, Feachem et al. 1981); they usually infect the alimentary tract and are excreted in large numbers by infected persons. The diseases they cause range from insignificant to serious and sometimes fatal. The groups of pathogenic excreted viruses are listed in Table 7.1

Excreted viruses cannot multiply outside living cells. However, they have the potential to survive for months, even years, in the environment and may infect new human hosts. They may be present in feces and sewage at concentrations greater than $10^6/g$ and $10^6/l$, respectively. The only excreted viruses that have been studied in depth in the environment are the enteroviruses and, to a less extent, the adenoviruses and reoviruses, because hepatitis A and rotavirus cannot yet be routinely cultivated in cell culture. Furthermore, there are major methodological problems in the quantification of viruses in the environment.

It is only recently that viruses have been discovered to be a major cause of diarrhea. Rotaviruses are known to be a major cause of childhood gastroenteritis and are perhaps the major viral cause of diarrheal disease.

7.2.2 Bacteria

Bacterial pathogens excreted in feces are shown in Table 7.2. Since a carrier state exists for all the infections listed, a proportion of healthy individuals will excrete pathogenic bacteria in communities where they are endemic, up to 10^6-10^8 bacterial cells/g

Table 7.1
Viruses in Human Excreta

Virus group	Family	Number of types	Diseases or symptoms caused
Enterovirus	Picornaviridae		
Poliovirus		3	Poliomyelitis, meningitis, fever
Coxsackievirus A		24	Herpangina, respiratory disease, meningitis, fever
Coxsackievirus B		6	Myocarditis, congenital heart anomalies, meningitis, respiratory disease, pleurodynia, rash, fever
Echovirus		34	Meningitis, respiratory disease, rash
New entero-viruses		4	Meningitis, encephalitis, respiratory disease, acute hemorrhagic conjunctivitis, fever
Adenovirus	Adenoviridae	>30	Respiratory disease, eye infections
Reovirus	Reoviridae	3	Not clearly established
Hepatitis A virus	? Picornaviridae	1	Infectious hepatitis
Rotavirus	Reoviridae	?	Vomiting and diarrhea
Astrovirus	?	?	?
Calicivirus	?	?	Vomiting and diarrhea
Coronavirus	Coronaviridae	?	Common cold
Norwalk agent and other small round viruses	?	?	Vomiting and diarrhea
Adeno-associated viruses	Parvoviridae	4	Not clearly established but associated with respiratory disease in children

of feces.   Not all bacterial pathogens are excreted entirely by humans; several refered to as zoonoses also infect a wide range of mammals, and this limits the possibility of successful disease control by the management of human excreta alone.

Campylobacteria have been recognized within the last decade to be the single most common bacterial cause of diarrhea in several countries, but the epidemiology of *Campylobacter*

Table 7.2
Bacterial Pathogens in Human Feces

Bacterium	Disease	Can symptomless infection occur?	Reservoir
Campylobacter fetus ssp. *jejuni*	Diarrhea	Yes	Animals, humans
Pathogenic *Escherichia coli*[a]	Diarrhea	Yes	Humans[b]
Salmonella			
S. typhi	Typhoid fever	Yes	Humans
S. paratyphi	Paratyphoid fever	Yes	Humans
Other salmonellae	Food poisoning and other salmonelloses	Yes	Animals, humans
Shigella ssp.	Bacillary dysentery	Yes	Humans
Vibrio			
V. cholerae	Cholera	Yes	Humans
Other vibrios	Diarrhea	Yes	Humans
Yersinia enterocolitica	Diarrhea and septicemia	Yes	Animals, humans[c]

Source: Feacham *et al.* (1983)

a Includes enterotoxigenic, enteroinvasive, and enteropathogenic *E. coli*.
b Although many animals are infected by pathogenic *E. coli*, each serotype is more or less specific to a particular animal host.
c Of the 30 or more serotypes identified so far, a number seem to be associated with particular animal species. There is at present insufficient epidemiological and serological evidence to say whether distinct serotypes are specific to primates.

enteritis is poorly understood. Various forms of *Escherichia coli* are a major cause of diarrhea, particularly in developing countries.

Salmonella bacteria cause diarrhea and, less commonly, enteric fever. They differ from most other major viral and bacterial causes of diarrhea in that, with the exception of typhoid and paratyphoid bacteria, they commonly infect many species of animals. There are about 2,000 named serotypes. *Salmonella* is primarily a pathogen of animals, including cold-blooded amphibians and reptiles (but not fish) and invertebrates. The control of salmonelloses is difficult because of the widespread animal reservoir.

Shigellosis, or bacillary dysentery, is an acute diarrheal disease caused by *Shigella* spp. Cholera is caused by *Vibrio cholerae*. *Yersinia enterocolitica* has only recently been recognized as an etiological agent of acute enteritis.

Leptospirosis (caused by *Leptospira*) is not usually transmitted from person to person but from animals such as rodents, which pass the bacteria to humans (and animals) via infected urine through skin abrasions or mucous membranes. Leptospirosis is usually a benign, self-limiting, febrile illness in humans, but it is occasionally severe and even

fatal, with jaundice and hemorrhage. Leptospirosis may be a risk to workers who handle excreta that may contain *Leptospira* from animal carriers such as rats or, occasionally, from infected humans (Feachem et al. 1983). Leptospirosis is a major problem in rice-field workers, and it also appears to be an occupational hazard among aquaculture workers: three reported cases of leptospirosis, including one fatality, have occurred among prawn farm workers in Hawaii since 1976. However, no pathogenic leptospires were isolated from pond water during a survey (Higa et al. 1982).

7.2.3 Protozoa

Many protozoa can infect humans, including three species of human intestinal protozoans that are frequently pathogenic: *Balantidium, Entamoeba histolytica,* and *Giardia* (Table 7.3). Infective stages are usually cysts which are passed in the feces.

7.2.4 Helminths

Helminths are divided into two main groups, roundworms (nematodes) and flatworms. Flatworms are further divided into tapeworms (cestodes), which are formed of chains of segments, and flukes (trematodes), with a single flat unsegmented body. It is generally believed that only the flukes are a potential health problem in excreta reuse in aquaculture and that intestinal nematode eggs are of no concern in waste reuse in aquaculture (IRCWD 1985). However, infection with the larval stage of *Gnathostoma* may occur through excreta reuse in aquaculture.

There are numerous excreted helminths, but only *Schistosoma haematobium* is voided in urine; the others are excreted in feces (Table 7.4). Urine is generally sterile and harmless, but three infections in which there is a significant appearance of pathogens in the urine are urinary schistosomiasis, typhoid, and leptospirosis.

7.2.4.1 *Gnathostoma*

Gnathostomiasis in humans is caused by infection with the larval stage of the nematode worm *Gnathostoma spinigerum,* the adult stages of which are normally found in stomach tumours of wild and domesticated cats and dogs (Wilcocks and Manson-Bahr 1972, Santasiri Sornmani, personal communication). The disease is commonest in Thailand but occurs also in Vietnam; cases have been reported from India and Malaysia.

Eggs are extruded from the lesions in the stomach of the definitive host and are passed into water where they embryonate and hatch. The larvae are ingested by *Cyclops,* a zooplankton (the first intermediate host) in which they develop into second-stage larvae. They are then eaten by a fish, frog or snake (the second intermediate host) in which a third-stage larva develops in the flesh. The life cycle is completed when the second intermediate host is eaten by a dog or cat and the adult stage develops in the stomach wall.

Humans become infected by consumption of inadequately cooked or processed fish containing the third-stage larva. In Thailand *Channa striata,* the snakehead, is the

Table 7.3
Protozoal Pathogens Excreted in Feces

Protozoon	Disease	Can symptomless infection occur?	Reservoir
Balantidium coli	Diarrhea, dysentery and colonic ulceration	Yes	Humans and animals, especially pigs and rats
Entamoeba histolytica	Colonic ulceration, ametic dysentery, liver abcess	Yes	Humans
Giardia lamblia	Diarrhea and malabsorption	Yes	Humans and animals

Source: Feachem et al. (1983)

species of fish responsible for transmission. As snakehead are carnivorous, they are not cultured intentionally in waste-fed ponds. However, they may be harvested in small numbers from such systems and there is a possibly of disease transfer if the fish are not well cooked.

The immature third-stage larva migrates through the tissues causing relatively superficial lesions in the skin, subcutaneous tissue, muscles and, more rarely, the visceraand brain. Cerebral gnathostomiasis is a growing cause of focal cerebral lesions in Thailand, often causing coma resembling cerebrovascular accidents.

7.2.4.2 *Clonorchis* and *Opisthorchis*

The trematode worms *Clonorchis* and *Opisthorchis*, which have a life cycle from vertebrate hosts through snails to fish and back to vertebrate hosts, are of special importance in the reuse of excreta in aquaculture (Fig. 7.1). According to Hickling (1948), the use of raw night soil in fertilizing ponds in China was responsible for much liver fluke disease. The symptoms of clonorchiasis and opisthorchiasis, infections of the bile ducts by these worms, may be absent or vague in light infections, but heavier infections cause diarrhea, abdominal discomfort, and splenomegaly. Heavy parasite infections may cause acute pain, liver enlargement and tenderness, and edema, and there may be recurrent gall bladder colic. A lethal complication is carcinoma of the bile ducts, and death can occur also from secondary bacterial infection. These diseases occur mainly in East Europe and East Asia (Fig. 7.2). Chinese liver fluke (*Clonorchis sinensis*) occurs in China, Korea, Japan and Vietnam. The cat liver flukes (*Opisthorchis viverrini* and *O. felineus*) occur in Thailand and southern Laos, and in Poland, the USSR and Turkey, respectively. Opisthorchiasis affects more than 5 million people in Northeast Thailand (Sornmani 1987).

Table 7.4
Helminthic Pathogens Excreted in Feces

Helminth	Common name	Disease	Transmission	Distribution
Ancylostoma duodenale	Hookworm	Hookworm	Human→soil→ human	Mainly in warm, wet climates
Ascaris lumbricoides	Round worm	Ascariasis	Human→soil→ human	Worldwide
Clonorchis sinensis	Chinese liver fluke	Clonorchiasis	Human or animal→ aquatic snail→fish→ human	Southeast Asia
Diphyllobothrium latum	Fish tapeworm	Diphyllobothriasis	Human or animal→ copepod→fish→ human	Widely distributed foci, mainly temperate regions
Enterobius vermicularis	Pinworm	Enterobiasis	Human→human	Worldwide
Fasciola hepatica	Sheep liver fluke	Fascioliasis	Sheep→ aquatic snail→ aquatic vegetation→ human	Worldwide in sheep- and cattle-raising areas
Fasciolopsis buski	Giant intestinal fluke	Fasciolopsiasis	Human or pig→ aquatic snail→ aquatic vegetation→ human	Southeast Asia, mainly China
Gastrodiscoides hominis	n.a.	Gastrodiscoidiasis	Pig→aquatic snail→ aquatic vegetation→ human	India, Bangladesh, Vietnam, Philippines
Heterophyes heterophyes	n.a.	Heterophyiasis	Dog or cat→brack-ishwater snail→ brackish-water fish→ human	Middle East, southern Europe, Asia
Hymenolepis nana	Dwarf tapeworm	Hymenolepiasis	Human or rodent→ human	Worldwide
Metagonimus yokogawai	n.a.	Metagonimiasis	Dog or cat→ aquatic snail→ freshwater fish→ human	East Asia, Siberia (USSR)
Necator americanus	Hookworm	Hookworm	Human→soil→ human	Mainly in warm, wet climates

Table 7.4
Continued from previous page

Helminth	Common name	Disease	Transmission	Distribution
Opisthorchis felineus	Cat liver fluke	Opisthorchiasis	Cat or human→ aquatic snail→ fish→human	USSR, Thailand
O. viverrini	n.a.			
Paragonimus westermani	Lung fluke	Paragonimiasis	Pig, human, dog, cat, or other animal→ aquatic snail→ crab or crayfish→ human	Southeast Asia, scattered foci in Africa and South America
Schistosoma haematobium	Schistosome	Schistosomiasis; bilharziasis	Human→ aquatic snail→ human	Africa, Middle East, India
S. japonicum			Animals and humans→snail→ human	Southeast Asia
S. mansoni			Human→ aquatic snail→ human	Africa, Middle East, Central and South America
Strongyloides stercoralis	Threadworm	Strongyloidiasis	Human→human	Mainly in warm, wet climates
Taenia saginata	Beef tapeworm	Taeniasis	Human→cow→ human	Worldwide
T. solium	Pork tapeworm	Taeniasis	Human→pig (or human)→ human	Worldwide
Trichuris trichiura	Whipworm	Trichuriasis	Human→soil→ human	Worldwide

The main vertebrate hosts for *C. sinensis* are humans and dogs; for *O. viverrini*, humans and cats; and for *O. felineus*, cats. The bile ducts can harbor up to 6,000 worms, each releasing 2,000-4,000 eggs per day. The eggs contain fully developed miracidial larvae and are passed in the feces. To develop further they must reach water and
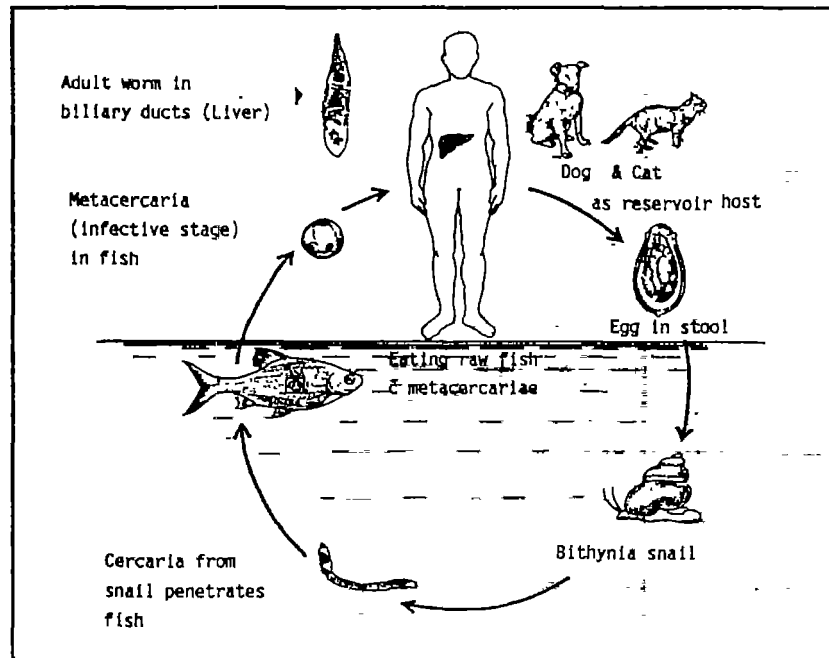
Figure 7.1 Life cycle of *Opisthorchis viverrini*
(Courtesy of Dr. Santasiri Sornmani)

be ingested by certain species of freshwater snails. Snail hosts include *Bulinus fuchsianus* (N. China), *Alocima longicornis* (S. China), and *Parafossarulus manchouricus* (most endemic areas) for *C. sinensis*; *Bithynia funiculata, B. laevis, B. goniomphalus*, and *B. siamensis* for *O. viverrini*; and usually *B. leachii* for *O. felineus*.

Asexual reproduction occurs in the snail, followed by the release of many free-swimming cercarial larvae three to four weeks after ingestion of the egg. The cercariae survive only one to two days unless they penetrate beneath the scales of practically any species of fish: there they form cysts called metacercariae in the connective tissue. More than 80 species of fish have been reported as hosts of *C. sinensis*. As many as 3,000 metacercariae have been found in a single fish. Metacercariae survive for some weeks after the death of the fish.

When an infected fish is consumed raw or partially cooked by a vertebrate host, the larvae hatch in the duodenum and migrate up the bile duct. One worm may develop from each ingested cyst, and it reaches maturity and produces eggs three to four weeks after ingestion of the cyst. Adult worms may live for 25-50 years and pass eggs in the feces. Eggs survive for one month in water.

The intensity of infection of fish with *Opisthorchis* in Northeast Thailand is related to the season of the year, with most human infections acquired towards the last third of the rainy season and the first third of the dry season, from September to February (Wykoff et al. 1965). Feces are deposited on dry ground in the dry season, and the

helminth eggs fail to come into contact with the snail hosts. Water bodies act as convenient latrines in the rainy season, and snails eat eggs either washed or deposited in water. Fish infection is largest by the end of the rainy season and fish are more easily caught as the waters recede until the ponds dry up in March.
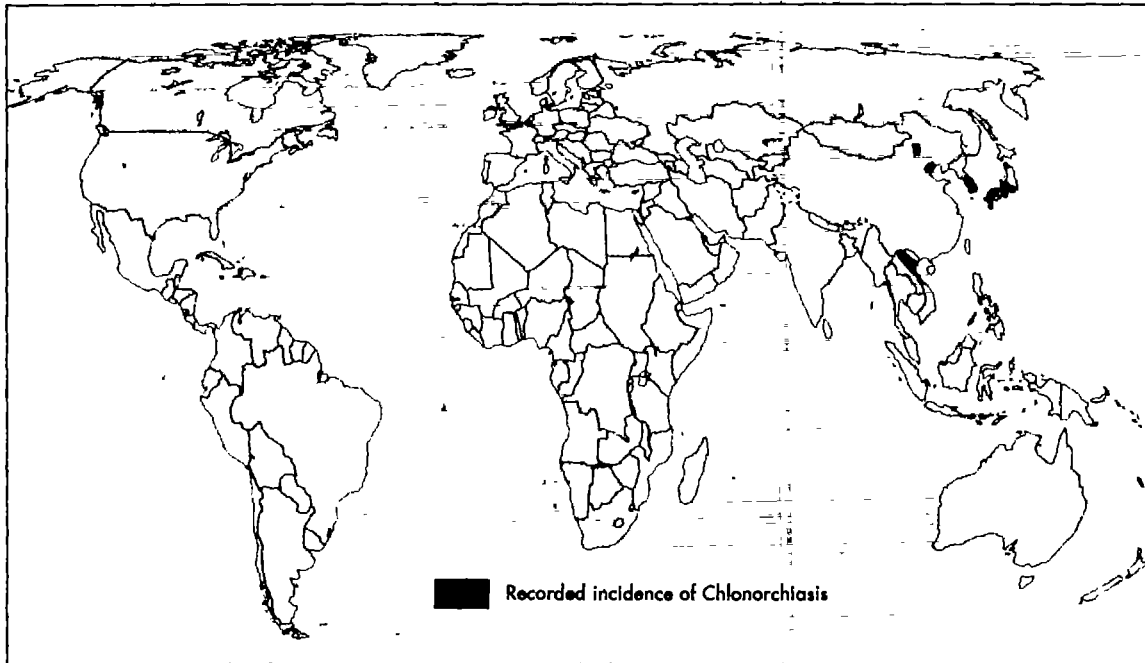
Figure 7.2 Distribution of *Clonorchis sinensis* (The infection may occur in areas as yet unrecorded. Source: Feachem et al. 1983)

7.2.4.3 Diphyllobothrium latum

The fish tape worm occurs in temperate areas, but it infects fish in lakes and rivers only, and not eutrophic ponds (Feachem et al. 1983). It is not of concern in excreta-fed aquaculture.

7.2.4.4 Fasciolopsis buski

Fasciolopsiasis is caused by the giant intestinal fluke (*Fasciolopsis buski*), a trematode which lives in the small intestine, particularly the duodenum. The infection is light and without symptoms in most cases. Heavy infections may cause intestinal obstruction and produce symptoms such as nausea, diarrhea, fever, abdominal pains, and edema.

Fasciolopsiasis occurs in humans in Asia, particularly in Central and South China, but there are endemic areas in Bangladesh, India, Indonesia, Kampuchea, Laos, Thailand, and Vietnam (Fig. 7.3). It was estimated in a 1947 study that there were ten

million cases of fasciolopsiasis in Asia, nearly half of which were ascribed to Chekiang Province, China (Cross 1969).
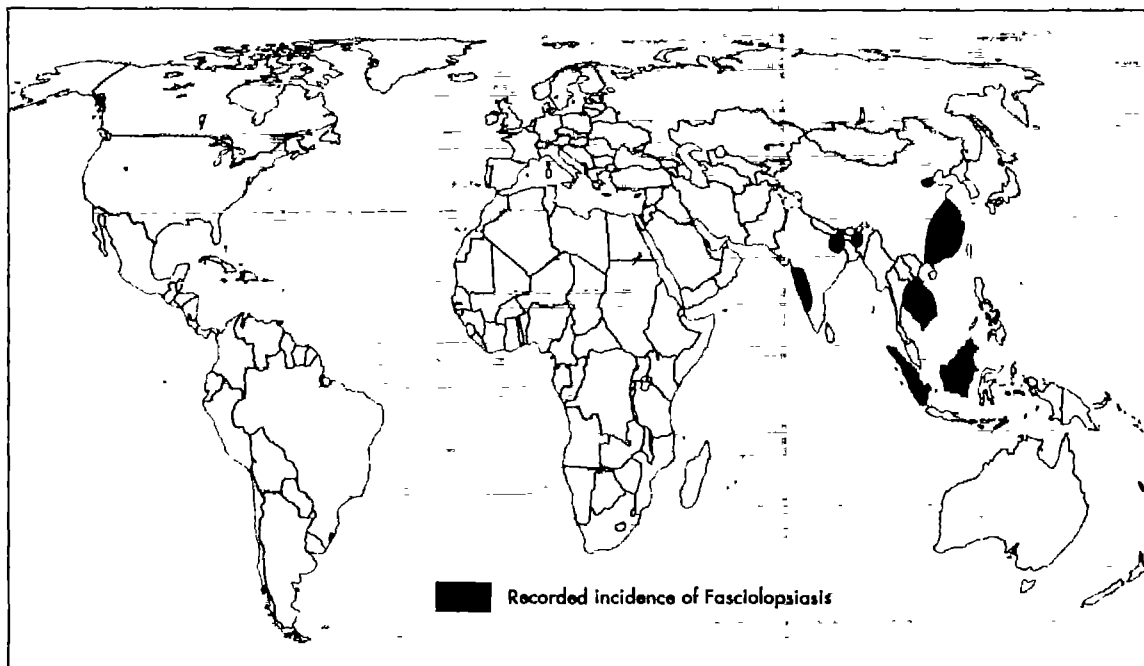
Figure 7.3 Distribution of *Fasciolopsis buski* (The infection may occur in areas as yet unrecorded. *Source:* Feachem et al. 1983)

In addition to humans, dogs and pigs are definitive reservoir hosts, and pigs are reported to be important in the maintenance of endemic fasciolopsiasis in central Thailand. An adult worm passess about 25,000 unembryonated eggs per day in its feces. They develop and hatch in three to seven weeks in favorable temperature conditions of 27-32°C in water. The miracidia must penetrate a freshwater planorbid snail within eight hours, or else it dies; in the snail it then undergoes asexual reproduction to produce cercariae. The swimming cercariae are released into the water and attach to aquatic macrophytes where they encyst as metacercariae. Metacercariae of fasciolopsis in China were found encysted on aquatic macrophytes such as water caltrop (*Trapa natans*), water chestnut (*Eliocharis tuberosa*), water hyacinth (*Eichhornia crassipes*), water bamboo (*Zizania aquatica*), *Salvinia natans* and duckweed (*Lemna polyrrhiza*) (Cross 1969). Infective stages of fasciolopsis were found encysted on virtually all species of aquatic macrophytes in an area endemic for the disease in Central Thailand, although only the following five species of aquatic macrophyte were reported to be consumed by humans, livestock, or both: water caltrop (*Trapa bicornis*), lotus (*Nymphaea lotus*), water mimosa (*Neptunia oleracea*), water spinach (*Ipomoea aquatica*), and water hyacinth (*Eichhornia crassipes*) (Manning and Ratanarat 1970). The metacercariae develop into worms in the duodenum of the human host when ingested with raw aquatic macrophytes. Flukes mature and start to lay eggs three to four months after ingestion of infective cysts. Eggs are passed

in feces as long as mature worms are present in the intestine. Adult worms live for only about six months in humans.

7.2.4.5 *Fasciola hepatica*

Fascioliasis, an infection of the bile ducts by a trematode called the liver fluke (*Fasciola hepatica*), is mainly an infection of sheep and cattle, but humans are sometimes infected. There is no good evidence for transmission from human to human, and it is probably very rare. A related fluke, *F. gigantea*, is a common parasite of cattle, camals and other herbivores, although infections of humans are known. The eggs of *Fasciola hepatica* mature in water or moist conditions and the miracidia invade amphibious snails, usually *Lymnaea* spp. The cercariae encyst as metacercariae on aquatic macrophytes such as watercress (*Rorippa nasturtium-aquaticum*), and sheep and cattle are infected by consumption of encysted metacercariae. Humans become infected when they eat encysted metacercariae on watercress or any water plant eaten raw. Although night soil is used to fertilize watercress in China (Herklots 1972), there need be little concern over night soil in the transmission of fascioliasis because transmission is by eggs in sheep and cattle feces (Feachem et al. 1983). However, watercress should be protected from contamination by feces of sheep and cattle.

7.2.4.6 *Heterophyes, Metagonimus,* and *Gastrodiscoides*

Three other trematodes besides *Fasciolopsis* infect the human intestine: *Heterophyes heterophyes, Metagonimus yokogawai,* and *Gastrodiscoides hominis.* All three infect the small intestine; infections are usually asymptomatic, although there may be occasional nausea, diarrhea, fever, and abdominal pain. These trematodes are of only minor public health importance, but they are quite common in limited geographical areas, particularly in parts of Asia. *Heterophyes* has a disjunct distribution in southern Europe (Greece and Romania), the Middle East (Egypt and Israel) and Southeast and East Asia (China, Japan, Philippines, South Korea). *Metagonimus* occurs in China, Japan, Korea, and eastern USSR. *Gastrodiscoides* occurs in Bangladesh, India, Philippines, and Vietnam.

All are primarily parasites of animals and can probably be maintained without humans. *Heterophyes* and *Metagonimus* infect cats, dogs, foxes, fish-eating mammals, and possibly birds. *Gastrodiscoides* infects monkeys, pigs and rats. Eggs passed in the feces develop further only in water. Larvae develop in certain species of freshwater snails and undergo asexual reproduction within the snail to release large numbers of free-swimming cercariae into the water. The cercariae encyst as metacercariae, those of *Heterophyes* and *Metagonimus* on the surface, under the scales, or in the superficial muscle of fish and *Gastrodiscoides* on aquatic macrophytes. Brackish water is the habitat for both snail and fish intermediate hosts of *Heterophyes.* Fresh water is the habit of the snail intermediate host of *Metagonimus,* whereas the fish intermediate host inhabits both fresh water and brackish water. Infection of animals and humans is by consumption of raw fish or aquatic macrophytes. The life cycles of *Heterophyes* and *Metagonimus* are similar to *Clonorchis,* and that of *Gastrodiscoides* resembles the life cycle of *Fasciolopsis.* Little is known of the epidemiology of these three trematodes.

7.2.4.7 Paragonimus

Paragonimiasis is an infection of the lungs, and sometimes of the brain, with the trematode lung fluke (*Paragonimus westermani*). The life cycle is similar to that of *Clonorchis*, *Heterophyes*, and *Metagonimus*, but metacercariae encyst in crabs and crayfish, not in fish. The disease in humans is limited to areas where raw crabs or crayfish are customarily consumed: infection is due to eating raw or pickled crustaceans or their juices. *P. westermani* infection of humans occurs mainly in China, Japan, Korea, and the Philippines, with cases also in India, Indonesia, Malaysia, Thailand, and Vietnam. However, there are other *Paragonimus* species that occasionally infect humans in Asia, Africa, and Latin America (Fig. 7.4). Paragonimiasis can be a very serious disease with severe chest pains and bronchitis. Cerebral paragonimiasis may cause epileptic seizures, headache, visual disturbances, and symptoms of meningitis.

Figure 7.4 Distribution of *Paragonimus* (The infection may occur in areas as yet unrecorded. *Source:* Feachem et al. 1983)

Eggs are passed out in sputum or are swallowed and passed out in the feces, but they must reach water for further development. A free-swimming miracidial larva develops in three weeks at an optimal temperature of 27°C and survives for about 24 hours; further development takes place in several species of freshwater operculate snail (*Semisulcospira libertina*, *S. amurensis*, *Thiara granifera*, *Oncomelania nosophora*). Asexual reproduction occurs in the snail, and in three months free-swimming cercarial larvae are released. The cercariae can survive for 24-48 hours, but further development takes place inside a second intermediate host, a freshwater crab or crayfish. Encysted metacercariae are formed in the gills or muscles of the crustaceans and the cysts hatch in

the duodenum of a new mammalian host when the crustaceans are eaten raw. Young flukes then migrate to the lungs, where the adult worm can live 6-20 years.

Some species of edible crabs are found in rivers and rice fields. In certain endemic areas, however, the crustacean hosts live in fast-flowing mountain streams some distance from human habitation, and humans probably become infected because of transmission via animal rather than human feces. A human excreta-disposal program would be unimportant in controlling transmission in such a situation.

7.2.4.8 Schistosoma

Schistosomiasis, or bilharziasis, is a disease caused by infection of the venous system by trematodes of the genus *Schistosoma* (Fig. 7.5). It is a major parasitic disease of humans, with 200 million cases, and it has increased with the construction of reservoirs and irrigation schemes (WHO 1980). A national survey in China revealed that about 10 million persons were suffering from schistosomiasis caused by *S. japonicum* (Cheng 1971). Urinary schistosomiasis is caused by *S. haematobium*, which inhabits veins around the bladder, whereas intestinal schistosomiasis is due to *S. japonicum* and *S. mansoni* in the portal venous system that transports blood from the intestines to the liver. *S. intercalatum* also causes intestinal schistosomiasis but has a localized distribution in West Africa.

Infection is through the skin and may be associated with inflammation and itching. There may be marked fever and respiratory symptoms during early developmental stages in the lungs. The worms present in the veins cause few disorders, but the large number of eggs laid daily damage the tissues. Most eggs are retained in either the bladder or bowel wall, or are carried to the liver, which is damaged most. Discharge of eggs causes tissue damage with loss of blood into the urine or feces. The range of disease produced is wide, from few or no symptoms to life-threatening complications.

S. haematobium is widespread in Africa, extends into parts of the Middle East, and has small foci in Europe and South Asia (Fig. 7.6). *S. japonicum* occurs in China, Japan and Southeast Asia, and a closely related form, *S. mekongi* (Sornmani 1984), occurs along the Mekong River (Fig. 7.6). *S. mansoni* is widespread in Africa and northeast South America, and patchy distribution in the Caribbean (Fig. 7.7). *S. intercalatum* has a restricted distribution in central West Africa. Schistosomiasis is much less widespread in Asia than in either Africa or Latin America. In Southeast Asia schistosomiasis is largely confined to the southern part of Luzon and Mindanao in the Philippines, and Khong Island in S. Laos. It is not a real health problem in Thailand, although there are occasional reports of cases (Sornmani 1987).

Humans are the major reservoir of *S. haematobium* and *S. mansoni*. Water buffalo, cattle, dogs, and rats are reservoirs of infection for *S. japonicum*, although humans are usually responsible for most transmission (Cheng 1971, Feachem et al. 1983).

The eggs are mature by the time they pass out of the body in excreta and hatch in water to form a free-swimming miracidial larva. The miracidium penetrates certain
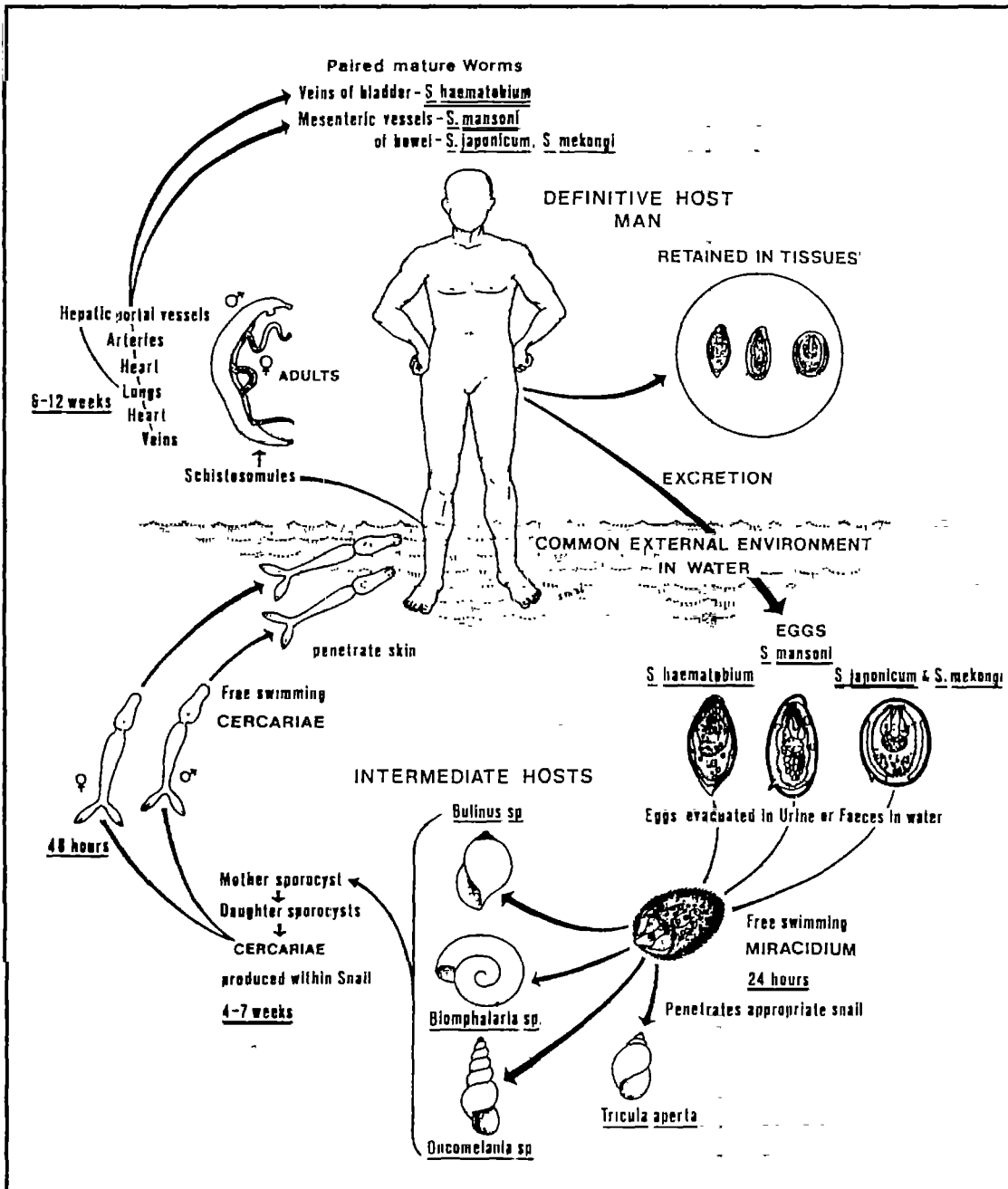
Figure 7.5 Life cycle of *Schistosoma*   (Courtesy of Dr. Santasiri Sornmani)
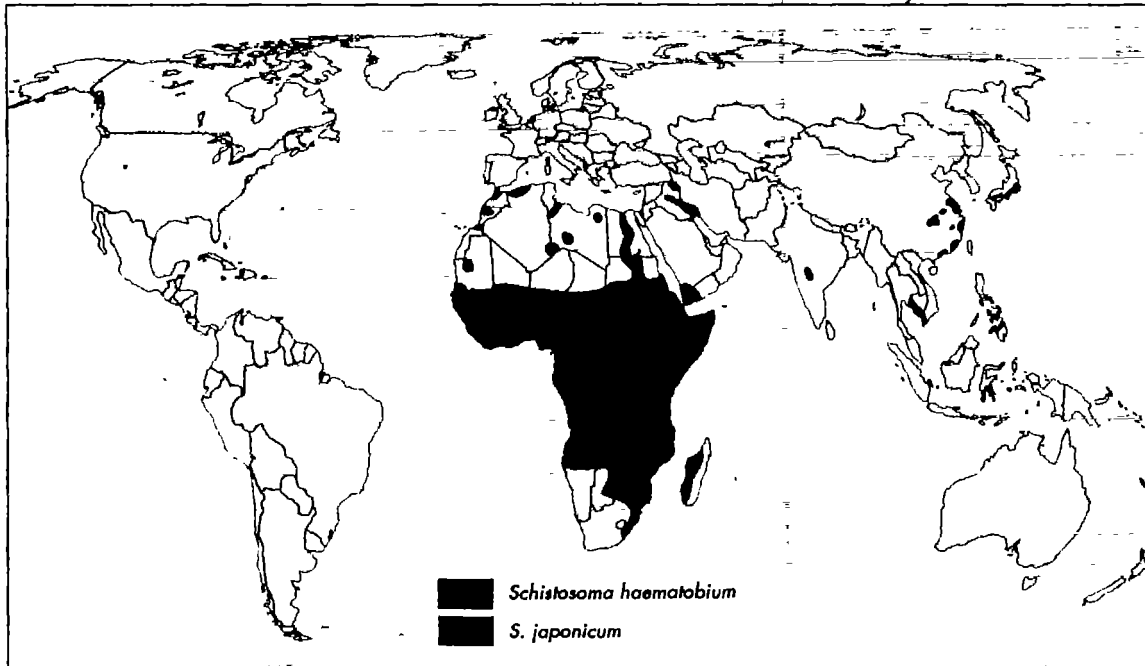
Figure 7.6 Distribution of *Schistosoma haematobium* and *S. japonicum* (The infection may occur in areas as yet unrecorded. *Source:* Feachem et al. 1983)

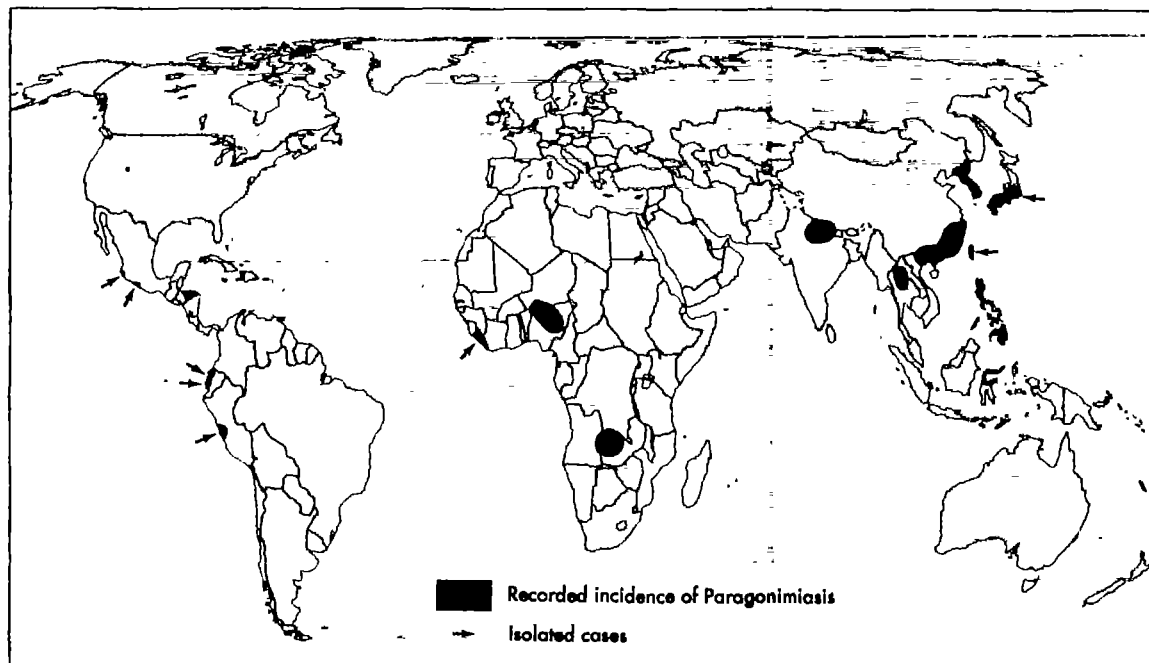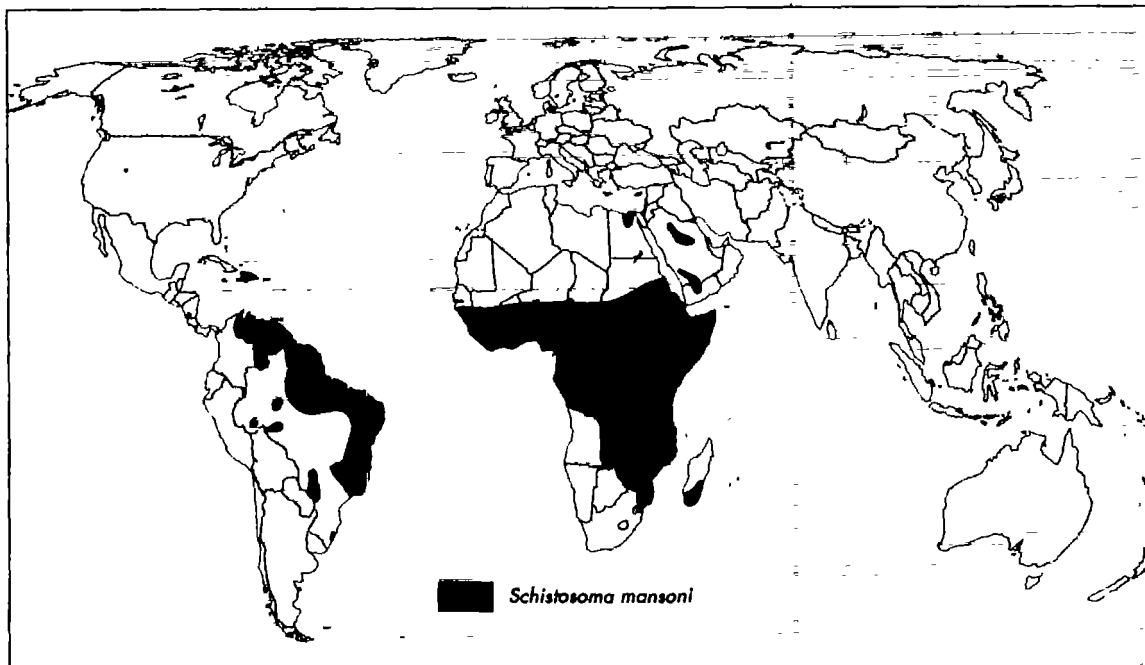**Figure 7.7 Distribution of *S. mansoni*** (The infection may occur in areas as yet unrecorded. *Source:* Feachem et al. 1983)

species of freshwater snail within six hours, undergoes asexual reproduction, and one to three months later free-swimming cercarial larvae emerge from the snail. If the cercariae encounter human skin within 48 hours of release from the snail, they rapidly penetrate it. The larvae migrate to the lungs where they develop for a few days and then move to the portal venous system of the liver to mature and pair before they migrate to the vesical or intestinal blood vessels.

Schistosomes are species-specific for intermediate snail hosts, which vary by geographical location. The main genera of snails that act as hosts are *Bulinus* for *S. haematobium*, *Biomphalaria* for *S. mansoni*, *Oncomelania* for *S. japonicum* (Feachem et al. 1983) and *Tricula* for *S. mekongi* (Sornmani 1984). The snail hosts of *S. japonicum* are amphibious, but those of other schistosomes are truly aquatic, although many can survive a dry season by burrowing into drying mud to estivate. The snails favor still or gently flowing water, as found in excreta-fed aquaculture systems.

The epidemiology of schistosomiasis is complex. For successful transmission, humans must live close to a water body that harbors the specific species of snail. Fresh human urine (*S. haematobium*) or feces (other schistosome species) must enter the water bodies harboring the snails for transmission from human to snail to occur. Finally, people must enter water bodies that harbor the snails and which have been loaded with excreta in order for transmission from snail to human to occur. Exposure may take place while playing, bathing, washing clothes, collecting water, tending water buffalo, working in flooded fields, fishing, or performing aquaculture operations.

7.3 Excreta-related infections and aquaculture

An environmental classification of excreta-related infections has been developed as a conceptual framework to link the various excreta-related infections to improved excreta disposal or reuse technologies, irrespective of the biological classification of infections into taxonomic groupings of viruses, bacteria, protozoans, and helminths (Feachem et al. 1983). An environmental classification should help to make the effectiveness of different control measures clear, including the design of excreta-reuse systems that do not pose an unacceptable hazard to public health (Table 7.5). Categories I (nonbacterial fecal-oral infections), II (bacterial fecal-oral infections), V (water-based helminths) and VI (excreta-related insect vectors) need to be considered potential sources of infection in excreta-fed aquaculture, whereas categories III (soil-transmitted helminths) and IV (beef and pork tapeworms) need not be considered.

The pathogens of categories III, IV and V demonstrate latency, which means that they cannot infect humans immediately after excretion but must undergo a period of development in soil, livestock, or aquatic animals. Pathogens also vary in the size of the dose required to cause an infection. A low infective dose means that few organisms are required to infect a human: one amebic cyst or one viral particle, for example. In general,

Table 7.5
Environmental Classification of Excreted Infections

Category and epidemiological features	Infection	Environmental transmission focus	Major control measures
I. Nonlatent; low infective dose	Amebiasis Balantidiasis Enterobiasis Enteroviral infections Giardiasis Hymenolepiasis Infectious hepatitis Rotavirus infection	Personal Domestic	Domestic water supply Health education Improved housing Provision of toilets
II. Nonlatent; medium or high infective dose; moderately persistent; able to multiply	*Campylobacter* infection Cholera Pathogenic *Escherichia coli* infection Salmonellosis Shigellosis Typhoid Yersiniosis	Personal Domestic Water Crop	Domestic water supply Health education Improved housing Provision of toilets Treatment of excreta prior to discharge or reuse
III. Latent and persistent; no intermediate host	Ascariasis Hookworm infection Strongyloidiasis Trichuriasis	Yard Field Crop	Provision of toilets Treatment of excreta prior to land application
IV. Latent and persistent; cow or pig as intermediate host	Taeniasis	Yard Field Fodder	Provision of toilets Treatment of excreta prior to land application Cooking, meat inspection
V. Latent and persistent; aquatic intermediate host(s)	Clonorchiasis Diphyllobothriasis Fascioliasis Fasciolopsiasis Gastrodiscoidiasis Heterophyiasis Metagonimiasis Opsthorchiasis Paragonimiasis Schistosomiasis	Water	Provision of toilets Treatment of excreta prior to discharge Control of animal reservoirs Control of intermediate hosts Cooking of water plants and fish Reducing water contact
VI. Spread by excreta-related insects	Bancroftian filariasis transmitted by *Culex pipiens*) All the infections in I-V can be transmitted mechanically by flies and cockroaches	Various fecally contaminated sites in which insects breed	Identification and elimination of suitable insect breeding sites

Source: Feachem et al. (1983)

the infective dose for bacteria is larger, a range of 10^4-10^7, and is related to health: the healthier the person, the larger the infective dose needed to cause disease.

7.4 Public health hazards of fish farming

There are three distinct potential health problems associated with the reuse of excreta in ponds (Feachem et al. 1983):

1. Passive transfer of pathogens by contaminated fish.
2. Transmission of helminths in which fish are intermediate hosts.
3. Transmission of helminths in which other pond fauna are intermediate hosts.

The first is cause for worldwide concern. The second and third occur only in areas with particular eating habits or where the helminths are endemic, or both.

7.4.1 Passive transfer of excreted pathogens

It is generally accepted that the intestinal bacteria of warm-blooded animals (humans and livestock) do not cause disease in fish and are absent from fish caught in unpolluted waters (Guelin 1962, Buras 1977, Feachem et al. 1983). There is no permanent coliform or strepotococcal bacterial flora in the intestinal tract of fish (Geldreich and Clarke 1966). Salmonellae have never been found to cause disease in aquatic animals (Buttiaux 1962).

However, fish growing in an environment contaminated with excreted pathogens may acquire substantial numbers of pathogens on their body surfaces and in their intestines. Enteric bacteria such as fecal coliforms, fecal streptococci, and salmonellae may be readily isolated from fish grown in water contaminated with excreted pathogens (Feachem et al. 1983). Viscera of fish caught on the high seas did not contain intestinal bacteria or viruses of human origin, although fish from coastal waters were often contaminated (Buttiaux 1962, Guelin 1962). Edible portions of seafish were found to be free of salmonellae, with the exception of a fish caught while feeding in inshore water in the local sewage plume (Mackenzie and Livingstone 1968). Geldreich and Clarke (1966), by examination of fish and water from various locations and by tank experiments, demonstrated that the bacteriological composition of the intestinal tract of freshwater fish is related to the level of contamination of water and food in the environment. That specific antibodies to several bacteria pathogenic to humans were detected in the serum of white perch from rivers flowing into the Chesapeake Bay through heavily populated areas suggests that fish may be infected with human pathogens by exposure to contaminated water (Janssen and Meyers 1968). Therefore, the bacterial flora of a fish reflects the bacteriological quality of the waters from which it was taken (Guelin 1962, Geldreich and Clarke 1966, Buras et al. 1987), and fish may be passive carriers of human pathogens in water polluted by sewage (Brown and Dorn 1977).

There also appears to be a concentration effect because densities of enteric bacteria in fish intestines tend to be higher than in polluted water (Feachem et al. 1983). There is evidence of enteric bacteria multiplying in the gut, mucus and fish tissues, for instance, *Vibrio parahaemolyticus* (Janssen 1970) and *Clostridium botulinum* type E, *C. tetani*, *Staphylococcus aureus*, *Erysipelothrix musiopathiae*, streptococci, *Shigella* and various serotypes of *Salmonella* (Lawton and Morse 1980). Fecal coliforms and fecal streptococci may survive, and perhaps even multiply, for up to 14 days in fish intestines (Glantz and Krantz 1965). However, there is disagreement whether pathogens can multiply in fish (Ghittino 1972).

There are very few data on the passive transfer of excreted pathogens causing disease in humans. Bryan (1974, 1977) listed outbreaks of disease caused by excreted pathogens which contaminated food from sewage or wastewater. Fish and shrimp were implicated in only three and one outbreaks, respectively, compared to shellfish and watercress in 28 and 10 outbreaks, respectively: shellfish and watercress are often consumed raw.

Public health problems concerning fish have usually been traced to contamination following harvest, during handling, transportation, and storage (Brown and Dorn 1977, Feachem et al. 1983, Scarpino 1983). Most salmonella contamination of fish occurs when handling, transporting, or processing operations are carried out under inadequate sanitary conditions (Buttiaux 1962). However, it is possible for pathogenic bacteria from excreta-fed ponds to be carried passively by harvested fish and then to infect those who handle, prepare or eat the contaminated fish (Feachem et al. 1983).

There are few data on the passive transfer of viruses, protozoan cysts, and soil-transmitted helminth eggs by fish, but it must be assumed that they can be carried and therefore can infect handlers or consumers of the fish (Feachem et al. 1983). It has been assumed that helminth eggs, which tend to settle to the pond bottom, will be ingested only by bottom-feeding fish such as the common carp (*Cyprinus carpio*). In a study of 14 different species of freshwater fish, the bottom-feeding channel catfish (*Ictalurus punctatus*) had the highest concentrations of fecal bacteria in the intestines (Geldreich and Clarke 1966). However, there may be potential for helminth eggs to infect a wide range of fish species since fish feeding habits may be much wider than is generally assumed (Schroeder 1980b).

There is little risk from insanitary disease in eating well-cooked fish because thorough cooking destroys pathogens; consumption of raw or partially cooked fish may lead to infection (Feachem et al. 1983). Fish are often eaten raw in China, Japan, Korea and Northeast Thailand (Viranuvatti and Stitnimankarn 1972, Sornmani et al. 1984a). Seow et al. (1979) reported the consumption of "yee sung" in Malaysia, a raw fish dish made from grass carp. Fish muscle is commonly eaten raw in a marinated salad called ceviche in Peru (Cointreau 1987). There appears to be little risk to public health in consuming raw marine fish as in Japan, Korea, and Peru, but the consumption of raw freshwater fish may be a health hazard. Bryan (1974) concluded from his study of disease from food contaminated by excreted pathogens that, although the epidemiological evidence often did

not stand up to critical evaluation, there were enough cases backed up by both epidemiologic and laboratory evidence to indicate that wastewater-contaminated foods (mainly shellfish and watercress) have caused disease when eaten raw (Bryan 1974).

However, the risk to persons who handle or prepare fish remains, irrespective of local eating habits (Feachem et al. 1983). Infection usually occurs when fish are gutted and cleaned. The gut contents come into contact with hands, kitchen utensils, and the kitchen table; these are potential foci of infection if they are not washed well (N. Buras, personal communication).

7.4.2 Helminths using fish as intermediate hosts

Worms parasitic to humans may be transmitted by fish which act as intermediate hosts for the worms. The major helminths are Chinese liver fluke (*Clonorchis sinensis*), the cat liver flukes (*Opisthorchis viverrini* and *O. felineus*), fish tapeworm (*Diphyllobothrium latum*), *Heterophyes heterophyes* and *Metagonimus yokogawai*. The latter two are not of major public health significance because they infect primarily cats and dogs, and *Heterophyes* infects fish only in brackish water. *Diphyllobothrium* infects fish from lakes and rivers but not eutrophic ponds (Feachem et al. 1983). *Gnathostoma spinigerum* infects snakehead, a carnivorous fish that is not cultured in waste-fed ponds but may be present as a contaminant.

Chinese liver flukes and cat liver flukes are transmitted intensively where fish are eaten raw or partially cooked. Most preservative and pickling techniques for fish are ineffective in killing encysted larvae. Thorough cooking of fish is effective and is the best method for personal protection.

Snail populations may be reduced by clearing aquatic macrophytes from ponds. Chemical control of snails using molluscicides is possible because the concentration needed to control snails is lower than the concentration toxic to fish. It may, however, be difficult in practice to apply the correct dosage.

Transmission occurs only by direct addition of fresh night soil or raw sewage to ponds. *Clonorochis* eggs settle from pretreated sewage; they are fragile and die if stored a few days in night soil or sludge. Although there are no specific data available, *Clonorchis* eggs should be destroyed by storage of night soil at 5°C for five days or 25°C for two days. Storage of night soil or sludge for seven days before adding to ponds is a good control strategy (Feachem et al. 1983, IRCWD 1985). However, management of human excreta may reduce transmission only partially because this helminth has other mammalian hosts such as cats and dogs (Feachem et al. 1983).

There is no safe and effective drug for mass chemotherapy available (Feachem et al. 1983), although opisthorchiasis was recently partially controlled with the relatively new drug praziquantel in a pilot project in Thailand (Sornmani et al. 1984ab).

A disturbing fact is that infection with *Opisthorchis* is closely related to water-resource development in Northeast Thailand, that is, it is concentrated in irrigated areas where the income of communities rose, but so did the prevalence of opisthorchiasis (Sornmani et al. 1984ab). An integrated approach using chemotherapy, health education, and improvement in environmental hygiene is needed to control the disease (Sornmani et al. 1984ab).

Paragonimus westermani was not considered by Feachem et al. (1983) to be associated with excreta-fed ponds, but it may be better to consider it a potential health hazard of excreta-fed aquaculture until concrete data are obtained to the contrary because it is transmitted from humans (or other mammals) to snails, to crabs or crayfish, to humans.

7.4.3 Helminths with aquatic intermediate hosts other than fish

There is substantial evidence that, in the past decade, water-resource development projects in tropical areas have led to an increase in schistosomiasis in areas where it is endemic (Rosenfield and Bower 1979, WHO 1980). Rates of infection with *Schistosoma* in China were reported to rise with increased contact with water. Fishers and boaters were often infected through frequent exposure to water (Cheng 1971). The possibility exists that schistosomiasis may occur in excreta-fed ponds and may infect farmers if the appropriate species of intermediate-host snail is present and fresh eggs or miracidia reach the pond (Feachem et al. 1983).

The recent proliferation of ponds in East Africa has caused concern because the ponds provide additional breeding sites for the intermediate-host snails of schistosomiasis near the human population (Berrie 1966). Although the ponds increase the amount of animal protein available to a generally malnourished population, it has been suggested that studies should be conducted on snail control in the ponds. The seriousness of schistosomiasis may invalidate the argument that persons in endemic areas are likely to contract the disease from natural waters and the additional small risk from a pond is acceptable because of the animal protein produced.

A variety of measures must be considered to control the disease in endemic areas. Attempts to control schistosomiasis by providing excreta-disposal facilities alone to prevent schistosome eggs from reaching water have failed. Failure was considered to be due to the population's not using the facilities because they were located in the village while people defecated in the fields, and because the facilities were offensive, ill-adapted to cultural traditions, and unsuited for use by children. Improved sanitation is unlikely to be effective in schistosomiasis control because a single stool or urination may contain many eggs, and a single miracidium's reaching a snail may produce thousands of infective larvae or cercariae (Feachem et al. 1983). With *S. haematobium* it is the disposal of urine that is important, and urine is far more difficult than feces to control.

In species except *S. mansoni* and *S. haematobium*, animals are an important reservoir of infection. Measures restricted solely to human excreta can be only partially

effective because multiplication of water-based helminths (except fish tapeworm) takes place in the intermediate hosts (Feachem et al. 1983).

Schistosome eggs are not long-lived in the environment compared to eggs of the soil-based helminths *Ascaris* and *Trichuris* and the beef and pork tapeworm *Taenia*, but they are much more persistent than the delicate eggs of other flukes (Feachem et al. 1983, IRCWD 1985). Although *Schistosoma japonicum* eggs survived for up to 14 days in summer in the anaerobic fecal liquor of a biogas plant in China (McGarry and Stainforth 1978), storage of night soil containing schistosome ova for 12 days at an air temperature of 20-30°C was reported to prevent further hatching of ova (Ye 1984). Three weeks of sludge drying in warm climates, irrespective of the moisture reached, should eliminate schistosome eggs (Feachem et al. 1983). It was shown in China that storage of a human feces-urine mixture at a ratio of 1:5 or higher for three days in summer destroyed schistosome eggs by ammonia toxicity. Further studies demonstrated that treatment of feces with urea, ammonium bicarbonate, and calcium cyanamide at 1 percent, 0.5 percent, and 0.25 percent, respectively, killed *S. japonicum* eggs within 24 hrs (Cheng 1971). There may also be specific differences in egg viability in *Schistosoma* because *S. mansonii* eggs are probably much less robust in the environment than those of *S. japonicum* (Feachem et al. 1983).

Other control strategies may involve the snail intermediate hosts. It is necessary to know the species of the intermediate snail hosts and also their ecology if environmental or biological controls are to be used effectively. Surveillance of snails is required in areas in which excreta-fed ponds may be developed. Not all areas, particularly in Asia where the distribution of schistosomiasis is much more localized than in Africa and Latin America, may have the snail intermediate hosts. *Bulinus* (*S. haematobium*) prefers stagnant or slow-moving water and is more numerous in moderately polluted waters with bottoms rich in silt and organic matter, but *Oncomelania* (*S. japonicum*) is basically a swamp animal (McJunkin 1970). *Biomphalaria* (*S. mansoni*) thrives in running water of moderate velocity such as streams and irrigation canals (McJunkin 1970), but *Tricula* (*S. mekongi*) inhabits slow-running rivers (Sornmani 1984). The pond environment is more similar to the natural habitat of the former than that of the latter two snail genera. It is possible that not all snail genera may inhabit stagnant, eutrophic, excreta-fed ponds. According to Arthur (1983), stabilization ponds do not provide a suitable environment for the snail hosts of schistosomiasis, which prefer relatively unpolluted water. However, *Bulinus* and *Biomphalaria* were reported from ponds in East Africa (Berrie 1966). Snails were also more likely to be present in large numbers in ponds with aquatic macrophytes, or with marginal vegetation overhanging the water, because the snails generally preferred to browse on plant surfaces. They occasionally thrived in ponds devoid of vegetation. Decaying vegetation such as leaves or grass, which may fall into ponds naturally or be given as supplementary feed, was also observed to be a favorable substrate for the snails. The occurrence of schistosomiasis in China was invariably correlated with the presence of the snail intermediate hosts (*Oncomelania hupensis*) which were reported to abound on banks of rivers and ditches and in weedy areas of lakes and marshes, including borders of ponds (Cheng 1971).

Snail hosts of all species except *S. japonicum* are aquatic and their abundance should diminish if no aquatic macrophytes are present, as in well-managed excreta-fed ponds. Ponds may prove satisfactory in terms of fish production without additional risk of disease if they are properly managed (Berrie 1966). Snails have been controlled by making the habitat unsuitable for them by environmental changes such as lining canals with concrete and intermittent drying of irrigation canals (Feachem et al. 1983), but such measures are hardly compatible with aquaculture.

Because of concern over the environmental effects of some molluscides, as well as their escalating costs, biological control of snail intermediate hosts has been widely studied in the last decade. Efforts so far have usually proven ineffective (McJunkin 1970). Several hundred species comprising a wide range of organisms — fish, fungi, parasites, and pathogens — have been proposed as potential competitors or predators. Only fish and insects have been studied in sufficient detail to merit consideration, but rigorous evaluation of their efficicacy in field situations is still lacking (WHO 1980). Berrie (1966) discussed some of the earlier work on the biological control of snail intermediate hosts by fish in Africa, although the results generally indicated incomplete control. An experiment was conducted in reservoirs in Kenya in which control of snails was attempted by stocking a snail-eating fish, *Astatoreochromis alluaudi*. Assessment of snail control was made over 15 years in the reservoirs, one of which was left as a control without introduction of fish. It was concluded that the fish did reduce the numbers of some species of snail, particularly *Biomphalaria* and, to a less, more uncertain extent, *Bulinus*. However, large numbers of *Bulinus* were often found in dense patches of aquatic macrophytes, presumably because the fish could not reach them (McMahon et al. 1977). The Chinese black carp (*Mylopharyngodon piceus*) was found to be most effective in reducing snails, including *Bulinus truncatus*, in reservoirs in Israel (Leventer 1981). Laboratory experiments indicated that the tilapia *Oreochromis mossambicus* may be a promising biological control agent of schistosomiasis by predation on eggs and young of *Biomphalaria* less than 10 mm diameter (Graber et al. 1981).

Snail control by molluscicides is a rapid and effective means of reducing transmission of schistosomiasis and is most cost-effective where the volume of water to be treated per person at risk is small, as in constructed water impoundments (McCullough et al. 1980, WHO 1980). It should be possible, therefore, to treat relatively small bodies of water such as ponds with molluscides. However, most of the molluscicides available or under trial were reported to be toxic to fish (Berrie 1966). The molluscides now in use are Bayluscide (niclosamide) and Frescon (n-trityl-morpholine), which are relatively nontoxic to humans but they may be toxic to fish (Feachem et al. 1983). Nicotinanilides (nicotinanilide and its 3'- and 4'- chloro-analogs) have been reported to be effective molluscides at a concentration in water of approximately 0.2 mg/l. No visible effect could be seen on fish at dosages of 2-5 mg/l to ponds. No acute toxicity of 4-chloronicotinanilide has been shown in adult tilapia (*Oreochromis mossambicus*) in laboratory tests of doses 200 times higher than the LC_{50} to *Biomphalaria glabrata*, a snail intermediate host. The compounds were reported to affect neither goldfish nor the zooplankton *Daphnia* at molluscicidal concentration. These compounds offer the possibility of a truly selective control of snails (WHO 1980).

There have been successful control programs that have attempted to reduce human contact with infected water (Feachem et al. 1983). This might be less effective with aquaculture in which management of the fish stock to produce maximum yields entails entering the pond to sein fish. A single harvest on draining the pond might reduce contact with water, although it would lead to a reduced fish yield.

Planned epidemiological and ecological studies must be conducted before the implementation of water development schemes in the tropics, including excreta-fed ponds, to prevent, or at least minimize, adverse health effects including schistosomiasis. Schistosomiasis control depends on a carefully designed combination of chemotherapy, health education, sanitation, and snail control (WHO 1980). However, some developing countries have achieved significant progress in schistosomiasis control. A national campaign was launched against the disease in China, where excreta reuse in ponds is traditional and widespread, with considerable success. The campaign involved destroying the snail host by cleaning irrigation ditches and streams, storage of excreta to destroy eggs, and chemotherapy for patients (Cheng 1971).

7.4.4 Ponds as breeding sites for mosquitoes

The construction of pond systems for the reuse of excreta may provide an environment for the breeding of vectors, particularly mosquitoes, that may transmit diseases such as malaria and filariasis, which themselves are not found in excreta

The eggs of *Culex pipiens* mosquitoes, the most likely disease vector in excreta-fed ponds, are laid in clumps known as rafts, and the larvae hatch in one to two days. Larvae pass through four stages, which last a total of one to two weeks in the tropics, during which time they breathe air through a siphon tube located at the posterior end of their bodies. The pupae are comma-shaped and give rise to the adult mosquito after about two days. The favored sources of blood are humans and birds (Feachem et al. 1983).

Many mosquitoes can transmit human disease, but three groups of species are of particular importance:

1. The *Culex pipens* complex are the vectors of the nematode worm Bancroftian filariasis (*Wuchereria bancroftii*), especially in continental Asia. However, in other places the vector for the disease may be *Anopheles* or *Aedes* mosquitoes, or *Mansonia* (Oemijati 1973). Adult worms live in the lymphatic ducts of humans. A reaction by the tissues of the infected person may block the lymphatic vessels and may lead to swelling of the arms, legs, or genitalia. Filariasis is not a lethal disease, but it can lead to the gross deformity of the arms, legs, or genitals known as elephantiasis (Feachem et al. 1983).

   The breeding places of *C. pipens* are mostly highly polluted water connected with sewage or sullage: stagnant open drains, pit latrines, septic tanks, and soakage pits that are not mosquito-proof, and poorly maintained waste stabilization ponds

(Feachem et al. 1983). This species is probably the most likely to breed in an excreta-fed pond.

2. The *Anopheles* species, vectors of malaria, breed in fairly clean stretches of water such as flood or irrigation water (Feachem et al. 1983), and are therefore probably unlikely to breed in eutrophic ponds.

3. *Aedes aegypti*, the vector of yellow fever, dengue, and dengue hemorrhagic fever viruses, breeds in clean water stored in pots and cisterns (Feachem et al. 1983) and also would be unlikely to breed in excreta-fed ponds.

Curtis and Feachem (1981) and Feachem et al. (1983) reviewed the literature on waste stabilization ponds as breeding sites for mosquitoes and concluded that the most important factor to prevent mosquito breeding is the avoidance of vegetation hanging into or emerging through the surface of the pond. They pointed out that it is easy to discourage aquatic macrophyte growth in ponds by making them more than 1 m deep. The use of concrete slabs, rip-rap, or soil cement at the water surface level discourages vegetation on pond dikes. Laborers could also help to control vegetation manually. They concluded that mosquito breeding in ponds can be well controlled by appropriate design and management.

There also appears to be little danger of mosquitoes breeding in ponds from the activity of fish themselves. Macrophagous fish eat vegetation and thereby destroy the breeding habitat of mosquitoes. Fish also eat mosquito larvae and pupae. Grass carp eat surface vegetation and silver and bighead carp eat mosquito larvae (Hickling 1947, cited by Mortimer and Hickling 1954). *Tilapia melanopleura* (*T. rendalli*) are effective for malaria control in brackish-water ponds because the fish eliminate floating and semisubmerged aquatic macrophytes which are breeding places of malaria-transmitting *Anopheles* mosquitoes, and the fish fry eat mosquito larvae (De Bont 1948). Malarial *Anopheles* mosquitoes were particularly attracted to brackish-water ponds in the coastal areas of Indonesia that were covered by floating masses of filamentous green algae. It was observed after World War II that in many such ponds the water surface was no longer covered with filamentous algae because of the presence of *Tilapia mossambica* (*Oreochromis mossambicus*) introduced into Java about 1938, with a concomitant control of malaria (Hofstede and Botke 1950). *Tilapia melanopleura* and *Tilapia mossambica* (*Oreochromis mossambicus*) were used in the biological control of mosquito larvae in sewage stabilization ponds in South Africa through their consumption of the submerged aquatic macrophyte *Vallisneria*, although rapid fish growth and reproduction led to a disposal problem (Mackenzie and Campbell 1963).

Filter-feeding species of tilapia (*Oreochromis*) suitable for excreta reuse systems also consume mosquito larvae. No undue breeding of mosquitoes occurred in ponds used to cultivate the aquatic vegetable water spinach (*Ipomoea aquatica*), because the ponds also contained *Sarotherodon mossambicus* (*Oreochromis mossambicus*), the young of which effectively consume mosquito larvae (Le Mare 1952). Mosquitoes may also be controlled in excreta reuse systems involving aquatic macrophytes. An almost complete cover of aquatic macrophytes leads to an anaerobic water column, but the mosquito fish (*Gambusia*

affinis), is tolerant of low dissolved oxygen and can be stocked to consume mosquito larvae. In a duckweed aquaculture system, a more or less complete cover of weed on the surface would preclude mosquito breeding because the larvae would be prevented from surfacing for air. The common name of *Azolla*, a minute floating fern with the same life form as duckweed, is "mosquito fern," probably from attempts in Europe and the United States to use it to prevent mosquitoes from breeding in shallow water by covering the water surface (Moore 1969).

The construction of ponds in marshes or swamps may lead to a decrease or elimination of a mosquito-transmitted disease by destruction of the vector habitat, for example, filariasis transmitted by *Mansonia* mosquitoes (Edwards 1980b). *Mansonia* lay eggs on the undersides of leaves of aquatic macrophytes, especially water lettuce (*Pistia stratiotes*) and water hyacinth (*Eichhornia crassipes*). Filariasis has now spread along the coast and to the central highlands of Sri Lanka because of the spread of *Pistia* and *Eichhornia* (Kotalawala 1976). However, in Indonesia there has been a tendency for a decrease in the infection rates of filariasis in many places (Oemijati 1973). A new endemic focus of *Brugia malayi* was described in Kresek in 1960 in a large swampy area with abundant water hyacinth (*Eichhornia crassipes*) and other aquatic macrophytes. The microfilaria rate of infection in the human population was 22 percent and the mosquito *Mansonia indiana*, incriminated as the vector, was abundant inside houses. When the area was reinvestigated 10 years later, in 1970, it had completely changed. Irrigation canals had been constructed and the swamps converted into rice fields. Both water hyacinth and the mosquito vector *M. indiana* had disappeared. Although the population had changed little, the microfilaria infection rate had dropped to 1 percent. A similar transformation occurred in the Serayu delta, which used to be a stagnant water area heavily infested with water lettuce (*Pistia stratiotes*).

7.5   Enteric pathogen indicator organisms

A reliable estimation of the total enteric pathogen concentration of aquatic organisms raised on excreta is required to determine whether or not the benefits from excreta reuse exceed potential adverse public health effects. Analyses for enteric pathogenic viruses and bacteria require well-equipped laboratories and skilled scientific personnel, and for viruses the analyses are costly. Reliance needs to be put on indicator bacteria and viruses to measure fecal contamination.

In addition to pathogenic organisms present in the feces of infected persons, there are also commensal species that live exclusively in the intestinal tract of humans and warm-blooded animals without causing disease. The presence of enteric commensal organisms in samples from the environment indicates that they have been contaminated with feces (and possibly with excreted pathogens) because commensal organisms are excreted in large concentrations, up to 10^9-10^{10} cells/g feces. Enteric commensal organisms can therefore be used as an indicator of fecal contamination (Feachem et al. 1983). Desirable attributes of microbial indicators of pathogens include presence whenever enteric pathogens are present, a reasonably longer survival time than the hardiest enteric pathogen, and an

inability to reproduce in large numbers in the environment (which would lead to an inflated concentration). It is particularly important that the concentration of indicator organism be related to that of excreted pathogens, but with the indicator present in greater numbers to provide a safety margin (Scarpino 1983).

Fecal coliforms are most commonly used as fecal indicator bacteria. There are two main groups of coliform bacteria, the fecal coliforms, mainly *Escherichia coli*, and the total coliforms, mainly *Citrobacter, Enterobacter, Escherichia* and *Klebsiella*. Fecal coliforms are exclusively fecal in origin, but the other coliforms occur naturally in unpolluted soil and water and can multiply in the environment. Thus, only fecal coliforms should be used as indicators of fecal bacterial pathogens (Feachem et al. 1983). Although *E. coli* has been used as an indicator for many years, it has recently been discovered that there are pathogenic strains (N. Buras, personal communication).

Thermotolerant fecal streptococci are as useful as fecal coliforms as fecal indicators. They include biotypes that are mainly associated with bovine animals and others that are associated with human pollution.

There have been many attempts to correlate concentrations of fecal coliforms with the presence of *Salmonella*, but there is no generally applicable relationship. *Salmonella* is found in surface waters wherever there are animal populations. *Salmonella* is not found in unpolluted water. Although there is a greater chance of isolating *Salmonella* as water pollution and therefore the number of fecal coliforms increase, *Salmonella* concentrations are sometimes difficult bacterial pathogens to correlate with indicator concentrations. However, it was shown in the San Juan sewage stabilization ponds in Lima that fecal coliforms were a reliable indicator of the removal of pathogenic bacteria such as *Salmonella* and fecal streptococci in ponds (Bartone et al. 1985). The factors affecting survival of *Salmonella* in the environment are probably similar to those for fecal coliforms (Feachem et al. 1983). *Salmonella typhimurium* declined rapidly when inoculated into plastic pools stocked with *Tilapia aurea* (*Oreochromis aureus*) and fertilized with pig manure (Baker et al. 1983). A 95 percent decline in cell concentration took place in the first six hours; viable *Salmonella* could be isolated at day 16 after inoculation in the fish digestive tract and epithelium, but not at day 32. However, there are few supportive data for a rapid decline of *Salmonella* from natural environments such as waste-fed ponds.

It has proven even more difficult to determine reliable indicator organisms for excreted pathogenic viruses. In a study on the relationship of viruses and indicator bacteria in water and wastewater in Israel, no statistically significant correlation was found between the occurrence of viruses and bacterial indicators. Sixteen isolations of viruses occurred when no fecal coliforms or fecal streptococci were detected. The study raised serious doubts on the validity of the concept of indicator bacteria to predict the virological quality of the water (Marzouk et al. 1980).

Bacteriophages or, more specifically, coliphages (bacterial viruses of coliform bacteria), are also candidates for indicators of excreted viruses. Coliphages are ubiquitous inhabitants of the intestinal tracts of humans and animals and are found wherever there is

fecal contamination. It was demonstrated that *E. coli* bacteriophages provide a satisfactory measure of the viral quality of wastewater (Kott et al. 1974), although this conclusion is not universally accepted. Scarpino (1983) assessed the use of indicator systems for the presence of pathogenic viruses and concluded that a convincing relationship between the numbers and/or types of different indicator bacteria and pathogenic viruses remains to be demonstrated, and that the best indicator of viral presence is the actual detection of the virus. He cautioned that data on the use of bacteriophages as indicators of enteric viruses vary, some showing correlations and some not.

Fecal indicators demonstrate fecal contamination only and may or may not include excreted pathogens; a pathogen indicator is needed rather than a fecal indicator organism. It is also difficult to determine what concentration of fecal indicator organisms indicates the absence of excreted pathogens. It is usually stated, in the absence of concrete data relating concentrations of fecal coliforms to excreted pathogens, that densities should be as low as possible, that is, at least $10^3/100$ ml of effluent and preferably below $10^2/100$ ml of effluent. Effluents used for irrigation of crops that may be consumed raw must have indicator bacterial counts under $10^3/100$ ml effluent (IRCWD 1985) (see Section 7.13). In general, health risks will be so minimal at these indicator-organism densities that further treatment would normally not be economic (Feachem et al. 1983). However, it is not possible to state with certainty that low concentrations of indicator organisms indicate the absence of excreted pathogens in water or aquatic organisms.

7.6 Excreta treatment

It has been shown that sewage usually contains the full range of pathogens found in the community that produced the sewage. For instance, in one study the pathogenic organisms that cause typhoid fever, bacillary and amoebic dysentery, ascariasis, and other protozoan and helminthic diseases were isolated from raw sewage; other studies have shown that all the major enteric viruses can be isolated from raw sewage (WHO 1973). The microbiological quality of wastewater reflects the health of a community since pathogens are usually excreted by both carriers and patients with clinical diseases, some of which are endemic to specific areas (Buras 1979).

The viability of excreted pathogens usually declines exponentially outside the host. There is a rapid decrease in numbers during the first hours or days after excretion, but a small number survive for a longer period (Cross 1985). Exceptions to this principle of pathogen die-off outside the host are a few bacteria which may temporarily multiply outside the host, and trematode worms which have a multiplication phase in intermediate hosts.

The current wisdom on excreta treatment processes is that temperature and time are the two most important parameters in pathogen attenuation (Feachem et al. 1983). To obtain an almost pathogen-free product, treatment needs to incorporate a long detention time (ponds, protracted digestion, drying) and heat (thermophilic digestion, thermophilic composting). It is beyond the scope of this review to consider all the public health aspects

of the various waste treatment processes (see Feachem et al. 1983, for an exhaustive review), but it is appropriate to consider two that are relevant for aquaculture: stabilization ponds and thermophilic composting.

Waste stabilization ponds are the most economically efficient method of excreta treatment where land is available at relatively low cost (Mara 1976, Arthur 1983), and their principal advantage in warm climates is the ability to achieve significantly lower survival rates of excreted pathogens than other methods of treatment. Pond systems can be designed to eliminate all excreted pathogens, but this is not usually done because the added benefits of attaining zero rather than very low pathogen survival are not worth the added cost (Feachem et al. 1983).

High fecal indicator bacteria removal rates, 99.99 percent or more, have been reported for series of three or more ponds. The key factor in the die-off of fecal coliforms in maturation ponds is probably the high pH; high oxygen concentrations alone do not seem to enhance die-off. However, fecal coliform die-off is complex and also includes protozoan grazing. Furthermore, the lethal effect of elevated pH is accentuated at higher temperatures, as occur in tropical ponds (Pearson and Konig 1986). Complete removal of *Salmonella* and other enteropathogenic bacteria can be achieved by pond systems with long retention times, 30-40 days, especially at temperatures above 25°C. A system with five to seven ponds, each with a retention time of five days[1] can produce an effluent safe for unrestricted irrigation (fewer than 10^3 fecal coliforms/100 ml). However, a well-designed pond system with a minimum of three cells and a minimum total retention time of 20 days will produce an effluent with only small concentrations of excreted bacteria and viruses (Fig. 7.8).
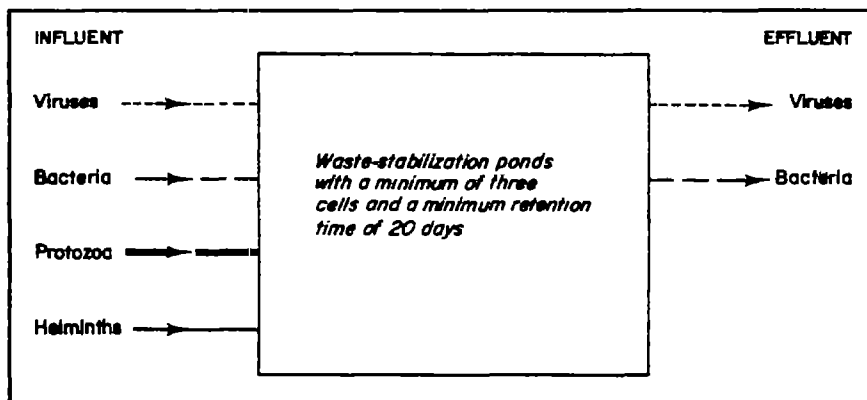
Figure 7.8 Pathogen flow through a waste stabilization pond system (*Source:* Feachem et al. 1983)

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1. It is known, from both theoretical considerations and field experience, that series of ponds perform better in removing excreted bacteria than a single pond with the same overall retention time.

There is much evidence that enteric viruses are much more resistant to various sewage treatment methods than either coliforms or enteropathogenic bacteria (Melnick et al. 1978, Melnick and Gerba 1980). Furthermore, rates of inactivation vary widely among different types of virus and also among different strains of a single type of virus. The absence of isolation techniques for certain viruses, for instance, hepatitis A virus, has precluded direct study on inactivation of the virus in sewage treatment (Feachem et al. 1983). However, Buras et al. (1985) suggested that the presence of viruses in excreta-fed ponds should be given serious attention because of their low infective dose.

Lund (1978b) reviewed factors influencing the persistence of viruses in the environment with special reference to the tropics and pointed out that natural inactivation processes in water are complex and poorly understood. Temperature, pH, ultraviolet light, adsorption to and sedimentation with suspended matter, and a number of biological processes connected with other organisms may all be involved. The higher temperatures in the tropics than in temperate latitudes lead to a higher rate of thermal inactivation, and virus inactivation might proceed in heavily polluted water at 1 log unit in 5 and 1 day at 32°C and 35°C, respectively (Lund 1978b). Enteric viruses are also stable at acid pH, since they are not destroyed by stomach acidity (Lund 1978b), so they might be expected to be adversely influenced by the elevated pH (Lund 1973, Melnick et al. 1978) found in excreta-fed ponds. However, some viruses may not be affected by high pH (N. Buras, personal communication); in fact, a recently devised method to concentrate viruses involves using a pH of 9-11. Over 99 percent of added poliovirus were removed within 5 days from model outdoor ponds in summer in Texas, whereas the same degree of removal required 15 and 25 days in spring and winter, respectively (Funderberg et al. 1978).

According to Feachem et al., (1983), there are scant systematically compiled data on virus removal in waste stabilization ponds in warm climates or in developing countries. Reported removal rates vary widely, probably due in part to poor pond design and short-circuiting of sewage flow across the ponds, and improper experimental techniques. Elevated pond temperatures, and elevated pH in particular, have been implicated in virucidal activity. A pond system with an overall retention time of 30 days in the tropics should achieve a reduction of excreted viruses of not less than six log units (99.9999 percent) (Feachem et al. 1983).

Conventional wisdom is that a well-managed waste stabilization pond system with at least three cells and at least 20 days' retention time produces an effluent which has no protozoan cysts or helminth eggs (Feachem et al. 1983). However, while most parasites are heavy and usually settle to the bottom of the pond, small protozoan parasites like *Cryptosporidium parvum* and *Giardia lamblia* float on the surface of the water and pass from one pond to the next (N. Buras, personal communication) unless connections between ponds are submerged.

Schistosome eggs, miracidia, and cercariae should be completely removed in a series of waste stabilization ponds. Eggs entering a pond system may die because hatching is inhibited, though not prevented, in anaerobic ponds. However, if they hatch they will not be carried through to the effluent; the miracidia may live up to three days, but

they are probably unable to penetrate a snail after a few hours. The miracidia may penetrate snails if an appropriate species is present in the ponds. Cercariae will be released by snails, but in a well-designed pond system with an overall detention time of 15 days or more, it is unlikely that they would reach the outfall and penetrate a human host within 24 hours. However, persons entering the water in the ponds would be at risk (Feachem et al. 1983).

A well-designed aerobic compost system can produce an almost pathogen-free compost that can be reused in aquaculture (Polprasert 1984, Polprasert et al. 1982) (Fig. 7.9). Pathogen survival depends on the time-temperature combinations of various parts of the pile, as indicated in the death curves for pathogens (Fig. 7.10: Lines represent conservative upper boundaries for pathogen death, that is, estimates of time-temperature combinations required for pathogen inactivation). Treatment with time and temperature falling within the "safety zone" should be lethal to all excreted pathogens, except possibly hepatitis A virus at short retention times. Time and temperature requirements are at least one hour at $\geq 62°C$, one day at $\geq 50°C$, and one week at $\geq 46°C$. Total destruction of a pathogen is represented by the time-temperature points above its curve. Complete pathogen destruction should be guaranteed if all parts of the compost pile can be brought to time-temperature combinations within the safety zone. Spore-forming bacteria, for instance, Clostridium perfringens, are more resistant but present little risk. Hepatitis A virus appears able to survive temperatures around 60°C for several hours (Feachem et al. 1983).
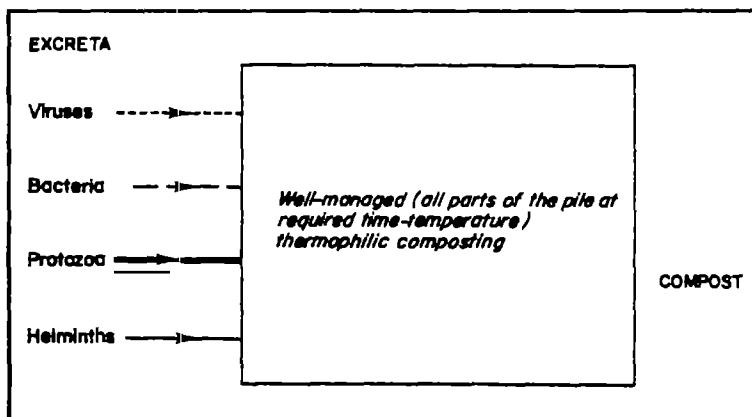
Figure 7.9 Pathogen flow through a well-managed thermophilic composting process. (Source: Feachem et al. 1983)
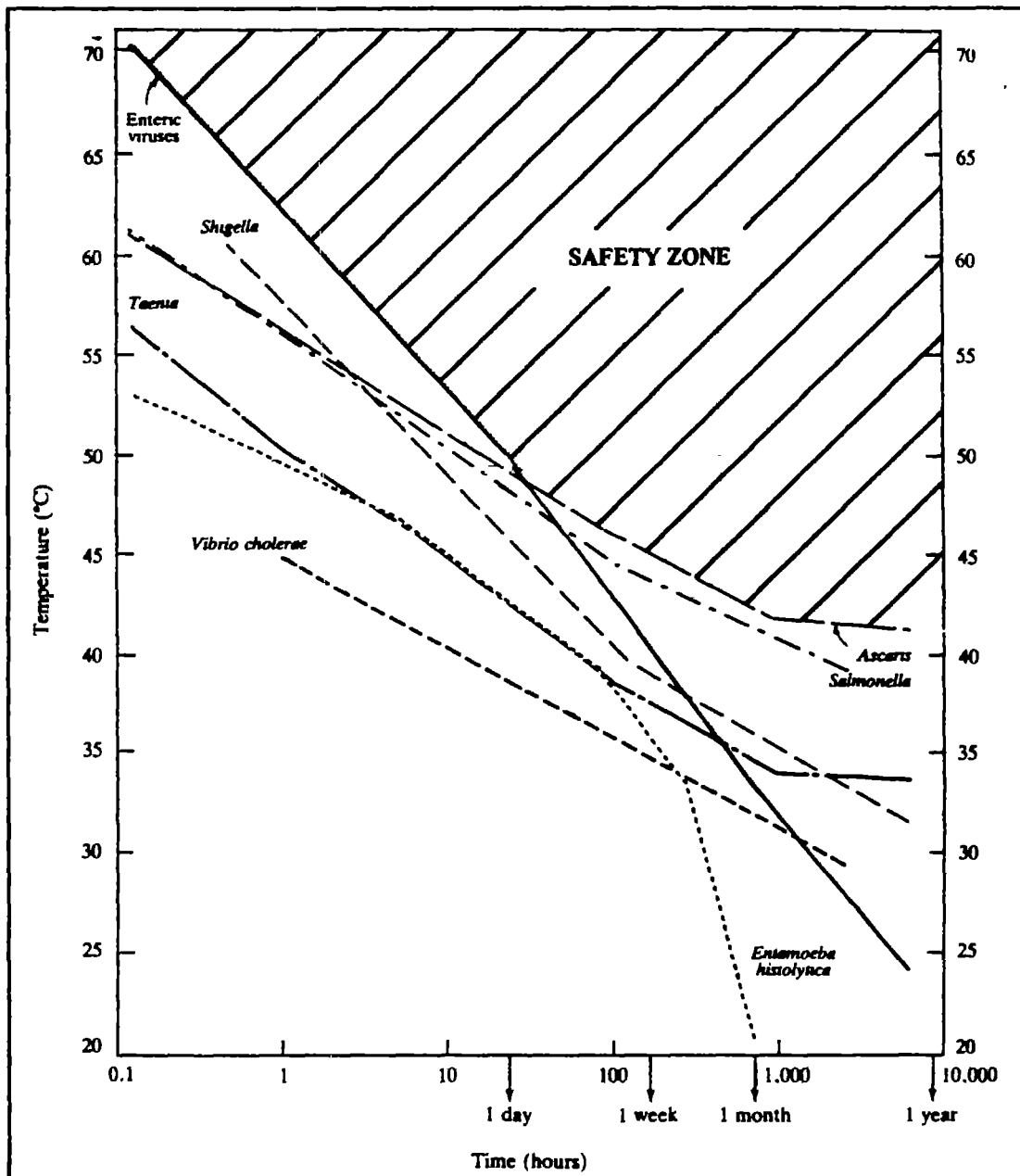
Figure 7.10 Influence of time and temperature on selected pathogens in night soil and sludge (*Source:* Feachem et al. 1983)

7.7 Fish and excreted bacteria and viruses

There is a considerable amount of data on the microbiology of fish, either raised in excreta-fed systems or inoculated with fecal microorganisms. Most of the data were collected during a relatively small number of excreta reuse projects of which outlines

are presented below. In addition, specific *E. coli* serotypes pathogenic for humans and animals were fed to trout by Glantz and Krantz (1965). Bacterial suspensions were mixed with powdered fish food and formed into small pellets, and bacterial suspensions were also dripped into the tank containing the fish. The trout showed no signs of illness but the *E. coli* serotypes were able to survive in the fish digestive tract. Neither fecal coliforms nor salmonellae were isolated from sterilely prepared 50-g fillets of *Oreochromis mossambicus* raised in six ponds which received mainly domestic sewage from a treatment plant in Pretoria (Nupen 1983). Mirror carp (*Cyprinus carpio*), tilapia (*Oreochromis mossambicus*) and silver carp (*Hypophthalmichthys molitrix*) were raised in three 50-m^2 cement tanks filled with humus-tank effluent (HTE), the effluent of a biological filter followed by a settling tank at the Pretoria Municipal sewage treatment plant. The HTE was matured for four weeks before stocking the fish, which were fed pelleted feed (Sandbank and Nupen 1984). No fecal coliforms or salmonellae were ever isolated from sterilely prepared fish fillets. Also, according to Nupen (1984), fish (four carp, four tilapia, and two catfish) which had been growing for several years in a series of sewage maturation ponds at Kimberley, South Africa, had no microbiological contamination of muscle tissue. Concentration of total and fecal coliforms were monitored in ponds enriched with either sewage stabilization pond effluent or livestock manure on kibbutzes in Israel (Guttman-Bass et al. 1986). The use of stabilization pond effluent did not consistently increase the levels of indicator bacteria compared to livestock-manured ponds.

7.7.1 Quail Creek

In a study of the Quail Creek sewage stabilization pond system in Oklahoma, 179 fish samples were collected on 12 different dates over a seven month period and were carefully dissected. Samples of skin, upper intestine, cloaca, and muscle tissue were cultured separately. However, after the first two collections, skin was combined with muscle, and all viscera were pooled. Water samples from the ponds were examined for total and fecal coliforms and fecal streptococci, but fish samples were examined only for pathogenic enteric bacteria and viruses. Pathogens were absent from water beyond the first two conventional ponds, water from ponds containing test fish, and from all the fish sampled (Carpenter et al. 1974).

7.7.2 Benton

Flesh of fish raised in the Benton sewage stabilization pond system in Arkansas was monitored quarterly for pathogenic bacteria (*Salmonella/Shigella, Staphylococcus, Edwardsiella* and *Clostridium*). All samples were either below standard detection limits or negative, with the exception of *Staphylococcus* (Henderson 1979). Viruses and pathogenic bacteria were monitored in both water and fish flesh, but no contaminant was ever found in fish flesh that would prevent its being consumed under prevailing United States Food and Drug Administration (USFDA) guidelines (Henderson 1982).

More comprehensive data on the Benton pond system were given by Hejkel et al. (1983). The six ponds, ranging in size from 1.55 ha to 1.83 ha, were loaded at 444 kg BOD$_5$/day with an average flow rate and total detention time for the serially operated ponds

of 1,711 m³/day and 72 days, respectively. Ponds 1 and 2 were for waste treatment only, and ponds 3 to 6 were stocked with silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*). Relatively high concentrations of between 10^2 and 10^4 fecal coliforms and fecal streptococci/100 g were isolated from the digestive tract and skin of the fish. Initially, samples for detecting bacterial concentrations in fish muscle tissue were taken with a normal filet procedure using a decontaminated knife. Sporadically high concentrations, up to 2.2 x 10^4 MPN/100 g, were obtained, presumably because of contamination of muscle by bacteria from fish skin. However, fecal coliform and fecal streptococci concentrations from fish muscle sampled aseptically ranged from <6.6 to <11, and <11 to 25/g, respectively. *Salmonella* was not isolated from any fish samples, nor were enteric viruses, but only extremely low levels were present in the influent. The fish raised in the sewage stabilization ponds were considered to be suitable for human consumption if proper precautions were taken in harvesting and processing the fish.

7.7.3 Haifa

Microbiological examinations were made of fish raised in experimental ponds which received treated domestic wastewater (extended aeration effluent) in Israel (Buras et al. 1987). Preliminary data showed the interdependence between the bacteriological quality of the water and the concentration of bacteria in various organs of fish (Buras 1977, 1979).

Healthy common carp (*Cyprinus carpio*) grown in unpolluted water did not harbor bacteria in the muscles. Small numbers of bacteria were detected in the kidneys and spleen and were present in the digestive tract in concentrations of 10^6/g. Small numbers were detected in the blood, kidneys and spleen and were present in the digestive tract in concentrations of 5.0 x 10^4/g in blue tilapia (*Oreochromis aureus*) (Buras et al. 1987).

A steady increase in the number of bacteria in fish muscles and organs was observed during an experiment in which the fish were raised in water containing 10^7 bacteria/ml (10^6 coliform bactera/100 ml). Concentrations ranged from 10^5 to 10^8/g of muscles and organs at the end of the growing season. Human enteric viruses were also recovered from kidneys of common carp.

Fish were also reared in ponds with various water qualities. There was a relationship between the bacteriological quality of the water and the number of bacteria recovered from the tissues and organs of fish reared in the water. High numbers of bacteria (standard plate count) were recovered from tissues and organs of fish when the concentration of bactera was as high as 10^6-10^7/ml in the water. Special emphasis was initially placed on the recovery of coliform and fecal coliform bacteria because they are widely used as bacterial indicators and were always present in pond water. However, they were not always recovered from fish organs and were very rarely recovered from fish muscle tissue. It was suggested that they were not performing their role as indicator organisms.

When the concentration of bacteria in the water was low, bacteria were never recovered from muscle tissue, although they were isolated in small numbers from the kidney, spleen and liver. Bacteria were recovered from muscle tissue only when the number of bacteria in all the fish organs reached high concentrations. The concentration of bacteria (standard plate count, not coliforms or fecal coliforms) in pond water, 1.0×10^4/ml, beyond which bacteria were detected in muscle tissues was named the threshold concentration (Buras et al. 1985, 1987). The concentration of bacteria in pond water that caused the appearance of bactera in the muscles, 5.0×10^4/ml, was called the critical concentration (Buras et al. 1987). Confirmatory evidence was obtained during one experiment in which fluctuations occurred in the quality of the extended-aeration effluent added to the ponds due to difficulties in the operation of the sewage treatment plant. The fluctuations occurred over a six month period with two peaks of decreased water quality in the experimental ponds, when bacteria were detected in muscle tissue with time lags of two weeks and about five weeks for the various organs and muscles, respectively.

Blue tilapia (*Oreochromis aureus*) and common carp (*Cyprinus carpio*) were inoculated with bacteria and viruses present in wastewater (Buras et al. 1985). The test microorganisms were inoculated directly into the esophagus of the fish in concentrations ranging from 10^2-10^7 in 0.1 ml of medium, after which inoculated organisms were detected from fish muscle and organs. The inoculated microorganisms were ingested within a short time and were detected in the blood, spleen, liver, and kidneys, and also in the muscles if the concentration of the inoculum were high enough. Large numbers of inoculated microorganisms were always recovered from the digestive tract, because of the high concentration of phagocytic cells in the gut wall which constitutes the first line of defense against microorganisms (Buras et al. 1985).

These laboratory experiments demonstrated a pattern of penetration of microorganisms into the organs and tissues of fish and led to the development of the concept of the threshold value. The threshold concentration varied for different microorganisms, 10^2 and 10^3/fish for bacteriophages T2 and T4, respectively, and 10^6 and 10^4/fish for *Escherichia coli* and *Salmonella montevideo*, respectively. Experiments performed with Polio 1 LSc virus suggested a very low threshold.

Repeated inoculation of blue tilapia for 23 consecutive days with a bacteriophage T2 at a concentration of 10^4/fish, above the threshold value, showed that the threshold value did not change. Nor was the threshold value influenced by the simultaneous inoculation of two microorganisms. There were only small differences in threshold values for different microorganisms for blue tilapia and common carp (Buras et al. 1985).

Fish were also exposed to a range of concentrations of microorganisms in aquaria. Both bacteria and bacteriophages penetrated into the fish and were recovered from various tissues and organs, including muscle. The concentration necessary for the microorganisms to reach muscle was lower when they were inoculated into the esophagus than when present in water in the aquaria (Buras et al. 1985).

The threshold value represents the limits of the natural defense mechanisms of the fish, the nonspecific cellular immunity, or reticuloendothelial system, above which pathogenic microorganisms are not destroyed but penetrate into muscle tissue (Buras et al. 1985 1987). Microorganisms that pass through the gut wall enter the blood and lymph streams. Phagocytic activity takes place in lymphatic organs and also in the spleen, liver, and kidneys. Microorganisms that escape being phagocytized eventually penetrate into the muscle tissue. It was suggested that the threshold value can be considered a satisfactory criterion for the design and management of excreta-fed ponds (Buras et al. 1985). It was also proposed that the presence of bacteria in muscle tissue of fish might be used to assess the bacteriological quality of fish (see Section 7.13).

7.7.4 Asian Institute of Technology

Considerable public health data have been collected at the Asian Institute of Technology (AIT) from experimental septage-fed ponds. In the first experiment run in a series of 200 m^2 earth ponds, an attempt was made to demonstrate a relationship between fish stocking density and yield before the relationship between organic loading and fish growth was understood because of project time constraints. The ponds were underloaded during the first part of the experiment because of concern about overloading (which may have stressed or killed the fish), but during the second part of the experiment most ponds were loaded at 100 kg COD/ha/day. Despite high concentrations of bacteria in the septage, concentrations of bacteria in pond water were two to three log units lower. Bacterial concentrations in the water in septage-loaded ponds were similar to control ponds which did not receive septage (ponds were filled with canal water which may have received some fecal contamination), irrespective of fish stocking density or sampling date. Bacteriophage densities in pond water were three to four log units lower than concentrations in septage, although concentrations in septage-loaded ponds tended to be slightly higher than those in the control (Polprasert et al. 1982). Polprasert et al. (1984) concluded from a parallel series of analyses taken during the same experiment discussed above that densities of coliform bacteria and bacteriophages in the pond water tended to increase with an increase in both septage loading and loading period. However, the data presented in the form of ranges without statistical analysis are not convincing and have not been confirmed.

The earlier conclusion (Polprasert et al. 1982) that excreted bacteria and bacteriophages do not increase with either an increase in the organic loading rate or time was confirmed from data collected during an additional three experiments in septage-loaded ponds (Edwards et al. 1984). The septage loaded into the ponds had high mean concentrations of microorganisms: 4.4 x 10^6 total bacteria/ml, 4.4 x 10^6 MPN total coliforms/100 ml, 3.0 x 10^6 MPN fecal coliforms/100 ml, and 1.6 x 10^6 MPN bacteriophage/100 ml. In addition, nine *Salmonella* serotypes and eggs of six species of helminths (*Ascaris, Hymenalepis diminuta*, hookworm, *Opisthorchis, Taenia*, and whipworm) were isolated from septage.

There was no evidence of a buildup in the concentration of excreted microorganisms in pond water with either an increase in organic loading or time (Fig. 7.11). Rather, the data indicated a rapid attenuation of microorganisms in the pond
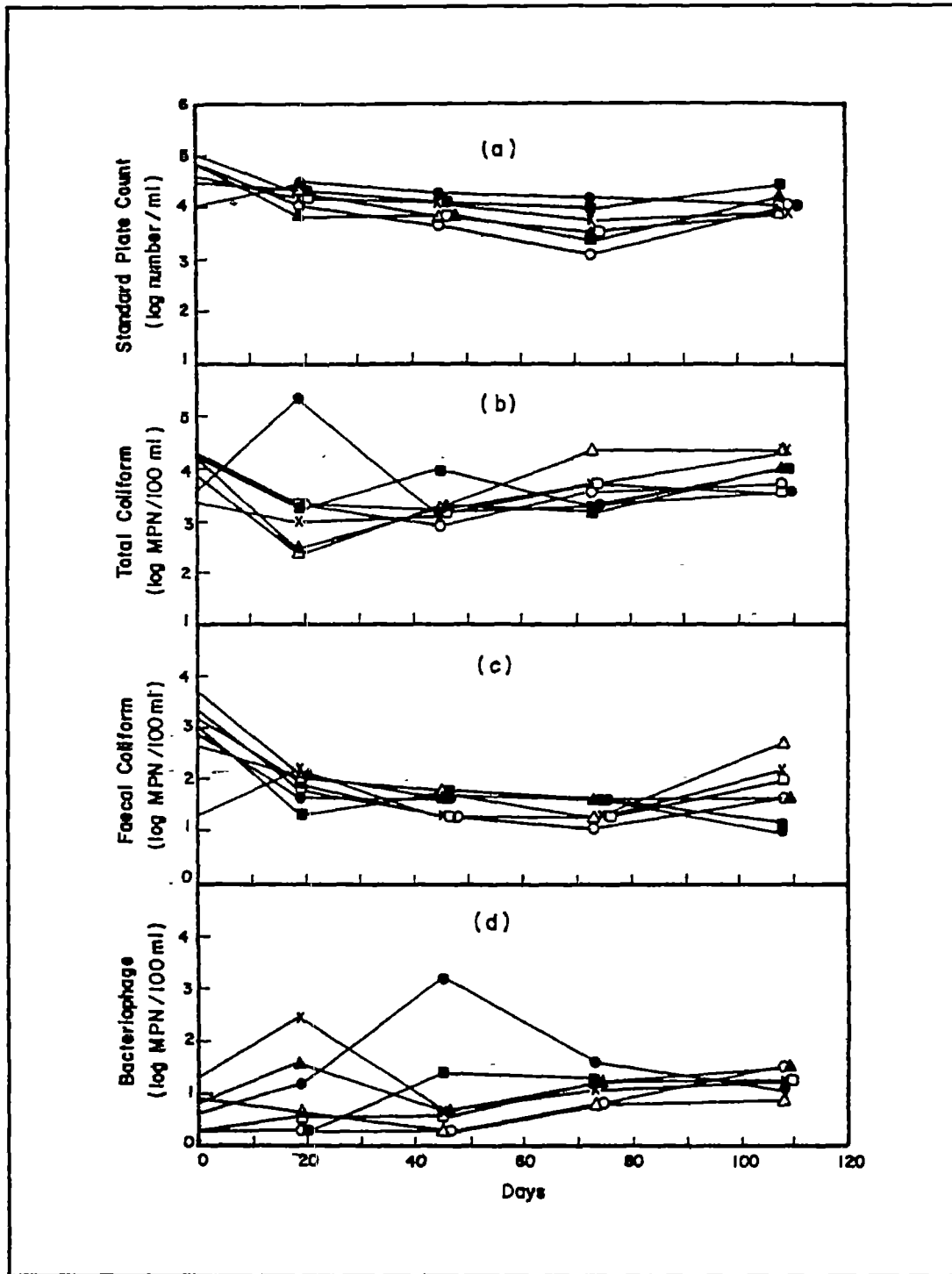
Figure 7.11 Bacteria and bacteriophage densities in water in the septage-fed pond system ([a] standard plate count, [b] total coliform, [c] fecal coliform, [d] bacteriophage; *Source:* Edwards et al. 1984)

water. Concentrations of total bacteria (standard plate count), total coliforms, fecal coliforms, and bacteriophages in the control pond (which received no septage) were usually lower than in septage-loaded ponds, but not always. Concentrations of total bacteria and total coliforms were the highest, around 10^4/ml and 10^4 MPN/100 ml, respectively, with concentrations of fecal coliforms and bacteriophages in pond water usually less than 10^2 MPN/100 ml. *Salmonella* was recovered in some pond water samples, including the control in one experiment. Birds taking fish from the pond may have been a source of *Salmonella* contamination.

After septage was added to pond water, concentrations of fecal coliforms and bacteriophages were measured at three hour intervals to determine the rate of attenuation. There was an initial reduction in concentration of two orders of magnitude (99 percent) because of septage dilution on loading: a maximum volume of 200 l of septage was loaded into the 200 m^2 x 1 m deep ponds every three days (Fig. 7.12). Fecal coliform concentrations fell rapidly to their baseline of below 10^2 MPN/100 ml within 24 hours. Bacteriophage concentrations also decreased rapidly to below 10^2 MPN/100 ml within 24 hours and continued to decline slowly for the next 24 hours. There was a regrowth of fecal coliforms during darkness on the first day. Substantial regrowth of fecal coliforms is possible in organically polluted waters, but this growth phase gives way to a progressive die-off (Feachem et al. 1983). Helminth eggs were not recovered from pond water.

The same die-off pattern of fecal coliforms and bacteriophages was also demonstrated for three 1,740 m2 septage-loaded ponds (Edwards et al. 1987). The rapid rate of attenuation of both fecal bacterial and viral indicator organisms in septage-fed ponds optimally loaded for fish culture was considerably higher than that reported for waste stabilization ponds (Shuval et al. 1986) (Fig. 7.13). Such rapid die-off rates may have been caused by maximum daily pH values of about 10 and maximum dissolved oxygen concentrations of double saturation, although high water temperatures, around 30°C, undoubtedly accelerated the process.

Fish were sampled just before harvest and total bacteria, total coliforms, fecal coliforms, and bacteriopahge concentrations were determined in various tissues and organs. Gills and digestive tract had very high, and liver had moderately high, concentrations of bacteria and bacteriophages. Most concentrations of microorganisms in the digestive tract were higher than in pond water. There were no microorganisms in blood, bile, and muscle in three experiments, with the exception of very low concentrations, 5-50 total bacteria per gram of muscle, in some samples in Experiment 1 and including the control pond with no septage load. No fecal coliforms or bacteriophages, indicator organisms for bacteria and viruses, respectively, were found in tissues or organs of fish. *Salmonella* presence was assessed in gill, digestive tract, liver and spleen, but all samples were negative with the exception of 2 out of 10 digestive tract samples in one experiment.

The infection of Nile tilapia (*Oreochromis niloticus*) was studied in aquaria with Salmonella typhimurium at concentrations of 3 x 10^4, 3 x 10^5 and 3 x 10^6 cells/ml of aquarium water at the Asian Institute of Technology (Edwards et al. 1987). Fish tissues and organs were examined for active *Salmonella* at weekly intervals. The digestive tract
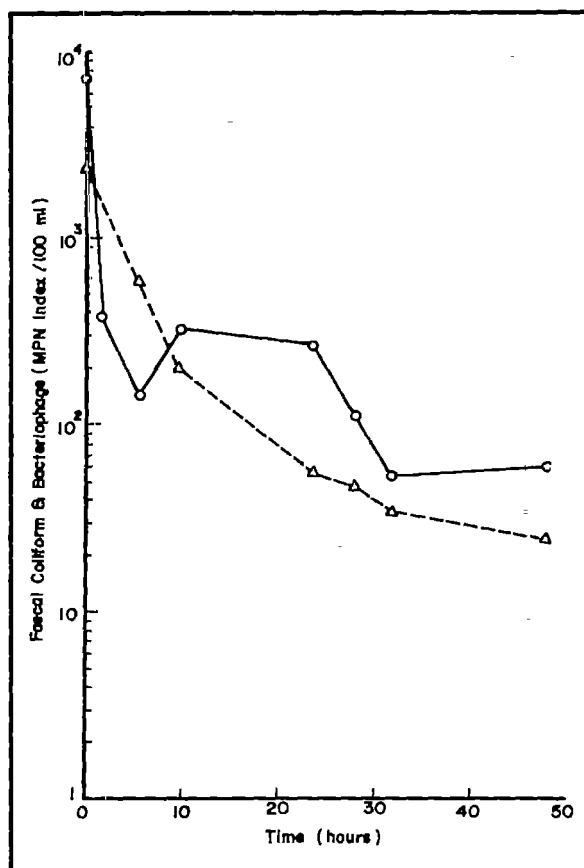
Figure 7.12 Rates of fecal coliform
(solid line) and bacteriophage (broken
line) die-off in septage-loaded ponds
(*Source:* Edwards et al. 1984)

was the most susceptible organ to infection, with infections to a lesser degree in spleen, liver, muscle, bile and blood. Muscle was infected after 14 days of exposure at a level of 3 x 10^5 cells/ml of aquarium water, which supports the hypothesis of threshold concentration proposed by Buras et al. (1985 1987).

7.7.5 Lima

Microbiological studies were carried out on Nile tilapia (*Oreochromis niloticus*) and common carp (*Cyprinus carpio*) sampled on 15 and 1 occasions, respectively, from the San Juan sewage stabilization ponds in Lima, Peru (Noe Moccetti et al. 1984). There was a decrease in both total coliforms and fecal coliforms with an increase in the level of wastewater treatment, as indicated by bacterial concentrations in the water of tertiary and pentary ponds. Mean total coliforms in the water of tertiary and pentary ponds were 3.15 x 10^5 and 4.39 x 10^3 MPN/100 ml, respectively. Mean fecal coliforms in the water of tertiary and pentary ponds were 1.67 x 10^4 and 1.58 x 10^2 MPN/100 ml,
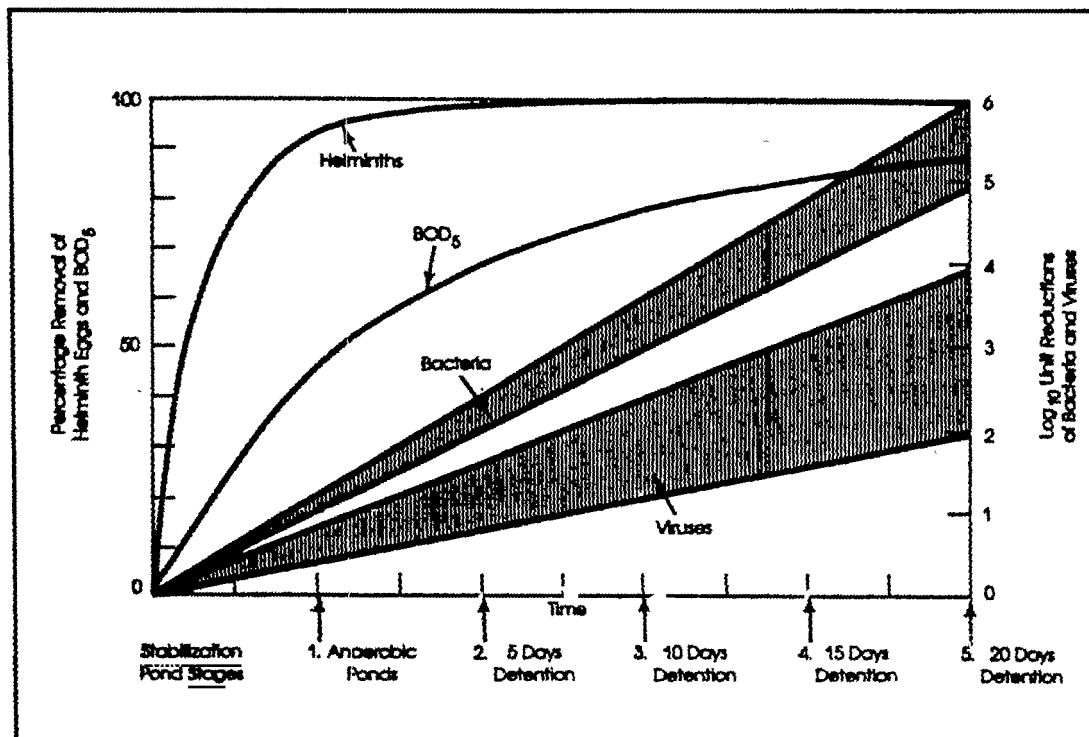
Figure 7.13 Generalized removal curves for BOD, helminth eggs, excreted bacteria, and viruses in waste stabilization ponds at temperatures above 20°C (*Source:* Shuval et al. 1986)

respectively. A comparison was made of the total and fecal coliforms in the water and in the digestive-tract contents of tilapia raised in the tertiary and pentary ponds. Four out of five total coliform samples and all five samples of fecal coliforms were greater in the digestive tract contents of tilapia than in pond water. The mean total and fecal coliforms in the digestive tract of fish from a tertiary pond were 6.6×10^6 and 3.68×10^5 MPN/100 ml, respectively. Fecal coliforms in the digestive tract of fish from a pentary pond were a mean of 2.35×10^4 MPN/100 ml. However, total coliforms were zero in fish muscle for all samples from tertiary and pentary pond waters with the exception of one sample from a pentary pond with a concentration of 5×10 MPN/100 ml.

Specific enteric bacteria isolated from the digestive tract of tilapia and common carp were *Enterobacter cloacae, Escherichia coli, Citrobacter freundii, Klebsiella* sp., *Proteus vulgaris, Salmonella* sp., and *Streptococcus faecalis*. Significant numbers of standard plate count were obtained from muscle tissue of tilapia cultivated in the sewage stabilization ponds. Ranges of standard plate counts on three occasions from a tertiary pond were 1.37×10 to $3.87 \times 10^2/g$ on nutrient agar, $0.0-1.87/g$ on MacConkey, and 6.25 to $1.9 \times 10/g$ on mFC. Standard plate counts were even higher on the single occasion they were measured in tilapia muscle tissue from a pentary pond: $4.59 \times 10/g$ on nutrient agar, $3.13 \times 10^2/g$ on MacConkey and $4.91 \times 10^2/g$ on mFC. All samples of gills, digestive tract, and muscle tissue were negative for protozoan cysts and helminths, although protozoan cysts (*Entamoeba, Giardia, Endolimax*) and helminth eggs (*Ascaris, Trichuris,*

Toxocara and *Taenia*) were isolated from pond sediments of primary ponds and amoeba cysts from sediments of pentary ponds. The fish were considered safe for human consumption because they conformed to recommended microbiological limits for freshwater fish (ICMSF 1974).

7.7.6 *Salmonella*

Considerable attention has been given the pathogenic bacterium *Salmonella* in excreta-fed aquaculture, although Feachem et al. (1983) consider that a great deal more research is still required on the uptake and elimination of *Salmonella* by fish grown on sewage.

Six *Tilapia melanopleura* (*T. rendalli*) and six *T. mossambica* (*Oreochromis mossambicus*) were netted from pond 2 in a maturation pond series near Durban, South Africa, when a certain amount of settled sewage was allowed to bypass the treatment plant to be fed directly into pond 1. The *E. coli* counts in the effluent leaving pond 1 for pond 2 were 4.0 x 10^3 to 1.2 x 10^4/ml. Direct gram stains performed on fish flesh indicated the presence of gram-negative bacteria but no significantly pathogenic organisms (Mackenzie and Campbell 1963). The authors concluded that the fish were safe for human consumption when cooked properly, and perhaps even raw or partly cooked. The fish were at one time netted weekly and distributed to the poor and needy (Mackenzie and Livingstone 1968).

As a result of a series of cultures performed on tilapia from the maturation ponds using a new method of recovering *Salmonella*, a number of serotypes of *Salmonella* were isolated from the muscle of tilapia raised in the sewage maturation ponds, and the distribution of fish to the poor was officially stopped. Netting of fish was still maintained to curtail overstocking, but the netted fish were usually destroyed. However, no epidemics of food poisoning were known to have occurred when waste-grown tilapia were distributed to the poor. Furthermore, no isolated cases were directly attributable to the consumption of these fish, despite individual consumer follow-up. However, there was a certain amount of circumstantial evidence that a pelican at the Durban Aquarium, the diet of which consisted entirely of the sewage maturation-pond tilapia, died of salmonellosis.

Heuschmann-Brunner (1974) also reported infection of fish muscle with *Salmonella*. She demonstrated infection of the freshwater fish tench (*Tinca tinca*) and common carp (*Cyprinus carpio*) with *Salmonella enteritidis* and *S. typhimurium* by holding them in heavily contaminated water or feeding them bacteria orally. *Salmonella* was found most regularly and for the longest time in the digestive tract, but they rapidly spread along blood and lymph vessels throughout the body including the muscle tissue, where they were found the least.

More recent studies have not reported the presence of *Salmonella* in fish muscle. Lawton and Morse (1980) demonstrated experimentally that *Salmonella* are capable of infecting fish in aquaria stocked with goldfish (*Carassius auratus*). All 32 strains (12 serotypes) were capable of infecting the digestive tract when inoculated into the water.

Al-Wakeel et al. (1982) stocked *Tilapia nilotica* (*Oreochromis niloticus*) in aquaria seeded with *Salmonella typhimurium* at 5.0 x 10^5 and 10^6 organisms/ml. The bacterial concentration on both slime and skin of live fish was correlated to total bacterial count in water, but no bacteria were detected in fish muscle. *Salmonella* was inoculated at 1,375 cells/ml muscle. Lawton and Morse (1980) demonstrated experimentally that *Salmonella* are capable of infecting fish in aquaria stocked with goldfish (*Carassius auratus*). All 32 strains (12 serotypes) were capable of infecting the digestive tract when inoculated into the water. *Salmonella* was inoculated at 1,375 cells/ml of pool water into plastic pools stocked with *Tilapia aurea* (*Oreochromis aureus*) and fertilized with pig manure (Baker et al. 1983). *Salmonella* was isolated from fish intestine but from only one of 24 samples of muscle, which was suspected to be due to experimental error. Nor was *Salmonella* reported from muscle in three major studies involving raising fish in excreta-reuse pond systems. No *Salmonella* was isolated from any fish samples from the sewage stabilization pond system at Benton, Arkansas (Hejkal et al. 1983). *Salmonella* was isolated in only two samples of digestive tract from numerous samples of tissue and organs from fish raised in septage-fed ponds at the Asian Institute of Technology (Edwards et al. 1984). *Salmonella* was isolated from some digestive tract samples of fish raised in a sewage stabilization pond system in Lima, but Buras et al. (1987) did not detect *Salmonella* in any of the fish examined from experimental ponds fed with the effluent of an extended aeration plant, even when fish had high concentrations of total bacteria in musculature.

A die-off pattern of *Salmonella* was discerned in three 1,740 m² septage-loaded ponds at the Asian Institute of Technology (Edwards et al. 1987). *Salmonella* was assayed from water samples collected in the ponds before, immediately after, and at 3, 6, 9, 12, 24, 48, and 72 hours after loading. Concentrations were low and fluctuated in the three ponds, with the highest concentration only 0.5 MPN/100 ml in one pond three hours after loading. However, the largest concentrations were found in the first three hours after loading, with a decline thereafter. No *Salmonella* were recovered at 72 hours.

The relationship between incidence of enteric disease and wastewater utilization in agriculture was studied in 79 kibbutzes in Israel (Fattal 1983). Ten kibbutzes (population 5,005) used wastewater effluent to feed ponds. No excess in crude rates of viral hepatitis was found in kibbutzes using wastewater effluents for aquaculture compared to noneffluent-using kibbutzes, but a significant (p <0.01) excess of salmonellosis was found in kibbutzes using effluent as feed-water for ponds. In a later epidemiological comparison of the enteric disease rates of three kibbutzes which used treated wastewater as a pond input and two kibbutzwa which used cow and chicken manure as pond inputs, there was no difference in eight enteric disease rates in any age group (Guttman-Bass et al. 1986). Two ponds were studied in detail in the same study. *Salmonella* was not isolated from either fish tissue or pond water in the wastewater-fed pond. However, *Salmonella* was isolated from both the intestinal tract contents of fish and water in the pond fertilized with livestock manure, which suggests that the latter may have been the source (Guttman-Bass et al. 1986).

In conclusion, there are several reports of *Salmonella* in fish digestive-tract contents, although it is by no means routinely isolated from the digestive tract. There

appears to be only a single case of the isolation of *Salmonella* from the muscles of fish raised in an excreta-reuse system (Mackenzie and Livingstone 1968). Although *Salmonella* was not isolated from fish muscle in several major excreta-reuse projects, the conclusion of Feachem et al. (1983), that more research is required on *Salmonella* uptake and elimination by fish grown on sewage, is emphasized. Mackenzie and Livingstone (1968) proposed a tentative working standard for raw foods that are to be cooked of no salmonellae somewhere in the range of a 5-50 g sample.

7.7.7 Poliovirus

Although routine analysis for enteric pathogenic viruses is not yet feasible (see Section 7.5), there is a report of the isolation of poliovirus at a low concentration from a pond enriched with sewage stabilization pond effluent on a kibbutz in Israel (Guttman-Bass et al. 1986). The isolate was not tested for virulence, but the presence of the virus in wastewater from a population in which young children receive oral poliovirus vaccine is not unexpected.

7.8 Depuration of fish

Shellfish are commonly held in clean water prior to marketing to remove excreted organisms, a process known as depuration. It is also generally believed that depuration is effective in excreta-fed aquaculture systems. Fish must be kept in clean water for a month, or at least two to three weeks, prior to harvest by stopping the introduction of sewage into ponds (Donaszy 1974). Depuration of fish in clean-water ponds for several weeks at the end of the growing season removes any residual objectionable odors and pathogens and provides fish acceptable for market (Schroeder and Hepher 1979). Depuration is the primary precautionary measure against transmission of excreted pathogens in waste-fed aquaculture (Allen and Hepher 1979). Fish can be flushed out in clean water before marketing (Hepher and Schroeder 1977). Arthur (1983) recommended depuration of fish in a washing pond for about 14 days prior to sale. According to Feachem et al. (1983), depuration of fish in clean water for several weeks prior to harvest can be used for pathogen control in excreta-fed aquaculture.

However, there is a surprising lack of data on both depuration in practice and on experimental evidence to support such firm recommendations. The taste of common carp (*Cyprinus carpio*) raised in the Munich sewage-fed ponds was reported to be good if the fish were kept in clean water for a few weeks (Scheuring 1939, cited by Mortimer and Hickling 1954). According to Hepher and Schroeder (1977), fish cultured in wastewater-fed ponds in Israel tasted good if kept in clean water for some time. Fish raised in night-soil-fed ponds in Java were reported to be held in clean running-water ponds for two or three days before sale or consumption (Djajadiredja et al. 1979; Kuhlthau 1979). Night-soil loading ceased on one night-soil-fed fish farm one month prior to fish harvest, but no special measures were taken before fish harvest on a second farm in Malaysia (Seow et al. 1979). Zhou (1986) reported that one fish farm in China did not discharge sewage into ponds for 10-15 days before fish harvest, but another farm was criticized by consumers

because fish were once marketed from ponds which had been fed with sewage on the previous day.

Guelin (1962) experimentally contaminated a marine fish (*Ctenolabrus rupestris*) with *E. coli* and coliphage and then placed the fish in clean water for observation. Bacteria and bacteriophages were isolated from the viscera of the fish five hours after contamination, but by the seventh day *E. coli* disappeared and bacteriophages disappeared between the eighth and twelfth days. In contrast, Heuschmann-Brunner (1974) was able to identify salmonellae in the intestines of common carp (*Cyprinus carpio*) 110 days after they were fed the bacteria. She concluded that freshwater fish can be carriers of enteritis, and there may be a potential public health problem with the German sewage-fed fisheries in which there is only preliminary mechanical clarification before effluents are added to ponds. Buras et al. (1985) exposed common carp (*Cyprinus carpio*) to *Salmonella montevideo* in laboratory tanks at a concentration of 5.0×10^5 cells/ml for eight days, and this led to the appearance of bacteria in muscle, kidney, liver, spleen, peritoneal fluid, and digestive tract contents. The fish were then transferred to tanks of clean water for one week, with daily changes of water. The depuration process was not very effective because *Salmonella* was recovered from the digestive tract contents, although at a much lower concentration of 3.0×10^2/g, compared to 7.0×10^5/g initially.

An attempt was made to depurate blue tilapia (*Oreochromis aureus*) and common carp (*Cyprinus carpio*) reared in treated domestic wastewater in Israel by holding them in clean, running water for various lengths of time (Buras et al. 1987). Depuration of heavily contaminated common carp with bacteria in muscle tissue was not very effective, even after six weeks. Depuration was more effective with blue tilapia, but the concentrations of bacteria in tissues and organs were lower than in common carp. It was concluded that depuration does not appear to be effective when bacteria are present in fish muscle tissue. It was only effective when the concentration of bacteria in the fish tissues and organs was low and when running water was used (Buras et al. 1987).

Depuration does not appear to be as effective as commonly supposed. Bacteria may be removed from fish tissues and organs only if present in low concentrations. Depuration is ineffective if bacteria heavily contaminate fish. Bacteria do not appear to be completely removed from fish digestive tract contents by relatively short depuration periods of one to two weeks.

There may be logistic and economic constraints to harvesting fish and holding them in clean water for one to two weeks, as generally recommended. A practical suggestion, which may reduce contamination of fish with excreted pathogens, is to suspend loading of stored night-soil or sludge for two to three weeks prior to fish harvest (Donaszy 1974). The likelihood of surviving excreted pathogens being present in land crops is high if excreta are repeatedly applied during the growing season, but in particular just before harvest (Strauss 1985), and the same may well apply to fish. It is also suggested that fish should be held in water immediately after harvest for at lease a few hours for them to evacuate their intestines and thus reduce contamination. Evacuation of the contents of the digestive tract usually occurs rapidly due to the shock of capture.

7.9 Macrophyte cultivation

Various public health hazards are associated with macrophyte cultivation when the water is directly or incidentally fertilized with excreta (Feachem et al. 1983). There is an occupational risk to persons who work in the water, who may accidentally swallow pathogens or carry pathogens away on their clothing or body. They may become infected percutaneously with schistosomiasis, if the disease is endemic in the area and the intermediate host snails are present. Harvested plants may be heavily contaminated with excreted pathogens and may infect those who harvest, handle, prepare, or eat them, especially when the plants are eaten raw.

A specific public health risk associated with aquatic macrophyte cultivation is fasciolopsiasis from eating metacercariae of the parasitic fluke *Fasciolopsis buski* encysted on water plants. The disease is restricted to areas where certain species of aquatic macrophyte are cultivated and eaten raw (Feachem et al. 1983). Most of the water bodies in which aquatic plants were cultivated in China were fertilized with excreta (Cross 1969). However, aquatic macrophytes were not directly fertilized with excreta during cultivation in an endemic area of the disease in Central Thailand (Manning and Ratanarat 1970). There were no toilet facilities and people defecated directly into standing water beneath houses built on stilts. Pigs were kept in corrals and their feces also dropped into water; they were reported to be likely to be exposed to the parasite as frequently as humans because they consumed large quantities of water plants. The primary mode of infection in humans may be nuts of water caltrop and corms of water chestnut, the outer covering of which are removed by the teeth (Cross 1969).

Control of fasciolopsiasis depends chiefly on the treatment of excreta prior to its use as a fertilizer for aquatic plants, and attention to crop harvesting, marketing and processing, particularly cooking prior to consumption (Feachem et al. 1983). Metacercariae are killed by desiccation, direct sunlight and warm temperatures. They can be killed by drying the plants, and they survive for only 30 minutes in direct sunlight; they survive for 15 minutes at 60°C, and 1 minute in boiling water. The transmission of fasciolopsiasis can also be controlled by storing excreta for 18 days, which is reported to kill the eggs. However, the eggs survived for up to 28 days in biogas plants in China (Feachem et al. 1983). Thorough cooking of aquatic macrophytes should also render them safe for consumption and may be the simplest way to control the disease.

7.10 High-rate sewage stabilization ponds

There is only minimal removal of excreted microorganisms in sewage-fed, high-rate stabilization ponds. Cooper (1962) discussed the potential of microalgae produced in a sewage-fed, high-rate stabilization pond as a source of disease. There was no change in the total bacterial count (influent $1.2 \times 10^{10}/100$ ml and effluent $1.1 \times 10^{10}/100$ ml) but

coliforms and enterococci decreased slightly from influent to effluent from 1.6×10^7 to $1.1 \times 10^6/100$ ml and from 8.4×10^6 to $3.6 \times 10^4/100$ ml, respectively. Furthermore, *Salmonella paratyphi* B variety *java* was constantly isolated from all stages of treatment, including the effluent. It was concluded that the sewage-grown microalgae would need to be treated before use, even for livestock feed. Concentrations of total bacteria (standard plate count), total coliforms, fecal coliforms, and fecal streptococci were measured on 13 occasions in raw sewage and in the effluent of a sewage-fed high-rate stabilization pond (Edwards et al. 1981b). Concentrations of total bacteria were usually similar and those of total and fecal coliforms and fecal streptococci similar or slightly reduced (one to two log units) in raw sewage compared to the effluent of the high-rate pond. Pathogen removal is minimal in high-rate ponds, which are usually continuously loaded with sewage, because of the short retention time. The harvested algae contain high concentrations of excreted viruses, bacteria, protozoans, and helmith eggs (Feachem et al. 1983).

A complete absence of fecal coliforms was reported in a laboratory high-rate stabilization pond fed with settled domestic sewage, although there were 9×10^7 MPN/100 ml in the feed wastewater (Bokil and Agrawal 1976). Removal of *E. coli* was studied in a sewage-fed, high-rate stabilization pond operated with batch, intermittent, and continuous-flow systems (Sebastian and Nair 1984). Total removal of *E. coli* was achieved in batch culture within four days. Total removal was achieved with a 0.25 but not with a 0.5 dilution rate/day with intermittent feeding. However, total removal could not be achieved with semicontinuous flow, even at a dilution rate of only 0.25/day. It would seem that complete pathogen removal is feasible in a batch-operated, high-rate pond system, although high-rate ponds are operated on a continuous-flow basis. Low removal of excreted microorganisms may occur in continuous-flow, high-rate ponds because of the continuous addition of raw sewage combined with a short detention time.

Further reduction in excreted microorganisms may take place in harvesting and processing the sewage-raised algae. Feachem et al. (1983) discussed one method of pathogen control, sun drying, which they stated would lead to complete pathogen removal if the algae were dried to less than 5 percent moisture. With a higher residual moisture content, pathogen survival would depend on drying time, final moisture content achieved, and sunlight intensity. There are no data on pathogen survival in drying algae, but it was assumed that protozoans would be removed in a few weeks and bacteria killed by algal toxins and other factors, but that viruses and helminth eggs would be long-term survivors, with helmith eggs lasting for at least one year if the moisture content of the algal sludge remained higher than 10 percent. The effluent of a sewage-fed, high-rate stabilization pond in Israel was reduced by three orders of magnitude from 3×10^7 coliforms/100 ml in raw sewage to 5×10^4 coliforms/100 ml by a combination of high-rate pond treatment followed by alum flocculation/flotation to separate the algae (Shelef et al. 1978). The public health aspects of microalgae production and processing in a sewage-fed, high-rate stabilization pond were studied in South Africa (Nupen and Sandbank 1982). While fecal coliforms and coliphage were reduced from means of 8.48×106 count/100 ml and 1.43×10^5 count/10 ml in raw sewage to 1.72×10^4 count/100 ml and $4.11 \times 10^5/10$ ml in the channel effluent, respectively, fecal coliforms and coliphage were reduced substantially from

4.83 x 10^3 MPN/g and > 1.8 x 10^4 count/g in the raw algae float to usually < 10 and < 31 after drum drying, respectively.

Health hazards in the reuse of the algal sludge would also depend on the livestock it was fed to: *Taenia saginata* eggs, *Salmonella* spp. and *Mycobacterium tuberculosis* for cattle, and *Salmonella* spp. and *Mycobacterium tuberculosis* for chickens (Feachem et al. 1983).

7.11 Biogas slurry

Pathogen removal is not very effective in biogas digesters because average retention times are commonly short, 5-30 days, and the operation is a continuous rather than a batch process. Protozoan cysts should not survive, but the effluent slurry may be expected to contain considerable concentrations of pathogenic viruses, bacteria, and helminth eggs. The effluent slurry from a biogas plant is unlikely to be significantly less pathogenic than raw sludge, although Chinese liver fluke (*Clonorchis sinensis*) eggs will be eliminated in the plant. There are few field data on pathogen removal by biogas plants (Feachem et al. 1983). The health hazard in the reuse of biogas slurry in ponds is the passive transmission of pathogens other than Chinese liver fluke in the harvested fish (Feachem et al. 1983).

7.12 Coastal aquaculture

It is generally accepted that excreted microorganisms are not part of the normal flora of fish, but fish caught in water contaminated by fecal discharges may contain fecal indicator bacteria and excreted pathogens. The same is presumed to be true for shellfish. Much of the following discussion of public health hazards in seawater is derived from the review by Feachem et al. (1983).

Enteric viruses and bacteria survive for considerably shorter periods in seawater than in fresh water. Fecal coliforms undergo a 90 percent reduction in 0.6-8 hours in seawater, compared to 20-100 hours in fresh water. Fecal streptococci may survive a little longer than fecal coliforms in seawater, and salmonellae even longer still. Enteroviruses undergo a 90 percent reduction in 15-70 hours in seawater, considerably shorter than their survival in fresh water, although longer than excreted bacteria. The elimination rate is much faster for both excreted viruses and bacteria in warm than in cool seawater. The survival of protozoan cysts and helminth eggs is similar in seawater to fresh water, but they present little health hazard because they tend to settle.

7.12.1 Shellfish

The most serious problem in seawater is the contamination of edible shellfish such as clams, cockles, oysters and mussels, which are often harvested from coastal water and estuaries where polluted water flows into the sea. These shellfish are filter feeders and concentrate bacteria and viruses in their tissue. A single oyster may filter up to 1.5 m^3 seawater per day. Excreted microorganisms may be concentrated in shellfish, mainly in the digestive system, at levels more than 100-fold higher than in the surrounding seawater. Furthermore, shellfish are often eaten raw or only lightly cooked.

Most documented disease associated with excreted virus contamination of shellfish is hepatitis A. As many as 8.6 percent of reported hepatitis A cases in the United States are associated with shellfish consumption, usually raw oysters and raw or steamed clams. However, salmonelloses and enteric fevers, and poliomyelitis have also been associated with consuming shellfish from fecally polluted waters.

Shellfish can be decontaminated fairly rapidly by depuration in disinfected water. Cleansing is more rapid at warmer temperatures, optimal salinity, and in flowing water because depuration is maximal when feeding activity is greatest. Purification of water by chlorination inhibits feeding and thereby delays depuration. Two days in disinfected water may be sufficient to remove *E. coli*, but several days and several weeks are required for enteroviruses and salmonellae, respectively. A major problem is that small numbers of pathogenic bacteria remaining in the shellfish may multiply in warm conditions and infect persons consuming inadequately cooked shellfish. The greatest risk to public health is the consumption of raw shellfish. However, there is a residual risk even with cooked shellfish. In one study a proportion of polioviruses in oysters survived baking, frying, stewing and steaming.

There is considerable uncertainly regarding the use of permissible concentrations of fecal indicator bacteria as water quality standards for shellfish-growing areas. The EEC standard is ≤ 10 fecal coliforms/100 ml and the United States standard is 70 coliforms and 14 fecal coliforms/100 ml (median values) for waters used for shellfish production. However, it is widely accepted that these bacteriological standards are poor indicators of viral contamination.

Another public health hazard from the consumption of shellfish is paralytic shellfish poisoning associated with the ingestion by shellfish of certain toxic dinoflagellates, in particular certain species of *Gonyaulax*, *Gymnodinium*, and *Pyrodinium*. The mussel *Mytilus californianus* was reported to be killed by a high concentration of *Gymnodinium breve*, but the oyster *Crassostrea virginica* suffered no mortality (Roberts 1976). Toxins of dinoflagellates in shellfish are not destroyed by boiling (Korringa 1976). Toxic dinoflagellates also bloom in response to eutrophication (Korringa 1976), which would be associated with excreta-fed aquaculture.

7.12.2 Crustacea

There are few data on the accumulation of excreted pathogens by Crustacea. It was shown in one study cited by Feachem et al. (1983) that crabs kept in contaminated seawater for two days at 10°C, or allowed to feed for 12 hours on contaminated mussels, accumulated over 10^3 polioviruses/g meat.

7.12.3 Fish

There are few data on excreted microorganisms in fish raised in excreta-fed marine systems. Bacteriological studies were carried out on wastewater-fed marine ponds at Humboldt Bay, California (Allen et al. 1979). The wastewater received primary settling, clarification and aeration prior to entering the ponds. Bacteriological examinations of rainbow trout and coho and chinook salmon revealed significant numbers of Enterobacteriaceae in the digestive tracts, although none were found in samples of kidney, liver and spleen. Nearly half of the microorganisms isolated from washings of the guts of rainbow trout and coho and chinook salmon cultivated in the marine ponds fertilized with secondarily treated effluent were Enteriobacteriacea (Allen et al. 1979, Allen and Gearheart 1980). However, the release of the juvenile salmonids raised in wastewater into the open ocean for later recovery as adults would provide adequate time for removal of bacteria from the digestive tract by depuration.

7.12.4 Free-living bacteria

Vibrio parahaemolyticus, which causes acute gastroenteritis, is frequently isolated from shellfish, crabs, prawns, and marine fish. It occurs widely in the marine environment and is not restricted to the animal intestine. Outbreaks of *V. parahaemolyticus* diarrhea in humans have usually been attributed to consuming inadequately cooked seafood, but it is not clear if the disease outbreaks were associated with bacteria from sewage or from naturally occurring reservoirs. The free-living bacterium *V. parahaemolyticus* is responsible for up to 20 percent of all cases of food poisoning in Japan (Roberts 1976).

7.13 Public health guidelines in the literature for excreta reuse in aquaculture

Excreta are used in a raw or only marginally treated state in most commercial excreta-reuse systems, but it is unknown whether this practice is a health hazard and the extent of disease transmission. There are no data on the relative importance of excreta reuse compared to other possible routes of pathogen transmission. Furthermore, guidelines and tentative standards for excreta reuse in aquaculture have tended to be unrealistic and unattainable. According to IRCWD (1985), they are "overtly conservative and unduly restrict appropriate project development thereby encouraging unregulated human waste use." Strict public health laws in some countries, for example, the United States, are a major constraint to the sale of fish raised on wastewater (Walker and Cox 1974, Henderson 1982).

Such unrealistic standards may prevent the production of badly needed fish to alleviate malnutrition among the poor in some countries. The small risk to public health of the reuse of sewage effluent for fish culture is minimal and needs to be evaluated against the value of the crop (Arthur 1983). A pragmatic, *de minimis* approach has been recommended to assess technology-associated risks (Comar 1979) and is germane to the promotion of waste-fed aquaculture. An attempt should be made to provide a risk estimate of the public health hazard of consuming food grown in excreta-reuse systems. Such risks should then be weighed against the improved health and welfare benefits of the culture of fish in, and consumption of fish from, excreta-reuse systems, or as aptly stated by Duckham et al. (1976), "the question may well then resolve itself into one of whether it is better to die safely or eat dangerously." It is essential to "avoid squandering resources in attempts to reduce small risks while leaving larger ones unattended" (Comar 1979).

The first international recommendations for excreta reuse were published by WHO (1973) in the report "Reuse of Effluents: Methods of Wastewater Treatment and Health Safeguard" based on the limited data then available. It was pointed out that while no economic method of treatment can remove all impurities added to water during use, the search must continue for more effective and economical methods of treatment and reuse "with the privoso that all systems . . . must be safe from a public health point of view at all times." The health criteria proposed for wastewater reuse in aquaculture were freedom from gross solids, significant removal of parasite eggs, and significant removal of bacteria; or not more than 10^2 coliforms/100 ml in 80 percent of samples of treated wastewater, and no chemicals that lead to undesirable residues in crops or fish.

Buras et al. (1985, 1987) questioned the role of fecal coliforms as bacterial indicators for fish muscle because they were not always detected in muscle tissue while other bacteria (total aerobic bacteria) were isolated. They proposed that the quality of fish grown in wastewater should be determined by the presence of *any* bacteria in the muscle tissue. They proposed that the indicators should be total aerobic bacteria (standard plate count) that grow on nutrient and mFC agar because if detectable bacteria are present in fish muscle, there may be a chance that pathogenic bacteria are also present (Table 7.6).

The bacteriological standards for fish raised in excreta reuse systems (Buras et al. 1987) are much more strict than those proposed by the International Commission on Microbiological Specifications for Foods (ICMSF 1974). This is because fish raised in excreta reuse systems may have been exposed throughout the culture period to pathogens, while the standards proposed by the ICMSF are for fish contaminated mainly by handling.

For freshwater fish normally cooked prior to consumption, the ICMSF proposed acceptable and maximum concentrations (three out of five samples) of standard plate count and fecal coliform MPN of 10^6-10^7/g and 4-400/g, respectively. They recommended routine *Salmonella* testing for warmwater fish (undetected in all five samples) and more stringent fecal coliform requirements. However, the ICMSF standards were not set up to include fish raised in excreta reuse systems.

The complete absence of fecal coliforms from muscle tissue of fish raised in excreta-fed systems is an enigma that requires further investigation. Fish raised in septage-fed ponds at the Asian Institute of Technology were also never contaminated with fecal coliforms (Edwards et al. 1984). Hejkal et al. (1983) found low concentrations of fecal coliforms in fish muscle but did not find a good correlation between concentrations of fecal coliforms (and fecal streptococci) in pond water and in fish muscle, possibly because fecal coliforms in the digestive tract are amplified in concentration relative to that in pond water. Total coliforms in low concentrations, but not fecal coliforms, were isolated from fish muscle on a single sampling date in a pond fed with sewage stabilization-pond effluent on a kibbutz in Israel (Guttman-Bass et al. 1986). However, the rest of the muscle samples were free of coliforms, and muscle penetration was considered rare. It is possible that fecal coliforms do not serve as indicators of bacterial pathogen presence in fish since fish exposed from a very early stage to fecal coliforms do not recognize them as antigens (foreign organisms) (N. Buras, personal communication).

Even fish raised in ponds fed with septage at the Asian Institute of Technology never had numbers of total bacteria in muscle tissue greater than 50 bacteria/g (Edwards et al. 1984). The quality of the fish varied from very good to medium according to the standard proposed in Table 7.6 by Buras et al. (1987). It is suggested that it is *unlikely* that fish will be of 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, ponds loaded with excreta that leads to the development of a relatively large biomass of phytoplankton for natural food for the fish but with adequate levels of dissolved oxygen maintained in the water for the fish. Very high pH and levels of dissolved oxygen associated with intense photosynthesis in such a system lead to extremely rapid fecal coliform and bacteriophage attenuation (Edwards et al. 1984).

Table 7.6
Bacteriological Quality of Fish from Excreta Reuse Systems

Total aerobic bacterial concentration in fish muscle tissue (no. of bacteria/g)	Fish quality
0-10	Very good
10-30	Medium
> 50	Unacceptable

Source: Buras et al. (1987)

Bacteria may occur in fish musculature in any well-fertilized eutrophic system, irrespective of the presence of fecal contamination. The critical concentration of bacteria in pond water that leads to the appearance of bacteria in fish muscle tissue was $5 \times 10^4/l$ (Buras et al. 1987). Mean concentrations of bacteria (standard plate count) in septage-fed ponds at the Asian Institute of Technology ranged from 7.3×10^3 to $2.6 \times 10^4/ml$, but the range was only slightly lower in control ponds that received no septage, 4.3×10^3 to $2.0 \times 10^4/ml$ (Edwards et al. 1984).

As a corollary, more studies are required of fish caught in the natural, freshwater environment. Fish grown in relatively clean and unpolluted water with a coliform bacteria concentration of only 20 MPN/100 ml had a high concentration of coliforms, 2.2×10^6 MPN/100 ml, in the contents of the digestive tract (Buras 1977). More work needs to be done to compare pathogenic organisms in fish from natural habitats and from wastewater-fed ponds (Gaigher and Cloete 1981). A preliminary study of two individuals of common carp (*Cyprinus carpio*) from a freshwater impoundment and two fish from a pond which formed part of a cattle-feedlot effluent-treatment system showed that the bacterial counts of fish from the impoundment were higher than those from the waste treatment pond. Large numbers of bacteria (total aerobes, coliforms, and *Salmonella*) were associated with the external surfaces, gills and intestines of common carp (*Cyprinus carpio*) from a natural fish population (Cloete et al. 1984). In Africa, where most rivers are fecally polluted, the potential for disease transmission from consumption of fish caught in rivers may be greater than eating fish grown in sewage stabilization ponds, where the water has already undergone settlement and several days of detention (Meadows 1983).

Edwards (1985) presented a rather conservative schema of various aquacultural reuse strategies with different types of excreta to reduce public health hazards to an absolute minimum. He proposed that:

1. Only fish cultured in maturation ponds of stabilization pond systems, or in ponds fertilized by aerobically composted night-soil or sludge, be used for direct human consumption; and

2. Night-soil, sludges, and partially treated sewage be used to raise either duckweed or fish for animal feed rather than for fish culture for direct human consumption.

Bryan (1974) discussed the complex of factors involved in the transmission of unsanitary disease from waste-fed aquaculture. He pointed out that for a person to contract a disease from ingesting a wastewater-contaminated product, the following circumstances must occur:

1. The excreta-related pathogens must be present in the human population or in animals on farms, or toxic agents must be used for industrial or agricultural purposes; and wastes from these sources must reach sewerage or drainage systems.

2. The pathogens or toxic agents must survive and pass through all wastewater treatment processes to which they are exposed, including the growing environment for fish or water crops.

3. The agents must contaminate the aquatic food product.

4. Sufficient quantities of the contaminated food containing enough pathogens or toxic agents to exceed a person's susceptibility threshold must be ingested.

It is now appreciated that an epidemiological as well as an environmental perspective is required because pathogen characteristics, anthropological factors, and the biology of the human host interact in a complex way to make it possible for pathogens which have survived in the environment outside the host to be transmitted to a human host and cause infection (Fig. 7.14) (Blum and Feachem 1985). Although many data have been collected on the survival of excreted pathogens in the environment to assess the efficacy of various excreta management strategies, these data alone are insufficient to determine potential public health hazards in excreta reuse in aquaculture.
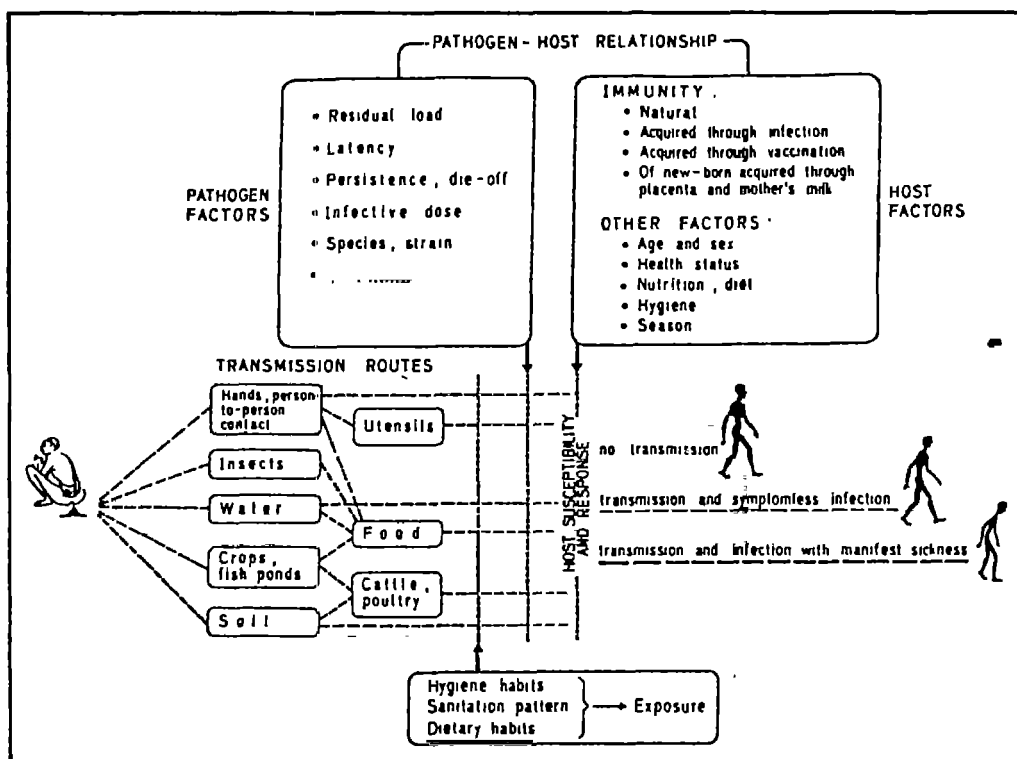
Figure 7.14 The pathogen-host relationship and possible transmission routes for excreta-related infections (Source: Cross and Strauss 1985)

The previous conventional view that public health risks from wastewater or excreta reuse can be derived from pathogen survival in wastewater, excreta, or fish was also rejected by a panel of environmental specialists and epidemiologists (IRCWD 1985).

Their approach was based on an analysis of credible epidemological studies showing demonstrable health effects from wastewater or excreta reuse. Theoretical considerations of those factors that influence the potential of various pathogens likely to be transmitted by waste reuse were also used to develop a tentative model of health risks from reuse of *untreated* wastewater and excreta (Table 7.7).

Table 7.7
Relative Health Risks from Reuse of Untreated Excreta and
Wastewater in Aquaculture

Class of pathogen	Relative amount of excess frequency of infection
Bacterial infections: bacterial diarrheas, e.g., typhoid	Low
Viral infections: viral diarrheas and hepatitis	Least
Trematode infections; clonorchiasis and schistosomiasis local disease	High to nil, depending on the reuse system and pattern

Source: Adapted from IRCWD (1985)

There are few epidemiological studies on potential health hazards of excreta reuse in aquaculture, with the exception of certain species of fluke with aquatic intermediate hosts such as fish and aquatic macrophytes (Blum and Feachem 1985). There are also few epidemiological studies on the risk of other insanitary diseases from consumption of fish raised in excreta-fed ponds or on occupational risks of excreta reuse in aquaculture (see Section 7.7.6 for two studies from Israel). The available epidemiological knowledge on public health hazards from the use of raw night-soil or sludge in aquaculture is summarized in Table 7.8.

The relative low excess of bacterial and viral infections is less well-founded than the high excess of intestinal nematode infections which occurs in the use of untreated excreta and wastewater in agriculture (but not in aquaculture). The latter is supported by several studies from both developed and developing countries. There is little epidemiological evidence for a low incidence of bacterial and viral infections associated with traditional waste reuse, but it is supported by theoretical considerations of potential risk (IRCWD 1985).

Table 7.8
Aquacultural Use: Current State of Epidemiologic Knowledge of Risks of Human Infection with the Major Groups of Pathogens, According to the Type of Excreta Use and Type of Exposure

Exposure group	Infectious disease risks from excreta fertilization of		
	Crops for humans	Crops for animals	Nonconsumable crops
Persons consuming crops	V B P C **░**	—	—
Persons consuming meat or milk	—	B	—
Aquacultural or sanitation workers at site of use	V B P T	V B P T	V B P T

Source: Blum and Feachem (1985)

V = excreted viruses
B = excreted bacteria
P = excreted parasites
C = excreted cestodes
T = excreted trematodes
— = not applicable

V = potential risk; no epidemiological data
░ = risk supported by epidemiological data

A series of standards was proposed by IRCWD (1985) to minimize health risks of excreta and wastewater reuse in agriculture and aquaculture, although little was written about aquaculture because of a lack of available data. Highest priority was given to appropriate treatment of wastes before application to fields or ponds. A major reduction to a geometric mean of $\leq 10^3$ fecal coliforms/100 ml in the concentration of excreted bacteria was recommended for unrestricted use of wastewater in agriculture. Other excreted pathogens such as trematode eggs and protozoal cysts would also be reduced to undetectable levels if these standards were met. Prolonged storage (more than six months) or a shorter time at an elevated temperature is required to achieve this degree of treatment of night-

soil or sludge. A sewage stabilization pond with four to five cells and an overallretention time of 20 days is needed to achieve the required degree of treatment of sewage. It was concluded that "less stringent standards" may be possible for excreta and sewage reuse in aquaculture, but no details were given. It was stated that appropriate treatment technologies for wastes reused in aquaculture are harder to specify than for agriculture, and further research on simple excreta-treatment systems and control strategies are needed before quality guidelines can be proposed for viruses, bacteria and trematode eggs.

Although appropriate treatment of wastes *before* their use in ponds for aquaculture was recommended by IRCWD (1985), it may be neither logistically nor economically feasible to consider thorough treatment of excreta prior to reuse. The reduction of nutrients during waste treatment might preclude the attainment of satisfactory fish yields. Furthermore, the remarkable ability of a fertilized pond to attenuate fecal indicator bacteria and viruses (Edwards et al. 1984) should be taken into consideration in the establishment of guidelines for excreta reuse in aquaculture, that is, pathogen attenuation *during* the fish culture cycle should be considered in the establishment of realistic guidelines, with provisos that attention be paid to good hygiene in all stages of handling and processing fish, particularly gutting and washing, and that fish be only eaten well cooked.

Revised public health guidelines for wastewater reuse in aquaculture have recently been published by WHO (1989). The previous guidelines and standards, based essentially on the microbiological criterion of zero risk with the aim of achieving a pathogen-free environment, were unjustifiably restrictive. More realistic guidelines are needed, based on an epidemiological approach. However, it was stressed that the guidelines for aquaculture are tentative because there is little epidemiological evidence to support them. According to the WHO report, current knowledge of the transmission of excreted pathogens indicates that helminth infection is the most important risk and viral disease the least important risk, with bacterial and protozoal diseases somewhere between the two extremes.

Epidemiological data are required to confirm the validity of this theoretical model for waste reuse in general and for aquaculture in particular. However, the transmission of soil-based helminths is unlikely to occur through aquaculture and the major helminthic health risk is from trematodes (clonorchiasis and schistosomiasis), the distribution of which is not universal. The appropriate WHO standard for helminths for aquaculture is the absence of viable trematode eggs. The tentative bacterial guideline recommended for pond water is a geometric mean of $\leq 10^3$ fecal coliforms/100 ml. This ambient bacterial-indicator concentration can normally be achieved by treating the wastewater influent to the pond to give a level of 10^3-10^4 fecal coliforms/100 ml, although such a high level of treatment may provide insufficient nutrients for satisfactory fish production.

7.14 Excreta reuse strategies to safeguard public health

A tentative schema is proposed for the reuse of excreta in aquaculture with a minimum of risk to public health (Fig. 7.15), taking into consideration suggestions recently published by WHO (1989). It is stressed that further research is required on the public health aspects of these systems, particularly using an epidemiological approach rather than relying on microbiological criteria of pathogen attenuation. Although the culture of fish in maturation ponds of stabilization-pond systems is included in the schema, a more integrated approach is recommended as an alternative to full treatment prior to waste reuse, that is, partial treatment of excreta or sewage to a lower level than that recommended, but combined with one or more of four main measures: control of wastewater application, exposure control, crop restriction (duckweed and fish culture for animal feed), and promotion of hygiene.

Although it is technically feasible to link all the various sanitation options discussed in Chapter 3 with aquaculture, only those most likely to be associated with aquaculture are considered: fresh night-soil (including vault contents and primary sewage sludge), composted night-soil and sludge (secondary sewage sludge and septage), and sewage.

The reuse of fresh night-soil and raw sewage in aquaculture, although a common practice, is not considered acceptable by WHO because of the potential danger to public health. Fresh night-soil should never be added to an excreta-reuse system without storage for a minimum of two weeks to eliminate fluke eggs. Storage also breaks up large pieces of fecal material to facilitate their rapid dispersal in water when added to the pond. It also minimizes direct consumption of feces and therefore high concentrations of excreted pathogens by fish.

A well-designed and well-managed aerobic composting system produces a pathogen-free material that can be used safely in aquaculture. Sludges are at least partially digested and may be reused without further storage since fluke eggs will have been destroyed. There is a chance that if an infected person used the toilet immediately prior to desludging, some eggs might survive. Sludges still contain high densities of enteric bacteria and viruses.

Schistosomiasis is much more difficult to control than flukes. Epidemiological and ecological studies must be conducted before excreta-fed ponds are introduced into an area. Schistosomiasis is not endemic to all tropical areas, particularly Asia where its distribution is localized, and it may not be of concern. Schistosome eggs are killed by storage for four weeks, but improved sanitation is generally ineffective in the control of the disease (Feachem et al. 1983). The best control strategies are directed at the snail intermediate host by clearing vegetation from pond dikes or perhaps by using molluscides that are not toxic to fish. Schistosomiasis control is usually effected by a carefully designed combination of chemotherapy, health education, sanitation, and snail control (WHO 1980).
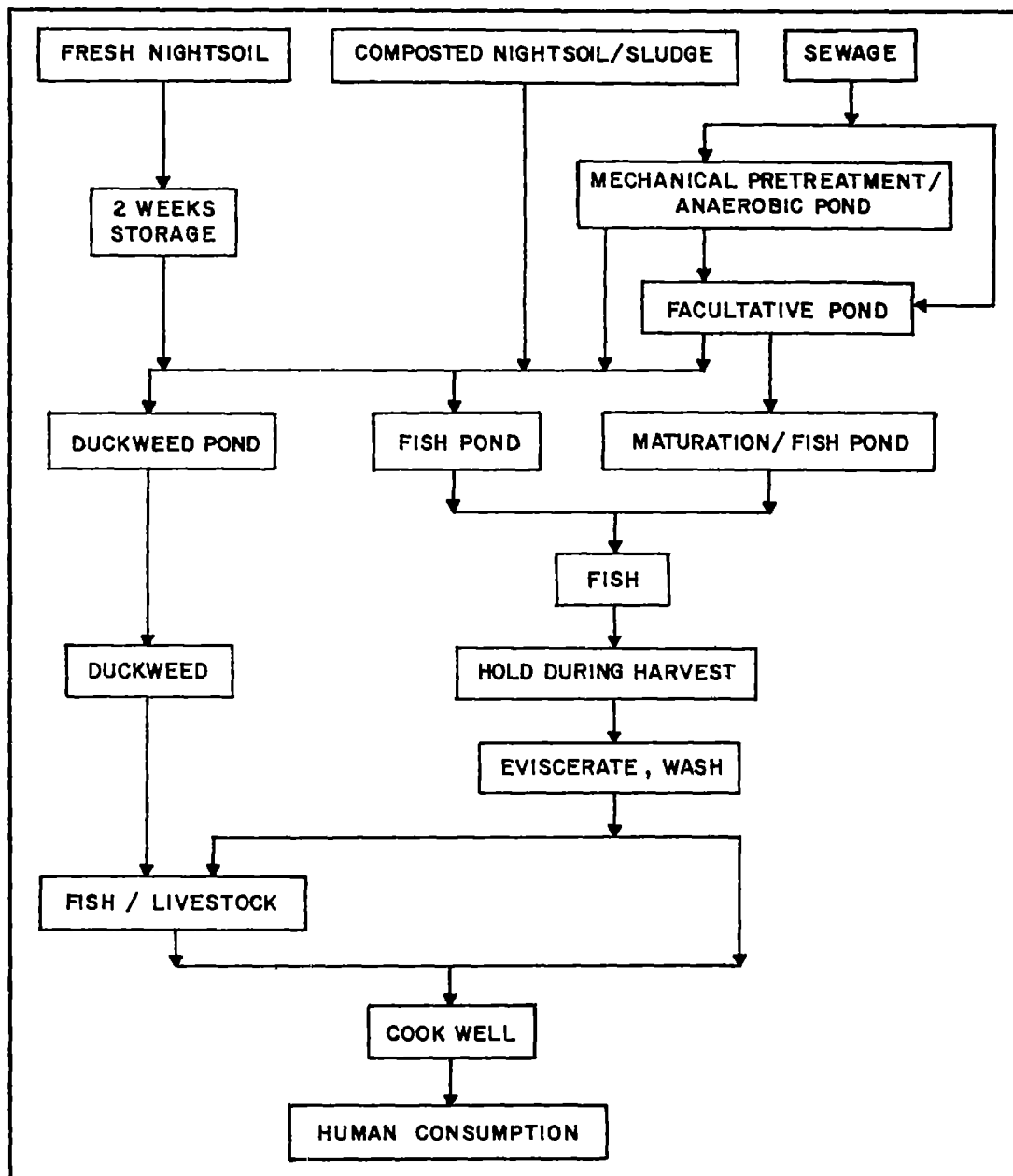
Figure 7.15 Aquaculture reuse strategies with different types of excreta to safeguard public health

WHO suggests that existing sewage reuse systems should be upgraded before the introduction of new systems is proposed. It is suggested that where raw sewage is being used for aquaculture, ponds should be connected in series, with the first pond purely for waste treatment. However, research is required to determine the minimum amount of pretreatment that safeguards public health.

Stabilization ponds with a retention time of eight to ten days are capable of removing large settleable pathogens, but research is required on both the attenuation and epidemiology of smaller protozoans such as *Cryptosporidium* and *Giardia*, which may not settle (N. Buras, personal communication). Fish can be raised in maturation ponds only in sewage stabilization pond systems which are more or less aerobic at all times, but such a degree of treatment before fish culture would be most inefficient in terms of nutrient reuse.

The schema takes into consideration the considerable attenuation of fecal coliforms and bacteriophages that occurs in waste-fed ponds. With the maintenance of the recommended tentative bacterial guideline of a geometric mean of $\leq 10^3$ fecal coliforms/100 ml of pond water, it is unlikely that microorganisms would invade fish muscles.

Depuration is not effective when bacteria occur in fish muscle tissue (Buras et al. 1987) so it is hardly worthwhile transfering fish to clean water for a few weeks. It is recommended that loading of night-soil, sludge, and wastewater should be suspended for at least one week prior to fish harvest in order to minimize contamination of fish with microorganisms. Fish should be held for a short time after harvest in the pond, perhaps a few hours, to empty their digestive tracts and reduce contamination.

It is essential to promote good hygiene in all stages of handling and processing excreta-raised fish to minimize potential contamination. The main point of human contamination with pathogens is evisceration and fish cleaning, during which pathogens can contaminate the hands and utensils of the fish handler. A final step which should render waste-grown fish safe for human consumption is adequate cooking; the consumption of raw, undercooked or improperly processed or preserved fish should be discouraged.

It may be necessary to lengthen the food chain in those societies in which the direct consumption of fish raised on excreta is socially unacceptable (see Chapters 1 and 8). Duckweed or fish could be raised in excreta-fed ponds as animal feed for fish, shrimp, or livestock rather than being fed directly to humans. The addition of an extra step in the food chain eliminates the direct human consumption of fish raised on excreta and should also lead to additional safeguards to public health.

7.15 Summary

There are more than 50 excreta-related infections that can be transmitted to humans, but not all can be transmitted by improperly designed or managed aquaculture excreta-reuse systems. Only Categories I (nonbacterial fecal-oral infections), II (bacterial fecal-oral infections), V (water-based helminths) and VI (excreta-related insect vectors) need to be considered as potential sources of infection in excreta-fed aquaculture systems. The intestinal bacteria and viruses of warm-blooded animals (humans and livestock) do not cause disease in fish but they may be passively transfered to humans by fish raised in excreta-fed systems. Water-based helminths parasitic to humans may be transmitted by fish which act

as worm intermediate hosts, for instance, liver flukes. Schistosomiasis, a disease caused by the water-based helminth *Schistosoma* has a snail intermediate host, and may also be spread through excreta-fed ponds. There does not appear to be much risk from the breeding of insect vectors such as mosquitoes in well-managed excreta-fed ponds.

The promotion of excreta-fed ponds might appear, on first consideration, to favor the transmission of unsanitary diseases with aquatic intermediate hosts or vectors with aquatic stages in their life cycle. However, there is evidence that the reverse is more likely to occur if marshes and swamps are converted into ponds. Marshes and swamps provide a better habitat for the amphibious and aquatic snail intermediate hosts of schistosomiasis and for the aquatic macrophyte habitat of *Mansonia* mosquitoes, a vector of filariasis, than do ponds. Construction of ponds in China may have reduced the incidence of schistosomiasis. There is evidence that the conversion of swamps to rice fields in Indonesia reduced the incidence of filariasis.

There are no currently accepted international standards for excreta reuse in aquaculture. Tentative guidelines have tended to be too conservative because they were based solely on microbiological criteria with a high level of waste treatment *prior* to fish culture to produce a pathogen-free environment. WHO has recently proposed more realistic guidelines, taking into account epidemiological studies which indicate that health risks may be lower for bacterial and viral infections than previously thought, and the substantial reduction of fecal coliforms and bacteriophages in waste-fed ponds. The revised WHO tentative guideline for pond water is a geometric mean of $\leq 10^3$ fecal coliforms/100 ml and the absence of viable trematode eggs.

WHO has also suggested a more integrated approach to minimize health risks in waste-fed aquaculture, with wastewater treatment only one of the measures to be considered together with control of wastewater application, exposure control, promotion of hygiene, and crop restriction.

A tentative schema is proposed for excreta reuse in aquaculture to safeguard public health based on the WHO recommendations. The use of fresh night soil or raw sewage is not recommended, but research is required to determine the appropriate degree of pretreatment. The cultivation of duckweed or fish as animal feed, rather than as direct human food, is recommended as an example of crop restriction for societies in which direct reuse of excreta is socially unacceptable. However, the extra step in the food chain should provide additional safeguards to public health.

Further research is required, particularly on the epidemiology of unsanitary disease associated with waste-fed aquaculture, before realistic and attainable public health standards can be established.

8. Sociological Aspects

8.1 Introduction

Providing public health can be safeguarded, excreta reuse is desirable both to reduce the indiscriminate discharge of fecal matter into the environment and to produce high-protein food to alleviate malnutrition (Edwards 1985). However, excreta reuse is not traditional in many societies, and there may be deep cultural prejudice or taboos concerning the consumption of fish raised on human excreta (Cross 1985).

This chapter discusses the limited data in the literature concerning social attitudes toward the consumption of waste-grown fish and possible ways to increase social acceptance of excreta reuse in aquaculture. Suggestions are also made about the implementation of excreta-reuse systems.

8.2 Social acceptance of excreta reuse

Human society has developed diverse responses to matters concerning human excreta. It is not possible to categorize cultures according to their attitudes towards excreta reuse because of a lack of information in the literature (Cross 1985). There is a need to understand a multitude of historical, sociocultural and ecological factors to understand the role potential foods play in the human diet (Simoons 1974a). Only a general indication of the amount of excreta reuse in different countries is possible.

There appears to be a correlation between traditional reuse of excreta in societies and their population density. This was called *the nutritional imperative* by Simoons (1974a) in reference to societies in which dietary importance overruled commitments to religious belief. The densely populated areas from Bengal through the lowlands of Southeast Asia have limited animal protein supplies, and even persons of high status (such as Bengali Brahmins and Buddhist monks) consume fish even though most of India follows the practice of nonviolence to sentient beings and refuses to take life or eat flesh. The nutritional imperative may explain in part the global distribution of excreta reuse in agriculture and aquaculture. The societies which reuse excreta, or have reused it in the recent past (Hamlin 1980), are the most densely populated: Europe, India, the Far East, and Java in Southeast Asia.

Until 10,000 years ago, low levels of population prevailed during food gathering and hunting stages of human civilization (Trewartha 1969). About 2,000 years ago, around the beginning of the Christian era, there were three principal centers of political power, each a focus of population containing (probably) many millions of persons: the Romans in the Mediterranean, Asoka in Northern India, and the Han in China. The European

population cluster shifted to the west and north during medieval and modern periods. By approximately 1850, India's population centers were found in the humid parts of the Indus-Ganges lowland and in the southern part of the Deccan. In recent centuries, regions of remarkably high population density have developed in Japan and Java.

Until the early 20th century, the technologically advanced peoples of European backgrounds, and the peoples of India and the Far East, grew in numbers most rapidly (Trewartha 1969). Over the last few decades, there has been a reversal of the positions of the more developed compared to the less developed regions in terms of population growth rates. The economically poorer, less literate, and predominantly rural populations of Africa, Asia, and Latin America are expanding the most rapidly. Most do not have a tradition of excreta reuse, inasmuch as their formerly lower population densities did not exert a nutritional imperative. The challenge is to augment precarious food supplies by developing socially acceptable excreta reuse systems in the societies that are now experiencing the highest population pressure.

Detailed field studies of sociological aspects of excreta reuse have rarely been carried out (Cross 1985). The only survey of attitudes concerning excreta reuse in aquaculture was reported by Ghosh (1984). The majority of the 52 respondents in Calcutta approved the reuse of excreta in ponds and the consumption of fish harvested from them, but no details about the study's methodology were provided (Table 8.1). Cross (1985) discussed three case studies to illustrate categories of cultural variation in response to excreta reuse: the Far East (China, Japan, Korea), where excreta reuse is an ancient and well-accepted custom; certain cultures of Islamic religion, in which excreta reuse is abhorred; and Sub-Saharan Africa, where there is little excreta reuse but no strong religious conviction against its use.

Most commercially viable excreta reuse systems involving aquaculture are found in Asia, particularly in West Bengal, India, and the Far East, where excreta reuse is traditional (see Chapter 2). Excreta reuse is also found in expatriate Chinese communities in Southeast Asia, especially in Malaysia, Singapore, and Thailand. The Chinese are the only ethnic group in Malaysia that uses night soil in aquaculture; Malay (Muslims) and Indian fish farmers (mainly Tamils of the Hindu religion) rarely fertilized their ponds (Seow et al. 1979). Malays were reported to object to fish, mainly on esthetic grounds, because of the Chinese practice of using pig and human excreta to raise fish (Birtwistle 1931).

The average Thai farmer (usually Buddhist) was reported to object to the use of excreta as a pond fertilizer, although ethnic Chinese farmers in Thailand used overhung latrines on fish ponds (FAO 1949). This was confirmed by a socioeconomic survey of 100 nonfish-farming households in Pathumthani province, Thailand, which included the respondents' willingness to raise fish on human waste (Edwards et al. 1983). The great majority (86 percent) rejected the idea of raising fish on untreated human excreta, mainly because they considered the practice dirty and disgusting. However, 31 percent of the respondents were willing to raise fish using composted human excreta, the main reason being that the compost would no longer smell. Thus, in a society for which excreta reuse

Table 8.1
Results of a Reuse Attitude Survey of 52 Respondents in Calcutta

Question	Strongly approve	Generally approve	Do not approve	Strongly disapprove
We will have to conserve as much as possible from conventional wastes. Municipal sewage is rich in fish nutrients. Do you approve its use in fisheries?	82.7	9.6	9.3	3.8
For about 50 years, Calcutta markets have been provided with a liberal supply of fish from adjoining sewage-fed fisheries. Do you approve your family's consuming such fish?	73.1	15.4	3.8	7.7
Calcutta has great potential to use its sewage in fisheries in the east suburban wetlands. The ponds can also act as sewage treatment plants to treat the water for safe disposal or for use in farming. This integrated system will be economically efficient and a simultaneous producer of human food. Do you approve of incorporating an integrated system as an essential urban service?	75.0	15.4	5.8	3.84

was not a traditional practice, more than twice the number of respondents were willing to use treated human excreta as were willing to use untreated excreta.

Fish raised in fecally polluted Beira Lake in Colombo, Sri Lanka, a region that is mainly Buddhist, were readily marketable to the lower socioeconomic stratum of society, although the indirect fertilization of the lake with fecally polluted surface water might be the reason for consumer acceptance of the fish.

Islam is the religion of about one fifth of the human race (Farooq and Ansari 1983), and most of its followers live in Asia. In contrast to the Chinese, who have a tradition of excreta reuse, Muslims avoid contact with human excreta which, according to the Koran, are regarded as spiritual pollutants (Cross 1985). Persons surveyed in Bangladesh, who are predominantly Muslim, were reluctant to accept fish harvested from ditches fertilized with excreta (Ahmad 1979). However, most of the farmers in Java, who

had overhung latrines on ponds, were practicing Muslims and were fastidious about excreta disposal (Djajadiredja et al. 1979). They were reported to be particularly offended by both the presence and smell of excreta, and a pond was a more favored place to defecate and dispose of excreta "completely out of sight" than on land or in pit latrines. Muslims are required by their religious faith to look to the teachings of Islam, particularly as embodied in the Koran, to guide them in their way of life. The reuse of sewage effluent seems to be perfectly legitimate from the Islamic religious view point. The organization of the Eminent Scholars of Saudi Arabia expressed unanimous approval of reuse of treated wastewater effluents for all purposes including religious washing (Farooq and Ansari 1983).

In the West, commercial sewage-fed aquaculture was well developed in only one country: Germany. However, there were marketing problems with common carp raised in the sewage-fed ponds at Munich in the 1930s, soon after the system was operational (M. Prein, personal communication 1989). The local nickname for these fish was *scheisshäusle-Karpfen*, "latrine" carp. A campaign to promote the sale of the fish failed, and the company running the sewage-fed ponds resorted to hiding the company name on the side of the trucks delivering their fish to shops and fish dealers in the city. Germans would eat sewage-fed fish only when they were unaware of its origin. The fish were marketed wholesale and made up only about 2-3 percent of the total annual production of common carp. The improbability of sewage-raised fish being acceptable as human food has been stated for other Western developed countries, for example, New Zealand (Slack 1974), the United Kingdom (Fish 1978), and the United States (Duffer and Moyer 1978, King 1979, Henderson 1982).

The diverse cultures in Africa do not have an all-embracing system of thought such as is found in China or the Islamic world. Many African societies profess distaste for handling excreta, but there are examples of excreta reuse: in Lusaka, for example, where sewage-fed fish farming was formally endorsed by several local authorities (Cross 1985). There does not appear to be a problem with marketability of fish raised in sewage stabilization ponds in fish-eating communities in Kenya, even among well-educated persons who are aware of the source of the fish; it was also reported to be extremely difficult to stop local fishermen from seining sewage stabilization ponds at night at both Thika and Kisumu sewage stabilization pond systems (Meadows 1983). A prejudice against the consumption of sewage-raised fish was reported in South Africa (Hey 1955), but fish used to control mosquito larvae in sewage stabilization ponds were acceptable to the Bantu people (Mackenzie and Campbell 1963). Certain groups in Africa do not eat fish of any kind, regardless of its source (Meadows 1983). This characteristic avoidance of fish as human food is prominent in semiarid and arid regions, especially among groups with a pastoral tradition (Simoons 1974b).

There is little information from Latin America concerning the acceptability of excreta-raised fish. Excreta reuse in agriculture is practiced informally in Latin America, mostly by individual households or in other, less advanced and systematic ways than in some Asian countries. The subject is seldom mentioned because it is culturally taboo (Elmendorf and Buckles 1980). Residents of the Dominican Republic refused tilapia raised in sewage stabilization ponds (Davies 1982).

8.3 Increasing social acceptance of excreta reuse

The initial adverse reaction of many persons to the idea of consuming fish raised in excreta reuse systems is probably largely due to the erroneous belief that fish feed directly on fecal solids. Fish will consume fecal solids if added to a reuse system, but in a system designed to minimize risks to public health, the fish derive nutrition from natural food organisms which develop as a result of the fertilizing effects of inorganic nutrients contained in excreta (Jayangoudar and Ganapati 1965, Saigal 1972).

In countries where the prejudice against the reuse of excreta is strong, the underlying cause is most often the stench and appearance of fresh excreta. Sanitary latrines designed to conserve night soil and eliminate odor should be set up in countries with a prejudice against night-soil reuse to demonstrate the conversion of night soil to an odorless and inocuous humus (Takahashi 1978). Treatment can transform excreta that are socially unacceptable into a more readily acceptable form (Feachem et al. 1983). Partially digested excreta from cesspools and septic tanks in Bangkok do not have an offensive odor; ethnic Thais, who have a strong cultural aversion to excreta, showed no reluctance to load it into ponds or to enter the water to seine fish in experiments conducted at the Asian Institute of Technology, Bangkok. It should be feasible to design relatively simple, appropriate technology to remove excreta from the toilet storage receptacle, to transport it to the reuse site, and to load it into the reuse system with minimum handling. Furthermore, the use of improved technologies requiring less direct handling of feces should lead to an increase in the status of excreta removers and handlers (Edwards 1985).

Excreta reuse can gain acceptance in societies with religious or cultural taboos against human excreta reuse. Human cultures are rarely so homogenous that they do not contain subcultures holding attitudes very different from those of the majority (Cross 1985). Furthermore, cultures are not fixed: beliefs, values, and customs evolve. This evolution is likely to occur if excreta reuse can be demonstrated to be low-cost, to provide real benefits to the population, and to carry no risk to public health.

The reluctance of Western consumers to accept food grown on wastes is directly related to socioeconomic development. Reuse was a traditional practice in the past, but the accumulation of wealth has enabled a great distance to be placed between production of food and the disposal of waste products. Furthermore, "the accumulation of wealth has bred contempt and distrust for any process that closed the gap between the biological processes of growth and degradation" (Goldman and Ryther 1976). Psychological barriers have been created to growing food on waste products, but these barriers should disappear once society accepts the need for closed-loop reuse systems.

There is a new consciousness in the West of the importance of ecologically sound farming practices, and this includes an awareness of the undesirability of polluting natural water bodies with raw or inadequately treated sewage and the need for alternatives to petroleum-based fertilizers. Constraints to effective excreta reuse may now be more a question of technical feasibility and cost than present-day cultural predisposition (Feachem et al. 1983). Those who approve of the reuse of potentially objectionable inputs assume

that reuse systems would include adequate controls. Public confidence in the safety and quality of the final product are doubtless the single most important factor in consumer acceptance of fish cultured in excreta reuse systems (Huguenin and Little 1977).

One major factor that leads a society to consider the reuse of human excreta is a shortage of resources (Wolman 1978). Reuse of excreta in agriculture was common in the West before the development of chemical fertilizers. There has been a recent decline in the use of night soil in fish ponds in Hong Kong, Malaysia, and Taiwan, societies which have experienced recent rapid rises in socioeconomic status, due to increased labor costs, the availability of relatively cheap inorganic fertilizers, and an increase in livestock manure which can be conveniently used to fertilize fish ponds in integrated farming systems.

Excreta reuse in aquaculture is more likely to be acceptable to the lower socioeconomic groups than to the privileged classes in a society. While privileged persons may consume marine and freshwater fish from other sources, usually at a higher price, the alternatives available to the poor may well be fish cultured in an excreta reuse system or a diet lower in protein. Laborers in aquacultural excreta reuse projects in Peru and Thailand readily ate fish from the ponds which they themselves had fertilized, although the consumption of such fish is socially unacceptable in both countries.

Persons whose occupations involve regular contact with excreta may be shunned and avoided because of taboos against excreta in many societies (Pacey 1978). Where excreta cartage is used, as in many developing countries, sweepers and night-soil removers may live in segregated communities. Cartage is associated with the sweeper castes and has untouchable status in the Indian subcontinent. A stigmatized occupation may be in demand where there are few alternatives for employment, but if excreta collection and reuse were to become profitable, a stigmatized occupation might become less of a disadvantage. Fishermen in the Indian subcontinent also have untouchable status, but members of higher castes became involved in aquaculture because it was profitable and thereby upgraded the status of fishermen (Edwards 1985). Low status is usually reinforced by low pay, so a financial return on excreta reuse should lead to more pay and an improvement in status. One priority of excreta reuse should be to establish a monetary value for excreta.

Huguenin and Little (1977) divided potential aquacultural products in a hierarchy of food use: eaten raw (oysters and clams); bought fresh but cooked (fish); frozen or canned (shellfish and fish); processed and/or contained in other products (fish stocks, chowder, and fish protein concentrate); and animal feed. Produce higher in the hierarchy are direct human food products with the greatest nutritional and economic value. Such food products may represent a marketing challenge in some societies if they are raised in excreta reuse systems. Another strategy is to aim for inclusion in processed foods where the identity of the produce is easily lost. Produce at the lower end of the hierarchy faces fewer technical problems in safeguarding public health and has less severe marketing problems. Such produce enters industrial markets and is sold primarily on the basis of quality and cost, although it tends to have a lower unit price.

Fish cultured in excreta reuse systems are of high quality and are equal or even superior in taste and odor to fish cultivated in other ways (Allen and Hepher 1979). Fish cultured in manured ponds feed on high-protein natural food and were much leaner, only 6 percent fat compared to fish raised on high-protein feed pellets and grain with 15 percent and 20 percent fat, respectively (Wohlfarth 1978). Fish cultured in well-managed excreta reuse systems are also safe to eat from a public health point of view (see Chapter 7). It has even been recommended that the most promising marketing strategy for waste-grown fish is to aim high and sell such premium products in the restaurant trade to the prime customer group in the initial years of marketing (Huguenin and Little 1977).

There is likely to be social resistance to the consumption of fish raised on excreta in some societies, even if the fish are of highest quality. In such societies it may be necessary to rely on the strategy of lengthening the food chain, reusing excreta to raise fish or macrophytes which are not consumed directly by humans but are fed to livestock, finfish or shrimp (see Chapter 1 and Sections 2.7.2, 4.9, and 4.12). The concept has considerable sociological relevance because it may permit excreta reuse in societies where it is otherwise unacceptable.

Regulatory agencies play a critical role in the implementation of excreta reuse systems because they have the power to prevent the marketing of produce (Huguenin and Little 1977). This is particularly true in certain Western countries, for example, the United States, where wastewater-fed aquaculture will be subject to a multitude of state and federal statues, regulations, and agencies and where it has legal, political and social implications of great complexity (Lohman 1979). Present laws in the United States exclude any product directly derived from wastewater from being sold for human consumption (Henderson 1979).

There is essentially a double standard used against the reuse of excreta in aquaculture in the United States. The presence of any uncertainty concerning the mere possibility of a public health hazard in excreta reuse can preclude acceptance by legal and political groups; but the same substance found "naturally" in foods must be shown to be dangerous to health for it to be condemned (Huguenin and Little 1977). However, approval is likely if quality control, particularly public health and safety, can be assured (Huguenin and Little 1977). Such negative attitudes may actually impede developments in sanitation with associated improvements in public health, since the implementation of hygienic excreta reuse may provide a financial incentive to install or improve existing sanitation technology (Edwards 1985). Excreta reuse in many developing countries is a reality with indiscriminate reuse occurring because of economic necessity. The risk to public health may be greater by not accepting reuse as a viable option than by planning defined excreta reuse systems with adequate safeguards (Bartone 1985).

8.4 Implementation of excreta reuse

The challenge is to develop commercially viable excreta reuse systems in societies where excreta reuse is not traditional, and to make it more widespread in those

societies in which it already occurs. Suggestions concerning pilot project implementation are discussed below.

The difficulties in inducing changes in tradition-bound societies are often overstated. The reason a given community does not accept a proposed new technology may be that the residents are not convinced they will benefit from the change, not that they have a general resistance to the new technology. Many peasant societies rapidly adopt new technology once they perceive that they will benefit, particularly financially. The emphasis for the implementation of excreta resource-recovery systems should be on economic returns, not on more nebulous public health benefits (Edwards 1985).

A critical consideration in the development of a sanitation system in a community is the system's acceptance by the community, and this acceptance is most likely to be achieved by involving the users in all stages of project planning and implementation. The design of systems which are socially acceptable is clearly easier when designers have a thorough understanding of local conditions, including the opinions and preferences of those who will use and operate the system (Pescod 1978). However, in a study of sociocultural factors in waste management, the widest possible concept of people should be adopted (Furedy 1986). It must include the views of planners and administrators, as well as the recipients, of basic services. It is often believed that the major task is to motivate the poor, who are generally thought to have low levels of education and awareness. Feachem (1980) also pointed out the need to provide training for engineers and engineering teachers in low-cost, appropriate technologies. Furedy (1986) discussed the case of the Calcutta sewage fisheries as an example of an indigenous system developed by farmers, which constitutes an appropriate low-cost system to treat and reuse city wastewater. Despite the great value of the sewage fisheries, officials have ignored it and have even promoted urbanization schemes that threaten its existence.

The prevailing attitudes to waste management in Asian cities have been formed, for the most part, by engineers and administrators who neglected sociopolitical considerations of resource recovery, even though their decisions may have an impact on the livelihood of large numbers of persons (Furedy 1984). Proposals for large-scale waste reuse systems should not be formulated without consideration of the consequences of diverting resources from the poor, who may depend on such wastes for their livelihood (Briscoe 1978, Furedy 1987). There may be fewer barriers to introducing the reuse of excreta, which may be new, because it does not involve changes in traditional methods of use of resources such as straw and animal manure. Most organic waste reuse takes place in rural areas, but reuse by lower socioeconomic groups in cities and peri-urban areas should not be overlooked.

Pilot projects to test the feasibility of excreta reuse should be carried out among a segment of society that is aware of the potential benefits of excreta reuse (Edwards 1985). Even in societies with widespread resistance to excreta reuse, there may be groups that appreciate its value and necessity. Project sites must be selected with sociological as well as technical considerations in view: a potentially viable, economically productive

excreta-reuse system could fail if sociological considerations are not given appropriate attention.

Once a pilot project is operating, the next step is the dissemination of viable excreta reuse technology. This dissemination may be aided by bringing observers from other areas to see the pilot system in operation.

It is generally acknowledged that self-help schemes based on a community's spirit of self-reliance are the best to achieve long-term improvements in the community environment, and these should include excreta-reuse systems if at all feasible. Self-help schemes are based on the willingness of individuals to participate, but it may be difficult to get everyone to cooperate, even if positive benefits of the reuse scheme have been demonstrated. Such schemes are usually more effective in short-term rather than long-term projects because it may be difficult to maintain enthusiasm unless there are significant benefits to the participants. The concept of self-help is probably best left to the dissemination of a given reuse technology following the successful conclusion of a pilot project (Edwards 1985).

The concept of community participation is often applied in an oversimplified way that diverts attention from fundamental political and administrative realities that determine the success of sanitation programs (Feachem 1980). Concepts of community participation are often vague and include other substantial concepts besides self-help, such as local perceptions, bottom-up planning, and latent development potential, all of which are highly complex and diffuse, and presuppose untapped resources of leadership, cooperation, money, and time that probably do not exist. Funds may be available for intense and sustained interaction between community and government at the demonstration project level; but to extend an individual demonstration project to a regional or national level may be impractical because of shortages of both money and staff. Furthermore, the successful implementation of a program depends as much on the presence of efficient and well-managed government organizations as on appropriate technology and community participation (Feachem 1980).

Most excreta reuse systems are likely to be at the urban rather than at the family or small-scale rural community level because of the more pressing need to dispose of large amounts of urban excreta. This may hinder the ability to guarantee that the products sold are always safe for human consumption. Subsistence farmers participate in the whole agricultural cycle from production of the food to its consumption, and they can supervise all aspects of system management. However, a commercial farmer who raises crops for a distant and impersonal market may adopt profit-enhancing shortcuts in the production cycle that may threaten public health (Feachem et al. 1983). The urban consumer, who can judge market produce only by its appearance, must be protected from unscrupulous and unhygienic practices to ensure that the product is safe. Enforcement of appropriate regulations to ensure that a given excreta reuse system is operated as intended can safeguard public health.

9. Economic and Financial Aspects

9.1 Introduction

The sanitary treatment and disposal of human wastes are costly, but neglect of them promotes disease and environmental degradation through eutrophication.[1] Although waste treatment alone is a benefit to society, most waste treatment systems only treat and dispose of excreta without generating income. Excreta reuse in aquaculture has the potential to defray some of the costs of waste treatment and produce fish at the same time. The ability of fish to improve sewage treatment in stabilization ponds remains to be demonstrated. If fish culture in stabilization ponds proves not to improve the process significantly, benefits would accrue only from profits from the sale of fish raised in such systems. Another benefit of excreta reuse in aquaculture is that once it is proved that fish can be cultured in excreta reuse systems without significant health hazards, excreta might become a saleable commodity with a decrease in insanitary disease because of a financial incentive for their collection and reuse (Edwards 1980a, 1985). The reuse of excreta already has considerable economic importance in many countries, and their number may increase. Reuse may become economically attractive as the costs of chemical fertilizers and the demand for food increase (IRCWD 1985).

According to Julius (1978), excreta exhibit what economists call the behavior of "inferior goods," with implications for the promotion of excreta reuse technologies. The quantity of most goods demanded by consumers rises with their income, but for inferior goods demand falls as consumer income rises. Japan, Korea, and Taiwan have somewhat similar cultural backgrounds but large differences in income and economic development. The relationship between income levels and demand for night soil in these countries follows that for inferior goods. Per capita incomes in Japan, Taiwan, and Korea were $3,600, $700, and $400, respectively, in the mid-1970s when the study was conducted. In Japan, the most affluent of the three societies, very little night soil, about 2 percent of that collected, was used. In Taiwan, there was still considerable (but decreasing) demand for night soil, while in Korea, the poorest of the three societies, night soil was used routinely.

However, excreta are not consumer goods. Furthermore, there are other economic reasons which are more likely to affect the prevalence of waste reuse. Night-soil reuse in Japan was reported to have declined because of increased labor costs, increased mechanization, easier application of chemical fertilizers (which were subsidized by the

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[1] Portions of this chapter were contributed by R. D. Zweig.

government) compared to labor-intensive application of organic fertilizers, higher incomes, and a decrease in the availability of night soil because of installation of septic tanks and sewers. As socioeconomic conditions improve in Asia, there is an increase in the consumption of animal produce, with a corresponding increase in intensive livestock production. In Taiwan, this has been associated with an increase in integrated livestock and fish culture in which bulky livestock manure has been substituted for bulky human excreta; less labor is required for the former because livestock are raised close to the ponds in such systems.

Countries with relatively low per capita incomes are most likely to be susceptible to the introduction of low-cost reuse technologies on economic grounds (Julius 1978). However, Far East societies with traditions of excreta reuse have rising incomes which may preclude more widespread excreta reuse there because of changing input cost relationships, particularly increasing labor costs. Most low-income countries in which excreta reuse has the greatest potential have cultural prejudices against it (see Chapter 8 on sociological aspects).

It is generally agreed that sewage stabilization ponds are the most effective and most economic sanitation treatment option for sewage in developing countries, provided that land is available at reasonable cost (Feachem et al. 1983). Aquaculture may be more conveniently associated with stabilization ponds than other sewage treatment systems. There is also a need to assess the economic potential for excreta reuse involving "dry" systems with night soil and septage. These have greater relevance at present for most developing countries because they are not encumbered by the very high cost of wastewater collection by conventional sewerage systems.

Attention has been directed to the culture of fish in maturation ponds of existing sewage stabilization pond systems to assess the potential of aquaculture to defray operating costs for sewage treatment. However, there may be little nutrient reuse potential in such a system because it is designed to treat excreta with minimum use of land. An alternative strategy that warrants assessment in developing countries because of widespread malnutrition is waste treatment to optimize fish culture. The latter strategy would require more land because of the relatively low organic loadings suitable for simultaneous waste treatment and reuse. However, it may be economically viable in many developing countries with relatively low land and labor costs and relatively high market prices for fish.

A discussion is presented of the factors that need to be considered for an economic assessment of aquaculture. Economic project analysis requires a reasonable estimate of costs and benefits, with and without the proposed project, and should include an evaluation of realistic disposal and reuse options. One likely option is unsanitary excreta disposal, so an estimate should include costs of environmental impact and health risks. Analyses should be made of excreta treatment alone and incorporating reuse through aquaculture. *The important question is, can aquaculture reduce the cost of waste treatment compared to systems without aquaculture?* Comparisons with commercial aquaculture in which financial benefits are concerned with profits of individuals or companies are not valid. Waste treatment is a government and not a private affair and governments are

concerned with economic benefits. The limited amount of data in the literature on economic aspects of excreta reuse are reviewed, followed by a discussion of economic and financial costs of sanitation technology.

9.2 Economic assessment of aquaculture

Profit in aquaculture, or net income per unit area of water (Y) is influenced by three major factors: the yield of the cultured organism (Q), the costs of production and marketing (C), and the price received for the organism (P), as indicated by the following basic equation (Shang 1981):

$$Y = QP - C$$

It follows that the major ways of increasing profits are to increase yield, reduce costs, and obtain a higher price for the cultured organism. The major factors that affect the economics of aquaculture are presented schematically in Fig. 9.1.
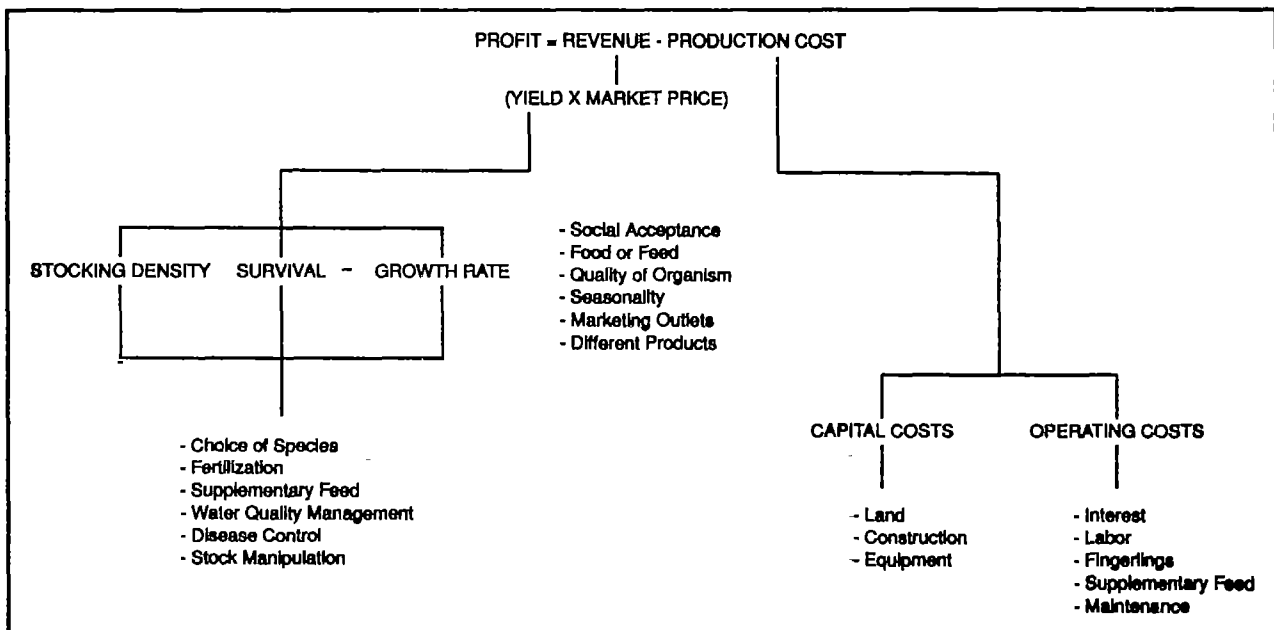
Figure 9.1   General framework of the major factors involved in the economics of aquaculture (Adapted from Shang 1981).

The yield is affected by the stocking density, survival, and growth rate of the cultured organisms, all of which are influenced by various factors (see Section 5.5, Dynamics of waste-fed ponds). Yields in excreta-fed ponds in which the only food in the system is natural food produced by the fertilizing effect of the organic matter input are lower than for most commercial aquacultural systems. Much higher yields are obtained in

the latter through the use of supplementary feeds, alone or in combination with fertilization, or nutritionally complete pelleted feeds.

The economic feasibility of excreta-fed aquaculture depends on the marketability of the produce. The sale of fish raised in excreta reuse systems for direct human consumption may not be feasible in certain societies because of cultural or religious aversion to such produce, particularly if alternative animal protein sources are available (see Chapter 8). The culture of fish (or duckweed) in excreta-reuse systems as animal feed is a possible option in such societies. However, the animal fed the excreta-raised feed would need to have a high market value to ensure the economic viability of the two-stage system because of the inefficiency of conversion of feed to target organisms (probably a maximum of 30 percent). Other alternatives suggested in the literature for waste-fed aquaculture are fish fingerlings for restocking in other aquacultural systems, and fish for bait and for sports fishing (Lin 1974, Henderson and Wert 1976), although only the former have real relevance for developing countries.

A further constraint to excreta-fed aquaculture is that fish which fetch the highest market prices in most societies are carnivorous species. The most appropriate species of fish for culture in waste-fed aquacultural systems are filter feeders which feed low down on the food chain, basically carps and tilapias. Such species are not readily marketable as food fish in most of the Western world (Ryther 1980, Henderson 1982), although they are in demand in most fish-eating Asian countries. However, there are indications that species normally considered unmarketable in the West are gaining in popularity and sell well when they are presented attractively and sold at reasonable prices. This is no doubt also due to the increasing cost of more popular carnivorous freshwater and marine fish (Ryther 1980). The most common way to market freshwater fish is fresh or frozen, although processing excreta-raised fish in various ways (cured, smoked, salted, fermented, canned) may improve their marketability. The most likely market outlets for excreta-raised fish are for rural and urban poor in developing countries to provide badly needed animal protein, rather than for local luxury and foreign markets. However, excreta-raised fish may provide an alternative source of animal protein to fish meal, which is an integral component in pelleted feeds used in the more intensive culture of carnivorous fish and penaeid shrimp.

An outline of items to consider in a cost-benefit analysis of aquaculture is given in Table 9.1. A comparison is made of the major items for conventional aquaculture and excreta-fed aquaculture, the latter with and without supplementary feeding. Economic data for aquaculture are extremely scarce and difficult to obtain (Rabanal and Shang 1979), particularly in developing countries with a wide variety of systems and where farmers seldom keep records. Furthermore, the economic viability of a given aquacultural system depends on many technical, social, and economic factors which are specific to a given area or country. The blueprint for the profitable operation of a certain aquacultural system in one area is no guarantee that it can be repeated under other socioeconomic conditions (Rabanal and Shang 1979).

Table 9.1
Guideline for Cost-Benefit Analysis of Conventional and Excreta-Fed Aquaculture in Existing Sewage Stabilization Ponds, with and without Supplementary Feed

Items	Conventional aquaculture	Excreta-fed aquaculture	Excreta-fed aquaculture with supplementary feeding
Capital costs			
Value of land	+	-	-
Pond construction	+	-	-
Equipment (pumps, nets)	+	+	+
Operating costs			
Seed	+	+	+
Fertilizer	+	-	-
Supplementary feed	+	-	+
Labor	+	+	+
Maintenance and repair	+	-	-
Depreciation	+	-	-
Interest on loans	+	-	-
Production (kg/ha/yr)	+	+	+
Cost/kg	+	+	+
Profit	+	+	+
Rate of return on investment	+	+	+
Rate of return on operating costs	+	+	+

The initial construction costs for a fish farm are usually high, and capital may not be readily available to produce relatively low-priced fish raised in fertilized systems suitable for the alleviation of malnutrition. The cost of land is probably not a major cost in most aquacultural operations sited in rural areas where land values are relatively low. However, the same may not apply to excreta-fed aquacultural systems which depend on urban excreta for fish nutrition. Fish farms which reuse sewage need to be located in suburban areas, where land costs are considerably higher, to reduce the cost of pumping sewage over long distances. Septage-fed ponds could be located in rural areas because it

may be feasible to transport septage with its much lower water content to rural areas, particularly by bulk water transportation.

Waste stabilization ponds require more land than conventional sewage treatment plants, but it is difficult to determine a price for land above which ponds cease to be economically viable (Arthur 1983). Since land values invariably rise over time, it is important to consider not only the cost of the land, but its resale value. More conventional treatment plants will provide less land for sale if the system is replaced or relocated, and the land will be more expensive to reclaim because existing concrete structures will require demolition or removal. Arthur (1983) discussed various ways to deal with the question of land resale when evaluating wastewater treatment alternatives. Least-cost feasible solution analysis was also given to demonstrate how a sewage stabilization pond system may often provide the cheapest technology, despite relatively high land costs. The same reasoning applies also to excreta reuse in aquaculture.

The culture of fish in sewage stabilization ponds should be economically viable compared to conventional aquaculture because most of the cost items are already covered by sewage treatment. The greatest overhead costs in the culture of freshwater fish in ponds are land, water, and nutrition for fish, but these costs are borne by the primary function of wastewater treatment in wastewater-fed aquaculture (Henderson 1982). Although data are lacking, production costs of fish in existing sewage stabilization ponds should be minimal because the incremental costs to modify and operate stabilization ponds to support aquaculture should not be significant and there should be little need for supplementary feed (Bartone et al. 1985). The comments above apply to the treatment of sewage in existing stabilization ponds using a minimal area of land with fish cultured in the maturation ponds. However, there is a need to conduct a parallel cost-benefit analysis for the treatment of sewage in new pond systems designed for maximal fish production, which would involve a considerable increase in land required (see Section 5.3.5). In fact, current estimates indicate that the area required for maturation ponds that incorporate fish culture is 15 to 20 times greater than those without fish culture, or a BOD_5 loading of 10-20 kg/ha/day with fish culture versus 200-300 kg/ha/day without. There would be additional construction and operation costs in the latter, but it could be an economically attractive option in areas where land and labor costs are low and fish market prices are high. However, the opportunity cost (current output value), if any, of the area considered for sewage stabilization pond development also needs to be evaluated to determine whether the loss of revenue from supplanting existing activities significantly reduces or exceeds the potential value of fish produced in the larger area required for maturation ponds designed to include aquaculture. The basic rationale for the optimization of fish culture using sewage or excreta is to provide "free" fish nutrition, which is often the single largest operating cost in conventional aquaculture.

Maturation ponds used for fish culture and excreta-fed ponds are fixed assets, the cost of which remains constant regardless of the fish yield. In general, intensification in aquaculture leads to an increase in fish productivity and a decrease in the cost of fish produced per unit of output (Hepher and Schroeder 1974, Rabanal and Shang 1979, Hepher and Pruginin 1981). The relatively low fish yields from a fertilized pond may be

insufficient to generate a profit if capital costs are relatively high (Hepher and Pruginin 1981). Intensification of an excreta-fed pond involves the use of supplementary feed, either relatively cheap, energy-rich cereal brans or more expensive nutritionally complete pelleted feed. There is also a need to increase the fish stocking density to benefit from the larger amount of food in the pond with supplementary feeding. Labor (employment) and operating costs also rise with intensification. The degree of intensification that gives the best economic return in a given situation is determined by cost-benefit analysis, but data are currently lacking to carry out more than a cursory analysis of excreta-fed systems. However, impressive fish yields can be attained in well-designed and managed systems fed only with excreta (see Section 5.5.4). The use of relatively cheap cereal brans economically rather than expensive pelleted feed might be expected to be a more viable management strategy in the culture of filter-feeding fish of comparatively low market value in excreta-reuse systems. This would be true under normal circumstances in which fish fetch the same market price irrespective of whether they are raised in excreta-fed or in conventional aquacultural systems, as in China and India. The main drawback is that the addition of supplementary feed of any kind contributes to the nutrient load in the pond water and reduces the effectiveness of the treatment process in the maturation ponds which are commonly the last step prior to discharge of treated water to the environment.

9.3 Case studies

Excreta reuse in aquaculture can be economically viable: it is carried out on a commerical basis in several countries (see Chapter 2). However, there are limited data on commercial excreta reuse systems. Furthermore, the economic assessment of many excreta reuse systems is complicated when excreta are but one of several inputs to the system. There are more data concerning fish production in experimental waste-treatment systems.

9.3.1 Commercial aquaculture systems

9.3.1.1 Overhung latrines in Java

Djajadiredja et al. (1979) conducted an economic assessment of overhung latrines on ponds in Java, Indonesia (Table 9.2) . There was a wide range of mean costs reported from the six villages studied, and a range of 22 percent to 92 percent and a mean of 67 percent rate of return.

9.3.1.2 Night-soil-fed aquaculture in Taiwan

There are some economic data in the literature for night-soil reuse in freshwater and brackish ponds in Taiwan (Kuhlthau 1979, Kalbermatten et al. 1982a), although the reuse of night soil in aquaculture appears to have been recently discontinued in Taiwan (see Section 2.4.2). In the city of Tainan, both public and private collectors removed excreta from vaults and septic tanks. The public system sold night soil for $0.65/ton plus

Table 9.2
Economic Assessment of Overhung Latrines on Fish Ponds in Java.

Input	Minimum	Maximum	Mean	Percent total input
Initial investment[a]	4,700	40,833	19,127	11.2
Building and equipment	1,208	11,007	5,326	3.1
Latrine	1,217	7,287	3,412	2.0
Labor	10,625	70,985	37,624	21.0
Fish seed	15,375	159,036	82,586	48.1
Fish feed	4,857	44,400	19,316	11.3
Fertilizer	0	5,313	1,516	0.8
Irrigation	0	5,000	1,328	0.8
Transportation	0	1,429	345	0.2
Taxes	308	1,800	922	0.5
Total input	**44,047**	**275,035**	**171,502**	**100**
Output	57,600	527,986	285,746	
Net return	13,553	252,951	114,244	
Rate of return (%)	22	92	67	

Source: Djajadiredja et al. (1979)
Note: Cost figures in rupiah ($1 = Rp 625); mean of 29 respondents from six villages.
[a] Cost of pond construction depreciated over 15 percent plus 10 percent yearly inflation.

$0.57/km for transportation, while private collectors sold night soil for $7.00/ton inclusive of transport. The total annual cost per household (TACH) of the public system was $28.85 and sale of night soil during the 10 months of the year when there was a demand for it yielded $1.28 per household. No investment or operating cost figures were available for private collectors. However, the public system must have incurred significantly higher costs and/or charged too little for night soil because private operators must have made a profit on their operations.

Kuhlthau (1979) presented an estimated economic analysis of brackishwater milkfish culture in Taiwan with night-soil reuse, but it is of little relevance to waste-fed aquaculture since night soil represented only 5 percent of the total cost of fertilizer and feed inputs to the system, according to the analysis given.

9.3.1.3 Sewage-fed aquaculture in China

There is also considerable reuse of sewage in aquaculture in China. The operating costs of a sewage-fed fish farm in China were considerably reduced compared to a conventional farm because the development of natural fish food organisms in sewage-fed ponds eliminated the need for artificial supplementary food and its transportation (Zhou 1986). Xiang Lake Fish Farm in Changsha produced 945 tons of fish from 142 ha of ponds in 1983, a yield of 6.7 tons/ha. Workers on the sewage-fed fish farm received twice the wage of city workers. Zhou (1986) also pointed out that the construction of a conventional secondary sewage treatment plant in Changsha would have cost 12-15 times the investment in a sewage-fed fish farm. In addition, the latter could produce 3.8-4.5 t fish/ha/yr with a net profit. Xiang Lake Fish Farm in Changsha recovered the initial investment in 8 years.

9.3.1.4 Sewage-fed aquaculture in India

The largest single system in the world in which sewage is reused in aquaculture is the Calcutta sewage-fed fisheries. Based on data from Calcutta, A. Ghosh et al. (1985) compiled a guide to carp production using domestic sewage. The guide includes the investment and operating requirements for the management for a sewage-fed aquacultural project that covers a total area of 8 ha, including 5 ha of ponds. From the data provided in the report, a cash flow and financial analysis model was produced (Table 9.3). Revenues are generated from the sale of table fish, fingerlings, fry, and freshwater prawns. At the production target for table fish of 7 tons/ha/yr (about 80 percent of projected revenue), the base case financial internal rate of return (FIRR) is 28 percent.

Using a sensitivity analysis where the investment and operating costs are independently increased by 10 percent and the total revenue is decreased by 10 percent, the FIRR drops to 26 percent, 27 percent, and 25 percent, respectively. A combination of the above factors would reduce the FIRR from 28 percent to 21 percent, proving that a project of this kind using the cost and revenue data presented would, from a financial viewpoint, be quite robust and the cash flow quite strong following the first year's negative result. The first year's working capital loan would need to be carried over to the next year as indicated. With the cost and revenue values collectively shifted negatively by 20 percent, the FIRR would drop only to 15 percent. The FIRR should then be compared to the commercial interest rate for medium-term loans. It is also important to note that fish derived from sewage-fed aquaculture in Calcutta fetch the same market price by species as those cultured in conventional ponds that do not use sewage.

The assumption that 7 tons/ha/yr is feasible for a large-scale operation (where the aquacultural activity is required as part of a sewage treatment facility) is probably optimistic. Fish production experience in the Calcutta sewage-fed fisheries has achieved a maximum yield of only 6.9 tons/ha/yr; annual yields on the same farm have been as low as 3.9 tons/ha (Captain Bhery Fishermen's Cooperative Society Ltd., unpublished data). Other farms in the same area have achieved yields only as high as about 2.4-4.0 tons/ha/yr (Mudialy Fishermen's Cooperative Society Ltd., and Nalban Fishery, The State Fishery

Table 9.3
Estimated Annual Cash Flow (Indian rupees, Rs) for a Model of Carp Production Using Domestic Sewage in West Bengal, India

	Year 1	Year 2	Year 3	Years 4-9	Year 10[j]
Production					
Spawn ('000)[a]		4,300	8,600	8,600	8,600
Fry ('000)[a]		1,150	2,300	2,300	2,300
Fingerlings ('000)[a]		15	30	30	30
Table fish (kg)[a,b]		17,500	26,250	35,000	35,000
Prawns (kg)[a,b]		141	212	282	282
Revenue					
Spawn (Rs 2.5/'000)		10,750	21,500	21,500	21,500
Fry (Rs 30/'000)		34,500	69,000	69,000	69,000
Fingerlings (Rs 225/'000)		3,375	6,750	6,750	6,750
Table fish (Rs 12/kg)		210,000	315,000	420,000	420,000
Prawns, 100 g ea (Rs 60/kg)		8,460	12,690	16,920	16,920
Total		**267,085**	**424,940**	**534,170**	**534,170**
Capital Investment					
Sewage distribution & drainage system	100,000				-60,000
Wells with pump, etc.	80,000				-40,000
Living quarters (2 watchmen)	50,000				-30,000
Hatchery, including equipment	50,000				-30,000
Lab & office storerooms	100,000				-2,400
Fencing	100,000				
Electric lines & halogen lights	40,000				-960
Generator	35,000				-1,143
Telephone	5,000				-5,000
Diesel pump system for sewage	10,000				-5,000
Sewage distribution pumps	25,000				-12,500
Tools, nets, hapas, etc.	20,000				-10,000
Fish seed & brood stock to start	15,000				
Earthwork (5 ha water area with dikes)	200,000				-200,000
Land (8 ha @ Rp 40,000/ha)	320,000				-320,000
Total	**1,150,000**	**0**	**0**	**0**	**-717,003**

Table 9.3
Continued

	Year 1	Year 2	Year 3	Years 4-9	Year 10[j]
Operating Costs					
Labor (4 watchmen/yr)		36,000	36,000	36,000	36,000
Labor (6 casual fishermen, 4 mos/yr)		10,800	10,800	10,800	10,800
Labor (farm mgr/yr)		16,500	16,500	16,500	16,500
Pond preparation & maintenance		2,500	2,500	2,500	2,500
Diesel fuel & electricity		7,000	7,000	7,000	7,000
General maintenance		15,000	15,000	15,000	15,000
Spawn production[a]		8,100	8,100	8,100	8,100
Fry production[b]		2,250	2,250	2,250	2,250
Fingerling production[c]		1,620	1,620	1,620	1,620
Market fish/prawn production[d]		2,750	2,750	2,750	2,750
Brood fish maintenance[e]		2,500	2,500	2,500	2,500
Office supplies & chemicals[f]		2,000	2,000	2,000	2,000
Subtotal		107,020	107,020	107,020	107,020
Taxes (Land & structure)		500	500	500	500
Total Costs	1,150,000	107,520	107,520	107,520	-609,483
Net Income Before Debt Service	-1,150,000	159,565	317,420	426,650	1,143,653
Debt Service					
Interest (12%) and principle on 100% of capital investment[g]		209,542	209,542	209,542	209,542
Working capital		60,000	118,977	28,946	
Interest (15%) on working capital		9,000	17,847	4,342	
Net Cash Flow		-58,977	31,054	183,821	217,108
Financial Rate of Return		28%			

Adapted from Ghosh et al. (1985)
a Year 2 yield equals 50% specification.
b Year 3 yield equals 75% specification.
c Pituitary gland (4,000 mg @ Rs 2/mg) and distilled water, saline solution, glycerol, etc., @ Rs 100).
d Lime (500 kg @ Rs 1/kg), pest control & management, and supplementary feed (500 kg @ Rs 1.5/kg)
e Lime (120 kg @ Rs 1/kg), and supplementary feed (1,000 kg @ Rs 1.5/kg)
f Lime (1,500 kg @ Rs 1/kg) and giant freshwater prawn juveniles (5,000 @ 4/Rs 1)
g Supplementary feed (1,500 kg @ Rs 1.5/kg) and disease control chemicals.
h Stationery (Rs 500) and chemicals, disinfectants, soaps, etc. (Rs 1,500).
i Assumes 1 year grace period during construction with loan paid back over 9 years.
j Salvage value of capital investments.

Development Corp., Ltd., unpublished data). That all these farms have had variable yields from year to year has been attributed to insufficient quantities of fingerlings. It would nevertheless be unrealistic to assume that yields as high as the 7 tons/ha/yr target would be achievable on a large-scale basis. Moreover, the current management of the sewage-fed fish farms in Calcutta depends on careful regulation of sewage flow into the ponds to assure high water quality for fish growth. The day-to-day inflow is varied depending on weather conditions and possibly current fish biomass in the pond, both of which have direct impact on water quality. If it would be dangerous to the fish to add sewage on a particular day, sewage is prevented from entering the ponds by use of sluice gates. With an adequate pond area, daily pulsing of sewage inflow may be possible, shifting from day to day from one pond to another, but the fluxes must be predictable in order to create a reliable treatment facility that can consistently accommodate the needs of the populace it serves.

An aquaculture sewage facility should be designed to accept all of the estimated flow from the community it serves. It is postulated that fish yields under these circumstances would be markedly lower since the sewage loading rate should be lower to provide a safety margin and allow for adverse weather and decreases in fish stocks because of periodic harvesting. This design precaution would also require a larger area for the ponds, thereby increasing investment costs concurrent with lower potential revenues. Using the model provided in Table 9.3 with a table fish yield of 3.5 tons/ha/yr with no change in operating costs, the FIRR would drop to 13 percent, which is somewhat below the commercial interest rate. However, more important is the economic internal rate of return. There is no need to prove that the FIRR is greater than the commercial interest rate. Instead, the FIRR should be equal to or greater than the FIRR achieved in other public projects. In addition, assuming 100 percent financing of capital investment and required operating cost advances, there would be a significant negative cash flow, threatening the financial viability of such a scheme. Cash contributions from the community or private operator could offset the cash flow shortfalls to some degree by reducing annual interest payments on loans for capital investments and working capital, but this would not improve the economic viability of such a project. Any wastewater treatment and reuse facility should be consistent in meeting treatment specifications which affect its capacity to protect the environment and its financial viability.

9.3.2 Experimental fish culture in sewage stabilization ponds

Most available economic data relating to sewage-fed fish culture refer to the culture of fish in maturation ponds of existing sewage stabilization ponds. The data pertain to either the experimental culture of fish in such systems or to the economic analysis of fish culture in hypothetical sewage stabilization pond systems.

9.3.2.1 Quail Creek

A cost-benefit analysis was made of the experimental culture of fish in the Quail Creek sewage lagoon system near Oklahoma City (Coleman et al. 1974). (See Section 4.2.3.1 for a description of the fish culture experiments). The economic conclusions were considered tentative because they were based on the first phase of the

Table 9.4
Estimates of Projected Costs and Income from an Advanced Biological Treatment System.

COSTS

180×10^6 gal/six mos X $0.08/1,000 gal	14,400
Additional operational & equipment costs @ $20,000 p.a.	10,000
Fish	
50,000 channel catfish @ $0.04 each	2,000
50 gallons minnows @ $15/gal	750
250 tilapia @ $1 each	250
$27,400/180 \times 10^6$ = $0.15/1,000 gal	**$27,400**

INCOME

50,000 channel catfish @ $0.25 each	12,500
1,200[a] gal minnows @ $15/gal	18,000
18,000 lbs tilapia and bullheads @ $0.06 pound	1,000
$31,500/180 \times 10^6$ = $0.023/1,000 gal	**$31,500**

Source: Coleman et al. (1974)
a Estimated production potential.

However, after the second phase, in which fish were not cultured in the system, it was still not possible to determine if the presence of fish improved water quality. The economic analysis is presented in Table 9.4. A total cost of $0.15/1,000 gallons raw sewage was estimated for treatment to produce an effluent of high quality which surpassed secondary standards. Such an effluent standard was said to be usually attainable only by mechanical advanced treatment technology at a cost of $0.40-0.45/1,000 gallons. Calculations of income were based on local market prices, with sale of catfish and tilapia assumed for human consumption (unlikely in the United States), and that of shiner and fathead minnows as baitfish (Henderson 1982). Fish yields were estimates based on project data and the literature for average yields in fertilized ponds. No further details of the economic analysis were given. Net return was estimated at $ 0.02/1,000 gallons raw of sewage.

9.3.2.2 Benton

An attempt was made to assess the potential value of the fish raised in the sewage stabilization ponds at Benton, Arkansas (see Section 4.2.3.2 for experimental details). Bighead and silver carp were considered for fish meal manufacture with a

conversion efficiency of 18 percent. Since market value for pure fish meal varied from $400/ton to $500/ton, an annual fish yield of 6,546 kg/ha (preliminary study) would produce an estimated gross return of $430-575/ha/yr. However, if the fish were marketed for direct human consumption at $0.55-0.65/kg, the gross return would be $3,600-4,525/ha (Henderson 1979).

9.3.3 Hypothetical studies

9.3.3.1 United States

A detailed study of the economics of aquaculture as a component of sewage treatment technology was conducted by a multidisciplinary team including a biologist, an engineer and two economists (Henderson and Wert 1976, Wert and Henderson 1978). The technique of cost-effective analysis was used to obtain given standards of water quality based on direct market costs. The application of cost-effectiveness analysis to conventional wastewater treatment was well documented, but a major constraint of the study was the lack of adequate data for aquaculture as an additional or alternative wastewater treatment strategy. Reliable information could not be obtained on the relationship between fish and water quality, nor on actual fish yields from wastewater-aquaculture systems. Furthermore, the projected estimates of net revenues from wastewater-aquaculture systems were weakened by the absence of reliable data on market price and market acceptability of produce from such systems in the United States.

The effectiveness of aquaculture to achieve given standards of water quality was obtained from only a single demonstration project, the cultivation of fish in the Quail Creek sewage stabilizations ponds, discussed above. An unsuccessful effort was made to derive a direct correlation between nutrient concentrations in the water and fish yield using the Quail Creek data of Coleman et al. (1974). Since there was no formula available to compute fish yield from water quality data, an indirect method was used. It was assumed that, since most ponds are either fertilized or fed to the maximum level possible to maintain water quality to sustain fish, the nutrient load and therefore the fish yield "should be approximately equal" to that of a sewage stabilization pond stocked with fish. The mean fish yield from data collected from a review of aquacultural literature was assumed to be the maximum yield that could be produced on the average in wastewater-fed aquaculture: 4,199 kg/ha/yr.

All wastewater treatment systems in the hypothetical study were designed for relatively small municipalities with 2,000 people and having an influent of 200,000 gallons/day. Conventional wastewater treatment systems and systems involving aquaculture were selected on the basis of technical feasibility. Fifteen technically feasible sewage treatment strategies were considered: pond aquacultural systems were used in six strategies, raceway aquacultural systems were used in five strategies, and four strategies were solely conventional mechanical, biological, and chemical treatment systems at all stages in the wastewater treatment process (Fig. 9.2). The three types of aquacultural facilities were a three cell aquacultural raceway designed primarily to facilitate fish handling, a single pond

as an additional stage of a conventional system, and a secondary stabilization pond for the direct cultivation of fish.
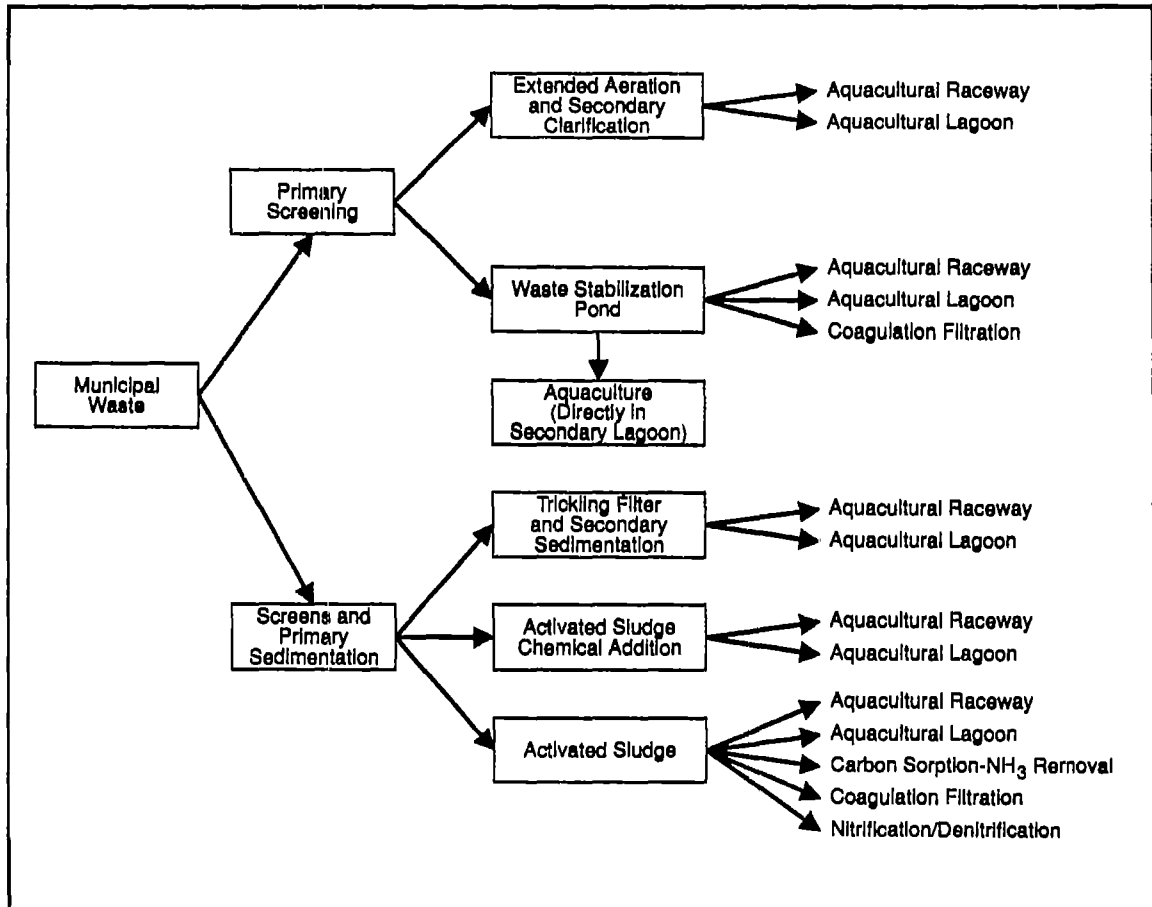
Figure 9.2 Stage processes for alternative strategies (*Source:* Henderson and Wert 1976)

It was assumed that a 5 pond system made up of 3 primary and 2 secondary treatment ponds each of 1.36 ha would be required to treat 200,000 gallons/day of wastewater, with fish cultivated in the secondary stabilization ponds which occupied 40 percent of the total pond area. Although one of the strategies did assume fish cultivation in the secondary ponds, it was emphasized that this could be achieved only under ideal conditions because of danger to fish from oxygen depletion, heavy metals, or pesticides, and would be less reliable than cultivation of fish in tertiary ponds or raceways. Fish yield was assumed to be a linear function of water quality, and fish yields were based on the resulting water quality from the wastewater treatment phase prior to the aquacultural phase. The water quality data were derived from those of the Quail Creek stabilization pond system. It was stressed that the data were highly tentative, but it was felt that they were useful for comparative purposes and to define the potential of wastewater-fed aquacultural systems.

Economic analysis of the different strategies was based on three criteria:

▶ Multiple objective levels of water quality for BOD_5 and suspended solids, with EPA secondary treatment standards as a minimum objective.

▶ Multiple objective levels of water quality for the removal of plant nutrients.

▶ Tertiary treatment objectives for BOD_5, suspended solids, and nutrient removal.

It was assumed that the aquacultural produce was marketable, although not for human consumption. The price used in the study was $2.24/kg, the average price received by commercial fish growers for all production in 1974 in Oklahoma, and assuming that the fish were sold for bait, minus the cost of stocked fish.

The least-expensive system was the stabilization pond system with fish cultivated directly in the secondary ponds, but it did not meet any water quality standards because of high suspended solids of 70.9 mg/l.

Aquacultural strategies were all more cost-effective than conventional alternatives when aquaculture was able to achieve desired BOD_5 and suspended solids removal rates, with cost differentials between aquaculture and conventional strategies ranging from 4 percent to 72 percent. The same applied to nutrient removal, with cost differentials ranging from 38 percent to 94 percent. The most cost-effective system to meet tertiary levels was activated sludge with carbon sorption and ammonia removal, but it was cost effective only because it was the only strategy capable of meeting such a high standard. A major conclusion of the study was that the strategy with primary and secondary stabilization ponds and a final aquacultural pond was the most cost-effective system to meet current secondary standards. The costs for this system were only 28 percent of the cost of using the most cost-effective conventional system, extended aeration, to achieve the same level of wastewater treatment.

Cost estimates were also made on the basis of the most pessimistic possible net revenues generated, net revenues of zero from the aquacultural system because of the tentative nature of the aquacultural data, that is, revenue from the sale of aquacultural produce equal to the cost of stocked fish. It was found that those systems that were cost-effective with positive net revenues were also cost-effective with zero net revenues. This implies that the major benefits of wastewater aquacultural systems are their ability to improve water quality relative to costs of treatment. The analysis also indicated that aquaculture cannot be expected to cover the costs of treating wastewater, only to reduce treatment costs.

The economic value of wastewater aquaculture is in cost savings relative to conventional systems and not in the market value of the aquatic produce, even when net

revenues of produce are zero. It was concluded that at this stage of our knowledge, aquaculture-wastewater treatment systems are economically viable alternatives to conventional systems and should be considered for achieving effluent standards at minimum cost. Although waste stabilization ponds require a larger land area than physicochemical techniques of wastewater treatment, aquaculture may increase the effectiveness of stabilization ponds so that such ponds stocked with fish should require less area. A constraint is the high degree of technical expertise and knowledge of aquaculture needed to operate a wastewater-aquacultural system. However, it would instil public confidence in a wastewater treatment system if it were able to be used for fish culture. Ponds are attractive structures that do not distract from the natural surroundings.

The hypothetical study discussed above was most positive in concluding that the revenues generated by aquaculture were highly significant and substantially reduced the costs of treatment, construction, and operation, although it was stressed that it must be used only as a first estimate of the probable magnitude of the economic viability of these systems because of the tentative nature of estimated fish yield. However, the theoretical design was flawed because it did not consider a system of well-designed stabilization ponds alone to achieve the desired effluent standards in the 15 wastewater treatment schemes. Furthermore, the ability of fish stocked in maturation ponds to improve sewage stabilization pond effluents remains to be conclusively demonstrated. In the wastewater treatment scheme with an extra lagoon stocked with fish, effluent standards may have been achieved *without* fish at a lower cost.

9.3.3.2 World Bank

Arthur (1983) presented an economic assessment of the benefits of fish culture in the maturation ponds of a sewage stabilization pond system. He used design assumptions to give a generalized case for a typical developing country. The following design assumptions were made:

Contributing population	250,000
Wastewater contribution	120 lcd
Average daily wastewater flow	30,000 m³/d
Per capita BOD_5 contribution	40 gcd
Average daily BOD_5 load	10,000 kg/d
Controlling temperature	20°C
FC concentration in raw sewage	2×10^7 FC/100 ml
Effluent standard for BOD_5	25 mg/l

Pumping required to inlet
works and for irrigation

• Waste stabilization pond system assumptions:

Depths: anaerobic ponds   4 m
         facultative ponds   1.8 m
         maturation ponds   1.5 m

Two parallel streams of ponds
Total site area required 46 ha.

• Capital costs in $'000:

	Land	Earthworks	Structures	Equipment
Waste stabilization ponds	2,300	2,300	2,500	200

Total capital costs,
including land for
each system, were
estimated to be: $7.3 million ($29 per capita, $20 per capita excluding land)

Land costs were assigned to year zero, so that the present value of land was equal to its actual cost. Subsequent capital spending was then spread between years two to five, after which any operating costs or benefits were expected to commence. On this basis, the capital cost of the waste stabilization pond system had a present value of $5.68 million.

Land was assumed to cost $5 per m², reflecting the reasonably low existing use value necessary to enable the land to be purchased for a low-cost housing development. Inexpensive land is a prerequisite of low-cost housing schemes since they must be affordable to the intended beneficiaries. This example assumed the treatment system was intended to serve such a development.

Operational costs, including power consumption, for the waste stabilization pond system were assumed to be $50,000 per year ($0.20 per capita).

The maturation ponds in the waste stabilization pond system were used for fish farming. If 18 ha of pond were used for fish culture in each case (39 percent of total pond area) with a productivity of 4,000 kg fish/ha/yr, a total fish yield of 72 mt/yr might be achieved. With the fish "conservatively priced" at $1/kg, an income in the first year of $72,000 was estimated.

Bringing the operation and maintenance (O & M) costs and income derived from fish farming to present values, using 12 percent as the opportunity cost of capital (subsequently referred to as discount factor) gave:

```
              O & M cost      Fish culture income
              -------  ($ million)  -------

                 0.4                  0.5
```

These figures are present values in $ million over 20 years commencing in year 5, but to find their present value at year zero they must be multiplied by a discount factor of 0.57 (that is, the present value of 1 spent 5 years from now at a discount rate of 12 percent).

The table is then converted to:

```
O & M cost    Fish culture income        Net

  - 0.21              + 0.30            + 0.09
```

These figures are present values in millions of dollars over 25 years; the actual operating and benefit costs would accrue in years 5-25, but the cost streams were discounted to year zero. Thus, net present values for the waste stabilization pond system were calculated as follows:

		($ million)
Costs:	Capital cost (inc. land)	5.68
	Operating cost	0.21
Total		5.89
Benefits:	Fish Culture income	0.30

Net present value: -$5.59 million (Fish reduced costs by 5.1 percent)

9.3.3.3 AIT Chonburi

A study was made of the economic, instutional and technical implications of alternative urban sanitation and reuse options for Chonburi, a typical medium-size town in Thailand (AIT 1988). Fish culture was economically viable in the maturation ponds of a sewage stabilization pond system comprising anaerobic, facultative and maturation ponds designed primarily for sewage treatment. The yields of tilapia stocked in the maturation ponds were assumed to be 7 tons/ha/yr, the same as obtained in experimental septage-fed ponds on the AIT campus. Fish were assumed to be stocked once every five years at an initial density of 1 fish/m^2 of pond surface area. Monthly harvesting of the freely breeding population was assumed by middlemen who used their own labor and harvesting equipment. It was assumed that there was no sludge accumulation in the maturation ponds but that ponds were drained every five years for general maintenance. The market value of the tilapia was assumed to be only $0.12/kg, for animal feed, because of a social acceptability problem in the direct human consumption of sewage-raised fish in Thailand. The economic analysis is presented in Table 9.5.

Table 9.5
Fish Culture in Hypothetical Sewage Stabilization Ponds in Chonburi, Thailand

Sewage load = 20,663 m³/day   BOD₅ = 4,400 kg/day
Anaerobic pond size = 3,800 m²   Facultative pond size = 40,000 m²
Maturation pond size = 68,900 m²   Total pond size = 113,100 m²
Total size of site ≈ 150,700 m²
Tilapia yield = 48,230 kg/yr
= 7 tons/ha/yr

Sewage load = 20,663 m^3/day   BOD$_5$ = 4,400 kg/day
Anaerobic pond size = 3,800 m^2 Facultative pond size = 40,000 m^2
Maturation pond size = 68,900 m^2 Total pond size = 113,100 m^2
Total size of site ≈ 150,700 m^2
Tilapia yield = 48,230 kg/yr
= 7 tons/ha/yr

	Description (unit)	Unit cost ($)	Quantity	Investment cost/rev ($)	Quantity	O & M cost/rev ($)
COSTS						
Treatment System						
Land (purchase)	m^2	3.75	150,700	**565,125**		
Construction and other						
Plant site, office, lab, pump room		20,000		20,000		
Laterite road	m	3.84	750	2,880		
Pond excavation	m^3	2.20	99,270	218,394		
Compacting dikes	m^3	2.40	5,972	14,333		
Piping		lump sum		20,000		
M & E works		lump sum		20,000		
Contingencies, administrative costs, taxes, profit, professional fees (40%)				118,243		
Subtotal				**413,850**		
Operation & Maintenance						
Labor: persons @ $1,280 p.a.					4	5,120
Pond maintenance 2% of total capital cost						8,277
Subtotal						**13,397**

Table 9.5
Continued

	Description (unit)	Unit cost ($)	Quantity	Investment cost/rev ($)	Quantity	O & M cost/rev ($)
Aquaculture						
Labor	persons	$840/yr			1	840
Tilapia fingerlings	each	$0.012			13,780	165
Subtotal						1,005
Total Investment Cost				**$978,975**		
Annual O & M Cost						**$14,402**
Revenues						
Tilapia as animal feed	kg	$0.12			48,230	5,788

Analysis
Assumed life of system   25 years
Total investment cost $978,975
Total O & M cost after
  25 years $360,050
Total cost after 25 years $1,339,025
Total revenue after 25 years $144,700

Fish Production
Revenue as percent of total cost   10.8%
Revenue as percent of capital cost 14.8%
Revenue as percent of
  O & M cost   40.8%
Revenue in $/m³ sewage $0.0008
Production in kg/m³ sewage   0.006 kg

9.3.3.4 AIT septage reuse

A study was made of the financial and economic feasibility of a proposed septage reuse system for the Bangkok metropolitan area based on experimental data (Edwards et al. 1987). The scheme involved the cultivation of Nile tilapia in septage-fed ponds and the use of the tilapia as high-protein animal feed for carnivorous fish of high market value. It was surmised that the use of tilapia as animal feed for more valuable carnivorous fish might be compensated for by the higher market price of the latter. The

system was not financially viable because of negative profit margins and NPVs with no rate of return on capital.

The proposed system was also analyzed as part of a complete septage collection, transportation, and disposal system as well as under private-sector ownership. Substantial savings could be made by the installation of the proposed system compared to the currently used activated sludge method. If the Bangkok Metropolitan Administration (BMA) were to install the proposed system to dispose of the estimated 600 m³ of septage collected daily, it would save $0.843 million to $0.644 million on capital costs and $0.633 million to $0.729 million on annual net operating costs for septage reuse to tilapia for sale as animal feed, or septage reuse to culture tilapia as feed for walking catfish and sale of walking catfish, respectively.

The culture of tilapia on septage as direct human food was not considered socially feasible in Thailand. A theoretical analysis of alternative septage stabilization pond systems indicated even greater potential cost savings. In view of relatively high labor costs and low market value of tilapia as animal feed in central Thailand, the best system for the BMA to dispose of septage may be a stabilization pond system with anaerobic, facultative, and maturation ponds designed solely for septage treatment, without aquacultural reuse. However, sensitivity analyses indicated that septage reuse in aquaculture may be aneconomically attractive option in countries with relatively low labor costs and high market prices for fish.

9.4 Economic and financial costing of sanitation technology

Once the sanitation technologies that are technically and socially acceptable to a community have been selected, an objective comparative economic costing based on the actual physical conditions of the community should be made to aid planners and policy makers in the selection of the most appropriate technology (Edwards 1985). The technique of cost-benefit analysis is used to derive the net contribution of the project to the national economy. The application of costing principles to sanitation projects is difficult because little is known about the technology or costs of nonconventional sanitation options. Another problem with identifying the most appropriate sanitation technology is that it is difficult to quantify most of the benefits of a sanitation program, for instance, improvements in public health and user convenience. However, excreta reuse may be quantified, and a sanitation option with a significant reuse component may be economically more feasible than one without resource recovery. An excreta reuse system would also create employment.

It is difficult to generalize in determining costs for a particular sanitation technology option because of considerable variations between countries for costs of unskilled labor, land, water, and materials, the main inputs to sanitation systems. The single most useful figure for cost comparisons of technologies is the total annual cost per household (TACH), which includes both investment (mainly capital) and recurrent costs (mainly labor).

A distinction between investment and recurrent costs is important for both technical and financial reasons. A community with limited financial resources might find it impossible to raise the investment finance to construct a system with a large initial capital requirement, but could afford to build and maintain a system with the same TACH but with relatively high recurrent costs. Since most developing countries with poor sanitation have plenty of relatively cheap labor, cartage systems are generally preferable to sewerage from a financial point of view since the latter have higher recurrent costs. A further advantage with systems having high recurrent costs is that they have considerable scope for reducing costs in response to decreasing demand since investment in new trucks can be delayed and fewer workers hired. Systems with high investment costs have little scope for reducing costs in response to reduced demand since construction of facilities is completed relatively quickly.

While economic costing of a particular sanitation option is of interest to planners, a consumer is more interested in financial costing, that is, what he will be asked to pay for the system and how the payment will be spread out over time. Financial costs are subject to interest rates, loan maturities, government subsidies, etc. The financial cost of a sanitation system to the consumer could be zero if the government pays for it out of the general tax fund. For most on-site sanitation systems, the consumer is usually expected to pay for construction of the original facility, in a lump sum or through a loan at an interest rate which reflects the opportunity cost of the capital, and then pay a periodic sum to cover operation and maintenance costs, if any; in this case financial and economic costs would be similar.

The government may be willing to subsidize part or all of the construction costs of a simple sanitation system to satisfy the basic sanitation needs of the population. Construction costs in the market place should be annuitized over the life of the facility at the prevailing market interest rate. If self-help labor can be used for part of the construction, the cost of hiring that labor should be subtracted from the total before annuitizing. Any operating and maintenance costs should be added to the total base financial cost and compared with household incomes to check affordability. If the technology is considered to be affordable by the target population, then financial arrangements can be made to help consumers to get loans from banks. If the technology's base financial cost is not affordable, then there would be a need to compute an alternative set of financial costs which include a financial subsidy, or to choose a less expensive technology.

Pilot projects for various excreta reuse options should be set up to determine the economic value of resource recovery in each case. These would have a significant bearing on determining financial costing of sanitation options. Depending on the economic viability of a particular excreta reuse option, the consumer may be able to sell excreta to either the government or the private sector for resource recovery. The sale of excreta could provide a financial incentive to use the toilet facility and defray construction and maintenance costs. To use a toilet when one has not been used previously, a person needs to perceive a tangible benefit. The financial return on sale of excreta or the products of the recycled excreta may provide such an incentive to maintain the toilet system.

Municipalities normally lack the incentive and entrepreneurial skill to manage a revenue-generating operation. Since good management is needed to organize the collection, delivery and distribution of excreta in an aquacultural excreta reuse system, and then to manage, harvest, and market the produce, it may be wise for a municipality to contract out the waste reuse part of the system to the private sector.

It is often stated that a municipal reuse scheme should not be considered as a profit making operation, but merely a way to reduce costs and motivate persons to cooperate in sanitation schemes by demonstrating a tangible benefit. It therefore follows that an economically appropriate test of a reuse system is not whether it makes a profit, but rather that its net cost should be lower in terms of discounted cash flow than that of other sanitation options. If the private sector is to be involved, the municipality may have to pay the private firm a commission, based on the lowest competitive bid, rather than expect to sell a franchise.

9.5 Summary

There is a scarcity of economic data on the reuse of excreta in commercial aquaculture. This applies particularly to large-scale systems and systems involving the reuse of sewage. Most of the economic data in the literature refer to either experimental or hypothetical reuse systems.

There is a dichotomy in emphasis in excreta reuse in aquaculture. Most economic data refer to the production of fish in sewage stabilization pond systems designed for optimal waste treatment using a minimum amount of land rather than using excreta as a pond fertilizer to maximize fish production on a larger area of land. It is suggested that the latter be considered as a possibility when assessing the feasibility of excreta reuse (see Section 5.2.5, Designs for optimal treatment or reuse). The reuse of excreta for maximal fish production may be viable in societies with low land and labor costs and high market prices for fish.

The limited data available do not indicate that fish have a major impact on water quality, that is, fish may not have an appreciable positive effect on the attainment of effluent standards. It may be more realistic at present to consider that the only positive benefit of fish in waste treatment systems is the production of fish itself as a potential economic crop that can reduce the cost of treatment.

A constraint to the reuse of excreta in aquaculture is the relatively low market prices of fish raised in such systems compared to carnivorous fish. Fish prices would be even lower in those societies in which fish raised in excreta-fed systems cannot be consumed directly as human food because of cultural aversion to such a practice and the fish have value only as high-protein animal feed.

The limited data in the literature suggest that the economic benefits from sale of fish from excreta reuse systems are usually small compared to the overall expense of the

wastewater treatment system, although net returns may be significant if only the aquaculture component is considered (Duffer and Moyer 1978). Clearly, aquaculture-excreta reuse systems cannot be expected to pay for sewage treatment (Wert and Henderson 1978). In the Chinese study reported by Zhou (1986) in which the initial investment in a sewage-fed fish farm was recovered in eight years, a full budget analysis may not have been done. However, if they facilitate more efficient excreta collection, they should lead to reductions in both environmental pollution and unsanitary disease, and augment food production.

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