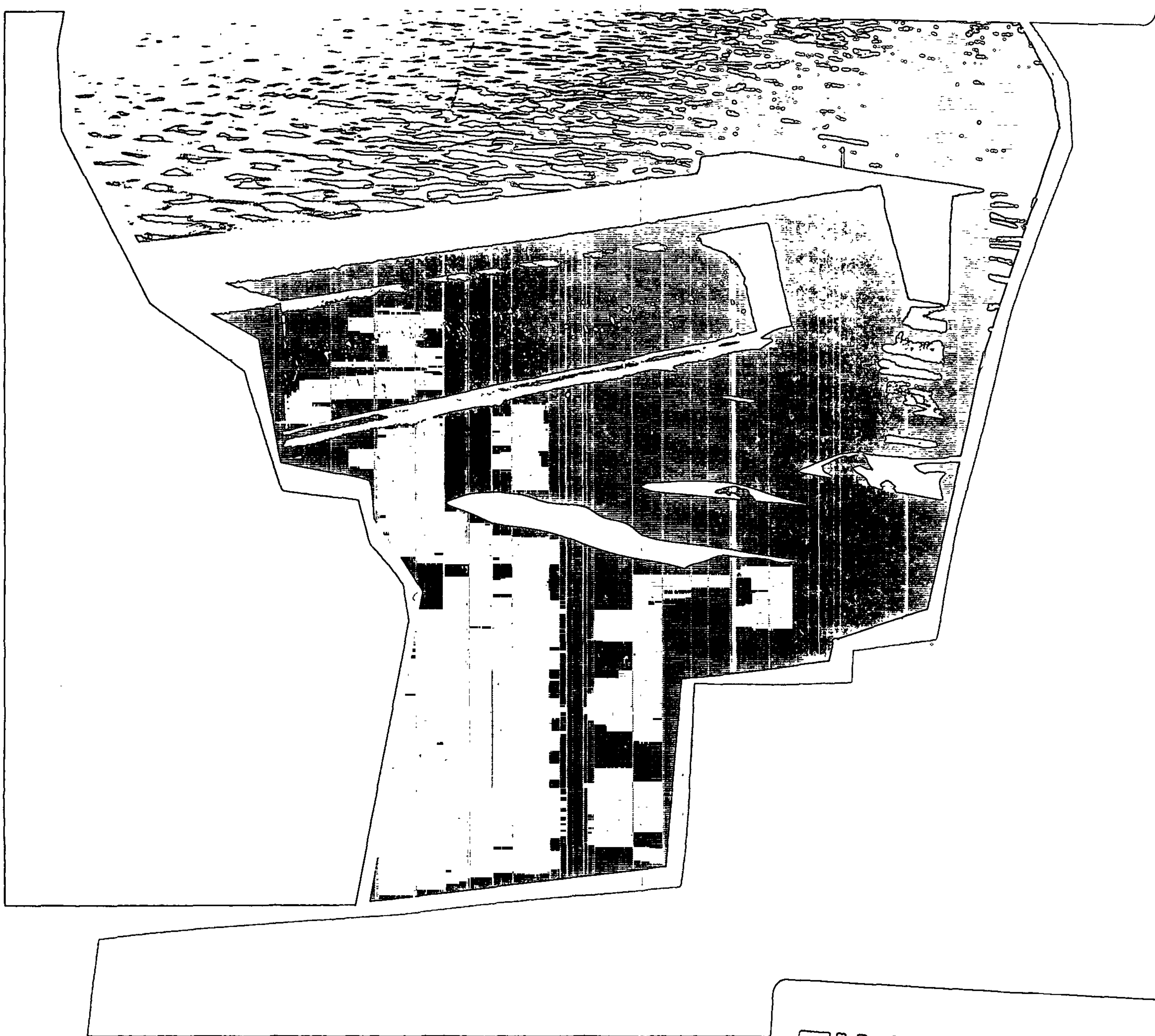
WORLD BANK TECHNICAL PAPER NUMBER 7

Notes on the Design and Operation of Waste Stabilization Ponds in Warm Climates of Developing Countries

J.P. Arthur



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The World Bank
Washington, D.C., U.S.A.

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First printing: April 1983
Second printing: September 1986

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Library of Congress Cataloging in Publication Data

Arthur, J. P., 1953-
Notes on the design and operation of waste stabilization ponds in warm climates of developing countries.

(Urban development Department technical paper ; no. 6)
(World Bank technical paper ; #7)
"November 1982."
Bibliography: p.
1. Sewage lagoons. 2. Underdeveloped areas--Sewage disposal. I. Title. II. Series: Urban development technical paper ; 6. III. Series: World Bank technical paper ; no. 7.
TD746.5.A78 1983 628.3'51 82-23707
ISBN 0-8213-0137-3

ACKNOWLEDGEMENTS

The effort to develop these design notes was directed and guided by David Cook, Engineering Adviser, Urban Development Department, World Bank.

Appendix 3, "The Israel Experience," was largely the contribution of Shaul Streit, a consultant with Tahal (Tel Aviv).

This work could not have been undertaken without the cooperation and help of staff in the countries visited as part of this project and in particular, a record of thanks should be made to the following:

Manila:	Col. Antonio Fernando Eduardo Arguilles Rosalinde Sotelo
Calcutta:	Mr. A.C. Gangully Mr. S.K. Roy Mr. P.M. Dutta Mr. S.K. Basu Mr. M.K. Nag
Israel:	Mr. Meir Ben Meir
Nairobi:	Mr. Peter Karimi Mr. Joe Nguigute
Lusaka	Mr. P. Muyangwa Mr. Leonard Sepiso Mr. M.C.S. Raju Mr. S.O. Mensa
Kingston:	Mr. A. Sailsman Mr. F. Lyn Mr. F. Rose Mr. R. Foster

Technical Review

The technical content of the paper was reviewed by Professor Duncan Mara (University of Leeds, England) and his amendments and suggestions for improvement are appreciated and acknowledged. Contributions have also been made by a number of the World Bank's advisory and projects staff, and by Mr. Jeremy Lumbers (Imperial College, London, England).

FOREWORD

The problems associated with the disposal of domestic and other liquid wastes have grown with the world's population. The problems are particularly acute in developing countries where only 32% of the population have adequate excreta and sewage disposal services and the situation is worsening. In the next twenty years, over one billion LDC citizens are expected to join those already living in urban areas and this will be paralleled by a large increase in rural dwellers. The situation becomes more complicated when one realizes that the people requiring sanitation services will be very poor.

The World Bank has already taken the first step towards developing an appropriate sanitation technology related to waste service levels and incomes 1/, and these notes take the treatment of offsite sewage in stabilization ponds a stage further.

This technical note prepared by the Urban Development Department, World Bank is one of a series aimed to assist both Bank Staff and country staff working in agencies in developing countries. The objectives are to assist and improve feasibility work, develop an awareness for effluent reuse and improve the design, operation and performance of stabilization ponds.

Anthony A. Churchill
Director
Urban Development Department
World Bank

1/ Technical Series--appropriate technology for Water Supply and Sanitation; Transportation, Water and Telecommunications Department, World Bank.

PRINCIPAL NOTATION

A	Mid depth area	ha
B	Fecal coliform concentration	Nos /100ml.
K	First order BOD_5 removal rate constant	day^{-1}
K_B	First order FC removal rate constant	day^{-1}
$K_{B(T)}$	First order FC removal rate constant at temperature T.	day^{-1}
L	BOD_5 concentration	mg/l
Q	Flow rate	m^3/day
T	Temperature (minimum monthly mean)	^oC
t	Time	
t*	Detention time	days
	Loading rate λ	kg BOD_5/ha/day or kg BOD_5/m^3/day

Subscripts

i influent concentration
e effluent concentration
s surface
v volumetric

Abbreviations

BOD	biochemical oxygen demand
BOD_5	5 day biochemical oxygen demand at 20^oC
FC	fecal coliforms
gcd	grams per capita per day
LDC	less developed country
lcd	liters per capita per day
SS	suspended solids

ABSTRACT

The paper acknowledges that water carriage sewerage systems are not always the most appropriate sanitation solution for the disposal of liquid domestic wastes in developing countries. However, where water carriage systems are proposed, the first treatment option which should always be considered is the use of stabilization ponds, because in many instances, they represent the most cost effective and efficient way of treating domestic sewage flows.

The paper results from a review of pond systems installed in six countries and concludes that: (i) designs differ widely; (ii) maximum use is not made of anaerobic ponds or the reuse potential of effluents; (iii) pond systems are frequently grossly overdesigned and (iv) the designs are not responsive to the incremental growth encountered in LDCs.

Practical design criteria are given for pond systems over a range of ambient temperature conditions and end use requirements together with notes on start up procedures, operation and trouble shooting.

The recommendations are derived in part from the Israeli experience where considerable use is made of treated sewage effluent for irrigation purposes.

NOTES ON THE DESIGN AND OPERATION OF WASTE STABILIZATION PONDS IN WARM CLIMATES OF DEVELOPING COUNTRIES

CONTENTS

Page No.

APPENDICES

Tables

Figures

Photographs

CHAPTER 1

BACKGROUNDS, OBJECTIVES AND FACTORS AFFECTING CHOICE IN SEWAGE TREATMENT

Background

The basis of this report is a review of some waste stabilization ponds installed in the following countries, the majority of which were constructed with World Bank financial support.

Philippines, Manila:	Dagat Dagatan Pond System
India, Calcutta:	East Calcutta Waste Treatment and Recycling System
Israel:	Review of pond systems in 19 towns
Kenya, Dandora:	Waste Stabilization Pond System
Zambia; Lusaka, Ngwewere	Waste Stabilization Pond Systems
Jamaica, Spanish Town:	Waste Stabilization Pond System

The detailed findings resulting from the field visits are given in Appendix 2. In summary they indicate that there is a wide diversity in the designs adopted, insufficient consideration has been given to the use of anaerobic ponds and little attention has been given to incremental development and slow build up of flow.

Discussions with staff responsible for sewage treatment in developing countries indicate that there is a need to summarize the practical experiences in designing, locating, constructing and operating waste stabilization pond systems in developing countries which will be useful both to nontechnical personnel as well as sanitary engineers. These notes are intended to address this need.

Objectives

The objectives of this paper are to highlight the advantages of using stabilization pond systems for the treatment of domestic sewage effluent in developing countries and to prepare simple design guidelines which will enable potential users to:

1. Develop "rule of thumb" techniques for the amount of land required, undertake preliminary design calculations and review feasibility work;

2. develop an awareness of opportunity for effluent reuse;

3. brief and control "in house" staff or consultants designing pond treatment systems;

4. improve the design, operation and performance of waste stabilization ponds.

These notes recognize that the design of stabilization ponds in developing countries is still evolving. They are not to be considered as the last word or a definitive statement; they reflect the practical aspects of the state of the art as perceived by the author. At best they are no more than a guide to designer's thinking and approach. They are not to be taken as a substitute for engineering judgment which can only be taken after local climatic, social, economic, financial, technical and political factors have been fully assessed and evaluated.

Factors Affecting Choice in Sewage Treatment

Conventional Treatment. Sewage treatment plants frequently involve the use of energy intensive mechanical treatment systems such as those most commonly installed in industrialized nations. While these systems offer a solution to liquid waste treatment problems, they are only one of many options open to sanitation planners in LDCs. The unfortunate fact is, that the historical reasons and climatic conditions which led to the development of these sewage treatment process are not generally relevant in developing countries. These plants are not only energy-intensive, but also costly to operate, require skilled operators and generally lead to a sludge disposal problem. 1/

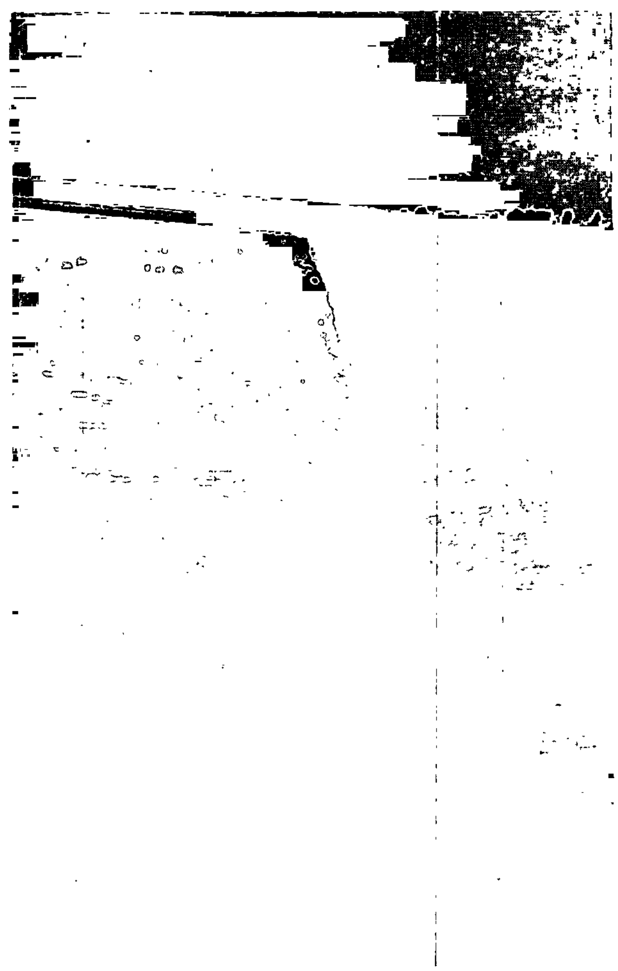
The thinking behind conventional sewage treatment has led to other problems related to treated effluent standards in LDCs. In Europe the standards are usually concerned with Biochemical Oxygen Demand (BOD) 2/ and suspended solids (SS); they arose from the need to reduce the organic loading of the sewage effluent to a level at which it places a suitably low demand for dissolved oxygen in the receiving water course (i.e., limits oxygen depletion to a level which will not endanger fish stocks). In addition, conventional plants do not provide for any significant degree of pathogen removal (which is very important in LDCs) unless a tertiary treatment process such as maturation ponds or chlorination is incorporated. However, effluent chlorination can lead to its own batch of problems and is not generally recommended.

1/ Sludge treatment and disposal can account for up to 50 percent of the total cost of conventional sewage treatment.

2/ See Chapter 2 for a discussion of BOD.

Photo 1. In this facultative pond, the absence of a hard edge detail and poor embankment maintenance resulted in the growth of excessive amounts of weeds, which, in turn, became a breeding ground for mosquitoes.

Photo 2. By contrast, this facultative pond at Dandora, Kenya (near Nairobi), has a good hard edge and reasonable embankment maintenance.



Waste stabilization pond systems. It has long been accepted that tropical and subtropical climates provide an ideal environment for the natural treatment of sewage in ponds. 1/ By detaining raw sewage in a series of shallow ponds for say, two to three weeks, a significant level of both BOD and pathogen removal can be achieved. The natural action of warmth and sunlight promotes the rapid growth of micro organisms which remove BOD both aerobically (in the presence of oxygen), and anaerobically (in the absence of oxygen).

Alternative arrangements of pond sizes and depths can be used to promote either aerobic or anaerobic activity. The resultant effluent will be nutrient rich through its high algal content but will be low in excreted pathogens and other fecal organisms. This is particularly relevant in hot climates where the spread of gastroenteritic and other diseases by excreted pathogens presents very serious problems particularly in densely populated urban areas.

Factors Affecting Choice. Providing sufficient land is available at reasonable cost and proximity, the case for choosing stabilization ponds for sewage treatment in LDCs is overwhelming. BOD and pathogens can be removed from sewage at less capital and operating cost than in conventional plants, and ponds are particularly effective where maintenance skills are limited, since maintenance can be carried out by unskilled labor under minimal supervision. Moreover, conventional sewage treatment plants require regular sludge removal resulting in a demand for large areas of drying beds or sophisticated and expensive sludge disposal facilities. On the other hand, anaerobic ponds will only require desludging every two or three years, and facultative and maturation ponds are generally capable of functioning satisfactorily for over 20 years before sludge buildup reaches a level that necessitates its removal.

The effluent from waste stabilization ponds is rich in nutrients through its high algal content, which can be recovered by direct irrigation 2/ or even by harvesting the algae to produce food for animals or for fertilizer, although simple methods of algal removal are yet to be developed. Alternatively, with careful design and good monitoring the tertiary and subsequent ponds can be used for aquaculture. Various fish,particularly carp and tilapia, thrive in the algal rich environment of these ponds and yields of up to 10 metric tons of fish per hectare per year have been recorded. On the other hand, effluent from conventional plants is seldom suitable for agricultural reuse due to its high pathogen content, unless costly tertiary treatment processes are incorporated. If chlorination is used it may be relatively ineffective and the after-effects may even be detrimental to crops.

1/ They also function well in temperate and very cold climates and are extensively used in North America.

2/ 1,000 m^3 of effluent, i.e., the discharge from a settlement of 15,000 people using 80 liters of water per day, can irrigate between 25 and 50 hectares of land depending on crop, soil conditions and climate, etc.

Some authorities and consultants have rejected ponds in the past on the grounds of odor nuisance and the risk of fly and mosquito breeding; these are not valid reasons for the rejection of ponds because: (a) odor problems can occur in any type of system where maintenance is neglected; and (b) fly breeding can be less of a nuisance in pond systems than in badly maintained conventional plants. Well designed operated and maintained pond systems will not cause odor problems. The simple maintenance function of removing surface scum and preventing vegetation from growing down into the ponds will preclude the creation of an environment suitable for fly and mosquito breeding. Flies breeding in the crust which forms on anaerobic ponds can be controlled by spraying with chemicals.

Pond systems have responded well even when overloaded beyond their theoretical design loads. An example is the ponds at Dandora, Nairobi. Originally designed as a treatment system to serve 200,000 persons, the ponds in 1981 were coping with a treatment load from 400,000 persons and still discharging an effluent of higher quality than the receiving watercourse with only minor modification to the plant. To a certain extent this represents overdesign, but it also demonstrates the resilience of pond systems.

The use of aerators, whilst costly and power-intensive, can theoretically provide another option for coping with increased flow when there is insufficient land available to extend the natural treatment process. Where facultative ponds become overloaded they could, with careful design, be converted into aerated lagoons by the installation of mechanical aerators. Although this option may be considered as a possible safety valve it could create difficulties for the responsible agency in terms of increased cost and complexity of plant operation and maintenance procedures. Furthermore, recent research suggests that health hazards can be caused by the aerosol effect releasing pathogens into the air. (1)

Overloaded anaerobic or facultative ponds can cause odor problems, but these may be resolved by:

1. providing mechanical aeration as outlined above for facultative ponds;

2. recirculating effluent from a downstream pond, in a ratio of up to 1:1, 1/

3. making physical changes to the way in which the pond system operates, to re-establish loading rates consistent with satisfactory facultative or anaerobic operation;

1/ In a personal communication Shaul Streit indicates that in Israel, recirculating 15-25 percent of secondary algal laden pond effluent to the inlet of the primary anaerobic pond has substantially overcome odor problems where these have been encountered.

4. odor may also be caused by floating algal mats on facultative ponds. This may be avoided by regular breaking up of these mats as they form, as part of the routine maintenance duties.

Objections to the use of ponds have occasionally been raised on the grounds of increased risk of schistosomiasis (bilharzia). In fact, ponds do not provide an environment suitable for the snail host which prefers relatively unpolluted waters. Furthermore, unlike fresh water lakes, ponds create few opportunities for human/water contact, and in the unlikely event of cercariae emerging in the ponds they can only survive for up to 48 hours. Thus there is little or no opportunity for conditions suitable for the transmission of this disease to become established.

If burgeoning urban growth results in pressure to resite and redevelop the sewage treatment works, then the cost of closing down a pond system and building a new system is not exhorbitant. The land area released can be used for urban development almost immediately. The cost of closing down and rebuilding a conventional plant however is considerable. The land area released is less than with ponds, and the expense of breaking out and removing the old concrete structures makes the site costlier to develop.

CHAPTER 2

COMPOSITION OF SEWAGE, EFFLUENT STANDARDS AND POND TREATMENT THEORY

Composition of Sewage

Domestic sewage consists mainly of feces, urine and sullage, and is approximately 99.9% water and 0.1% solids. These solids are about 70% organic (mainly proteins, carbohydrates and fats) and about 30% inorganic (mainly grit, salts and metals). (2) The large number of chemicals present in sewage makes it impossible to list them all, which is why sewage is generally characterized using other parameters. Industrial and commercial waste will generally differ from domestic wastes in the proportion of organic materials and inorganic salts present in the sewage. This may take the form of a high organic content or a high proportion of salts. The high organic content may be easily biodegradable (such as slaughterhouse or milk processing waste) or not readily biodegradable (such as textile industry waste). The organic and inorganic strength of sewage will depend on water usage, since a low water consumption will result in a "stronger" sewage. It will also depend on the degree of groundwater infiltration into the sewerage network.

Organic Strengths of Sewage

The organic strength of sewage is normally expressed in terms of the oxygen demand exerted by the waste matter during oxidation. The most commonly used parameters are Chemical Oxygen Demand (COD, where wastes are oxidized chemically), and Biochemical Oxygen Demand (BOD, where the wastes are biologically oxidized through bacterial degradation). The oxygen demand after five days of biodegradation is the parameter most commonly used (BOD_5) since this can be measured in a reasonably short period of time and generally has a fairly consistent relationship with the ultimate biochemical oxygen demand (BOD_{ult}). The BOD 1/ contribution per capita can vary from around 25 grams/day in African developing countries to about 60 grams/day in the U.S.A. and Western Europe. These figures include sullage which has a far greater impact than dietary variations on the BOD of the sewage. 2/ In fact the quantity of feces produced per capita in developing countries tends to be greater than that produced in the developed world in wet weight terms (averaging 400 grams as opposed to about 150 grams). However, due to the higher protein diet of the Western countries and the higher fiber diet in developing countries,

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1/ Mara DD, Sewage Treatment in Hot Climates (7) gives a range of 23g BOD_5 per capita per day in Kenya to 78 g in the U.S. Gloyna EF, Waste Stabilization Ponds, WHO Monograph Series (17), suggests 50 g per capita per day is probably on the high side, but will be a safe estimate.

2/ BOD_5 per capita noticeably increases in areas where there are a large number of waste disposal units fitted to houshold sinks; a typical situation in most US cities.

the BOD_5 per capita per day of excreta is about the same. (3) A typical design figure for an urban area in a developing country would be 40 to 50 grams BOD_5/capita/day. It is not possible to give typical allowances for industrial and commercial contributions. Where these are large they should be treated separately and individually; where small they may be considered as part of the domestic sewage flow.

Other commonly used parameters are suspended solids (SS) expressed as mg per liter and fecal coliforms (FC) expressed as numbers per 100 ml. The suspended solids are the discrete particles present in suspension in the sewage or effluent and are responsible for turbidity. The fecal coliforms are a group of bacteria which are exclusively fecal in origin, the most common of which is Escherichia coli. This group is used as an indicator organism for pathogenic bacteria since their die off rates are broadly similar. (4) There are usually between 10^7 and 10^8 FC per 100 ml in raw domestic sewage.

The total organic load produced by a community can be estimated from the number of people served, a knowledge of the probable per capita BOD_5 production, and the contribution from industrial and commercial establishments. As stated previously where there is no major industrial contributor, the BOD_5 load from industry may be incorporated into the figure for domestic production by considering industry in terms of so many population equivalents. Where contributions from industry are large, they should be considered separately in calculating the total organic loading on the system. Although it is dangerous to generalize in view of the wide variations which can be expected with differing social customs, religion, etc., a BOD_5 contribution per capita of 40 grams/day with a wastewater contribution of about 100 liters/capita/day is probably a reasonable initial estimate where there is a household water supply, although flows may be considerably less. Approximate probable BOD_5 loadings from communities of various sizes are tabulated below, based on a contribution of 40 g BOD_5 per capita per day.

Population Equivalent	BOD_5 Load (kg/day)
10,000	400
25,000	1,000
50,000	2,000
100,000	4,000
250,000	10,000

Hydraulic load is a function of water availability, with about 80% of water consumption ending up as sewage. Assuming sewers are fairly well constructed so that infiltration of groundwater is kept down to about 15% of wastewater flow, this gives a raw sewage with a BOD_5 of 350 mg/l, assuming daily per capita contributions of 40 g BOD_5 and 100 litres of wastewater. There is likely to be some increase in both per capita BOD_5 and wastewater contribution as income levels rise. Since water consumption generally rises faster than BOD_5 contribution, this will usually result in a reduction in raw sewage strength.

Industrial Effluents

Wherever industrial effluents are included in the sewage to be treated by a pond system, information should be sought on the nature of the effluents involved. Particular attention should be paid to this aspect when the proportion of industrial effluent is greater than about 20% of the total sewage flow. There are basically three types of effluent which can cause particular problems with a pond treatment system:

1. Effluents containing a high proportion of phenol based hydrocarbons will cause inhibition of algal photosynthesis, and should not be allowed to discharge into pond systems unless pretreated in anaerobic units.

2. Effluents with a nutrient balance which differs widely from that of domestic sewage may cause reduced treatment efficiency, or algal inhibition and hence increased risk of anaerobicity in facultative ponds. Some form of pre-treatment may be required, or the nutrient balance may be artificially restored by addition of other chemical or organic waste.

3. Effluents with a very high organic content may require separate pretreatment in an anaerobic pond before discharge to the sewerage system.

In spite of the potential problems, the reservoir effect of pond systems makes them the ideal treatment method for the absorption of both organic and hydraulic shock loadings.

Effluent Standards

The Royal Commission Standard 1/ of 20 mg/l BOD_5 and 30 mg/l SS, and other effluent standards based on these parameters are generally inappropriate in developing countries. This is because:

1. the BOD_5 and SS of pond effluents depend to a large extent on the algal concentration, and are not, therefore, a measure of the degree to which the sewage has been treated;

2. where discharge is into a river or watercourse, water from which is likely to be abstracted for domestic purposes downstream, or where the final effluent is to be reused for pisciculture or irrigation, a standard that includes bacteriological parameters is required.

Effluent standards should be based on intended end use. Various standards are recommended for effluents which are utilized for the irrigation of crops or are discharged to receiving streams. (1, 5, 6, 7, 8, 9) All these are considered in the production of the effluent standard recommendations given in Table 1, although other factors should also be borne in mind when the effluent is to be used for irrigation including:

1/ The United Kingdom Royal Commission on Sewage Disposal, 1898-1915, considered appropriate methods of sewage treatment and disposal in the United Kingdom and recommended standards of 20 mg BOD/l and 30 mg Suspended Soils (S S)/l where there was an 8 times dilution with clean river water. These standards have been arbitrarily adopted by a number of countries where conditions are not the same.

Table 1: RECOMMENDED IRRIGATION AND DISCHARGE STANDARDS

Method of Reuse	BOD_5 mg/l	Fecal Coliforms No/100 ml /a
Irrigation of trees, cotton, and other non-edible crops	60	50,000
Irrigation of citrus fruit trees, fodder crops & nuts	45	10,000
Irrigation of deciduous fruit trees, /b sugar cane, cooked vegetables, and sports fields	35	1,000
Discharge to a receiving stream /c	25	5,000
Unrestricted crop irrigation including parks and lawns	25	100

/a These concentrations should not be exceeded in 80% of samples.

/b Irrigation should stop two weeks before picking and no fruit should be picked from the ground.

/c Depends on dilution available; effluent should contain less than 10^5 algal cells/ml (7).

Note: These figures represent rough guidelines. Effluent quality may have to satisfy other standards in different countries, or under particular circumstances or conditions. (1, 5, 6, 7, 8, 9)

1. Method of application;

2. Use of labor-intensive agricultural methods; and

3. Proximity to residential areas.

The area of land which may be irrigated with a given volume of effluent is clearly dependent on climate, soil type and crop, as well as the method of application. If an efficient irrigation system is operated, between 25 and 50 hectares of land used for, say, fodder crops can be irrigated with 1,000 m^3 per day, which might be produced from a pond system serving a population of 10,000 to 15,000. Effluent storage in deep ponds can be usefully employed to serve certain cropping patterns.

There are no effluent or pond standards relating to pisciculture in ponds. The limiting factor is usually the existence of some dissolved oxygen in the pond throughout the day and night, which will generally only occur in secondary, tertiary and subsequent units in a pond series. High ammonia levels (>5 mg/l) may also form a constraint to the use of primary and sometimes secondary units for fish culture. Fish will not absorb viral and bacterial pathogens into the meat, but may retain them on the scales or in the gut. Consequently a small depuration or fish washing pond is advisable which should contain fresh or lightly chlorinated water. The fish should be retained in this pond for about 14 days prior to sale and consumption. Tilapia productivities of up to 10,000 kg/ha/year have been reported (10).

The use of the standards and precautions outlined above will ensure that any health risk attached to the reuse of sewage effluent for irrigation and pisciculture is minimal. What small risk there is must be offset against the value of the recycled nutrient expressed in terms of increased crop yields or fish productivity. Furthermore, the reduction in health risk compared to that experienced with the direct use of night soil or raw sewage for irrigation or pisciculture is considerable.

Chlorination of pond effluents is seldom necessary or desirable for the following reasons:

1. High cost;

2. Possible risks associated with carcenogenic chlorinated hydrocarbons;

3. The resistance of many fecal bacteria to chlorine, resulting in aftergrowth;

4. Preferential uptake of chlorine by BOD, resulting in a high dosing rate and wastage of chlorine;

5. A well-designed pond system can provide an effluent with <100 fecal coliforms per 100 ml, a high enough standard for unrestricted irrigation without the need for chlorination;

6. The inability of chlorine to kill viruses, protozoa or helminths except at very high, (and hence very costly) concentrations; and

7. Maintenance of the dosing system and continuity of supplies are likely to be at best difficult, and at worst impossible in most developing country situations.

Chlorination may be necessary under certain circumstances particularly with conventional treatment plants where no other alternative is available, but is still subject to the disadvantages listed above.

Sewage Treatment Options

Table 2 shows some of the advantages and disadvantages of the most widely used sewage treatment processes.

Table 2: ADVANTAGES AND DISADVANTAGES OF VARIOUS SEWAGE TREATMENT SYSTEMS

Criteria	Package Plant	Activated Sludge Plant	Trickling Filter	Extended Aeration Plant	Oxidation Ditch	Aerated Lagoon System	Waste Stabilization Pond System (including anaerobic units)	Waste Stabilization Pond System (excluding anaerobic units)
BOD_5 Removal	**	**	**	**	***	***	***	***
FC Removal	*	*	*	**	**	***	***	***
SS Removal	**	***	***	***	***	**	**	**
Helminth Removal	*	**	*	*	**	**	***	***
Virus Removal	*	**	*	**	**	***	***	***
Ancillary Use Possibilities	*	*	*	*	*	***	***	***
Effluent Reuse Possibilities	*/a	*/a	*/a	**	**	***	***	***
Simple and Cheap Construction	*	*	*	*	**	**	***	***
Simple Operation	*	*	**	*	**	*	***	***
Land Requirement	***	***	***	***	***	**	**	*
Maintenance Costs	*	*	**	*	*	*	***	***
Energy Demand	*	*	**	*	*	*	***	***
Minimization of sludge for removal	*	**/b	**/b	**/b	*	**	***	***

a/ The effluents from activated sludge, trickling filter and package plants frequently have high ammonia levels (>5mg/l) and fecal bacterial concentrations, and are usually not suitable for irrigation or fish farming without tertiary treatment.

b/ Assumes provision of sludge digesters.

Key: ***good; ** fair; * poor.

Table 2 highlights the many advantages of waste stabilization pond systems, which only fare worse than the other systems in respect of SS removal (due to the algae in their effluents) and land requirements.

Waste Stabilization Pond Treatment Mechanisms

The major treatment processes which occur in waste stabilization ponds are:

1. the reservoir effect, enabling ponds to absorb both organic and hydraulic shock loadings;

2. primary sedimentation, allowing settleable solids to sink to the benthal sludge layer; and

3. treatment of the organic waste by aerobic bacterial oxidation (in the presence of oxygen) and anaerobic digestion (in the absence of oxygen).

Waste stabilization ponds are classified according to the relative dominence of the two processes by which organic material, expressed as BOD_5, is removed. Anaerobic ponds operate under heavy organic loading rates as the primary units in a pond system, and rely totaly on anaerobic digestion to achieve organic removal. Facultative ponds operate under a lighter organic loading enabling algae to develop in the surface layers and an oxypause to form. Below this oxypause anaerobic digestion continues in the absence of oxygen. Above the oxypause aerobic bacterial oxidation occurs in symbiosis with algal photosynthesis, which provides the bulk of the oxygen for the oxidation process. Facultative ponds may be used as primary or secondary units in a pond series. Maturation ponds follow facultative ponds and are largely aerobic since most of the organic load is removed in the anaerobic and facultative units and thus the organic loading on these ponds is light.

The anaerobic and aerobic processes can be represented by simple formulae as follows:

1. Anaerobic digestion is basically a two stage process, the first of which is putrefaction:

   $$\text{Organic matter} \xrightarrow{\text{bacteria}} \text{new bacterial cells + mixed organic acids.}$$

   In the second stage methanogenic bacteria break down the products of the first stage to methane and other simple products.

Mixed organic acids $\xrightarrow{\text{bacteria}}$ new bacterial cells + methane + carbon dioxide + water + ammonia, etc. 1/

2. Aerobic oxidation can be represented as a single stage process.

Organic matter + oxygen $\xrightarrow{\text{bacteria}}$ new bacterial cells + water + carbon dioxide + phosphate + ammonia, etc. 1/

The oxygen is largely provided by algal photosynthesis which can be simply expressed by:

Carbon dioxide + water $\xrightarrow[\text{light}]{\text{algae}}$ new algal cells + water + oxygen

Both the aerobic and anaerobic processes are highly temperature dependent, increasing logarithmically with a linear increase in temperature. Figure 1 illustrates the pathways of BOD_5 removal in facultative ponds.

Efficient absorption of shock loadings and equalization of loading peaks are dependent upon achieving reasonably good mixing of the influent throughout the pond contents. Mixing is also important to minimize hydraulic short circuiting in ponds, and to achieve a good vertical distribution of both oxygen and algae in facultative and maturation ponds. Non-motile algae which are the most efficient oxygen producers rely on pond mixing to bring them into the surface layers of the pond where light intensity is greatest. Mixing also destroys thermal stratification.

Suspended solids will settle to the benthos under the quiescent conditions found in ponds. Finer particles will only settle out after flocculation and coagulation, and active anaerobic digestion will cause the resuspension of organic material as shown in figure 1.

Fecal indicator bacteria and also pathogenic bacteria are removed by starvation and the other effects of a hostile environment. Thus detention time is the key factor although other factors such as temperature, ultra violet radiation and algal concentration also play a part. Most recent research on the subject suggests that bacterial removal rate is mainly dependent on temperature and algal concentration, increases in both of which increase the fecal bacterial removal rate. Virus die off appears to be effected more by the level of ultra

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1/ The ammonia many subsequently undergo nitrification to nitrite and finally nitrate.

violet light than does fecal bacterial die off, although there is only scant evidence that the level of ultra violet light has a significant effect on virus removal from pond systems (12).

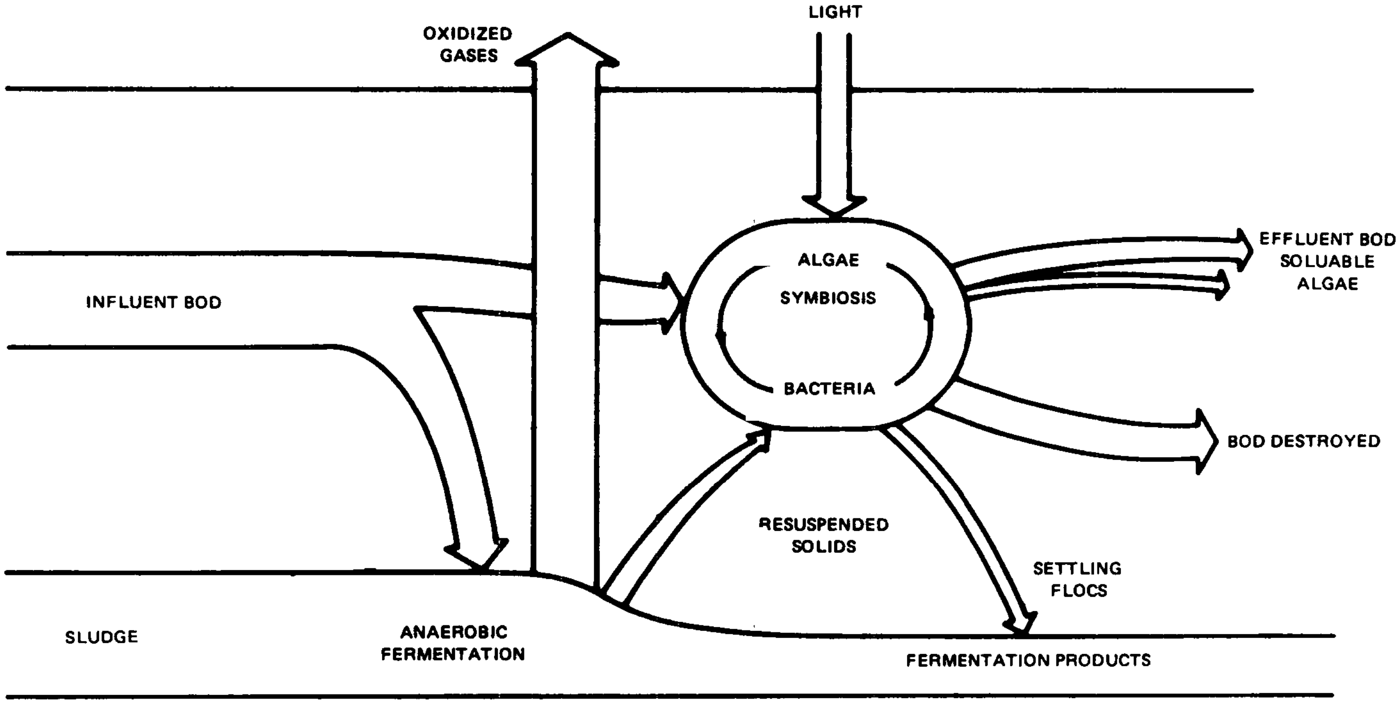
Climatic Factors

Climate is important inasmuch as the processes responsible for BOD_5 removal and fecal bacterial removal are temperature dependent. Furthermore algal photosynthesis depends on solar insolation, itself a function of latitude and cloud cover.

The pond liquid temperature is probably the parameter which has the greatest bearing on pond performance, and is usually two or three degrees centigrade above the average ambient temperature. Periods of cloud are seldom a problem because the solar insolation during the day in tropical and subtropical regions generally greatly exceeds the saturation light intensity of the algae in the ponds.

Since the bacteria responsible for treatment operate in the mesophilic temperature range, high temperatures are not a problem. Low temperatures can be, since they slow down the treatment process. In the case of the methanogenic bacteria crucial to anaerobic digestion, methane production virtually ceases below temperatures of 15°C. Thus in areas where the pond liquid temperature remains below 15°C for more than a couple of months of the year, careful consideration should be given to the decision as to whether anaerobic units are desirable. Allowing for ponds to be about 3°C warmer than average ambient temperature, this would be in areas where the mean monthly average temperature was below 12°C for two months or more.

Figure 1: PATHWAYS OF BOD REMOVAL IN A FACULTATIVE WASTE STABILIZATION POND AFTER MARAIS (35)



CHAPTER 3

DESIGN OF POND SYSTEMS

Anaerobic Ponds

Anaerobic ponds (utilizing anaerobic digestion only) should be designed on the basis of volumetric organic loadings between 0.1 and 0.4 kg BOD_5/m^3/day (100 to 400 grams BOD_5/m^3/day). Values around 0.1 should be used for areas where there is a pronounced cold season (around 12°C), and 0.4 where there are uniform annual very warm temperatures (27-30°C). Evidence suggests that it is reasonable to assume a straight line relationship for loading rates between temperatures of 12° and 30°C, but field verification of this relationship has yet to be fully carried out. These loadings are equivalent to areal BOD_5 loading rates of between 4,000 and 16,000 kg BOD_5/ha/day, assuming an anaerobic pond depth of 4 m; and to between 2.5 and 10 persons served per cubic meter of pond volume, assuming a BOD_5 contribution of 40 grams per capita per day. The anaerobic pond detention time can be calculated by dividing the influent BOD_5 concentration in mg/l by the organic loading rate in grams of BOD_5 per m^3 per day. In cases where the average ambient temperature remains below 20°C for several months of the year, a detention time of about 2 days or more is desirable to achieve sufficient BOD_5 removal (6, 7, 13, 14, 15). There appears to be little treatment advantage in extending anaerobic pond detention time to more than 2 days, although this may be inevitable with a high raw sewage BOD_5 and low permissible loading rate. (13)

There is theoretically no limit to how deep an anaerobic pond should be, although a depth of about 4 m is about optimal from the point of view of treatment efficiency. Depth of less than 2.5 m should not be used if possible, although still shallower depths may be necessary due to local soil and ground conditions.

Anaerobic ponds should generally be constructed as parallel units, although where the loading rate is likely to build up slowly one unit may be constructed initially, provided another can be added before the first requires desludging. When a third unit becomes necessary, it may be found desirable to operate two anaerobic ponds in series, and consequently the necessary pipework to enable the ponds to be used in parallel or series should be included in construction. (14)

To ensure rapid development of both acid forming and methanogenic bacterial populations in anaerobic ponds, seeding with a digesting sludge is advisable if this is possible. The best source for this sludge is likely to be from local existing septic tanks. Odor problems may result from treatment of wastes with a sulphur concentration > 100 mg/l (as sulphate) in which case anaerobic ponds should be avoided. Methane fermentation is inhibited by a pH < 7, and highly acidic raw waste requires pH elevation by dosing with alkaline salts before treatment in anaerobic ponds.

Facultative Ponds

Facultative ponds can be the first in a series, i.e., the primary pond, or follow anaerobic ponds. Many different design procedures have been recommended for facultative ponds (15, 16, 17, 18, 19, 20), generally based on either temperature or solar insolation. In hot climates temperature based methods should be used unless long cool and very overcast periods are experienced, in which case other methods may need to be considered. The simplest methods relate permissible areal loading rate expressed in kg BOD_5/ha/day to minimum monthly average temperature. Several design equations have been developed (19, 20, 21), but there is conflicting evidence as to the relationship between average ambient temperature and reversion of facultative ponds to complete anaerobicity, resulting in reduced treatment efficiency and the possibility of odor release. The relationship providing best agreement with all the available data is:

$$\text{areal loading rate } \lambda_s = 20T - 60 \quad \text{--- } 1$$ 1/

Where λ_s is the areal loading rate in kg BOD_5/ha/day and T is the minimum mean monthly ambient temperature in °C.

This provides a safety factor of about 1.5 before complete failure of a facultative pond according to the most data (19, 21, 22) although failure at slightly lower loadings has been observed in South America. (23) There are a number of factors which can cause variations in the loading rates at which facultative ponds become anaerobic at a given temperature, including:

(a) concentration of ammoniacal nitrogen;

(b) whether ponds are treating raw sewage, settled sewage or pretreated sewage; and

(c) pH variations which may cause algal toxicity.

There is a need for more work to be carried out on this aspect of sewage treatment in ponds. The area may be calculcated using the formula:

$$A = \frac{10 \times L_i \times Q}{\lambda_s} \quad \text{------ } 2$$

where A = facultative pond area in m^2
L_i = influent BOD_5 concentration in mg/l
Q = influent flow rate in m^3/day

and λ_s is defined above.

1/ Personal communication with Prof. D.D. Mara following recent unpublished work carried out in northeast Brazil.

For design temperatures between 15 and 30°C and assuming a BOD_5 contribution of 40 grams/capita/day, equations 1 and 2 give between 5,000 and 14,500 people served per hectare of facultative pond. Depths for facultative ponds of between 1.0 and 1.8 meters are generally used although there appears to be no reason why greater depths should not be used to increase detention times and thus pathogen removal. However, areal organic loading is, of course, independent of depth. Depths of more than 1.2 m are advisable to allow some space for sludge accumulation. Depths of less than 1m should be avoided to prevent vegetation from growing on the pond bottom.

Where a facultative pond forms the primary unit in a series, it is advisable to provide for pond desludging when this becomes necessary by including a pond bypass or by the construction of parallel units. These measures may be avoided if facultative ponds are made sufficiently deep so as not to require desludging during their lifetime. A sludge accumulation of about 0.04 m^3 per capita served per year can be expected in the primary unit.

Maturation Ponds

Maturation ponds, which are largely aerobic, should primarily be designed to achieve fecal bacterial removals since the bulk of BOD_5 is removed in the anaerobic and facultative ponds. The design procedure assumes that fecal coliform removal is a first order kinetic reaction given by:

$$B_e = \frac{B_i}{1 + K_{B(T)} t^*} \qquad \text{------- } \underline{3}$$

where B_e = bacterial concentration in no. FC/100 ml of effluent.

B_i = bacterial concentration in no. FC/100 ml of influent.

$K_{B(T)}$ = first order FC removal rate constant at T°C in day $^{-1}$.

t^* = detention time.

Due to this form of removal, it has been shown (24) that removal is more efficient with a greater number of ponds for the same total detention time, and with these ponds each having the same detention time. Furthermore, the first order removal rate constant has been shown (21) to be retarded with increasing time as well as reducing temperature. Thus a series of maturation ponds with a detention time of about 5 days is recommended, the number used depending on the effluent standard required. For general purposes the following equation may be used for calculation of the value $K_{B(T)}$. To simplify matters $K_{B(T)}$ may be assumed to be the same for each pond in the series.

$$K_{B(T)} = 2.6\,(1.19)^{(T-20)} \qquad \text{------- } \underline{4}$$

The total fecal coliform removal in a series can be found from:

$$B_e = \frac{B_i}{(1+K_{B(T)}\ t^*_{an})\ (1+K_{B(T)}\ t^*_{fac})\ (1+K_{B(T)}\ t^*_{mat})^n} \quad \text{--- } \underline{5}$$

where t^*_{an}, t^*_{fac}, and t^*_{mat} are the detention times of the anaerobic, facultative and maturation ponds respectively and n is the number of maturation units in series.

As an alternative to a series of maturation ponds, one large reservoir may be constructed, as is often the practice in Israel, (Appendix 3, page 95). Bacterial removal is less efficient, e.g., using equations 4 and 5; a series of three 5-day ponds give a bacterial removal equivalent to 1 reservoir with a detention time of 1,055 days at 20°C, although in reality the last, say, 1,000 days, will contribute only fractionally to the total bacterial removal. But under certain circumstances, particularly where irrigation requirements are seasonal, a large and deep (6 to 8m) reservoir may provide adequate treatment and prove cheaper than a greater number of smaller and shallow maturation ponds. Maturation ponds are generally shallow (1.2 to 1.5m) to maintain largely aerobic conditions, with the added advantage that viral removals are marginally better in shallow than in deep ponds (12). However, where pressure on land is great, the pond depth may be increased without significant reduction in pathogen removal efficiency, although the BOD_5 surface loading rate should be kept well below the maximum permissible loading rate for facultative ponds. Where reservoirs are used, care should be taken to ensure that adequate bacterial removals are achieved when the reservoir is drawn down. The light organic loading and deep aerobic surface layer on the reservoirs ensures no nuisance results from any anaerobic activity below the surface layers, which should in any case be minimal.

Pond systems may be designed so that there is no effluent discharge, i.e. with inflow equal to seepage plus evaporation. In such cases particular care should be taken to ensure that groundwater pollution is minimized and that water resources are not put under risk. The area of ponds required for such a system is large, 1/ and assuming losses of about 10 mm per day, approximately 10 m^2 of pond area would be required per capita. This system is only likely to be appropriate for arid and semi-arid areas where rainfall is very low.2/

1/ Ponds, even those constructed from sandy soils, are often self sealing over time. Evaporation loss is generally between 3 and 6 mm per day, depending on the climate.

2/ There is however the danger that accumulation of inorganic salts (e.g. chlorides) may in the long term cause algal toxicity problems, with a consequent decrease in pond performance.

Aerated Lagoons

Design of aerated lagoons may be based on assumptions of first order BOD_5 removal (7, 25, 26, 27). However, such lagoons are generally designed using empirical methods, a 4-day detention time achieving 70 to 90% BOD_5 removal in a partially mixed aerated lagoon. Power requirements are about 4 watts/m^3 for a partially mixed lagoon 1/ and 20 watts/m^3 for one which is completely mixed. A lagoon depth of 3-4 m is generally used.

Aerated lagoons should be followed by settling ponds which may be either

(a) short detention (say 2 day) units in parallel which require frequent desludging; or

(b) a single 10-day facultative pond with sufficient depth to allow long-term sludge storage (1.5-2m).

Care should be taken in the siting of aerators to avoid dead areas in aerated lagoons where solids are able to settle out in the quiescent conditions. This can cause sludge banks to form with the associated nuisance problems. More small aerators rather than fewer large ones provide more evenly spread mixing, and rounded pond corners are also a help in avoiding dead areas.

Table 3 shows anticipated BOD_5 and FC removals for pond systems including and excluding aerated lagoons and anaerobic ponds at 12°C, 20°C, and 25°C. Table 4 shows the effect on fecal coliform concentrations of 1, 2 and 3 maturation ponds at 12°C, 20°C, and 25°C. Table 5 gives the net pond areas and detention times for various pond systems serving a range of populations at 12°C, 20°C, and 25°C.

Other Design Considerations

During design careful consideration should be given to:

(a) Including the length of pipe between the dwelling unit or plot and the sewer main, as part of the project. Schemes where householders are relied upon to make, or directly pay, for their own sewer connections should be avoided, since this results in a very slow build up in sewage flow and hence underutilization of sewerage and treatment system.

(b) Allowing for low water consumption and thus low waste water flow rate per capita, particularly where pour flush toilets are used.

1/ Aerators used in a partially mixed lagoon provide enough energy to satisfy the oxygen demand for aerobic oxidation. They also allow a sludge layer to form at the bottom of the pond. Aerators used in a completely mixed lagoon provide enough energy to maintain the solids in suspension. Completely mixed aerated lagoons are in essence activated sludge units without sludge return.

Table 3: ANTICIPATED BOD_5 AND FC CUMULATIVE PERCENTAGE REDUCTIONS FOR VARIOUS POND SYSTEMS AT 12°C, 20°, AND 25°C

	Cum. % BOD_5 Reduction			Cum. % FC Reduction		
	12°C	20°C	25°C	12°C	20°C	25°C
Anaerobic Pond	45	62	70	60	86	93
an. + fac.	80	88	90	96	99.50	99.2
an. + fac. + mat.	86	92	94	99.0	99.975	99.95
an. + fac. + 3 x mat.	94	95	95 +	99.95	99.9996	99.99999
Facultative Pond	75	80	84	91	97	98
fac. + mat.	86	90	93	98.2	99.94	99.98
fac. + 3 x mat.	93	95	95 +	99.90	99.998	99.99993
Aerated Lagoon	70	80	82	72	93	96
aer. + mat. (10 day)	84	92	93	95	99.50	99.9
aer. + 3 x mat.	93	95	95 +	99.90	99.996	99.999

Key: an. anaerobic pond; fac. facultative pond; mat. maturation pond; aer. aerated lagoon.

Assumptions:

1. Systems treating normal domestic sewage.
2. Anaerobic pond detention time of 2 days.
3. Facultative pond detention time 7 to 15 days depending on ambient temperature.
4. Maturation ponds detention time of 5 days, accept first maturation pond following aerated lagoons - 10 days.
5. Aerated lagoon detention time of 4 days.
6. First order removal of FC according to equations 4 and 5; BOD_5 removal according to a retarded exponential relationship using a variety of field data (30).

Table 4: EFFECT ON FC CONTENT OF MATURATION PONDS OF 5-DAY DETENTION TIME AT 12°C, 20°, and 25°

	Temperature		
	12°C	20°C	25°C
Inflow to first maturation pond FC concentration/100 ml	1,000,000	1,000,000	1,000,000
Pond 1 Effluent	235,294	60,500	31,250
Pond 2 Effluent	55,363	3,770	976
Pond 3 Effluent	13,026	222	30

Note: Based on equations 4 and 5.

Table 5: PREDICTED NET POND AREA REQUIREMENTS AND SYSTEM DETENTION TIMES TO SATISFY EFFLUENT STANDARD 25 mg/1 BOD_5 and 5,000 FC/100 ml

System	Detention Time Days			Population Served	Pond Area (ha)			Power Requirement (kW)
	12°C	20°C	25°C		12°C	20°C	25°C	
Anaerobic pond plus facultative pond and maturation ponds	29.7	18.8	13.0	10,000	2.2	1.6	1.1	-
				25,000	5.5	4.0	2.6	-
				50,000	10.7	7.7	5.1	-
				100,000	20.9	15.1	10.1	-
				250,000	50.8	36.5	24.3	-
Facultative pond plus maturation ponds	48.9	25.4	17.6	10,000	3.9	2.0	1.4	-
				25,000	9.5	4.9	3.5	-
				50,000	18.5	9.4	6.8	-
				100,000	36.4	18.5	13.3	-
				250,000	88.2	44.9	32.2	-
Aerated lagoon plus maturation ponds	34.0	21.0	16.9	10,000	2.6	1.8	1.3	25
				25,000	6.3	4.3	3.2	63
				50,000	12.3	8.4	6.3	125
				100,000	24.1	16.5	12.3	250
				250,000	58.5	39.9	29.9	630

Assumptions: Water consumption: 130 lcd.
Percentage water reaching sewers: 80%
BOD_5 contribution: 40 grams/capita/day
Depth of ponds: anaerobic 4 m
facultative 1.8 m
maturation 1.5 m
aerated lagoon 3 m
Detention times: maturation ponds 5 days 1/
aerated lagoon 4 days
FC in raw sewage: 2×10^7/100 ml.

1/ A pond offering a detention of 10 days is recommended after aeration.

(c) Allowing for raw sewage dilution by groundwater infiltration into the sewer network, thus markedly reducing sewage strength. This will be particularly significant immediately after system construction when sewage flows are low.

In general, the pond system should not initially be constructed to satisfy the 20 or 25 year design horizon. This is particularly true where pond systems are to serve areas undergoing progressive development or where sewerage is being newly installed. To minimize costs, only the land required for the full system should be purchased initially, and the first stream of ponds to serve, say, years 1 to 5 should be constructed. After 5 years, or whenever this first stream becomes overloaded, a second stream parallel and adjacent to the first may be added. This process may be repeated at intervals until the full design loading is achieved when perhaps four of five streams of ponds will be in use. 1/

Maintenance problems can be minimized at the design stage by ensuring the following:

1. Inlet designs should give good inflow distribution to avoid sludge and grit settlement and accumulation near the inlet pipe. Alternatively, a deep sump may be constructed near the inlet to hold grit if grit channels are not provided in pretreatment. Best distribution of inflow is achieved by use of multiple inlet pipes.

2. Outlets should be able to draw off from various depths, or at least surface outlets should be provided with scum guards. Variable depth draw off will allow the algal band which generally forms in the upper 50 cm of pond liquid to be avoided;

3. Embankments should have a hard edge detail at the water surface level to avoid erosion by wave action:

4. Embankments should have a side slope not greater than 1:3 to avoid embankment failure (unless the soil is stable and can be highly compacted); and

5. Anaerobic ponds should be provided with a pitched access ramp if vehicular sludge removal is to be used. In systems with large facultative and maturation ponds (say, $\not>$ 2 ha each), a paved area of embankment should be included to enable a small boat to be launched for weed and scum removal. A paved area is also useful in anaerobic ponds where raft mounted sludge pumps are to be used.

Flow measurement should be facilitated by provision of a flume at the inlet to, and where appropriate a V notch at the outlet from, the pond system. Where the flow rate exceeds 10,000 m^3/day and the required technical staff is available, an automatic recording venturi flume may be preferred, allowing continuous monitoring of flow rate.

1/ The advantage of incremental pond construction is simply economic: construction costs incurred in the future have a lower present value and thus this results in a minimum net present value economic solution.

Some kind of pretreatment should always be included to provide removal of large solids which would otherwise float on the pond surface causing nuisance and scum formation, or where applicable would foul aerators. Screens are preferable to comminutors, being cheaper and easier to maintain. At systems without a workman permanently on duty one fairly coarse screen which will not require too frequent cleaning is sufficient. Where there is someone on duty 24 hours a day, a coarse screen followed by a fine screen may be used. Mechanically raked screens often prove unreliable and should only be used as secondary screens if at all. Screenings should be burned or buried.

Grit channels or detritus tanks may be avoided by deepening the primary ponds around the inlet. With larger facilities (10,000 m^3/day) or where the raw sewage contains large amounts of grit or sand, grit channels or detritus tanks are required. These should be constructed in parallel and if possible should be manually cleaned. Where grit removal facilities are excluded, the grit sump at the inlet to the primary pond should be designed for 2-year emptying frequency in anaerobic ponds and longer in facultative ponds if possible. The invert level of the sump should be at least 1 m below the invert level of the pond with sides sloping at about 1 in 2. The pond inlets should be designed to give as high a velocity and as good a dispersion of the influent as possible, to try and ensure disposal of settleable solids over the full area of the sump.

Removal of the detritus collected in the sump should be carried out at the same time that sludge is removed from the primary pond. This should be when the pond becomes half full of sludge; about two years for a primary anaerobic pond and perhaps 20 years for a primary facultative pond. Secondary facultative ponds should not require desludging more frequently than every 40 years, and may never need desludging during the life of the pond system. Sludge depth can be determined by sampling a column of pond liquid in a clear plastic tube or by feeling for the top of the sludge blanket with a disc on a vertically held pole. Where desludging is required frequently, (i.e., anaerobic ponds and possibly facultative ponds incorporating a grit sump), and where a long dry season is likely to allow sludge drying and hence removal by excavation, a concrete or pitched stone access ramp should be provided.

Algae may cause a problem in the pond system final effluent if it is to be used for drip irrigation (clogging) or discharged to a small watercourse (dissolved oxygen depletion downstream). Algal concentration will reduce with an increasing number of maturation ponds as the dissolved nutrient concentration reduces. If further removal is required, a number of physical removal methods are available but all are expensive and difficult to maintain (28, 29). The least complicated of these is a pebble bed clarifier which will reduce algal concentration by about 50%. A similar reduction can be achieved by a horizontal rock filter which may be constructed in the pond adjacent to the outlet and avoids the construction and backwashing problems of the pebble bed clarifier. The rock filter uses 135 to 150 mm grading, and the effluent should be retained for about 24 hours in the filter. Drawing the effluent off from below the algal rich surface layers remains the best method of reducing algal concentration in the effluent, although this may have repercussions on other effluent parameters (e.g., bacterial concentration). Algal concentration in maturation ponds will be considerably reduced if the ponds are stocked with primary feeding fish such as tilapia or carp. The use of floating macrophytes on maturation ponds will also reduce algal concentration. These plants remove dissolved nutrients from the pond liquid and restrict the light penetrating the pond surface, resulting in reduced algal growth rates. 1/

Containing algal growth is also possible using chemicals which inhibit algal respiration and photosynthesis. However, this is generally undesirable since it is likely to interfere with the treatment process.

Odor nuisance from overloaded facultative or anaerobic ponds may be controlled by using forced mechanical aeration (facultative ponds only), or effluent recirculation to provide an oxidizing environment at the pond surface. Provision for addition of aerators or future recirculation adds to the flexibility of the system and provides an insurance against possible future nuisance problems. However, the capital cost of the system is certain to increase. If aerators are added these should be of the floating direct vertical drive type, positioned so as to avoid dead areas. It must be remembered that inclusion of aeration or recirculation will dramatically increase the maintenance requirements and operational costs of a pond system. Furthermore the aerosol problems associated with surface aeration cause a potential health hazard over a wide area.

For the larger pond systems in particular, (say, flowrate $>5,000$ m^3/day), interconnecting pipework should be provided to allow maximum flexibility of operation. The pipework should ideally allow anaerobic and facultative units to be operated in series or parallel and permit continuity of operation with one pond removed from service for cleaning. A bypass which serves each unit is also useful, and may be combined with drain-down facilities which can be provided for each pond. However, a bypass for the whole system may provide an opportunity for the operator to avoid treating the waste at all when operational problems arise. Consequently it may be prudent to provide bypass and drain-down facilities for anaerobic ponds and primary facultative ponds only, since these are the only units likely to require regular cleaning during the lifetime of the system.

Pond Location

The most important factor in pond location is generally one of where the land is available in sufficient quantities. If large areas of land are available reasonably close to the center of population and can be acquired cheaply, then it may be worth while to acquire this site even though some extra "off site" works may be required.

1/ If floating macrophytes are to be used on the final maturation pond, care should be taken to use local macrophytes, rather than introduce a new (non-local) species which may cause severe ecological problems when it "escapes" to the local environment.

Pond Sites should preferably be adjacent to a disposal or reuse facility, and for pond effluents there are many advantages to be gained from using land disposal by irrigation rather than discharging directly to a river or watercourse.

The pond system should wherever possible be located on ground at a lower elevation than the contributing population, thus allowing discharge to the ponds under gravity. If pumping into or out of the pond system is required, pumping of the effluent is preferable to pumping the raw sewage (smaller volume and less large solids).

The ideal location for ponds is on gently sloping land, and on impermeable soil. If this is not possible there should preferably be a supply of clay close by for use as a pond lining or in embankment construction. A small degree of percolation is unlikely to cause a problem where the groundwater is not used as a water resource, and here ponds may be constructed of a more permeable material. In any event ponds are generally found to be self sealing over time.

It is generally recommended that wherever possible, pond systems should be located at least 500 m from the nearest residential area and where anaerobic ponds are also used, this distance should ideally be increased to 1 km. Although these distances may be recommended, there are many examples of people living within 100 m of pond systems without suffering any nuisance. One precaution which can be taken if pond systems are very close to residential areas is to place anaerobic units at the center of the system, thus minimizing any effects on the community resulting from poor control of flies which may breed on the pond crust.

To minimize the nuisance caused if any odor problems do develop, pond systems are best situated to the leeward of contributing communities for night time prevailing winds.

Areas which include old river beds or similar topographical or geological features should not be used for pond systems unless:

1. the effluent is not to be reused and groundwater pollution from the high rate of percolation will not threaten water resources or;

2. the cost of lining the pond system with plastic sheeting or impermeable soil can be borne.

Sites with high water tables should be avoided for the construction of pond systems if possible since the use of heavy machinery close to, or below, the water table can cause problems. In such cases alternative methods of embankment construction such as manual methods or use of drag lines may have to be considered.

Wherever possible pond systems should be sited so as to avoid wind shadows. Furthermore, to aid wind mixing the ponds should as far as possible be constructed with their longest dimension parallel to the prevailing wind direction.

The siting of the pond system may be constrained to some extent by the position of the outfall sewer in cases where an existing sewerage system is being served.

Civil Engineering and Earthworks

Good earthwork guidelines are contained in many general specifications including the one produced for the World Bank-funded Israeli Sewerage Project. The items of these specifications which relate to site preparation and embankment construction, and other important factors to be considered in the construction of ponds in hot climates, are given in Appendix 1.

In addition to those construction specifications outlined in Appendix 1, outside embankments should be seeded with grass or some other suitable ground cover to minimize erosion. Inside embankments should as far as possible be made to resist root taking and accept weed prevention sprays, and a hard edge should be provided at the water surface level around the entire perimeter of the pond. This should extend at least 200 mm above and below the water surface level. This edge detail is required in order to avoid embankment damage caused through wave action and should ideally comprise either concrete slabs or grouted rip rap. The embankment crest should be provided with an all-weather surface. Grass may be permitted to grow on the inside embankments of ponds above the hard edge detail provided it is kept short.

Pond details should incorporate the following: 1/

1. Multiple submerged inlets to the primary pond, (two for small anaerobic ponds but more for large facultative ponds). Subsequent units may also be provided with dual inlets and outlets;

2. Preferably variable level outlets, or alternatively, outlets which will draw off from just below the surface. In the case of a final pond in the series, effluent should be extracted from well below the surface so as to avoid drawing off from the algal rich layers;

3. Submerged inlets to all ponds treating raw sewage and to facultative ponds receiving anaerobic pond effluent;

4. Measuring devices at inlet and outlet of system;

5. Bypass for the pretreatment and primary pond in the system; and

6. Draw down facilities for the primary units.

1/ In small plants it may not be reasonable or affordable to incorporate all these items, or to keep to the specification outlined in Appendix 1.

Expansion of Pond Systems

There are several ways in which the capacity of a pond system can be increased, and these are:

1. additional units in series;

2. additional units in parallel;

3. excavation to give increased pond depth;

4. any or all of (1) to (3) plus embankment removal to provide one large pond from two or three small ones.

This increased capacity will result in either increased treatment efficiency or ability of the system to handle a greater volume of wastewater, or both. Such structural changes may be preferred to installation of aerators or recirculation with the associated operational problems and additional costs.

Where it is planned to increase progressively the wastewater flow to a pond system over a long period, the use of parallel systems is probably preferable. Additional pond series can be constructed in parallel with existing units, using one common embankment. Thus, as each new series becomes necessary, one embankment running the full length of the system is already constructed. The inlet and outlet works may be designed to take the total future design flow as part of the initial construction stage. The Dandora pond series in Nairobi is an excellent example of this type of system.

Where planning has not been so far-sighted and a pond system becomes overloaded, construction of additional units in series may be the most satisfactory method. Previously constructed embankments can also be utilized in this case -- for instance, constructing an anaerobic pond to reduce loading on an existing facultative unit, or providing an additional maturation pond to improve effluent quality. An example of this system of expansion is Einsheimer in Israel.

Excavation to give increased pond depth causes particular problems in that the ponds must be emptied before the excavation can be carried out. This problem may be overcome if the opportunity to increase pond depth is taken when the pond is being desludged. This was one of the features of the extension and rehabilitation of the Ramat Hasharon ponds in Israel. Increased pond depth results in increased detention time of the system and will allow a grossly overloaded facultative pond which may be causing odor nuisance to operate as an anaerobic pond, or enable aerators to be used if so desired.

Combining several ponds in a pond system to create one larger unit also suffers from problems related to the need for all the ponds involved to be emptied. The advantages of such a system are that additional volume and pond surface area can be created without the need for any additional land or construction. It should be borne in mind that the treatment efficiency would be unlikely to improve after such modifications since the system as a whole would be operating less as a plug flow reactor and more as a completely mixed reactor. 1/ However, such modifications could be justified if increased effluent storage was required for irrigation, or where it was desired to combine existing anaerobic ponds to make a single aerated lagoon (thus increasing detention time closer to the four days required for aerated lagoons). Conversely, where a low initial sewage flow has dictated the use of a primary facultative pond in the early stages of operation, an embankment may be built across this pond as the inflow rate builds up, to provide anaerobic and facultative ponds in series.

Land Requirements and Costs

Where land is difficult to find or expensive, suitable land may be obtained by compulsory purchase or attempts can be made to trade for the land by encouraging the client to:

1. offer the owner the right to the effluent;

2. offer tax or rate concessions to the landowner;

3. exchange municipally owned land for the required land.

Although waste stabilization pond systems require more land than conventional sewage treatment plants, it is difficult to establish a price for land above which pond systems cease to provide economically viable sewage treatment. The decision as to whether a pond system is appropriate must be based on economic costs and benefits of a pond system compared to those for other treatment methods. However, since land values invariably rise with time, it is important to include not only the land costs but also the resale and reuse value in any such analysis. Where appropriate, land used for pond systems may be relatively easily levelled and reused for housing or other development when the pond system is replaced or relocated. Other more conventional treatment plants may be more costly to relocate and will release less land for reuse. Furthermore, this land will be more expensive to reclaim for development use, particularly where there are extensive concrete structures which will require demolition and removal or filling.

In the majority of urban development projects, wastewater treatment plants will be required to serve extensive areas of new housing development, since few cities and towns in developing countries have piped sewerage systems serving the existing community in which spare capacity is readily available. In these cases it will generally be appropriate to purchase land for the pond system as part of the general development area. The cost of such land, particularly when purchased for the development of low income housing, will be low but its value will increase as the adjacent land is developed, and is likely to go on appreciating in value almost indefinitely.

1/ Completely mixed flow assumes that the influent is instantaneously and completely distributed throughout the reactor contents. Plug flow assumes the total absence of longitudinal mixing and that the influent flows uniformly through the reactor from inlet to outlet.

When wastewater treatment alternatives are being evaluated to establish the least cost affordable system, there are likely to be three ways in which the question of land resale can be dealt with, depending on circumstances. These are as follows:

1. The treatment plant will be required only until the wastewater from a proposed urban development project can be handled by a new or extended wastewater treatment system serving the complete city. In this case the land will become available for development in the relatively short term, and may be sold at a price many times higher than the original cost. Only simple site preparation measures will be required where a pond system has been used;

2. The system will be required either until it becomes overloaded or until development and environmental pressures resulting from natural growth demand the construction of a new treatment works at a location further out from the city center. In this case the land will become available for development in the long term, and, as in the example above, the resale value will greatly exceed in real terms the original purchase price;

3. The system will be required indefinitely because of physical constraints on the city which prevent the treatment plant being suitably relocated. In this case the land will have no future development value and the economic evaluation of wastewater treatment alternatives will exclude land resale. It is only in this case that very high land costs may result in treatment systems other than ponds being the least cost alternative.

Much the same arguments apply where land is purchased for waste water treatment away from the development area. Land is an appreciating asset and its value for alternative use once treatment systems become obsolete or are relocated will invariably exceed its original purchase price. Where a treatment system is to be provided to serve a city with an existing sewerage system, land relatively close to the city may be purchased with a view to the treatment system being relocated at some time in the future. This land may be resold for development once the original treatment plant becomes obsolete, and the sewage is pumped further away to a new site as outlined above. Where physical constraints prevent any possibility of future relocation, then the economic feasibility for the treatment system must reflect this fact at the outset. If, under such circumstances, land is very expensive, pond systems may cease to be an economically attractive proposition. However, land cost is only one factor, and considerations such as low maintenance requirements, operational simplicity and high pathogen removal may override the economic disadvantages of pond systems resulting from very high land prices.

In the case of a pond system reaching full design loading and being surrounded by development which prevents any extension to the system, relocation may not always be the most economical solution. The capacity of the pond system may be increased by the introduction of aeration equipment, or a change in effluent reuse may allow a poorer effluent quality to be tolerated. In the long term it may occasionally be economically desirable to convert progressively a waste stabilization pond system to a more intensive conventional treatment plant using the same site, rather than relocating the entire system and selling off the original site.

The major factors which affect the amount of land required for the construction of a pond system are:

1. contributing population;
2. wastewater and organic contribution per capita;
3. temperature;
4. type of system used (i.e., inclusive or exclusive of anaerobic ponds);
5. effluent standard required.

The major factors which affect the cost of a pond system are:

1. the cost, location and elevation of land;
2. the type of soil (i.e., permeable soils may require pond lining, with considerably increased costs);
3. the type of system used.

The major factors affecting the operational costs of the pond system are:

1. cost of labor;
2. amount of mechanical equipment used; e.g., for pumping;
3. level of maintenance;
4. cost of energy and chemicals.

Table 6 shows the approximate total site area requirements, capital costs and operating costs for pond systems serving between 30,000 and 100,000 population. These figures should be treated as rough guidelines in view of the many variable factors for which assumptions have had to be made.

Table 6: APPROXIMATE PER CAPITA REQUIREMENTS FOR A WASTE STABILIZATION POND SYSTEM SERVING A TOTAL POPULATION OF BETWEEN 30,000 AND 100,000

	With Anaerobic Pond		Without Anaerobic Pond	
	25°C	12°C	25°C	12°C
Effluent standard 100 FC/100 ml				
Land per capita (gross) m^2	2.0	3.9	2.5	6.0
Capital cost US$/capita	20	30	25	40
Operational cost US$/capita/annum	0.5	0.7	0.5	0.7
Effluent standard 1,000 FC/100 ml				
Land per capita (gross) m^2	1.7	3.4	2.2	5.5
Capital cost US$/capita	18	28	23	38
Operational cost US$/capita/annum	0.4	0.6	0.4	0.6
Effluent standard 10,000 FC/100 ml				
Land per capita (gross) m^2	1.4	2.9	1.9	5.0
Capital cost US$/capita	15	25	20	35
Operational cost US$/capita/annum	0.3	0.5	0.3	0.5

Note: Assumes no pond lining required. Land costs excluded.
Costs at 1981 levels based on recent field visits and less recent literature (15,33,34).

Use of more mechanically intensive sewage treatment systems should be avoided and other systems should only be considered where there is already experience of such systems in the area. Where consideration is given to other more mechanically intensive waste treatment methods as well as ponds, factors other than the purely financial should also be considered. Weighting in favor of pond systems should reflect the absence of mechanical equipment and the consequently increased reliability of the system. However, this will often not be necessary since pond systems will frequently form the least cost economic solution to sewage treatment problems in any case.

Photo 3 - Anaerobic ponds such as this one in Shelomi, Israel, may be completely or partially covered by a crust.

Although it was originally designed as an aerated lagoon, problems with the aerators have led to its being operated as an anaerobic pond.

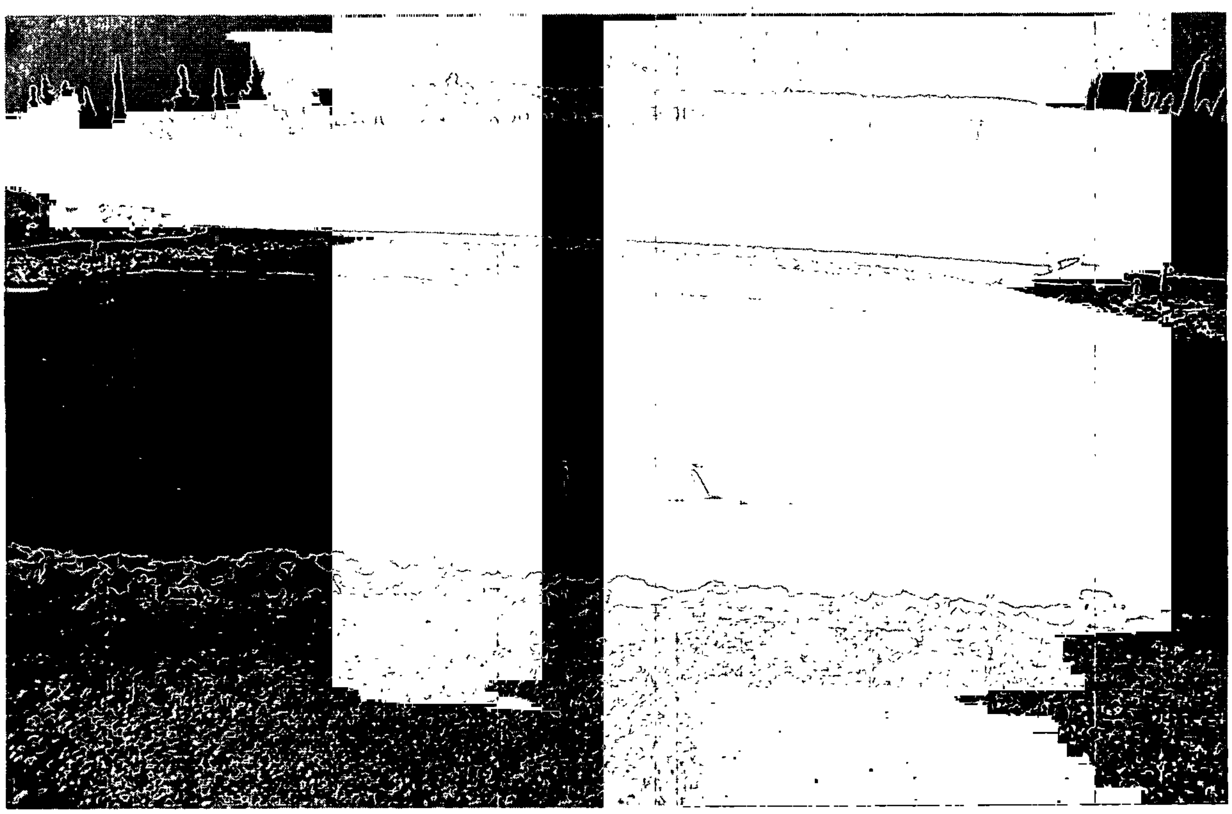


Photo 4 - Some anaerobic ponds, such as this one in Bet Shemesh, Israel, do not become encrusted because the surface draw-off may be preventing a crust from forming.

CHAPTER 4

START-UP PROCEDURES, OPERATION, MAINTENANCE, AND TROUBLE SHOOTING

Start-Up Procedures

The start-up of pond systems can present a number of problems and allowance should be made for:

1. low initial sewage flows as new connections are progressively brought into the system;

2. the slow establishment of the microbiological populations necessary for the treatment processes;

3. low initial sewage strength due to a high proportion of groundwater in the sewage;

Where land is acquired and a system is designed and constructed for long-term needs, the low initial flows can be catered for by:

1. operating only one of a number of parallel anaerobic units;

2. operating only one series of a total of 2 or more series of facultative and maturation ponds;

3. operating only some of a single stream of facultative and maturation ponds (care should be taken since a reduced number of units in series will reduce the pathogen removal efficiency);

4. using only part of the total area of facultative and maturation ponds by bunding across them. (This however raises problems of removing the bunds when the entire system is required).

Where there is a cold season, pond systems should be commissioned immediately following this period. This allows the early months of operation to coincide with the warmest time of the year, and enables the treatment system to become well established before the ensuing cold season.

The ponds should be vegetation free when filled, and should be filled as rapidly as possible to prevent both emergent vegetation and erosion of pond embankments while the pond surface level is below the edge protection.

Anaerobic ponds should be initially filled with raw sewage and wherever possible be seeded with digesting sludge, which helps in the rapid establishment of methanogenic bacteria. The pond(s) may then be left for a few days to allow acid forming and methanogenic bacterial populations to develop. Where seeding has been carried out, the loading

Photo 5. This facultative pond has both good edge detail and embankment maintenance, but the slow rate at which the pond fills, plus the shallow depth of 1.2m and very low organic loading cause vegetation to grow (visible in the background). This photo shows a maintenance worker breaking up algal mats.

Photo 6. Where ponds fill slowly and are poorly maintained, the conditions are ripe for mosquito breeding, as has occurred in this maturation pond.

rate should be brought up toward the design loading rate over the following few days. Where there has been no seeding it may take longer for the methanogenic bacteria to become established, and loading should be increased slowly over the next 20 days or so. The acid forming bacteria have a much more rapid reproduction rate than the methanogenic bacteria which are inhibited by pH < 7. Thus loading should always be maintained at a sufficiently high level to avoid the presence of dissolved oxygen in the pond(s) which inhibit both bacterial groups, and the pH should (if necessary) be kept above 7 by the addition of lime.

Facultative ponds may also be seeded with digesting sludge at startup if readily available. They should also initially be filled with fresh water if possible, either from the mains supply, a river or lake, or a well. In the case of a primary facultative pond, the raw sewage should then be introduced slowly (say initially 1/10 of final flow rate), allowing the development of bacterial and algal populations (taking about 10-20 days) and reaching full loading rate after about one month. Where there is a primary anaerobic pond the water-filled secondary facultative pond may be allowed to take the effluent as it flows from the anaerobic pond which is itself being progressively loaded with raw sewage. Seeding facultative ponds with algal rich water is not generally necessary, although if a source of such water is readily available locally it may be used to seed the pond(s) and so speed up algal development.

Maturation ponds should, wherever possible, be filled with water prior to loading. The first of a series of maturation ponds can then be allowed to take effluent from the facultative pond as it becomes available. Other maturation ponds will in turn accept effluent from the preceding unit until they are each receiving their full load. How long this takes will be dictated by the rate at which the primary unit is being loaded. In each case water flowing into the maturation ponds should be drawn from the algal rich surface layers of the preceding pond.

Where there is no water available to fill facultative and maturation ponds before the sewage is added, the ponds will be filled with raw sewage and left for 20 days for algal and bacterial populations to develop. Further sewage should be added to make up for evaporation and seepage loss, and then following the adaptation period, loading on the facultative pond should be increased progressively as outlined above. As the loading is increased on the facultative ponds, so it will increase on the maturation ponds as the displaced pond liquid passes through the surface overflows to successive ponds.

Where the ponds serve a new community from which the sewage flow is likely to increase only slowly, and to be weak initially due to a high proportion of infiltration water, the following steps should be taken:

1. Any anaerobic unit should be bypassed initially until there is sufficient strength and quantity of raw sewage to enable a loading of at least 0.1 kg $BOD_5/m^3/day$ to be achieved;

2. Facultative and maturation ponds should be filled with water initially, and should be kept full. Where the raw sewage is not sufficient to keep the ponds topped up to compensate for seepage and evaporation losses, then further water should be added. Where no water is available the raw sewage should be used to fill the facultative pond, care being taken to prevent vegetation growth and embankment damage as the facultative and then the maturation ponds fill slowly.

Operation and Maintenance

Waste stabilization ponds are unique among sewage treatment systems in their ability to continue in operation, providing a high quality effluent, despite poor or even non-existent maintenance; although such neglect may cause mosquito, fly and odor nuisance. However, regular maintenance should be carried out to maintain a high standard of effluent, to avoid nuisance problems which may otherwise develop, and to avoid rapid physical depreciation of the system. Pond systems require only minimal simple maintenance and if they cannot be properly maintained, then there is no hope whatsoever that any other type of mechanically intensive sewage treatment plant can be maintained properly.

The operation and maintenance duties for a typical waste stabilization pond system include the following items:

1. Where manual bar screens and/or grit channels are used, regular cleaning and daily burial or burning of screenings and detritus, or removal from site, should be carried out;

2. Where automatically operated bar screens, grit removal chambers and pumping stations are installed, regular lubrication of the working parts should be carried out and frequent checks on the operational efficiency of the equipment should be made. Equipment of this nature should be used only in large systems in areas where mechanical equipment is widely used, and wage levels will attract the appropriate skill levels. Screenings and detritus should be disposed of as in (1) above;

3. Embankment vegetation should be kept short and not be allowed to extend into the ponds. Grass may be permitted to grow down to the edge protection slabs where these are used. Otherwise the water's edge should be sprayed with weed killer (e.g., "Simazine" or Dow Silvex);

4. Scum on facultative ponds should be removed and broken up. Scum and algal mats should not be left at the water's edge but should be dried and disposed of by burial nearby. Scum on anaerobic ponds aids the treatment process and should be left to form a hard

crust, but sprayed to prevent any fly breeding (e.g., "Abate" or "Fenthion");

5. Inlets and outlets should be kept free from accumulating solids;

6. Any vegetation emerging through the hard edge protection or from the pond liquid should be removed;

7. Where appropriate, regular records should be kept of flow rates into and out of the pond system, and the influent and effluent quality should be regularly monitored; and

8. A careful watch should be kept for evidence of embankment damage caused by burrowing rodents, snakes, ants, etc. If this occurs the embankment should be reinstated immediately and the animals or insects kept clear of the ponds by spraying, providing a more hostile environment, or if necessary laying poison or trapping. Fencing should keep out larger animals such as water buffalo or hippopotamus, although if the fencing is continually broken down by these animals it maybe necessary to tolerate them using the ponds occasionally.

Maintenance laborers should be given clear instructions on their duties and the frequency at which these should be carried out. Maintenance manuals are advisable either written or, in the case of illiterate staff, explained by illustration.

Pond cleaning should be undertaken when the pond is approximately half full of sludge, although the liquid depth should not be allowed to reduce to less than 1 m in facultative ponds. This will generally occur every two years with an anaerobic pond, or every twenty years or more for a primary facultative pond. In the case of anaerobic ponds this could mean up to 2 m depth of sludge, whereas for facultative ponds the depth will generally be less than 1 m. Estimation of the quantity of sludge to be removed has been found to cause problems for contractors in Israel. A solids content of about 25% can be expected after drying, although sludge bulking might mean a volume of dry sludge equal to about 50% of the volume of wet sludge.

Sludge removal can be carried out by raft mounted sludge pumps or by manual removal and carting away, which appears to be a more common method. The main problems appear to be provision of sludge drying beds in the case of the first option and achieving complete sludge drying in the case of the second. It may prove cheaper to provide a small anaerobic sludge lagoon as an alternative to sludge drying beds.

1. Raft mounted sludge pumps are probably a preferable alternative where (a) there is a short dry season limiting sludge drying time; or (b) the sludge is very deep. One advantage is that the pond can quickly be

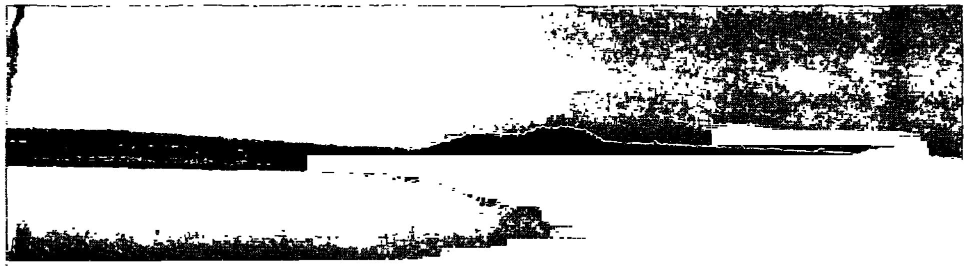


Photo 7 (above). Sludge should be removed long before it reaches the surface -- as has occurred in this pond.

Photo 8. The partially dried sludge in this anaerobic pond at Sederot, Israel, will be removed.

returned to normal use once the sludge has been pumped out. The main disadvantage is the need for sludge drying beds (assuming sludge accumulation of 0.04 m^3/capita/yr and pond desludging every two years, about 0.5 m^2 per capita of drying bed would be required), or a sludge lagoon (0.10 m^3/capita).

2. Sludge drying in situ is probably a preferable alternative where, (a) there is a long dry season; or (b) the sludge layer is not too deep (say 1 m or less).

Problems may still be encountered with the surface of the sludge drying to form a crust whilst the sub-surface layers remain wet. Once the sludge has dried throughout its depth it should be bulldozed or excavated to one side. If there is a market for the sludge, local farmers should be encouraged to come and collect it themselves, otherwise it will have to be carted away. 1/ To facilitate this, ramps should be constructed to ponds which are likely to require frequent desludging by this method. Otherwise the embankment will have to be removed or flattened to allow access, and carefully reinstated after use.

In addition to the above duties, general repairs to the structural elements such as fencing, lighting and embankments must be carried out. Guards should be provided at plants where there are buildings and mechanical equipment, which will otherwise be subject to burglary and vandalism.

The operational staff requirement for a pond system depends on the following:-

1. size of the system;

2. method of preliminary treatment employed;

3. existence of a laboratory on site;

4. nature of the labor market in relation to laborer's rates of pay;

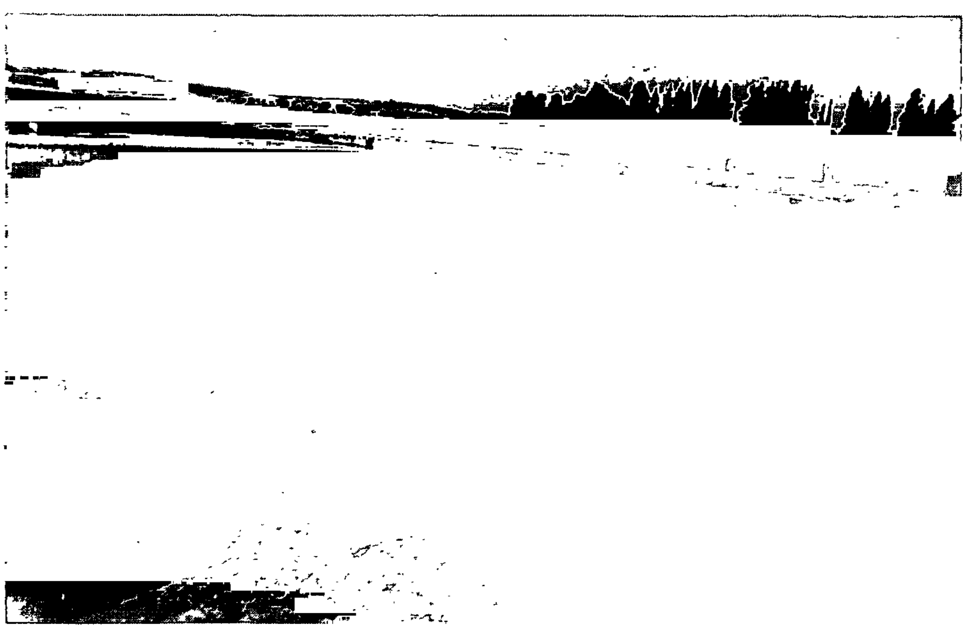
5. availability of mechanical maintenance equipment (e.g., lawn mowers); and

6. existence of ancillary facilities.

1/ In any consideration of sludge reused for agriculture, particular attention should be paid to the possibility of viable helminth ova remaining in the dried sludge. Although many helminths are eliminated by the combined effects of anaerobic digestion, temperature and dessication, Ascaris ova in particular have been shown able to survive sludge drying after conventional sludge digestion (31). There is virtually no data on the survival of helminthic ova in waste stabilization pond sludge. (1).

Photo 9. For small or medium-sized treatment plants, anaerobic ponds need only be small, such as this one at Karmiel, Israel, which is one of two parallel ponds treating a total of 1,100 m^3/day and is about 25m square.

Photo 10 (below). The slightly larger anaerobic unit at Sederot, Israel, has developed a good surface scum. The embankment in the foreground, however, is badly eroded due to poor maintenance, lack of a hard edge detail, and poor surface drainage around the pond.



The diversity in numbers of staff employed at each facility is best demonstrated by the following examples.

1. Beer Sheva, Israel, treating 16,000 m^3/day in 16 ha of ponds - 1 part-time operator. Population served: 110,000;

2. Dandora, Nairobi, treating approx. 60,000 m^3/day in 95 ha of ponds - approx. 40 full time staff. Population served 400,000.

The recommended staffing levels for systems serving populations of 10,000 to 250,000 in an area where labor is relatively cheap are shown in Table 7.

Table 7: RECOMMENDED STAFFING LEVELS

Populated Served	10,000	25,000	50,0000	100,000	250,000
Foreman/Supervisor	-	-	1	1	1
Mechanical Engineer /a	-	-	-	1	1
Laboratory Technician /b	-	1	1	1	2
Assistant Foreman	-	1	2	2	2
Laborers	1	2	4	6	10
Driver /c	-	1	1	1	2
Watchman /d	1	1	1	3	5
Total	2	6	10	15	23

/a Dependent upon amount of mechanical equipment used.
/b Dependent upon existence of laboratory facilities.
/c Dependent upon use of vehicle-towed lawn mowers, etc.
/d Dependent upon location and amount of equipment used.

At the design stage consideration should be given to:

(1) provision of paved ramps to facilitate sludge removal from anaerobic ponds; and

(2) purchase of boat and provision of launching facilities for large ponds.

Wherever possible the client body (e.g., government agency or local municipality) should also be responsible for the operation and maintenance of the system. Where this is not possible, the body responsible for maintenance should be involved in the project during both the design and implementation phases. This will improve their understanding of the system, and should result in a higher standard of operation and maintenance.

Treatment Monitoring

Regular monitoring of flow rates and influent and effluent quality is desirable at all treatment plants, since it allows:

1. Monitoring of effluent quality;

2. Measurement of water losses;

3. Calculation of hydraulic and organic loading rates, enabling impending overloading of the system to be predicted and possibly avoided.

Smaller systems are unlikely to be provided with laboratory facilities, although efforts should be made to have occasional checks made on influent and effluent quality so that potential overloading may be predicted, and effluent quality can be checked against the required standards. This is particularly important where fish culture or irrigation are practiced. Laboratories which are able to make these occasional checks must be found, possible sources being neighboring treatment plants, universities, regional laboratories or private laboratories. With large systems which include their own laboratory, the necessary equipment and staff should be obtained to allow measurement of the BOD_5, SS and fecal coliform concentrations at the very least. Measurement of in-pond parameters such as the dissolved oxygen and pH is also important in checking whether the ponds are operating satisfactorily.

Monitoring of fecal bacterial concentrations, which is regretably seldom undertaken at present, should be included in all pond monitoring programs. Exclusively fecal indicator organisms such as the fecal coliforms or fecal streptococci should be used in preference to the non-exclusively fecal Total Coliform group. The best technique for determining bacterial concentrations in pond effluent samples is the membrance filtration method. 1/

Troubleshooting

Problems can develop with pond systems in spite of their relative operational simplicity, and these can cause a reduction in operational efficiency, nuisance, and/or damage to the system. Many of these problems can be avoided or minimized by good design, and the rest can be prevented if good operational control is maintained. The following is a list of possible problems and solutions, commencing with those likely to occur during start-up.

Problem	Solutions
(1) Odors during start-up of anaerobic ponds	(a) If pH below 7 add lime (preferably as slurry) at inlet to anaerobic pond
	(b) If dissolved oxygen present in pond, increase loading rate to maintain anaerobic conditions
	(c) Use straw or polystyrene etc., to help establish a good scum mat
(2) High rate of seepage during early stages of pond operation	Under most circumstances ponds will eventually seal themselves. If this does not occur and high seepage persists, ponds will require draining and sealing with impermeable soil or plastic membrane. Alternatively, an expensive sealing clay such as "Volclay" may be added to the pond
(3) Vegetation growth as ponds are filled	All vegetation should be removed from the pond bottom before filling. Final pond liquid depth should be greater than 1 m. Ponds should be filled as rapidly as possible. Any vegetation growing through water surface during filling should be removed from a boat.

1/ The membrane filtration method involves filtering a given volume of sample (which may be diluted using standard serial dilution techniques) through a plastic membrane filter which has a pore size (generally 0.45 μm) that causes bacteria to be retained on the filter. The filter is then placed on a medium that is selective for the particular bacteria required, and incubated at the appropriate temperature for the required period (e.g. fecal coliforms - 24 hours at 44°C on m-FC. Broth, of fecal streptococci - 48 hours at 37°C on m- Enterococcus Agar). After incubation the colonies can easily be counted on the squared filter paper to give the bacterial concentration per unit volume of filtered sample, and so permit the number per 100 ml of sample to be calculated.

Problem	Solutions
(4) Poor algal development during start up	Check nature of discharges to ponds--particularly from industrial/commercial concerns. Algal inhibition may be due to poor nutrient balance or toxic compounds in influent. Pre-treat wastewater concerned before discharge to sewerage system.
(5) Development of algal scum on facultative and maturation ponds	Break up scums (usually blue-green algae) with water jets or from boats. In extreme and persistant cases, copper sulphate may be added to give approximately a 1 mg/l solution in the pond concerned. Scum removed from ponds and dried should be applied to grassed embankment or buried.
(6) Vegetation at water's edge	Design ponds with a hard edge detail. Spray water's edge with weed killer (e.g., "Simazine" or "Dow Silvex").
(7) High vegetation growth on embankments	Periodic mowing or bushing is best control method. Grazing animals may be used but will also add organic material and fecal bacteria to the pond system.
(8) Vegetation growth through pond surface	Increase pond depth or loading rate to shut light off from pond bottom. Remove weeds from pond bottom using boat. Care should be taken to avoid damaging pond seal when removing clumps of weeds. Remove any sludge banks causing shallow areas.
(9) Burrowing animals or insects in embankments	Plug holes as they occur, remove any animal food supply growing close to ponds. Trap or poison animals if necessary; spray insects.
(10) Fly or mosquito nuisance	Keep ponds and pond edges clear of vegetation. Keep facultative and maturation ponds free from scum. Spray scum layer of anaerobic ponds and other areas if necessary (e.g., "Abate" or "Fenthion"). Remove any exposed sludge banks. Stock maturation ponds with fish (e.g., Gambusia).
(11) High algal concentration in effluent flowing to the receiving stream	Draw off effluent from below the surface or wherever algal population is low (may vary). Use horizontal rock filters.

(12) Lightly loaded ponds causing waste of space and inefficient treatment, and dominance of filamentous algae causing algal mats	Use fewer ponds but beware of effect on final effluent quality particularly with regard to increased fecal bacterial concentration.
(13) Overloaded ponds causing poor effluent quality	Add additional units in either series or parallel. Increase operational depth of anaerobic pond.
(14) Overloaded ponds causing odor nuisance	Add additional units in parallel to anaerobic and/or facultative units. Increase operational depth of anaerobic units. Use surface aeration for facultative ponds or interpond recirculation for primary units.
(15) Short circuiting causing poor treatment efficiency or odor problems	Improve circulation by adding additional inlets and/or outlets, or use baffles. Improve wind mixing if possible, clean out sludge if necessary, recirculate if necessary.

CHAPTER 5

LEAST COST FEASIBLE SOLUTION ANALYSIS

To demonstrate the way in which a waste stabilization pond system will often provide the least cost feasible solution in spite of relatively high land costs, an example is given below. This compares costs calculated on a life cycle discounted cash flow basis for four different systems. These are:

1. Waste stabilization pond system, comprising anaerobic, facultative and maturation ponds in series;

2. Aerated lagoon system, comprising aerated lagoons, facultative and maturation ponds in series;

3. Oxidation ditch system comprising oxidation ditches, secondary sedimentation tanks and sludge drying beds;

4. Biological filtration plant comprising primary sedimentation tanks, biological filters and secondary sedimentaton tanks with associated sludge digesters 1/ and drying beds.

In order to use reasonably reliant cost data, the following case study has utilized unit capital, operation and maintenance costs and certain other costs (converted to US dollars) quoted in a recently published feasibility study. (32) The population, water supply forecasts, design temperature and other parameters have been changed to give a more generalized case, and one which should more closely represent the typical problem in LDCs. Anaerobic ponds are also considered as a design option; these were not considered in the feasibility study, presumably on account of the cold season. 2/

1/ Digestors should be included because to put raw primary and secondary sludge straight on to drying beds gives rise to serious odor problems. Digestors are not needed with oxidation ditches due to long (20-30d) solids retention in the ditch.

2/ The City is Sana'a, N. Yemen. The ambient design temperature used in the feasibility report is 11°C which would result in a sewage temperature of about 14°C. This is just below the level at which methanogenic bacteria cease to operate efficiently.

The following assumptions have been made in the system designs.

Contributing population	250,000
Wastewater contribution	120 lcd
Average daily wastewater flow	30,000 m^3/d
Per capita BOD_5 contribution	40gcd
Average daily BOD_5 load	10,000 kg/d
Controlling temperature	20°C
FC concentration in raw sewage	2 x 10^7FC/100 ml
Effluent standard for BOD_5	25 mg/l
Effluent standard for FC	10,000 FC/100 ml
Pumping required to inlet works and for irrigation	

1. Waste stabilization pond system assumptions:

Depths -	anaerobic ponds	4 m
	facultative ponds	1.8 m
	maturation ponds	1.5 m

2 parallel streams of ponds

Total site area required 46 ha.

2. Aerated lagoon system assumptions:

Partially mixed primary aerated lagoon

Detention time of aerated lagoons	4 days
Depth of aerated lagoons	3.5 m
Depth of facultative ponds	1.75 m
Depth of maturation ponds	1.5 m

2 parallel streams of ponds

Total site area required 50 ha.

3. Oxidation ditch assumptions: 1/

Detention time in ditches	1 day
Detention time in settlement tanks	4.5 hours
Sludge drying bed area	10 persons/m^2

Total site area required 20 ha.

1/ To attain the required FC effluent standard it is assumed that some form of tertiary treatment, probably effluent chlorination, would be required for the oxidation ditch and biological filter.

4. Biological filter assumptions: 1/

Primary sedimentation tanks detention	6 hours
Biological filter media depth	2 m
Up to 2 x average flow recirculation rate	
Secondary sedimentation tanks detention	6 hours
Sludge drying bed area	8 persons/m^2

Total site area required 25 ha.

Capital costs of the alternative systems in US$:

	Land 2/	Earthworks	Structures	Equipment
Waste Stabilization Ponds	2,300,000	2,300,000	2,500,000	200,000
Aerated Lagoon System	2,500,000	2,500,000	3,000,000	1,100,000
Oxidation Ditch	1,000,000	200,000	4,100,000	1,300,000
Biological Filter	1,250,000	180,000	7,500,000	1,900,000

Total capital costs, including land for each system are estimated at:

Waste stabilization pond	US$7.3 m	(US$29/capita, US$20 excluding land)
Aerated lagoon	US$9.1 m	(US$36/capita, US$26 excluding land)
Oxidation ditch system	US$6.6 m	(US$26/capita, US$22 excluding land)
Biological filter system	US$10.8 m	(US$45/capita, US$38 excluding land)

For the purpose of this example land costs have been considered to have been spent in year zero, so the present value of land is equal to its actual cost. Subsequent capital spending has then been spread between years 2 to 5, after which any operating costs or benefits are expected to commence.

On this basis the capital costs have present values as follows:

	US$ m.
Waste Stabilization Pond System	5.68
Aerated Lagoon System	6.98
Oxidation Ditch System	4.80
Biological Filter System	7.77

1/ To attain the required effluent standard it is assumed that some form of tertiary treatment, probably effluent chlorination, would be required for the oxidation ditch and biological filter.

2/ Land is assumed to cost US$5 per m^2, reflecting a reasonably low existing use value which would be necessary to enable the land to be purchased for a low cost housing development. Cheap land is a prerequisite of low cost housing schemes which must of necessity be affordable to the beneficiaries. This example assumes that the treatment system is serving such a scheme.

Operational costs including power consumption, etc., are assumed as follows:

Waste stabilization pond system	US$ 50,000/annum (US$0.2/capita)
Aerated lagoon system	US$300,000/annum (US$1.2/capita)
Oxidation ditch system	US$350,000/annum (US$1.4/capita)
Biological filter system	US$200,000/annum (US$0.8/capita)

Benefits accrued from effluent irrigation are assumed equal for all systems since the additional value of algae as soil conditioner will depend on the type of soil at the pond location. With irrigation water sold at US$1 per m^3, the value in the first year will be US$100,000 per annum.

The maturation ponds in the waste stabilization pond system and some of the polishing ponds in the aerated lagoon system may be used for fish farming. If 18 ha of pond are used for fish culture in each case, with a productivity of 4,000 kg fish/ha/annum, a total yield of 72 metric tons of fish per annum might be achieved. Allowing this fish to be conservatively priced at US$1 per kg, this means an income in the first year of US$72,000.

Bringing the operation and maintenance costs and income derived from irrigation and fish farming to present values, using 12% as the opportunity cost of capital (subsequently referred to as discount factor) gives:

	O & M Cost	Irrigation Income	Pisciculture Income
		(US$ million)	
WSP system	0.4	0.75	0.5
AL system	2.2	0.75	0.5
OD system	2.6	0.75	-
BF system	1.5	0.75	-

These figures are present values in US$ million over 20 years commencing in year 5; it is therefore necessary to find their present value at year zero. In order to do this we must multiply by a discount factor of 0.57 (i.e. the present value of 1 spent 5 years from now at a discount rate of 12%).

The table then converts to:

	Op. & Maint. Cost	Irrigation Income	Pisci-culture Income	Net
Waste stabilization pond system	- 0.21	+ 0.43	+ 0.30	+ 0.52 1/
Aerated lagoon system	- 1.28	+ 0.43	+ 0.30	- 0.55
Oxidation ditch system	- 1.49	+ 0.43		- 1.06
Biological filter system	- 0.86	+ 0.43		- 0.42

1/ Benefits exceed costs.

These figures are present values in million US$ over 25 years; the actual operating and benefit costs would accrue in years 5-25 but the costs streams have been discounted to year 0. Thus net present values for each of the proposed systems can be calculated as follows:

1. Waste stabilization pond system:

		(US$ million)
Costs:	Capital cost (inc. land)	5.68
	Operating cost	0.21
		5.89
Benefits:	Irrigation income	0.43
	Pisciculture income	0.30
		0.73

Net present value: US$ - 5.16 million

2. Aerated lagoon system:

		(US$ million)
Costs:	Capital cost (inc. land)	6.98
	Operating cost	1.28
		8.26
Benefits:	Irrigation income	.43
	Pisciculture income	.30
		0.73

Net present value: US$ - 7.53 million

3. Oxidation ditch system:

		(US$ million)
Costs:	Capital cost (inc. land)	4.80
	Operating cost	1.49
		6.29
Benefits:	Irrigation income	0.43

Net present value: US$ - 5.86 million

4. <u>Biological filter system</u>:

		(US$ million)
Costs:	Capital cost (inc. land)	7.77
	Operating cost	0.86
		8.63
Benefits:	Irrigation income	0.43

Net present value: US$ - 8.20 million

Thus on this analysis a waste stabilization pond system with land values of US$5 per sq m offers the most economic solution under the circumstances set out in this example.

Frequently a pond system is proposed to serve a new development rather than an existing one, and such a development will generally be located as close as possible to an existing population center. The land for a development such as low cost housing would have a low existing use value, and would be purchased en bloc for the development. The proposed sewage treatment and disposal system could be located either on-site, or off-site at some distance from the development. In most cases the cost of pumping sewage long distances to off-site treatment works and absence of sufficient fall to allow works to be fed under gravity will militate against the location of works off-site. For on-site works the land cost is relatively cheap, and the land which would be saved by using a more mechanically intensive system than waste stabilization ponds (which use more land) would be taken up for housing and thus passed on to the beneficiaries at cost. Any increase in value of this land with time and further development will in this case accrue to the individual beneficiary. On the other hand, where this land is still owned by the municipality and used for sewage treatment, the increased value accrues to the municipality.

As pressure to develop the land used by the treatment plant increases, and as the plant becomes obsolete, the city can sell the land for development. In the case of a pond system there is more of this land, and it is easier to prepare for development than land which has been used for treatment systems involving large concrete structures. The treatment plant will require resiting, and the process outlined above may be repeated, the new treatment facility picking up existing and proposed sewage flows.

If the pond system is located off-site and away from the developed area, either development will ultimately reach the site, resulting in the same situation as outlined above; or alternatively,development will not reach the site in which case the system can be extended as required using the relatively cheap neighboring land. There should then be no need to relocate the system until the situation outlined above does arise.

If the potential income from resale of land is included in the foregoing least cost feasible solution analysis, the net present value of each of the systems evaluated will decrease. The systems which will benefit most are those which use the greatest area of land i.e., the pond systems.

To illustrate this possibility the previous example may be used. If it is assumed that the real value of this land used for the treatment plant has doubled over the 25 year lifespan 1/ (in many cases this could be a conservative estimate), the resale incomes at present values for each of the systems is as follows:

	US$ million
Waste stabilization ponds	4.6
Aerated lagoon system	5.0
Oxidation ditch system	2.0
Biological filter system	2.5

Costs will also be incurred in site preparation for development, and these will be greater where large concrete structures must be removed. These costs may be assumed as follows:

Cost US$ m	Cost US$ m	Present Value US$ m
Waste stabilization ponds	0.2	0.01
Aerated lagoon system	0.3	0.02
Oxidation ditch system	0.5	0.03
Biological filter system	0.5	0.03

The net present value of each of the systems previously evaluated will now become:

Waste stabilization ponds	US$ - 0.57 million
Aerated lagoon system	US$ - 2.55 million
Oxidation ditch system	US$ - 3.89 million
Biological filter system	US$ - 5.73 million

Where there is no likelihood of the treatment system requiring relocation in the future and where physical constraints prevent cheap land being available for a sewage treatment plant, then systems other than ponds may prove more economical. Using the example outlined above, if land is assumed at US$20 per square meter, ponds cease to be the most economical option where land resale is excluded, as shown below.

Net Present Value

US$ million

Waste stabilization ponds	US$ - 12.06 million
Aerated lagoon system	US$ - 15.03 million
Oxidation ditch system	US$ - 8.86 million
Biological filter system	US$ - 11.95 million

1/ This assumption infers that a piece of land on the edge of a rapidly expanding city would appreciate 34 times, at a discount rate of 12%, i.e. a piece of land costing US$ 100 today would theoretically sell for US$ 3400 in 25 years time, i.e. have a present worth of $200.

In this example, oxidation ditches take over from ponds as the most economical option at a land cost of about US$7.8 per square meter, i.e. at a discount rate of 12% and excluding resale values.

The sensitivity and influence of land price to the choice of the preferred solution can be illustrated by the use of graphs. Taking numbers from our example, we can calculate the net present values of the various treatment options at varying land prices and discount factors.

Present worth values

Waste Stabilization Ponds	Land Price $ per m2	Discount Factor %			
		5	10	12	15
	1	3.50	3.40	3.33	3.19
	5	5.34	5.24	5.17	5.03
	10	7.64	7.54	7.47	7.33
	15	9.94	9.84	9.77	9.63
Aerated Lagoon	1	7.35	5.92	5.63	5.01
	5	9.35	7.92	7.53	7.01
	10	11.85	10.42	10.03	9.51
	15	14.35	12.92	12.53	12.01
Oxidation Ditch	1	7.32	5.53	5.06	4.46
	5	8.12	6.33	5.86	5.26
	10	9.12	7.33	6.86	6.26
	15	10.12	8.33	7.86	7.26
Biological Filter	1	9.31	7.66	7.20	6.53
	5	10.31	8.66	8.20	7.53
	10	11.56	9.91	9.45	8.78
	15	12.81	11.16	10.70	10.03

Graphs can now be drawn and are shown on Figures 2, 3, and 4.

It can be seen that the present values of waste stabilization ponds are relatively insensitive to discount factor variation and the oxidation ditches are the only real competitor to waste stabilization ponds. This holds true unless the resale value of land is included, as was discussed previously.

The combined effect of escalating land values and high discount factors argues economically against waste stabilization pond systems and assists oxidation ditch proposals. The figures indicate that at land prices of US$1 per square meter waste stabilization pond systems win easily; at US$5 per square meter oxidation ponds overtake them at a discount factor of 16%; and again at 9.7% and 5.3% at land prices of $10 per square meter and US$15 per square meter respectively.

Figure 2: PRESENT VALUES, CONSTANT LAND PRICES, VARIABLE DISCOUNT FACTOR

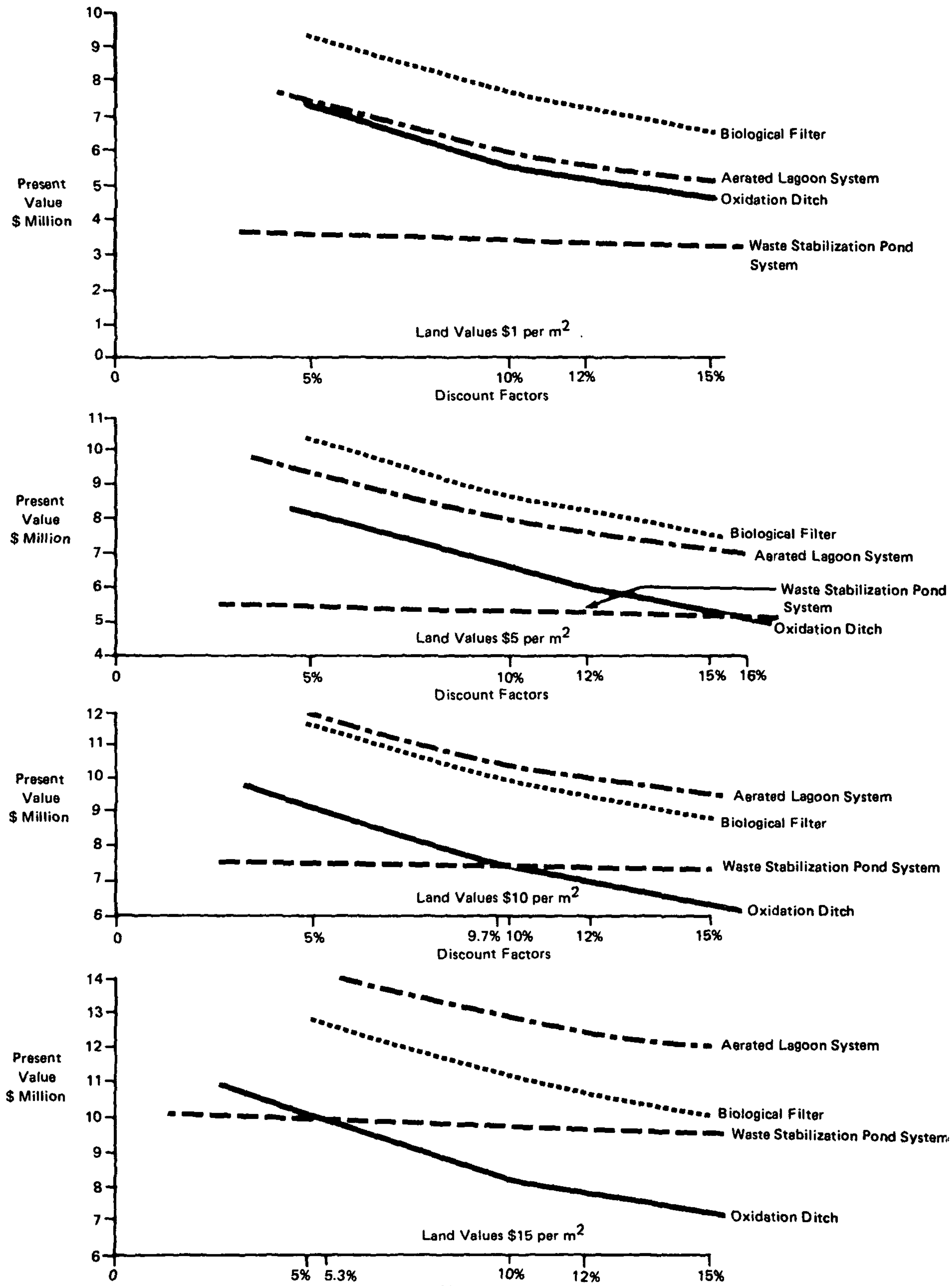


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Figure 3: PRESENT VALUES, CONSTANT DISCOUNT FACTOR, VARIABLE LAND VALUE

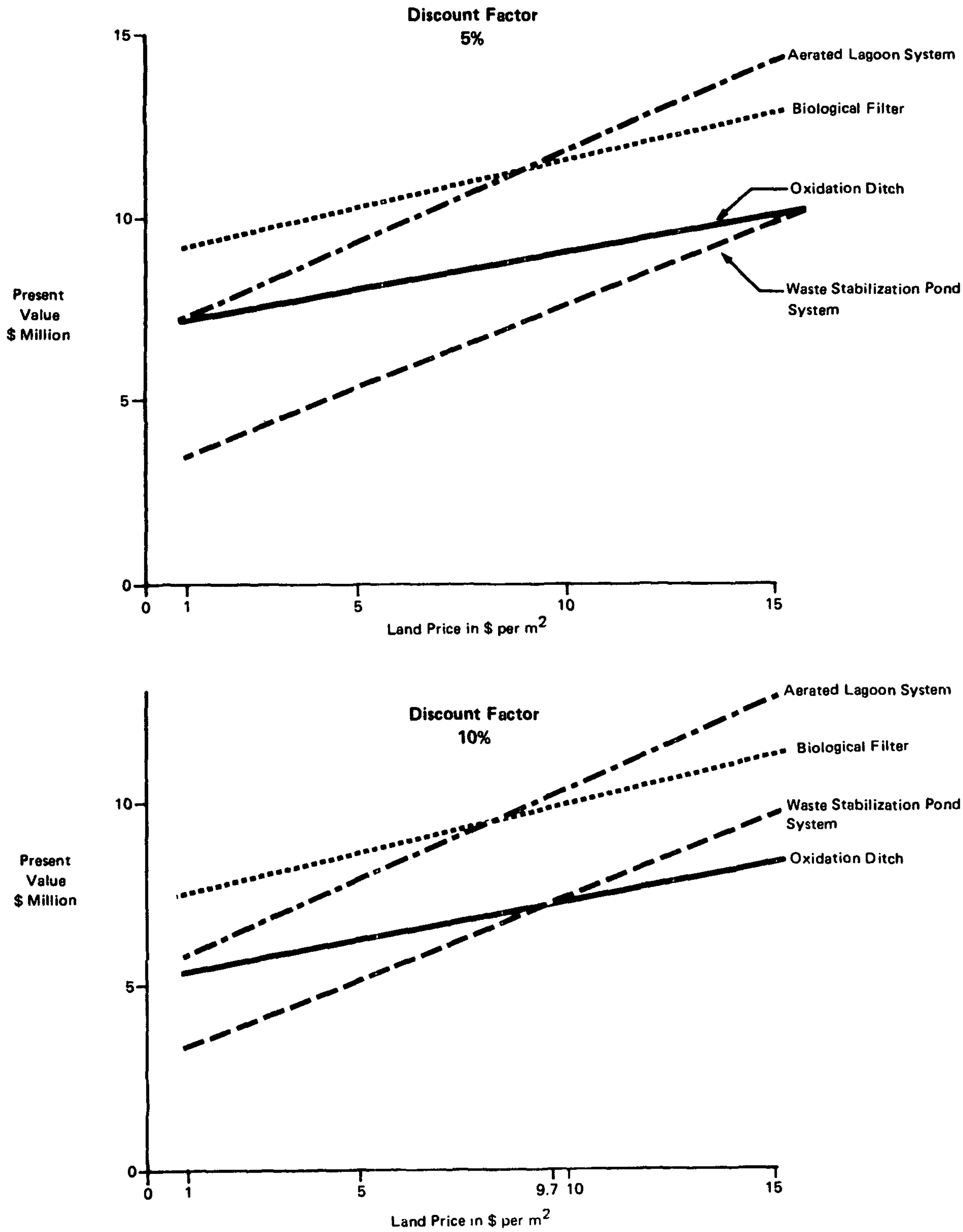

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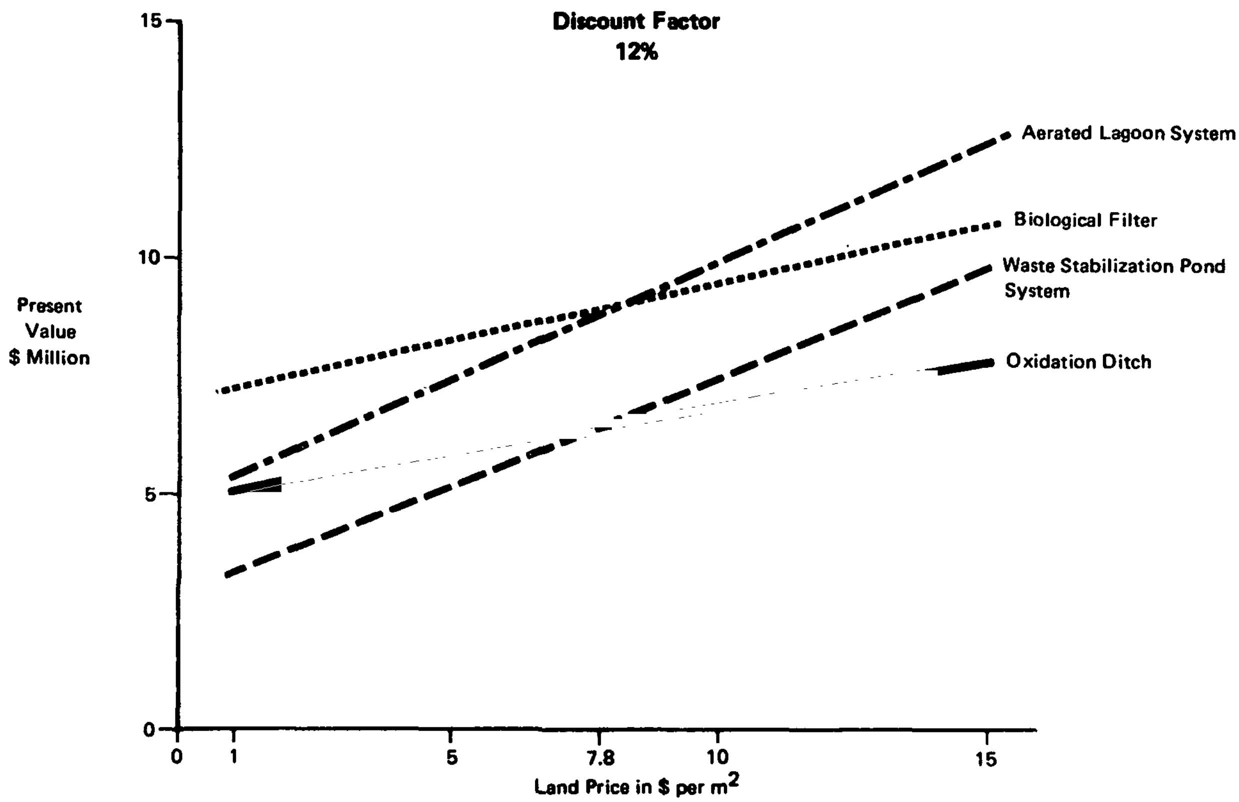
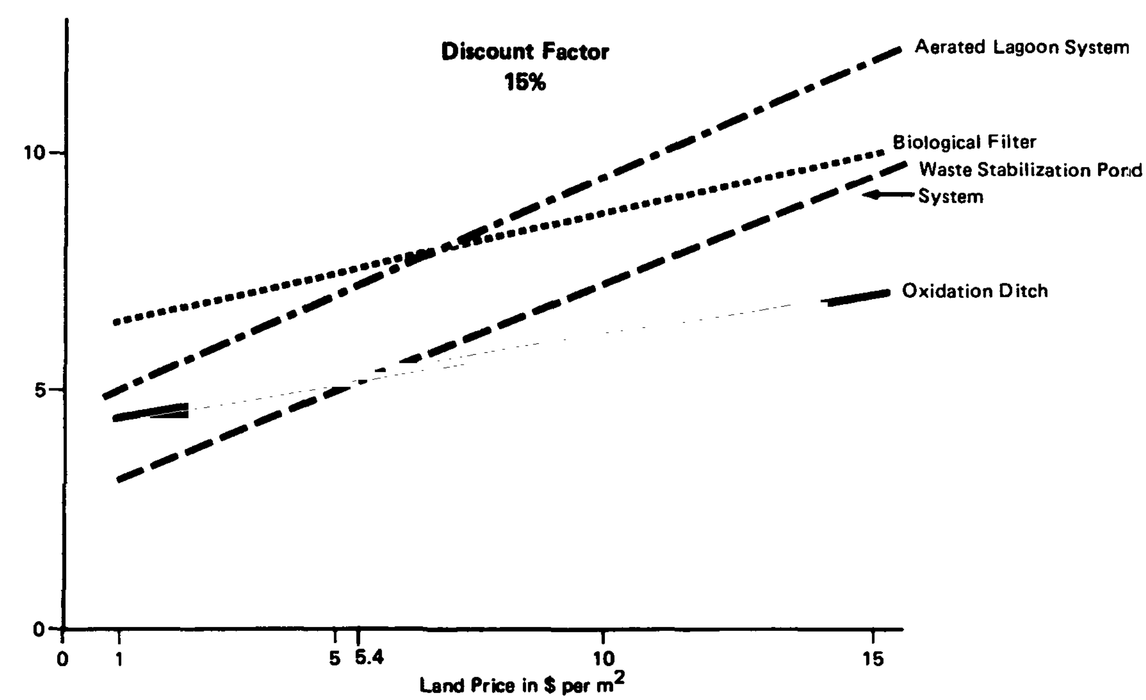
Figure 4: PRESENT VALUES, CONSTANT DISCOUNT FACTOR, VARIABLE LAND VALUE





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On the numbers used in this example, Biological Filters and Aerated Lagoons are never serious contenders for the preferred solution, but in situations where energy costs are cheap 1/ and/or forecast resale land values are allowed for, the position could change. The other variable which impinges heavily on land costs is temperature. In the example, the ambient design temperate was 20°C and in situations where temperatures are higher than this, waste stabilization ponds must be favorites in the economic stakes. In cooler climates this will not always be so. It is clear, however, that in situations of relatively cheap land and warm temperatures, the economic case for waste stabilization ponds becomes very strong.

It should be pointed out that this chapter deveoted as it is to engineering economic analysis, is part of a paper concerned with the design of stabilization ponds. It does not aim to teach engineering economics, 2/ but hopefully it has alerted the reader to the sensitivity of land prices together with the type of analysis which should be undertaken. Each case must be taken on its merits and the judgment and assumptions involved in an economic analysis of this type must be carefully weighed.

1/ From cheap fuel or hydro power.

2/ A good introductory book is Engineering Economics, published in 1969 by the Institution of Civil Engineers, Great George Street, London.

CHAPTER 6

WORKED EXAMPLES

To demonstrate some of the recommendations presented in this paper two examples follow; one for a small community and another for a much larger one. Sketches of the pond details relating to each facility are also included (15, 17, 36, 37).

EXAMPLE 1

Assumed to be a new development (e.g., sites and services project) due to be fully implemented and occupied within 5 years of first raw sewage arriving at plant. It is intended that the effluent will eventually be used for channel irrigation of vegetables.

Design assumptions and requirements

Population (ultimate)	10,000
Per capita wastewater contribution	80 lcd
Per capita BOD_5 contribution	40 gcd
Total infiltration to sewers estimated at	100 m^3/day
Influent bacterial concentration assumed	5×10^7 FC/100 ml
Mean minimum monthly temperature	21°C
Effluent standard required for unrestricted irrigation	<25 mg/l BOD_5 <100 FC/100 ml

Design Calculations

Sewage flow	10,000 x 80 l	=	800 m^3/day
	plus infiltration	=	100 m^3/day
	Total flow rate		900 m^3/day

Total organic load 10,000 x 40 g — 400 kg

Influent BOD_5 concentration = 400/900 = 445 mg/l

(a) Anaerobic ponds

At 21°C anaerobic ponds designed using volumetric loading (λv) of 0.25 kg $BOD_5/m^3/d$

Volume of ponds = 400 / 0.25 = 1,600 m^3

Check detention time (t*) = 1,600/900 = 1.78 days

Since 2-day detention time pond will only decrease loading to 0.22 kg $BOD_5/m^3/d$ use 2 day t*.

Volume required = 1,800 m^3

For flexibility of operation use 2 anaerobic units each 900 m^3 volume plus one reserve pond 900 m^3 volume.

Assuming operational depth of 4 m mid depth
area of each pond = 225 m^2 (say 10m x 22.5 m)

Total (mid depth) area of anaerobic ponds is 675 m^2

(b) Facultative Ponds

Facultative pond designed according to equation 1
with T = 21°C.

$$\lambda_s = 20 \times 21 - 60 = 360 \text{ kg } BOD_5\text{/ha/day}$$

Assuming BOD_5 removal of anaerobic ponds conservatively at 60% (Table 3)

Influent BOD_5 to facultative pond = 0.4 x 445 = 178 mg/l

From equation 2 facultative pond mid-depth area can
be calculated from:

$$A = \frac{10 \times 178 \times 900}{360} = 4{,}450 \text{ m}^2$$

Assuming depth of 1.75 m, volume = 7,780 m^3

Facultative pond can remain a single unit since
cleaning should not be required during its lifetime.

Detention time of facultative pond = 8.6 days

Probable BOD_5 removal in facultative pond is 70%
giving cumulative removal of 88%.

(c) Maturation Ponds

Maturation ponds designed to achieve an effluent FC
concentration 100 FC/100 ml.

Using equations 4 and 5 and assuming three 5-day
maturation ponds in series.

$$K_B(T) = 2.6 \times (1.19)^{(21-20)} = 3.1$$

$$B_e = \frac{5 \times 10^7}{(1 + 2x3.1)\ (1+8.6x3.1)\ (1+5x3.1)^3} = 64 \text{ FC/100 ml}$$

Thus a series of three 5-day maturation ponds will
satisfy the bacterial effluent standard.

Check for BOD_5: probable cumulative percentage
removal = 95% (Table 3)

Effluent BOD_5 = 0.05 x 445 = 22.3 mg/l

Thus effluent should also satisfy BOD_5 effluent standard.

Maturation pond volumes each 4,500 m^2
Assume depth = 1.5 m
Then mid-depth area of each maturation pond = 3,000 m^2

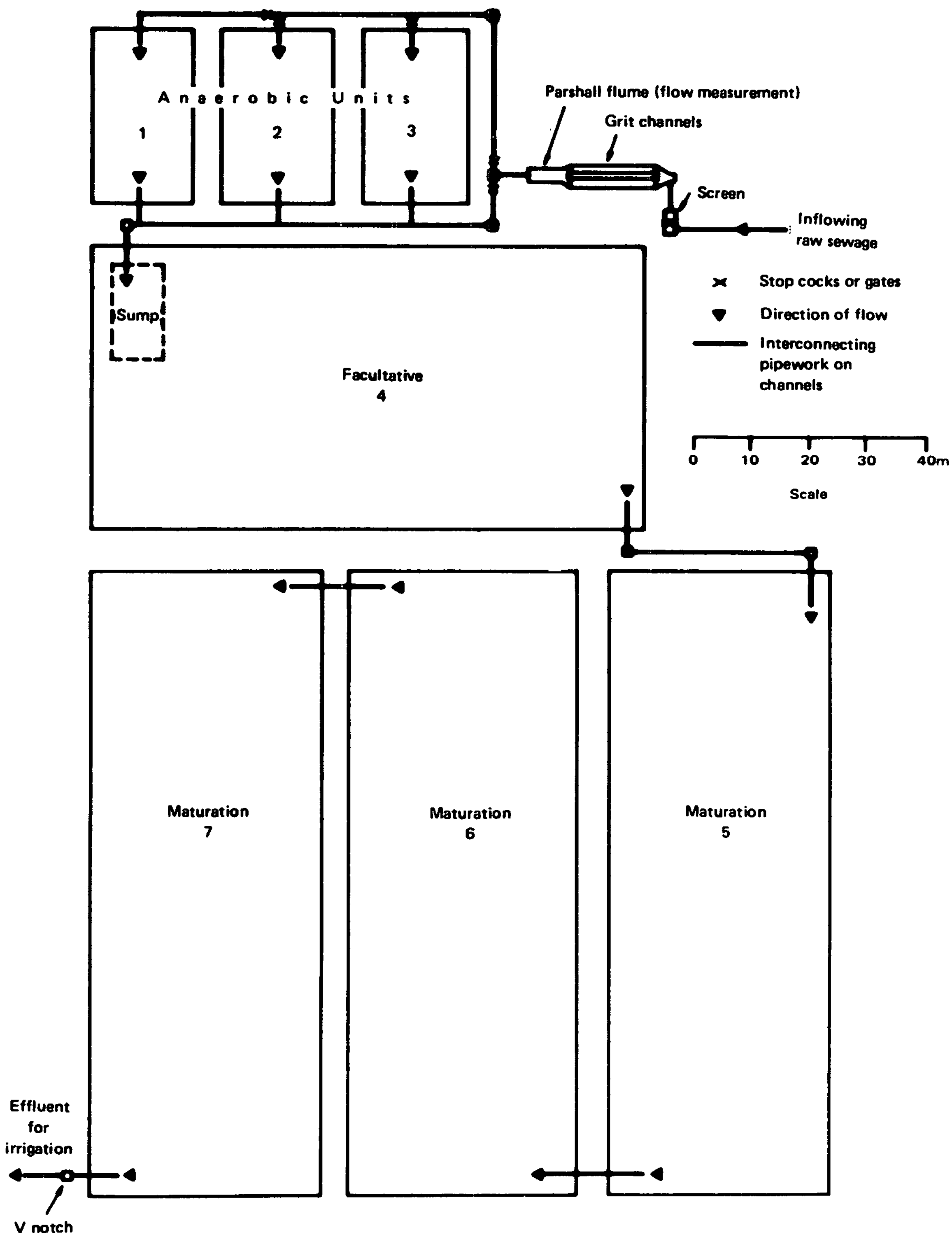
(d) Comments

Total mid-depth area of pond system	=	14,125 m^2
Approximate surface area	=	18,000 m^2
Approximate area required for system	=	2.25 ha

Due to likely slow build-up of flow, the system would initially be run with the anaerobic units bypassed until the raw sewage flow and strength is sufficient to enable one anaerobic unit to be operated at a loading rate > 0.1 kg $BOD_5/m^3/d$.

To ensure no problems are created by solids build up in the facultative pond during the period when it is being used as a primary unit, a sump will be included at the inlet to the facultative pond. Furthermore, preliminary treatment by a screen and two parallel grit channels is provided and a venturi flume is located at the inlet to the pond system with a V notch at the outlet. The layout, system of operation, and some typical details are shown in figures 5, 6 and 7.

Figure 5: EXAMPLE 1, LAYOUT OF PONDS



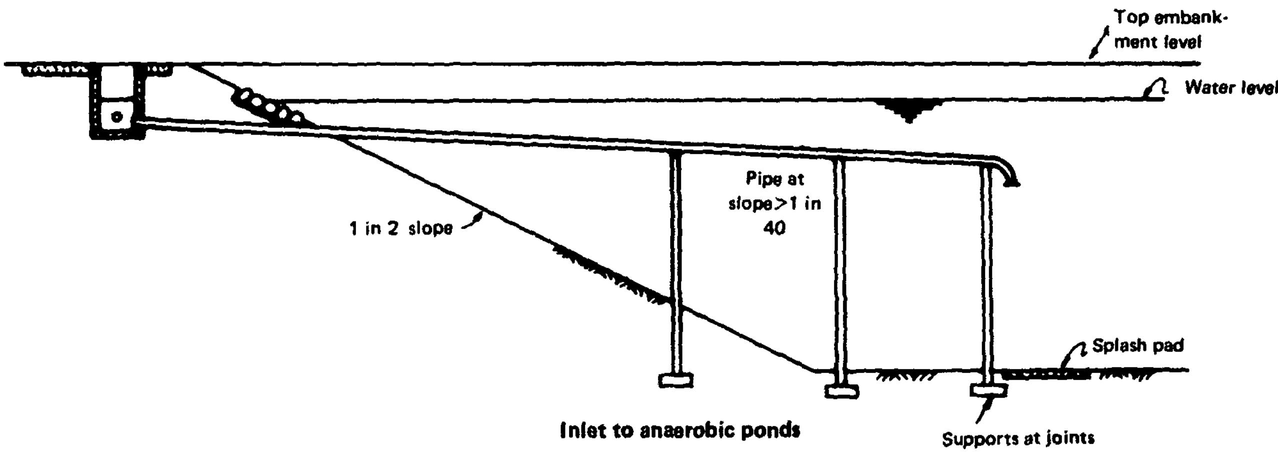
Initially system operates 4 → 5 → 6 → 7

then 1 → 4 → 5 → 6 → 7

then (1 + 2) → 4 → 5 → 6 → 7

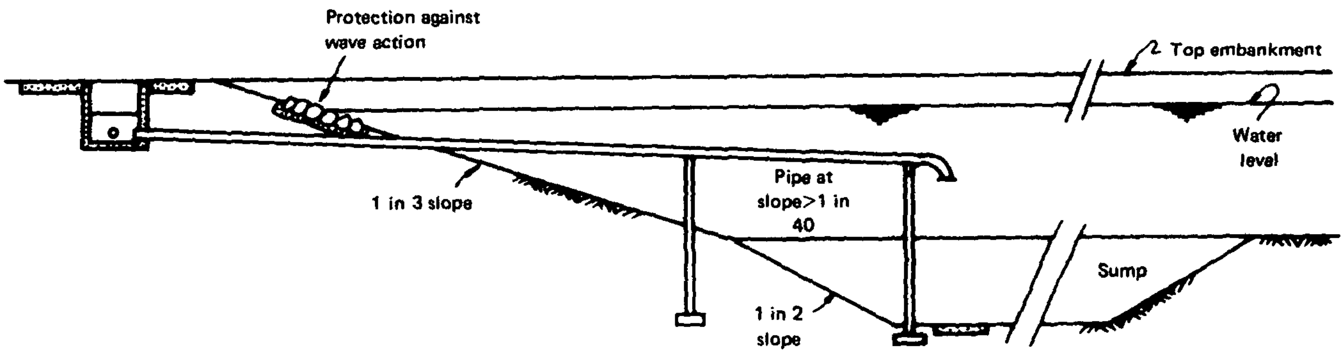
Pond 3 interchanges with 1 and 2.

Figure 6: DETAILS FOR EXAMPLE 1



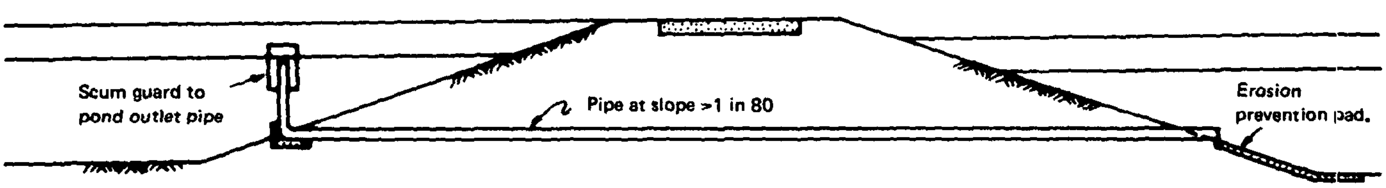
Inlet to anaerobic ponds

SECTION



Inlet to facultative pond

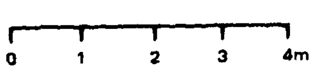
SECTION



Typical interpond connection

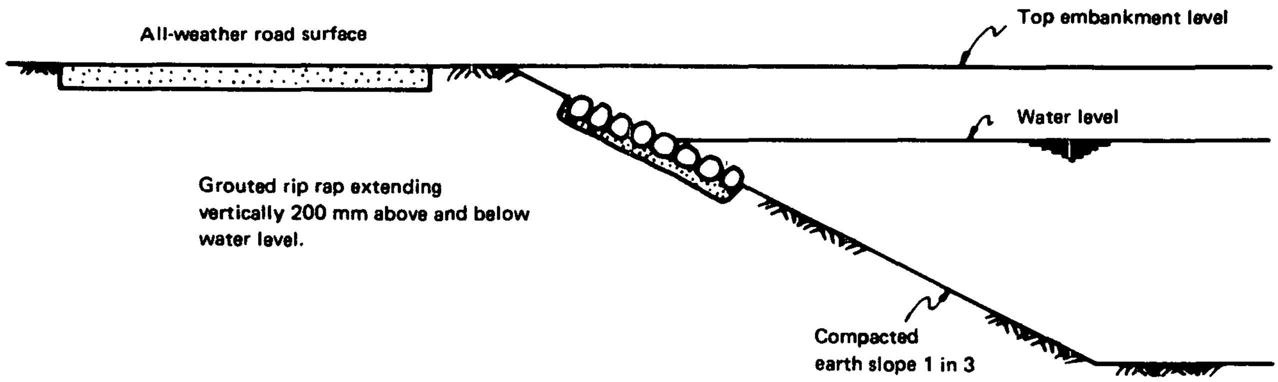
SECTION

Interconnecting pipes designed for flow of 1.5 maximum average flow.

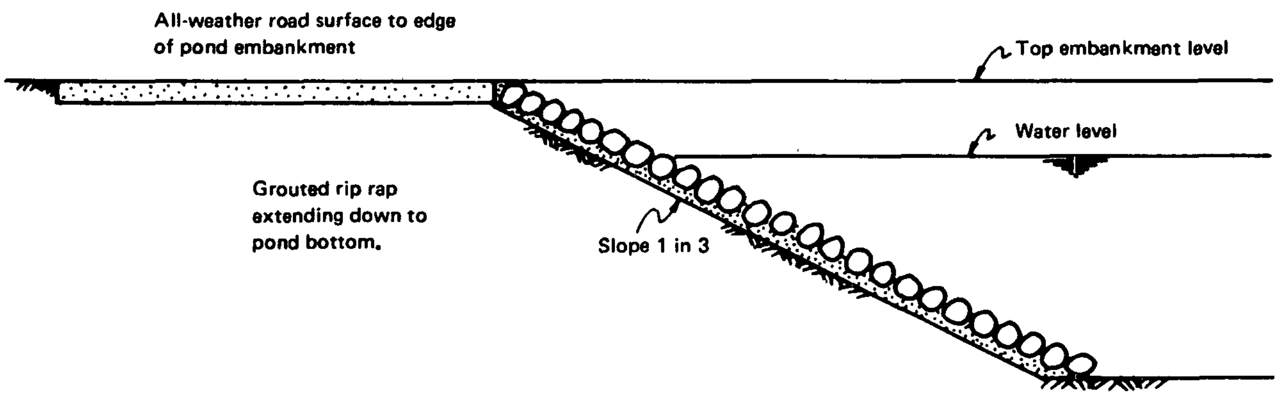


Scale

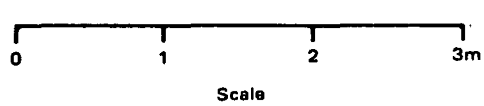
Figure 7: DETAILS FOR EXAMPLE 1



Section showing typical edge detail



Section of embankment 4 m wide for launching of maintenance boat in facultative and maturation ponds.



EXAMPLE 2

Assumed to be an existing community with some existing sewerage, where additional sewerage is being laid and further residential, commercial and industrial development is planned. The system has a design horizon of 20 years and the effluent is to be discharged into a receiving stream.

Design assumptions and requirements

Population (ultimate)	250,000
Population already sewered	80,000
Per capita waste water contribution (including contribution from industry)	110 lcd
Per capita BOD_5 contribution (including contribution from industry)	50 gcd
Assumed total infiltration to sewers	5,000 m^3/day
Assumed influent bacterial concentration	2 x 10^7 FC/100 ml
Mean minimum monthly temperature	25°C
Effluent standard required to allow discharge into stream	<25 mg/l BOD_5 <5,000 FC/100 ml

Design calculatations

Sewage flow = 250,000 x 110 liters	=	27,500 m^3/d
plus infiltration	=	5,000 m^3/d
Total flow rate	=	32,500 m^3/d
Total organic load 250,000 x 50 g	=	12,500 kg/d
Influent BOD_5 concentration = $\frac{12,500}{32,500}$	=	385 mg/l

(a) Anaerobic ponds

At 25°C anaerobic ponds designed using volumetric loading (λv) of 0.35 kg $BOD_5/m^3/d$

Volume of ponds = $\frac{12,500}{0.35}$ = 35,715 m^3

Check detention time (t*) = $\frac{35,715}{32,500}$ = 1.1 days

Since t* < 2 days, calculate anaerobic pond volumes for 2-day detention time since this gives loading rate of 0.192 kg $BOD_5/m^3/d$ which is acceptable. 1/

Volume required = 65,000 m^3

For flexibility of operation use three anaerobic units each 22,000 m^3 volume plus one spare of 22,000 m^2

1/ At this ambient temperature it would be permissible to leave the detention time at 1.1 days without a significant reduction in treatment efficiency of the anaerobic ponds.

Thus total volume of anaerobic ponds = 88,000 m^3
Assume 4 m depth for ponds
Each pond mid depth area = 5,500 m^2 (say 100 m x 55 m)

Total mid-depth area for anaerobic ponds = <u>2.2 ha</u>

(b) <u>Facultative ponds</u>
Facultative ponds designed according to equation <u>1</u> with T = 25°C.

$\lambda_s = 20 \times 25 - 60 = 440$ kg BOD_5/ha/d.

Assuming BOD_5 removal in anaerobic ponds conservatively at 65% (Table 3).

Influent BOD_5 to facultative pond = 0.35 x 385 = <u>135 mg/l</u>

From equation <u>2</u> facultative pond mid-depth area can be calculated from:

$$A = 10 \times 135 \times \frac{32{,}500}{440} = 99{,}630 \text{ m}^2$$

with depth assumed at 1.75 m.

Volume of facultative ponds = 174,350 m^3

$$\text{Detention time} = \frac{174{,}350}{32{,}500} = 5.4 \text{ days}$$

Probable BOD_5 removal in facultative ponds with 5.4-day detention is 70% giving cumulative BOD_5 removal of 89%.

Since the flow is large and will initially be far less than final design flow, two parallel facultative units are proposed each of each 50,000 m^2.

(c) <u>Maturation ponds</u>
Maturation pond(s) are designed to achieve the required bacterial removal to give 5,000 FC/100 ml in the effluent.

Using equations <u>4</u> and <u>5</u> and assuming one 5-day maturation pond in series with each facultative pond.

$$K_{B(T)} = 2.6 \times (1.19)^{(25-20)} = 6.2$$

$$B_e = \frac{2 \times 10^7}{(1+2\times6.2)\,(1+5.4\times6.2)\,(1+5\times6.2)} = 1{,}460 \text{ FC/100 ml}$$

Thus a series of anaerobic, facultative and a single 5-day maturation pond will satisfy the bacterial effluent standard.

Check for BOD_5, probable cumulative percentage removal = 94% (Table 3).

Effluent BOD_5 = 0.06 x 385 = <u>23.1 mg/l</u>

Thus effluent should also satisfy BOD_5 criteria providing effluent is drawn off from below the algal rich surface layers.

Maturation pond volumes each 81,250 m^3 (2 units in parallel).

With maturation pond depth of 1.5 m mid-depth area of each pond is 54,200 m^2

Thus total mid-depth area of maturation ponds = 108,400 m^2

(d) Comments

Total mid-depth area of pond system = 23.03 ha

Total surface area of pond system = 24.2 ha

Approximate total area required for system = 36 ha

Due to the initial flow likely to be about 30% of the final flow, only one anaerobic pond and one stream of facultative and maturation ponds will be required until the flow rate builds up sufficiently to allow other units to be brought into use. At about 11,000 m^3/day a second anaerobic unit could be brought into use and at about 17,000 m^3/day the second stream of facultative and maturation ponds should be used. The third anaerobic unit would not be required until the flow rate reached 22,000 m /day and the fourth would be used as a reserve to be operated as other units were being cleaned. Preliminary treatment should be provided by screens and grit channels with venturi flume flow measurement at the inlet to the pond system and a V notch at the outlet. Use of mechanical equipment would depend on the level of technical ability available at the site. All these functions can be manually carried out if necessary. In a system of this size it is advisable to provide draw down facilities for the anaerobic units (at least) and a system bypass. The layout, system of operation, and some typical details, are shown in Figures 8, 9, 10 and 11.

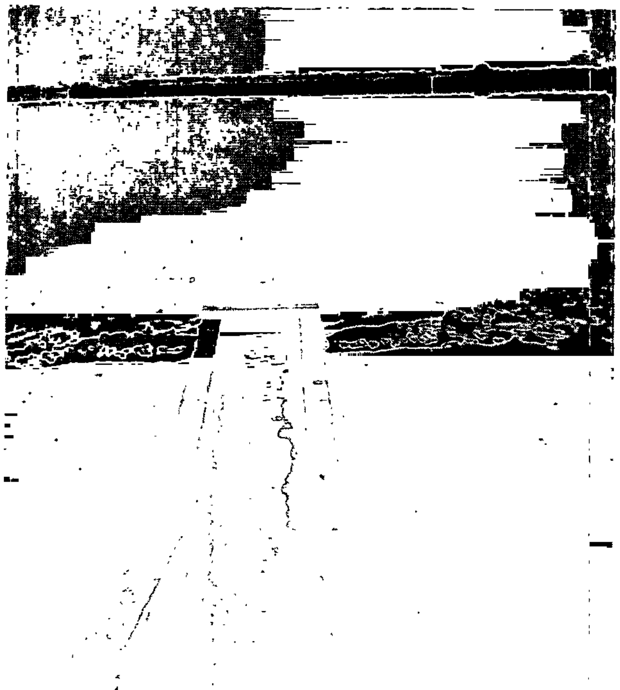


Photo 11. The inlet end of a channel type of interpond connection feeds into a maturation pond at the Dandora Industrial Estate pond system near Nairobi, Kenya.

Photo 12 (below). The surface outlet (foreground) serves a maturation pond at the Manchichi pond system in Lusaka, Zambia. A penstock at the end of the outlet structure allows the pond to be emptied.

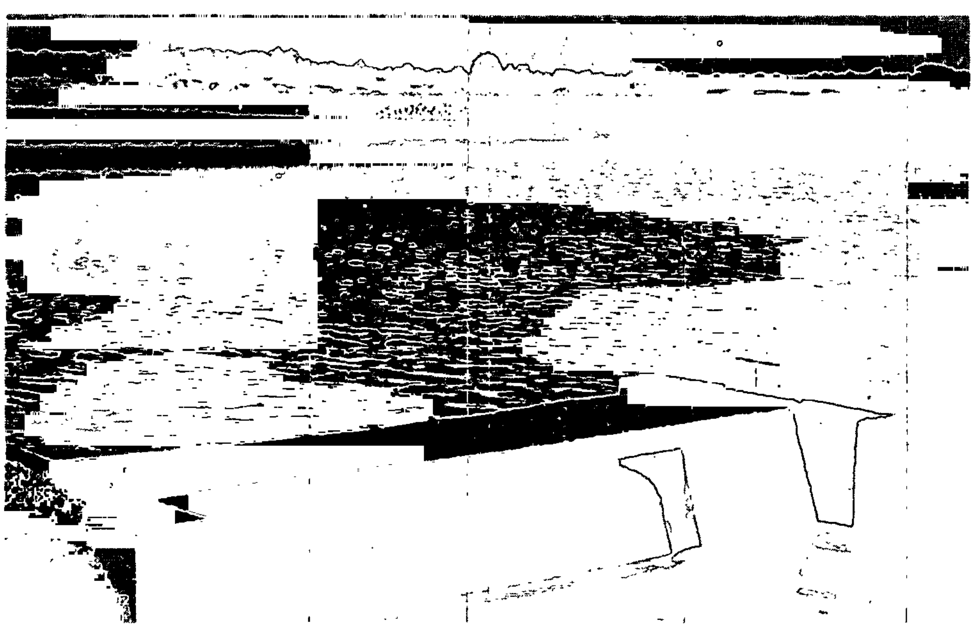


Figure 8: EXAMPLE 2 LAYOUT

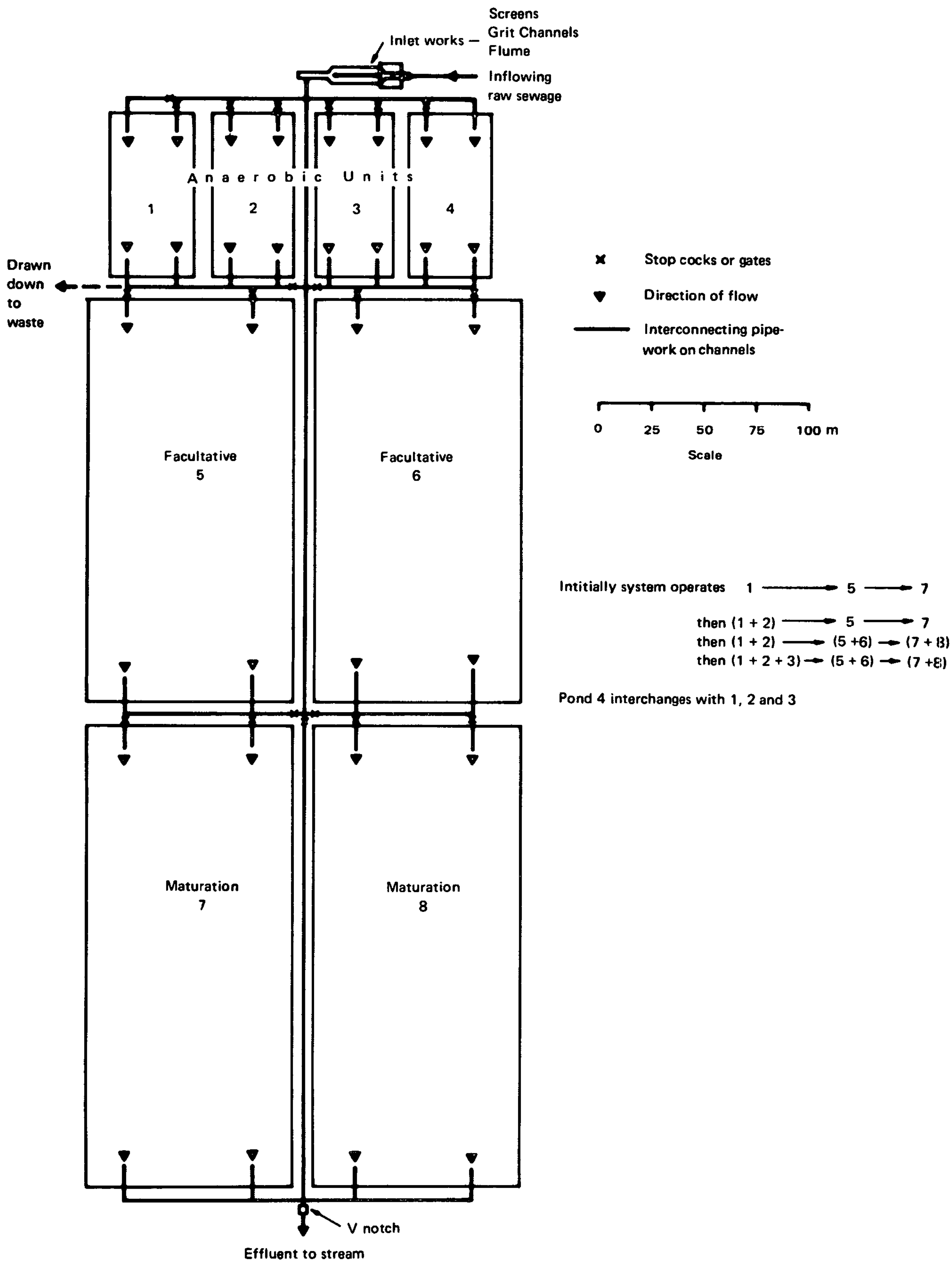
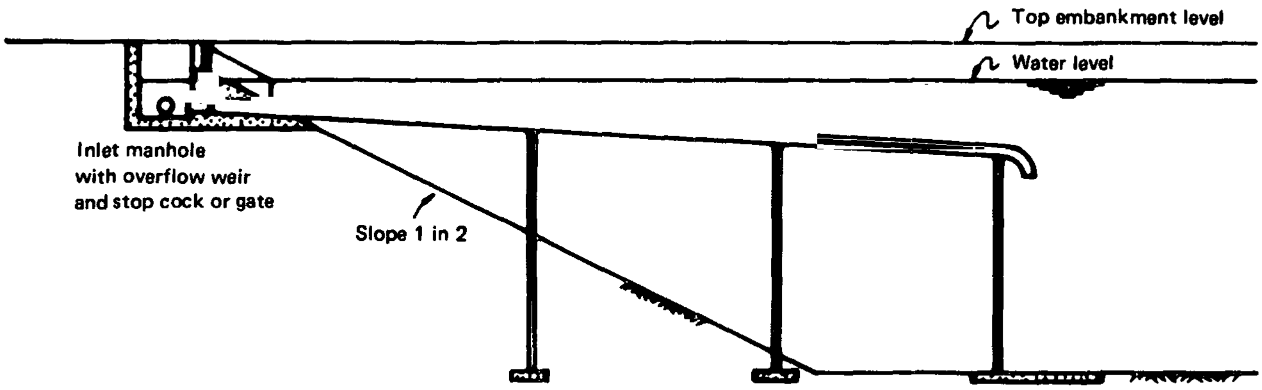
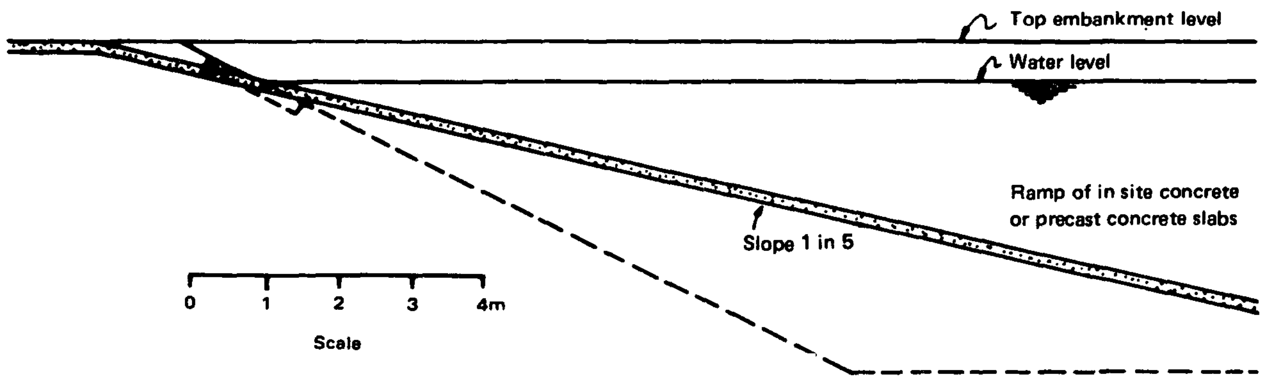


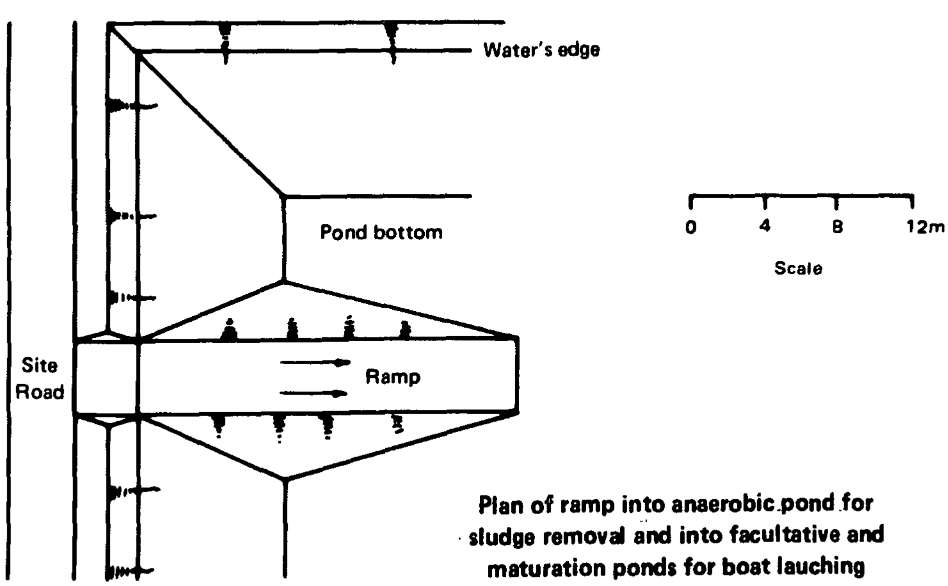
Figure 9: DETAILS FOR EXAMPLE 2



Section through embankment inlet to anaerobic pond

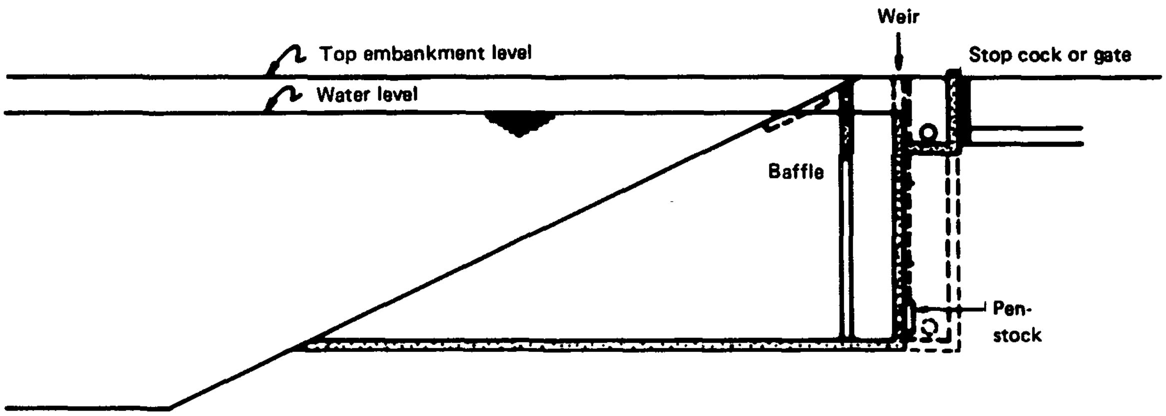


Section through embankment showing ramp into anaerobic pond to facilitate sludge removal

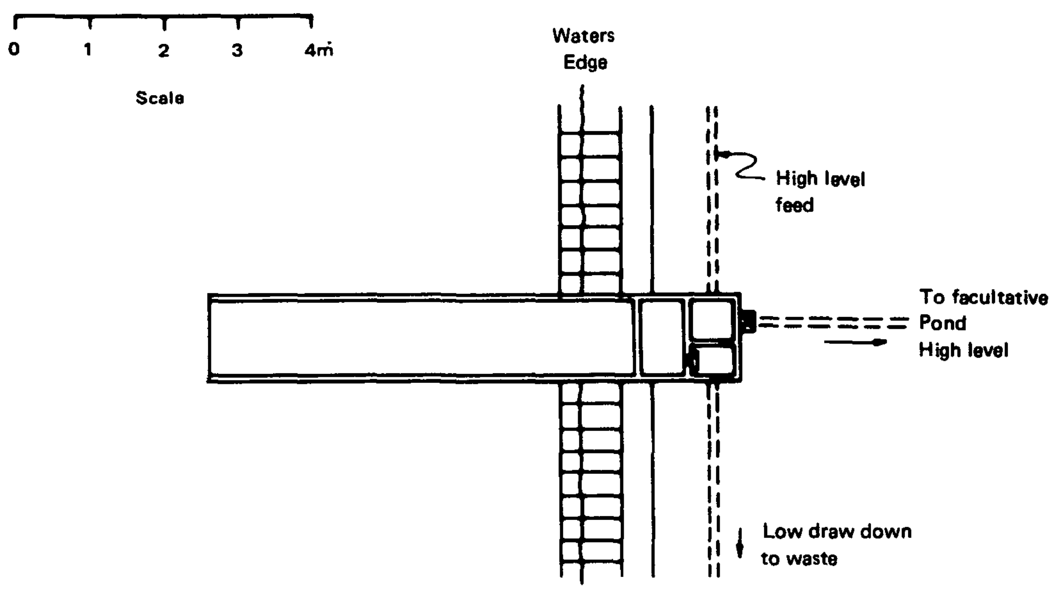


Plan of ramp into anaerobic pond for sludge removal and into facultative and maturation ponds for boat lauching

Figure 10: DETAILS FOR EXAMPLE 2



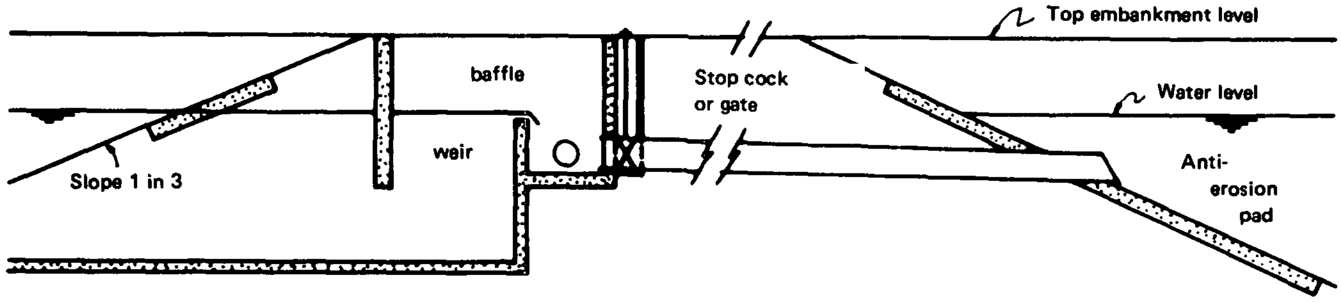
Section



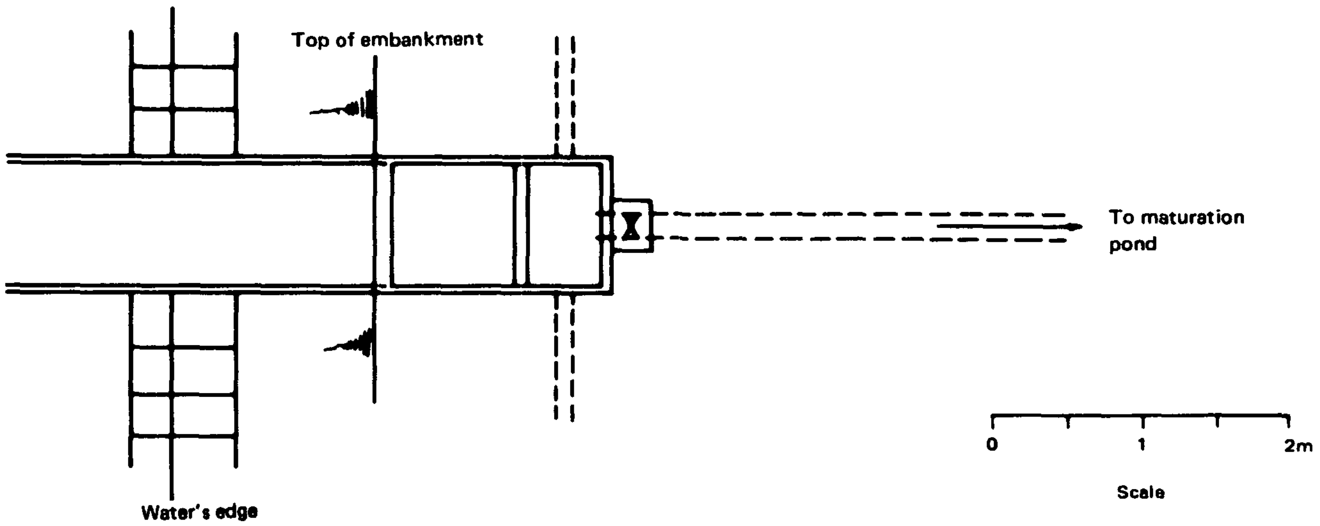
Plan

Section and plan of outlet structure showing draw down arrangements from anaerobic pond

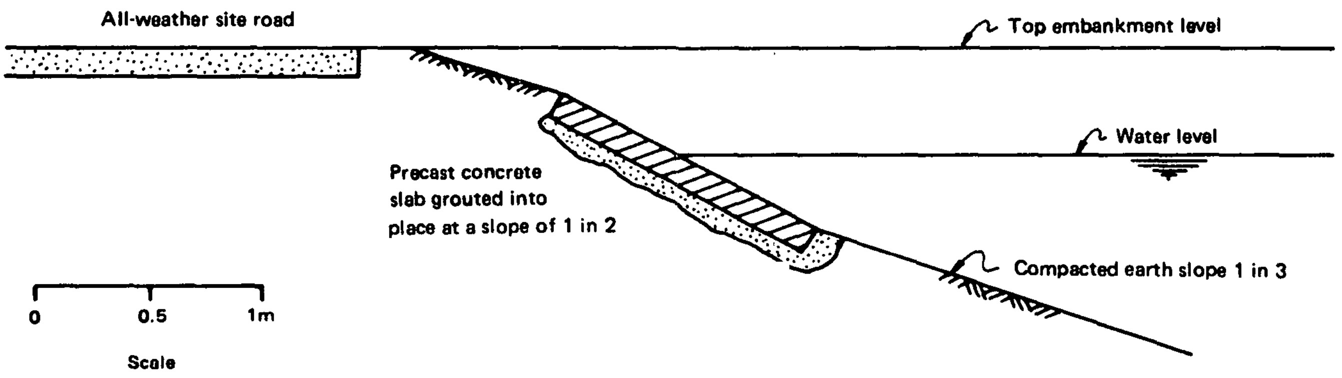
Figure 11: DETAILS FOR EXAMPLE 2



Section showing typical interpond connection to maturation pond



Plan of interpond connection structure



Typical embankment Section

FACTORS TO BE CONSIDERED IN SITE PREPARATION AND EMBANKMENT CONSTRUCTION

Soil sampling and testing should be carried out to determine the compactability and permeability of the soil at the site, and of any offsite material to be used in construction. Compaction and permeability tests shall be conducted according to American Society of Testing Materials (ASTM), or British Standards Institution (BSI) standards, or equivalent.

The program of works should be drawn up so that wherever possible the need for heavy earth moving equipment to be used on site is restricted to the dry season. The attention of contractors should be drawn to possible problems of using heavy earth moving equipment in areas to be excavated to levels only just above the water table. Particular attention should be paid to the careful checking of calculations for the earthworks required, to avoid cost overruns on this item.

All areas on which construction is to take place, including pond areas, should be cleared of all vegetation together with roots and all other deleterious matter. Top soil should be stripped to a minimum depth of 150 mm, and unsatisfactory or weak soil should be excavated. This material should be stored for reuse, but on no account should it be used as compacted fill in embankment construction.

The excavations should be operated in such a way as to yield the maximum of materials suitable for construction purposes. These materials should be stored in temporary stockpiles for later placing in designated locations. Excavated materials which are unsuitable for reuse or are in excess of material required for reuse should be removed from the site. Additional material required for compacted fill in embankments should be excavated from borrow pits after stripping of topsoil and other unsuitable material.

The embankments should be constructed with a top width sufficient to allow passage of a small truck (i.e. width >3 m), and with side slopes as steep as is possible and also consistent with slope stability, minimal slope erosion, and ability of earth moving machines to work on the slope (generally a slope of 1 in 3).

Embankment foundations should be suitably prepared before the placing of material for embankment construction. In clayey cohesive soils the foundations should be scarified, wetted and compacted to 95% modified American Association of State Highway Officials (AASHO) dry density standard or equivalent, or as specified for the earthfill to be placed thereon. In sandy or gravely uncohesive soils, the foundations should be compacted by vibrating rollers to a depth of not less than 300 mm to the same relative density as specified for the overlaying earth fill (normally 70% relative density or equivalent). Foundation surfaces should be moistened before placing the first layer of earth fill. Where an impermeable core is to be used in embankment construction, a key trench should be excavated along the line of the embankment and compacted and prepared as described above.

Embankment construction materials should be placed in horizontal layers over the entire embankment width. For clayey and silty cohesive materials these layers should not exceed 150 mm thick after compaction. Optimum moisture content should be maintained during compaction which should be to not less than 95% of the modified AASHO dry density. For sandy and gravely cohesionless free-draining materials, the thickness of horizontal layers after compaction should be not more than 300 mm if crawler tractors or surface vibrators are used, and 150 mm where tampers and rollers are used. Compaction should be to relative density of not less than 70%. For borderline cases between cohesive and cohesionless soils, 70% relative density or 95% modified ASSHO dry density should be achieved, whichever is the higher. At least six passes of compacting equipment is required, and the overlapping of adjacent passes should be not less than 300 mm.

Where manual excavation and embankment construction are used, and where access by machine is not possible, hand tamping of layers should be carried out to achieve the same densities as above. The thickness of such compacted layers should not exceed 150 mm.

Where embankments are constructed of uncohesive free-draining soils, some form of sealing will generally be required. This may be an impermeable embankment core, a clay blanket on the inside embankment slope, or a plastic sheet lining. If an impermeable core is used, construction should be carried out as outlined above, with the core material laid in layers not exceeding 150 mm in thickness after compaction. In the case of a clay blanket, this shall be laid on the inside of the embankment in a layer not less than 200 mm thick after compaction to 95% modified AASHO dry density standard. If this density cannot be achieved, a thicker clay blanket should be used.

FINDINGS FROM THE FIELD TRIP

This appendix gives a brief status note on each of the 30 pond systems visited in the course of this work, together with notes and tables summarizing the findings.

A. Status of Pond Systems Visited 1/

1. Following are brief statements on the status of the facilities visited. For those which are not operational, more detailed discussions of the reason for this are provided in the field notes. 2/

DAGAT DAGATAN, Manila, Philippines.
Aerated lagoon and polishing ponds not in operation due to minimal supply of sewage resulting from problems with the sewer main.

EAST CALCUTTA, Calcutta, India.
Proposal to use a system of anaerobic, facultative and maturation ponds to treat sewage; effluent to be used for fish ponds, the construction of which is completed.

RAMAT HASHARON, Israel.
Aerated lagoons and polishing pond in operation.

BET SHEMESH, Israel.
System of facultative and maturation ponds operational.

RAMLE, Israel.
Facultative ponds in parallel operating as facultative/anaerobic ponds.

NAAN, Israel.
Single maturation reservoir fed from Ramle ponds, in operation.

LOD, Israel.
Aerated lagoons in operation.

OR YEHUDA, Israel.
System of facultative and maturation ponds not operational due to overloading and operator's belief that treatment not necessary since effluent not used for irrigation. Sewage flows straight through plant to receiving stream.

NETANYA, Israel.
Aerated lagoons, settling ponds and maturation ponds in operation.

1/ The field visits were made in the period May-August 1981.

2/ A Review of Waste Stabilization Ponds, Consultant's Final Report Vol. 2, April 1982.

TEL MOND, Israel.
System of anaerobic, facultative and maturation ponds,operational, with anaerobic units behaving as anaerobic/facultative ponds.

SEDEROT, Israel.
System of anaerobic and facultative ponds plus maturation reservoir, in operation.

YAVNEH, Israel.
Aerated lagoons in operation although full aeration capacity not yet required.

ASHDOD, Israel.
System of anaerobic and facultative ponds only part operational; all ponds behave as anaerobic/facultative.

EINSHEIMER, Israel.
System of anaerobic and facultative ponds in operation, anaerobic units operating as facultative ponds.

MIGDAL HAEMEQ, Israel.
Single facultative pond cum reservoir in operation.

NAZARETH, Israel.
Anaerobic cum facultative pond and maturation reservoir in operation.

KARMIEL, Israel.
Anaerobic ponds and maturation reservoir in operation. One anaerobic pond being cleaned.

SHELOMI, Israel.
Aerated lagoons and maturation reservoir. Due to percolation and aerator problems only one unit is in operation as an anaerobic pond.

KIRIYAT GAT, Israel.
System of facultative ponds in operation but as facultative cum anaerobic ponds.

OFAQIM, Israel.
System of anaerobic, facultative and maturation ponds. Only half system operated since average flow well below design flow.

BEER SHEVA, Israel.
System of anaerobic, facultative and maturation ponds and reservoir. Half anaerobic ponds not being used in order to increase load on others and so improve their operation.

ARAD, Israel.
System of anaerobic and facultative ponds with only half system operational since flow much less than design flow.

EILAT, Israel.
Two aerated lagoons in operation; high rate pond not used due to rapid sludge build up.

DANDORA, Nairobi, Kenya.
System of facultative ponds and maturation ponds in operation.

DANDORA INDUSTRIAL ESTATE. Nairobi, Kenya.
System of facultative and maturation ponds in operation.

MANCHICHI, Lusaka, Zambia.
Parallel systems of maturation ponds following biological filter plant, in operation.

MATERO, Lusaka, Zambia.
Three parallel systems of facultative and maturation ponds, in operation.

NGWERERE, Lusaka, Zambia.
System of facultative and maturation ponds filling slowly due to few sewer connections, thus not yet fully operational.

CHELSTON, Lusaka, Zambia.
System of facultative and maturation ponds in operation.

MUNALI, Lusaka, Zambia.
System of facultative and maturation ponds in operation.

DE LA VEGA, Spanish Town, Kingston, Jamaica.
System of facultative and maturation ponds in operation.

2. Of the thirty pond systems visited:

(a) 8 included aerated lagoons.

(b) 8 incorporated anaerobic ponds; and

(c) 14 comprised facultative and/or reservoirs or maturation ponds only.

3. Table 1 is a summary table giving the population served, net pond areas, costs, type of system, pond areas per capita and costs per capita. The costs per capita are based on design populations unless the design figure is not available, in which case the actual population served is used. The table also shows the power intensity for the aerated lagoons in watts per cubic meter of pond volume. The table shows:

Table 1: POPULATION SERVED, AREAS, COSTS AND POWER INTENSITY OF POND SYSTEMS VISITED

Location	Population Served Design	Population Served Actual	Net Pond Area (ha)	Cost /a (US$ million)	Type of System /b	Net Pond Area per Capita Design	Net Pond Area per Capita Actual	Cost per Capita (US$) Design	Cost per Capita (US$) Actual	Watt/m3 Power Intensity Where Appropriate: Primary Pond	Watt/m3 Power Intensity Where Appropriate: Secondary Pond
Dagat Dagatan	45,000	-	5.[illegible]	2.0	AL,M	1.5	-	44.4	-	2.7	
Ramat HaSharon /c	50,000	31,000	4.0	0.54 (3)	AL,M	0.80	1.29	10.8	17.4	3.5	1.8
Bet Shemesh	23,000	-	4.8	0.97	F,M (1)	1.92	-	38.8		3.2	
Ramle	50,000	41,500	3.2	-	F	0.64	0.77				
Naan /d	-	41,500	11.1	-	F,R		2.67				
Lod	-	42,000	2.8	-	AL,M		0.66			2.6	2.0
Or Yehuda	67,000	47,000	2.2	-	An,F,M (2)	0.33	0.47				
Netanya	-	100,000	15.3	2.23	AL,M		1.53	22.3		3.3	1.4
Tel Mond	12,000	3,500	1.3	0.28	An,F,M	1.08	3.71	23.3	80.0		
Sederot	18,000	9,000	2.4	0.42	An,F,R	1.33	2.67	23.3	46.6		
Yavneh	15,000	12,500	2.2	0.67	AL	1.37	1.76	41.9	53.6	2.7	1.1
Ashdod	95,000	56,000	13.0	-	F	1.37	1.97				
Einshemer	11,000	7,000	3.3	-	An,F	3.00	4.71				
Migdal Haemeq	15,000	13,800	12.0	-	R	8.00	8.69				
Nazaret Illit	-	47,000	9.2	-	F,R		1.96				
Karmiel	-	13,000	4.2	-	An,R		3.23				
Shelomi	7,200	2,600	5.5	0.91	AL,R (1)	7.6	21.15	126.4	330.0	6.0	2.4
Kiriyat Gat	-	26,000	2.8	-	F		1.07				
Ofaqim	15,000	12,500	5.8	0.44	An,F,M	3.86	4.64	29.3	35.2		
Beer Sheva	140,000	110,000	13.4	-	An,F,M	0.96	1.22				
Arad	20,000	12,500	5.4	0.33	An,F	2.70	4.37	16.5	26.4		
Eilat	-	30,000	3.2	-	AL		1.06			4.0	1.2
Dandora	200,000	400,000	95.0	4.5	F,M	4.75	2.37	22.5	11.3		
Dandora Industrial	-	32,000	9.5	-	F,M		2.97				
Ngwerere	-	36,000	13,8	0.52	F,M		3.83		14.4		
Manchichi	-	100,000	23	-	M		2.30				
Matero	-	30,000	10.6	-	F,M		3.53				
Chelston	-	20,000	2.7	-	F,M		1.35				
Mumali	-	20,000	5.0	-	F,M		2.50				
Spanish Town	3,400	2,600	2.5	0.28	F,M	7.30	9.61	82.3	107.7		
East Calcutta	100,000	-	12.0 (4)	0.9	T,F	1.20		9.0			

/a Costs brought to October 1980 prices.
/b AL = Aerated lagoon
An = Anaerobic pond(s)
F = Facultative pond(s)
M = Maturation pond(s)
(1) = Aerators not in use, operated as a system of anaerobic facultative and maturation ponds
(2) = System not operational
(3) = Cost for improvements only
(4) = Area for proposed pond system
R = Reservoir.
/c Rehabilitation of existing systems only.
/d Following pretreatment in other works.

(a) a wide variation in the capital cost and area of pond per capita, reflecting the wide variety of design procedures used, as well as the economies of scale;

(b) savings in pond area per capita with inclusion of anaerobic ponds or aerated lagoons in the system; and

(c) a general increase in the capital cost per capita of the system with the inclusion of aeration equipment.

B. Design

4. As indicated in Table 1, the design methods used for the systems visited varied considerably. In many cases the pond designs were very conservative, leading to excessively large and expensive systems. This was often combined with over estimation of the sewage flow rate leading to problems during commissioning (e.g., Spanish Town, Kingston, ponds over one year in operation and still not full; Ngewerere, Lusaka, ponds six months in operation and the secondary units still empty). Use of the design equations given in the practical guidelines above would have resulted in considerable savings in land used, earthworks, and hence cost of the system.

5. Of those systems visited which had several pond units, the pipework required to allow flexibility of operation was often not present. Bypass pipes and facilities for drain down of ponds were also often not included.

6. Where a hard edge detail at the water surface level was not used in ponds, embankments were frequently suffering from erosion problems. This was found to be particularly true in aerated lagoons where the aerators induced greater wave action and scouring.

7. Many of the systems visited were designed without either preliminary treatment for the removal or breaking up of large solids, or flow measuring devices.

8. With the exception of eight of the systems visited in Israel, anaerobic ponds had not been incorporated in the pond systems investigated. In many cases the option of using anaerobic ponds had either not been considered or had been rejected on grounds of odor or fly nuisance. In none of the systems visited where the feasibility study was available had a pond system including anaerobic units been considered in a least cost solution analysis.

9. In aerated lagoons the positioning of the aerators often left dead areas at pond corners where sludge settlement and scum accumulation caused problems.

C. Construction

10. Problems were sometimes encountered during construction due to difficulty of operating earthmoving equipment during the rainy season, or where the water table was high. Where change orders were required, most related to earthworks.

11. It has been found in Israel (38) that problems were encountered in drawing up estimates for pond cleaning. Estimates of the quantity of material to be removed were often inaccurate, and problems were experienced in using heavy machinery to move the sludge before it was fully dried throughout its depth. Disputes regarding the quantity of sludge to be removed can be reduced by careful wording in the contract documents used for sludge removal.

D. Operation and Maintenance

12. Of those systems visited which would not be considered to be operating in a completely satisfactory manner, the problems generally related to parts of the systems other than the ponds themselves. The exceptions to this were some of the systems visited in Israel where considerable overloading or very poor maintenance was causing odor nuisance or poor effluent quality.

13. With well maintained and operated systems client and user reaction was highly favorable. In Lusaka, housing plots adjacent to an existing pond system have been taken in preference to those further away.

14. Clients and government or local authority officials with some experience of pond systems were invariably favorably disposed toward them. Potential clients and government or local authority officials without experience of pond systems were invariably unfavorably disposed toward them, fearing poor performance and odor problems.

15. Maintenance costs for the systems visited were often not available. Where costs were available they varied considerably as shown in Table 2 which gives the operating costs per capita served. As can be seen from this table, the cost per capita of operating an aerated lagoon system is generally almost an order of magnitude greater than the cost of operating a waste stabilization pond system.

16. Many of the systems visited suffered from poor maintenance, generally in the form of:

(a) Failure to remove vegetation from embankments at water level.

(b) Failure to repair badly eroded embankments.

(c) Failure to remove scum from facultative ponds.

(d) Failure to prevent sludge buildup around inlet pipes and subsequent breaking of the water surface;

(e) Failure to keep grass cut on embankments; and

(f) Failure to repair and maintain boundary fencing.

These maintenance problems were especially, in the cases of (a), (b) and (d), caused in part by poor design.

17. Industrial effluents caused problems in some of the pond systems visited but appeared to cause no problems in others. In some cases insufficient attention had been given at the design stage to the nature of the industrial effluent to be treated.

E. Performance and Monitoring

18. At very few of the systems visited was any kind of regular monitoring of flow rates, or raw sewage and effluent biological and chemical parameters carried out. In cities where both conventional and waste stabilization pond sewage treatment systems were located, the laboratory, laboratory staff, and usually over 90% of the samples taken, were restricted to conventional plants. At only one of the systems visited (Netanya in Israel) was there an operating laboratory at the pond site, although Dagat Dagatan had both laboratory and equipment but nothing to measure!

19. Where flow measuring devices had been included in construction, these were often of the automatic venturi flume type, and were invariably broken.

20. Standards were often not specified for effluents from the systems visited, and when they were, tended to be the 'Royal Commission standard' of 20 mg/l BOD_5 and 30 mg/l SS. Effluents from many of the pond systems were rich in algae and consequently unlikely to satisfy the Royal Commission standard. Although the algae can cause a problems where pond effluents are disposed of to a watercourse, they are an advantage where complete disposal is achieved by use of the effluent for irrigation. Improved crop yields invariably result from irrigation with pond effluent, although only in Israel was the effluent being reused in this way.

APPENDIX 2
Page 8

Table 2: OPERATING COSTS FOR POND SYSTEMS WHERE COSTS WERE AVAILABLE

Location	Total operating cost US$ for 1981 (predicted)	Operating Cost per capita served per annum US$	Type of system /a
Dagat Dagatan	92,300	2.05	AL
Netanya	260,000	2.60	AL
Yavneh	100,000	6.30	AL
Eilat	40,000	1.33	AL
Dandora	5,200	0.03	WSP
Ngwerere	9,000	0.25	WSP
Manchichi	11,000	0.11	WSP
Matero	9,000	0.30	WSP
Chelston	3,500	0.18	WSP
Munali	2,300	0.12	WSP
Spanish Town	5,500	1.61	WSP

/a AL = Aerated lagoon system; WSP = Waste stabilization pond system.

Note: At Ramat Hasharon the income from sale of the effluent for irrigation of citrus orchards is greater than the expenditure on operation and maintenance.

F. Israeli "Kibbutz" System

21. This system, which was being operated at a number of the pond locations visited in Israel, usually functions in one of two ways:

(a) Kibbutz operates and maintains municipal wastewater treatment plant in exchange for use of the effluent for irrigation.

(b) Kibbutz uses effluent from municipally owned and operated treatment plant, either free of charge or for payment.

Usually the land on which the treatment plant (invariably a waste stabilization pond system) is constructed by the municipality is owned by the kibbutz. The kibbutz is prepared to give up this land in exchange for the increased crop yields achieved by use of the effluent. The exchange is based mainly on the net increase in the water supplied for irrigation, as water for agriculture in Israel is strictly limited and allocated under a legal procedure, and the approval of the Water Commissioner for the treatment and reuse system has to be sought.

22. The system works particularly well because both parties are satisfied. The municipality finds land at some distance from the community to construct a treatment plant thus getting rid of the sewage without having a treatment plant on their doorstep. The kibbutz is happy to give up the land in exchange for the increased crop yields obtained by irrigating with the effluent. By operating the system themselves they are also able to organize it in such a way as to satisfy their water management requirements.

23. Effluent standards are very seldom specified nor are effluent analyses carried out, since the vast majority of irrigation in Israel is of nonedible crops such as cotton, alfalfa and other fodder crops. Permission to irrigate edible crops with a particular effluent must be obtained from the Ministry of Health. There are no official effluent standards relating effluent quality to crops irrigated or to stream discharge. Matters relating to effluent requirements for irrigation are dealt with by consultation between the Ministries of Health and Agriculture. Although these ministries do fix effluent standards, they appear not to have the means to monitor the effluent quality on a regular basis.

24. Factors which limit the application of this system to other countries are:

(a) Irrelevant effluent standards in some countries.

(b) The more sophisticated agricultural methods employed in Israel than in most developing countries.

(c) The social attitude to use of effluents for irrigation, often sensitive in developing countries.

(d) The types of crop grown.

25. From the point of view of pond operation, many examples were found of ponds being used in slightly unorthodox ways in order to maximize effluent reuse. Thus systems were often not being used in the way in which they were intended to be used, and doubtless treatment efficiency was suffering accordingly. It was also often the case that routine maintenance was badly neglected particularly during the irrigation season. This sometimes resulted in malfunctioning systems with scum and vegetation growth problems and in some cases odor nuisance.

26. All the systems visited in Israel were situated outside, or on the periphery of, towns or small cities. The type of effluent reuse system operated under these circumstances would not be possible in large urban conurbations where pond systems are situated within the built up area of the city.

G. Additional Findings

27. The following additional findings reinforce some of the points made in the main report.

(a) Feasibility Studies. Detailed design should proceed only after a review of alternatives based on rational design procedures outlined in recent technical literature. A review of the available design documents for the visited pond systems suggests a tendency for designers to use very conservative design procedures. Furthermore, when a least-cost design was sought in feasibility work, the options, including primary treatment by anaerobic ponds, were either not considered or excluded for reasons of odor or fly nuisance.

(b) Odor and Fly Nuisance. Anaerobic Ponds. Fears of odor and fly nuisance are unfounded if the anaerobic units are properly designed and maintained. 1/ A properly functioning pond will often have a thick crust over the entire surface, and of the systems visited a good example of a satisfactorily operating anaerobic pond was at Sederot, Israel. The pond was odor and fly free and operating with the following characteristics:

Detention time	3.3 days
Areal loading rate	2,035 kg BOD_5/da/day
Volumetric loading rate	0.11 kg BOD_5/m^3/day

The depth of 1.85 m is rather shallow and increases the frequency with which the anaerobic ponds required desludging. One pond was being desludged at the time of the visit.

At Beer Sheva the pond operation had been changed shortly before the vist in an effort to reduce an odor and fly nuisance problem and improve effluent quality.

1/ i.e., in accordance with the design and operation and maintenance procedures outlined in this paper.

An increase in the volumetric loading rate from .054 kg BOD_5/m^3/day to 0.108 kg BOD_5/m^3/day, and in the areal loading rate from 1,212 to 2,425 kg BOD_5/ha/day on the primary units had caused some improvement according to the pond operator.

(c) Conversion of Facultative Ponds into Aerated Lagoons. Nervousness on the part of the client with respect to use of ponds can be overcome by the provision of aerators as an "insurance policy" (for example at Bet Shemesh). Aerators can be used to control odor problems resulting from overloading of facultative ponds. Where shallow ponds require aeration a large number of low powered aerators can be used. Recirculation can also be used to overcome nuisance problems resulting from overloading. Both systems work on the same principle which is providing oxygen to the surface layers of the pond, thus oxidizing gases as they pass through this layer. Both these alternatives result in additional maintenance problems and operational costs.

(d) End-use--Irrigation. Wherever possible waste stabilization pond effluents should be used for irrigation. This makes a valuable contribution to nutrient recycling by providing increased crop yields, and can allow effluent quality to be geared to the reuse method instead of having to satisfy statutory discharge standards, which may be irrelevant (e.g., the Royal Commission standard). The pond system may be designed to achieve the bacteriological standard required for the type of irrigation being undertaken which will depend on:

(i) the crop being irrigated (i.e., inedible, low quality; edible, high quality effluent);

(ii) the method of application (i.e., spray irrigation higher quality than drip or channel irrigation);

(iii) whether mechanically or manually intensive methods of agriculture are employed.

(iv) proximity to residential areas.

With the exception of Israel, potentially valuable waste stabilization pond effluents from all the other systems visited were not being reused. Where effluent is to be used for irrigation of a particular crop, the pond system can be designed to achieve the required standard of effluent and to produce the required quantities of water at the right time of year. A good example of this is the irrigation of cotton in Israel, where a large volume of water is required from June to August, and the quality is not particularly important since the crop is not eaten and mechanically intensive irrigation and farming methods are used. Thus large reservoirs are constructed, designed to be full at the beginning of the irrigation season and empty at the end.

Careful choice of the crops to be irrigated can maximize the reuse potential of the pond effluent. A good example is Beer Sheva in Israel with a winter crop (wheat), a summer crop (cotton), and a buffer crop (alfalfa).

(2) Pisciculture. Although no facilities were visited where fish farming was being carried out on a commercial basis, many of the systems contained fish which local residents occasionally removed for their own use or to sell, (e.g., Manchichi, Zambia). Over some years the fish had migrated to the primary pond in the system where critical dissolved oxygen levels at night meant many of them did not survive. Fish farming in waste stabilization ponds is undoubtedly a viable proposition, but should only be carried out in accordance with the recommendations made in this paper.

Carefully managed fish farming in waste stabilization ponds has provided up to 10 metric tons of fish per ha per year. (3) The most widely used species are tilapia and carp, or a polyculture of a variety of species. Where fish farming is carried out in waste stabilization ponds, a fresh water depuration pond is advisable in which fish are retained before sale for consumption.

APPENDIX 3

NOTES ON THE DESIGN AND OPERATION OF WASTE STABILIZATION PONDS IN WARM CLIMATES OF DEVELOPING COUNTRIES

THE ISRAELI EXPERIENCE

NOTES ON THE ISRAELI EXPERIENCE

A. Preface

1. These notes are based on reports prepared by Shaul Streit of Tahal Consulting Engineers Ltd of Tel Aviv. Mr. Streit is the Assistant Director of the Israel Sewerage project.

B. Background--Israel Sewerage Sector

Urban Areas

2. In 1971 when Israeli authorities applied to the World Bank for a loan to support the Urban Sewerage Sector, only 78% of the population was served by a central sewer system. At that time only 35% or approximately 50 million m^3/year out of a total flow of approximately 130 million m^3/year was treated.

3. By 1980 considerable progress had been made; 90% of the urban population was centrally sewered with about 56% or 112 million m^3/annum treated, with 37% or 41 million m^3/year reused for irrigation. On completion of the Greater Tel Aviv (Dan Region) 1/ sewage treatment facility the amount of sewage treated will increase to 179 million m^3/year or 98% of total flow.

4. The situation existing in 1980 is summarized in Tables 2 and 3.

Rural Areas

5. In 1980 there was a population of 123,110 connected to the sewerage system and living in 356 settlements in the rural areas of Israel. Or alternatively, 396,890 persons (out of 520,000 persons).

Table 1: SEWAGE DISTRIBUTION, RURAL SECTOR

Distribution of Flows	Daily (m^3)	Annual ('000 m^3)	Percentage
Potential	70,865	24,920	100
Sewered	65,926	23,541	93.3
Reused	-	10,816	43.5

1/ The Dan Region sewage treatment facility will serve a population of over 1 million, i.e., 183,000 m^3/day or about 180 lcd. Most of the treated effluent will be reused.

APPENDIX 3
Page 2

do not have access to a piped sewerage system, but only to other sanitation technologies. The sewage flows are given in the following table and amplified in Tables 4 and 5.

Table 2: DISTRIBUTION OF SEWAGE TREATMENT MODES AS OF 1980; URBAN SECTOR

No.	Treatment Method	Sewage Treatment Plants No.	Sewage Treatment Plants %	Annual Flow '000 m^3/ per year	Annual Flow % distribution
1	Activated Sludge (conventional)	2	3.4	14,410	12.9
2	Activated Sludge (extended aeration)	2	3.4	3,380	3.0
3	Biological Filters	2	3.4	11,280	10.1
4	Ponds, Lagoons & Ditches (operated w/mechanical aeration)	15	25.9	18,520	16.6
5	High Rate Recirculation Ponds followed by Lime Clarification	1	1.7	25,550	22.8
6	Stabilization by Different Types of Earth Ponds (anaerobic, aerobic, deep storage, etc.)	36	62.2	38,740	34.6
	Total Treated	58	100.0	111,880	100.0
	Total Sewage in Sector			182,000	
	Total Reused Effluent			41,510 /a	

/a Table 3 gives breakdown.

Table 3 DISTRIBUTION BY CROPS IRRIGATED; 1980 REUSE OF URBAN SECTOR'S EFFLUENT

Crop Irrigated and Industry	Area Irrigated ha	Area Irrigated %	Annual Effluent Utilized '000 m^3/year	Annual Effluent Utilized %
Cotton	5,749	79.2	26,290	63.3
Fodder	286	3.9	2,600	6.4
Citrus Groves	574	7.9	4,740	11.4
Orchards	305	4.2	4,500	10.8
Field Crops	347	4.8	2,070	5.0
Industry	-	-	1,300	3.1
Total	7,261	100.0	41,510	100.0

6. The distribution of sewage treatment is shown as follows:

Table 4: DISTRIBUTION OF SEWAGE TREATMENT MODES, RURAL SECTOR (1980)

Method or Sequence of Treatment	Number of Treatment Plants	% Distribution
Extended Aeration	1	0.3
Ponds with Mechanical Aeration	6	1.7
Stabilization Ponds (anaerobic and facultative/aerobic)	154	43.0
Primary (Settling) Stage and Facultative/ Aerobic Ponds	31	8.6
Anaerobic Ponds Followed by Seasonal Deep Storage Pond	7	2.0
Primary (Settling Tanks) Stage Only	63	17.6
Aerobic/Facultative Ponds	32	8.9
Septic Tanks, Cesspools and Percolation Pits	7	2.0
No Treatment Facilities	31	8.6
Sewered into a Nearby Municipal or Other Network	26	7.3
Total	358	100.0

7. The distribution by crops irrigated is as follows:

Table 5: DISTRIBUTION BY CROPS IRRIGATED; 1980
REUSE OF RURAL SECTOR'S EFFLUENT

Crops	Area Irrigated		Flow Utilized	
	Ha	%	'000 m^3/year	%
Cotton	1,050	68.5	4,913	45.5
Fodder	292	19.1	2,864	26.5
Citrus Groves	53	3.5	385	3.6
Orchards	32	2.0	232	2.1
Field Crops	106	6.9	476	4.4
Fish Farming	-	-	1,946	18.0
Total	1,533	100.0	10,816	100.0

8. In 1980 there were a total of 8,794 ha being irrigated in Israel from a treated sewage effluent of approximately 52,000 m^3.

C. Further Findings and Recommendations

Pre-Design Phase

9. Communities frequently resist the provision of waste stabilization ponds for reasons which are not well substantiated. For one reason or another farmers or local authorities may not wish to release very much land for the purpose of sewage treatment or they object to the proposed location. Time spent in explaining pond proposals and the irrigation and other benefits which will ensue is well spent, and can save time later on.

Anaerobic Ponds

10. Pond systems and particularly those incorporating anaerobic ponds should be developed in a phased manner. It is not good enough, however, to designate a pond as anaerobic and expect a good odor-free process. An anaerobic pond only operates in an odorless way when properly loaded. In this regard it is the Israel experience that a minimum BOD_5 load of 4,000 kg/BOD_5 per ha per day (0.1 kg/m^3 in a 4 m deep pond) with a hydraulic retention time of approximately 48 hours is necessary for efficient operation. To ensure these criteria it is necessary to have at least two anaerobic ponds operating in parallel followed by a facultative pond. In the initial stages the anaerobic ponds will be bypassed, but as flow builds up and house connections are completed, a time comes when they are required and can be loaded satisfactorily.

11. In order to understand anaerobic pond operations it is necessary to distinguish between putrefaction and anaerobic digestion, i.e., treatment. The former is accompanied by offensive smells and generally develops rapidly from the storage of strong organic wastes whereas anaerobic digestion effectively avoids offensive odors. The wide variety of bacteria involved in the process may be classified into two broad groups according to their different functions: acid producers (non-methanogenic bacteria) and methane producers (methanogenic bacteria). Acid producing bacteria and their associated enzymes degrade most types of organic material, whether in solution or in suspension, mainly into the lower fatty acids (acetic acid accounting for about 80% of the total), with much smaller amounts of low aldehydes and ketones. The methanogenic bacteria convert soluble products of the acid producers into a mixture of methane and carbon dioxide.

12. Because the acid producers have a relatively short doubling time (in the order of minutes or hours) they quickly predominate when an organic waste is stored, causing putrefaction. The methanogenic bacteria, however, have a much longer doubling time (4-6 days) and are more

susceptible to inhibition by a variety of materials, including the products of the acid producers (fatty acids, ammonia, and soluble sulphide). Putrefaction, if allowed to develop during the start-up of a digestion system, will severly retard the establishment of digestion, so conditions should be initially controlled to allow the methanogenic bacteria to develop, after which, provided certain operating conditions are adhered to, the two groups of bacteria maintain a natural balance with none of the manifestations of putrefaction.

13. It is necessary to ensure that the pH remains over 7, but no special problems should be encountered with domestic wastes, (i.e, wastes containing less than 100 mg/l of sulphur (as sulphate ion) providing the depth, loading and temperature (over 15°C) criteria are met.

14. In summary, anaerobic ponds can be considered to be large septic tanks without cover. Properly designed they will form a crust and bubble away merrily without offensive odors. Avoiding the anaerobic-intensive stage may jeopardize a treatment project suitable for pond treatment by bringing a high demand for land which cannot be met.

Pond Systems with Deep Reservoirs

15. It took a long time and a lot of effort before health authorities and environmentalists were persuaded to allow a sequence of ponds in Israel which, after anaerobic and facultative digestion, consist mainly of one long deep detention lagoon called in Israel a reservoir. In the reservoir, effluent is stored until the beginning of the cotton irrigation season. The deep (4.5-8 m) reservoir serves as an odor-free aquatic ecosystem and as a source of good quality effluent for the irrigation of cash crops. In some instances the complicated economic land and environmental issues were solved by cooperation and sharing of costs between the urban and agricultural sectors. This is very important and leads to the conclusions that wherever possible it is wise for the municipalities to enter into a formal agreement with end users, to share responsibilities as well as costs and benefits.

Ambient Temperature

16. Ambient temperature is an important guide, but not the ideal figure to choose for process design as sewage tempertures will invariably give a higher reading. For example, at the Netanya works the long-term official figures for ambient temperature are 12°C for winter and 26°C for summer. On-site round-the-year research has revealed that the average temperatures of the raw sewage is:

Spring	22°C
Summer	28°C
Autumun	23°C
Winter	18.6°C

Costs

17. In the semi-arid climate of Israel irrigation has become the accepted "receiving body" to effluent disposal. This has proved to have environmental as well as economic benefits.

18. The provision of reservoirs came about because the farmers perceived the need to conserve effluent for the irrigation season. It is only with subsequent analysis that they have been shown to provide an effective treatment phase in themselves. What is interesting is that systems incorporating reservoirs have emerged as least cost. This is demonstrated in the following table.

Table 6: INVESTMENTS IN POND SYSTEMS, OVERALL COST PER HECTARE OF LIQUID SURFACE: SELECTED CASE STUDIES, ADJUSTED TO 1980 US$

No.	Name	Total Liquid Surface Area (ha)	Project With Installed Aeration (US$/ha) /a	Stabilization Ponds & Deep Reservoirs (US$/ha)	Remarks
1	Yavne	2.2	220,000		Sand dunes, above an aquifer, lined
2	Tel Mond	1.4	-	200,000	Steep land on sandy loam, small plant
3	Bet Shemesh	5.0	154,000		Polishing pond included
4	Shelomi	5.5	142,000		Polishing pond included
5	Netanya	15.3	121,000		Polishing pond included
6	Ramat Hasharon	4.0	116,000		Polishing pond included
7	Sederot	6.0	-	70,000	Serves industry
8	Ofaqim	5.8	-	69,000	
9	Arad	5.3	-	62,000	
10	Karmiel	4.2	-	36,000	Not through an open bid. Kibbutz served as a main contractor and costs were controlled by project office

/a Equipment and electro-mechanical costs excluded.

19. A capital cost comparison in 1980 US$ terms of various systems installed in Israel gives the following results:

	US$ per Capita
Stabilization ponds	11-18
Ponds with partial areration	27-32
Aeration ponds followed by polishing ponds	50-55

20. In Israel, operating and maintenance costs in 1980 US$ millions range from US$0.42-0.81 for stabilization pond systems serving 20,000-100,000 persons respectively. In Israel, the 1980 operation and maintenance costs for ponds without aeration equipment range from US$0.5 to US$0.6 per capita for well maintained system. The comparative costs for aerated lagoon systems ranged from US$6 to US$13.0 per capita.

D. Conclusion

21. As far as Israel is concerned, and certainly in the smaller towns, it can be concluded that a properly designed anaerobic pond followed by a deep seasonal reservoir is the ideal solution for the treatment of municipal sewage; this has enabled practically all of the effluent to be used for irrigation with no effluent discharge except through the irrigation network. Systems designed in this way have proved to be least cost, both in capital cost and operation and maintenance expenses.

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World Bank Technical Paper IS[illegible]94
Urban Development Technical Paper IS[illegible]24
ISBN 0-8213-0137-3

$ 6.95