WASTE STABILIZATION PONDS

Design Manual for Mediterranean Europe

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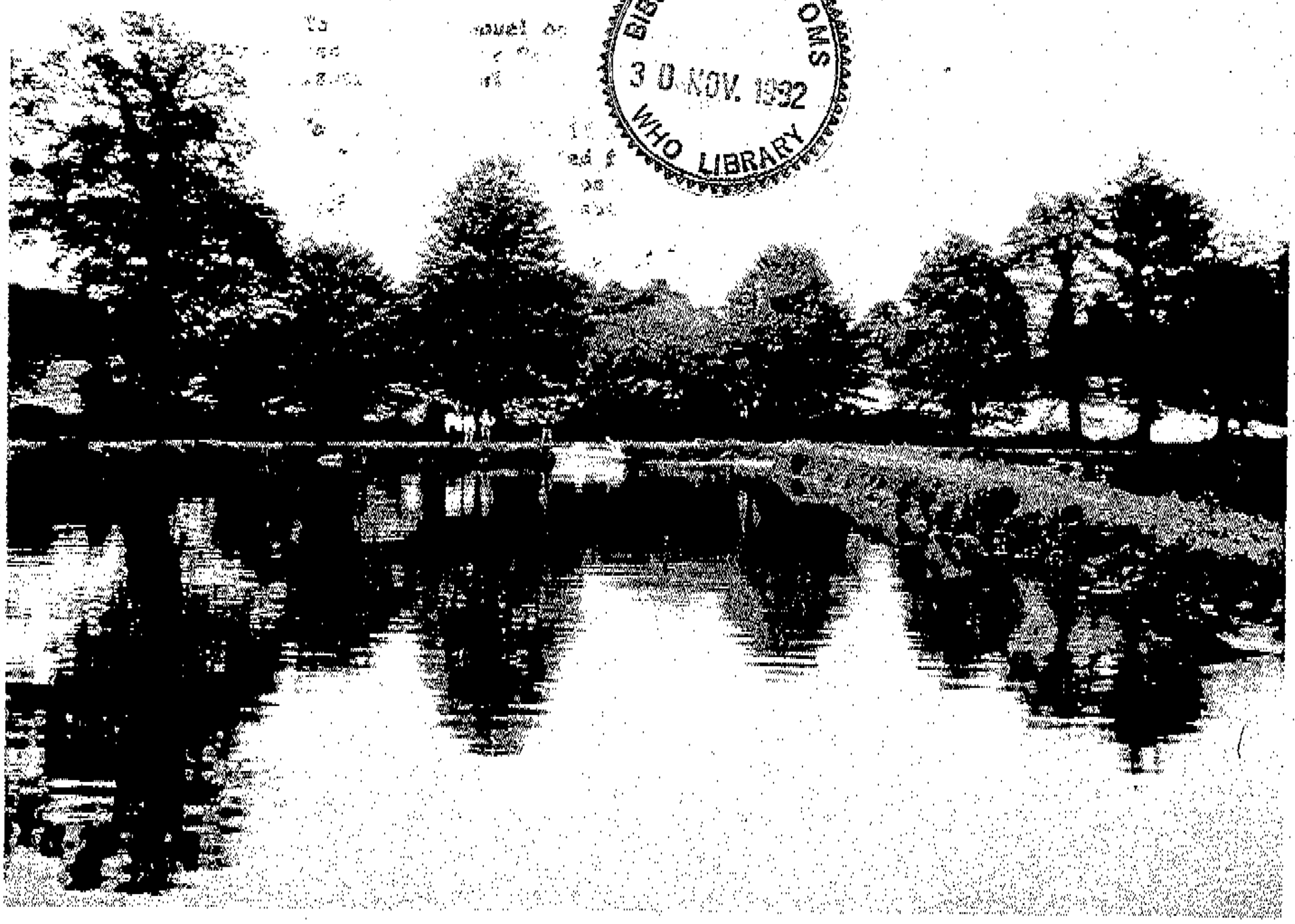

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TARGET 20

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WASTE STABILIZATION PONDS

Design Manual for Mediterranean Europe

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CONTENTS

PREFACE

This manual, on the design of waste stabilization ponds in Mediterranean Europe, is addressed primarily to design engineers responsible for wastewater treatment. It contains recommendations for the process and physical design of pond systems to treat domestic, or predominantly domestic, wastewater, although these recommendations are also suitable for ponds treating industrial wastewaters that have biodegradability characteristics similar to domestic wastewaters. Recommendations are also made for the operation and maintenance of pond systems, for their monitoring and evaluation, and for the agricultural reuse of pond effluents. The recommendations are made primarily for countries in southern Europe, from Portugal to Greece, but they will also be applicable to other countries with a similar climate.

Comments on the manual will be gratefully received by the Regional Office for Europe of the World Health Organization.

ACKNOWLEDGEMENTS

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1. Introduction

Waste stabilization ponds are large, shallow, usually rectangular basins in which there is a continuous inflow and outflow of wastewater. The biological treatment that occurs in ponds is an entirely natural process achieved principally by bacteria and microalgae, and one that is unaided by man who merely allocates sufficient space for them to occur in a controlled manner.

1.1 Types of pond

There are three principal types of waste stabilization pond commonly used in Mediterranean Europe and elsewhere: anaerobic ponds, facultative ponds and maturation ponds.

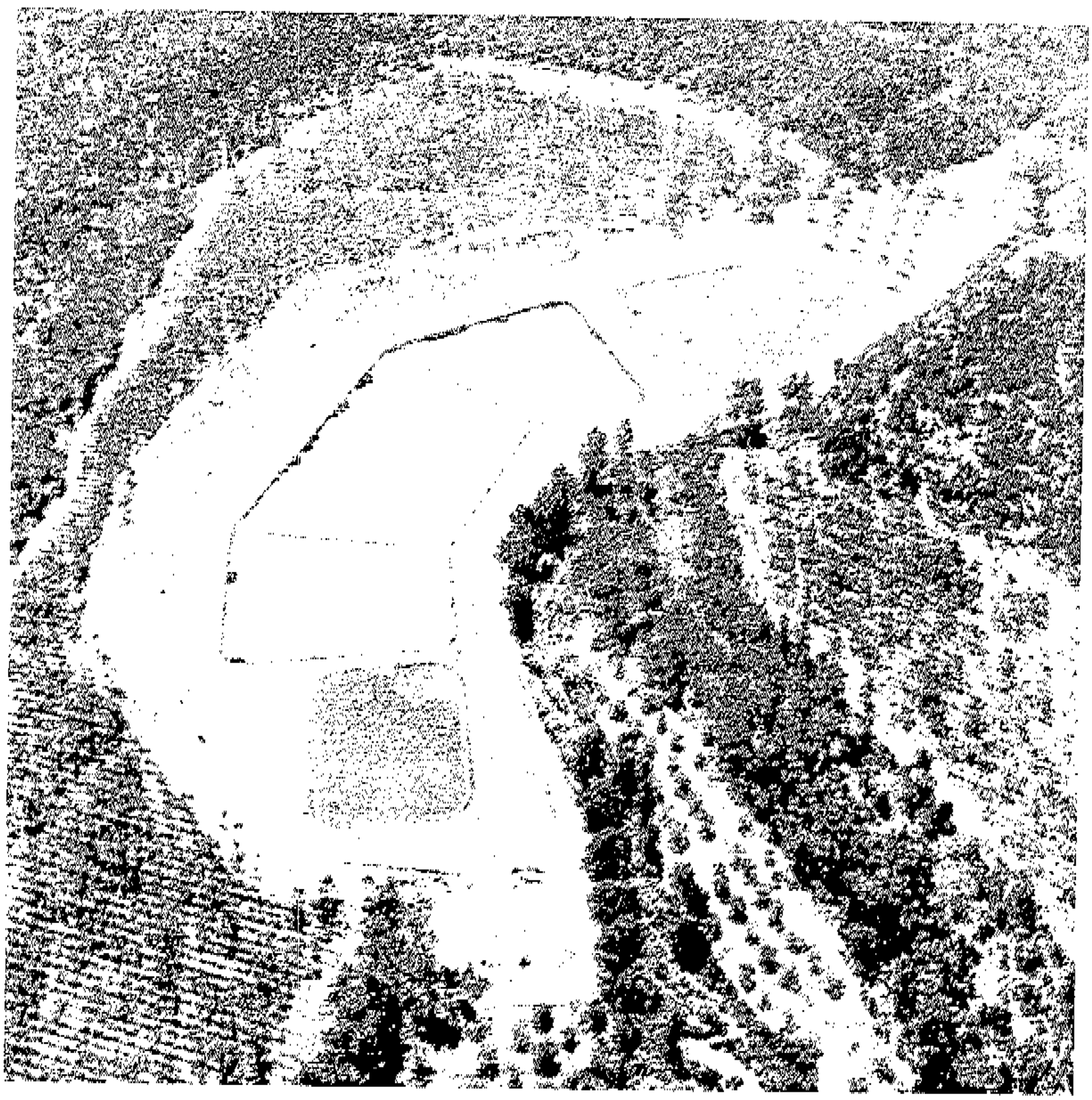
Anaerobic ponds, as their name implies, are devoid of dissolved oxygen and contain no (or very few) algae. Facultative and maturation ponds have large algal populations, which play an essential role in waste stabilization; they are thus sometimes called photosynthetic or natural ponds. There are some variations of these types: for example, facultative ponds may be divided into primary and secondary facultative ponds, which receive raw and settled sewage respectively (the latter commonly being the effluent from anaerobic ponds); and maturation ponds are sometimes used to improve the bacteriological quality of the final effluent from conventional sewage treatment works, and are then often referred to as polishing ponds. Maturation ponds are also occasionally planted with floating or rooted macrophytes, when they are known as macrophyte ponds, but this is not generally recommended for the reasons given in Annex 1. In addition, there is a fourth type of pond, high-rate algal ponds, which are primarily for the production of algal protein (rather than wastewater treatment). This type of pond, which is still largely experimental, is not recommended for general use at the present time for the reasons given in Annex 2.

The three main types of pond are usually arranged in a series comprising either a primary facultative pond followed by one or more maturation ponds, or an anaerobic pond followed by a secondary facultative pond and one or more maturation ponds (Fig. 1). Such series of ponds are very advantageous, as they enable the different types of pond to perform their different functions in wastewater treatment and so produce an effluent of the desired quality. Anaerobic ponds are most advantageously used for the treatment of strong wastewaters (BOD_5 > 300 mg/l) and those containing a high concentration of suspended solids. They, and facultative ponds, are designed primarily for the removal of organic compounds, usually expressed in terms of their biochemical oxygen demand (BOD), whereas maturation ponds are designed mainly for the removal of excreted pathogens (for which faecal coliform bacteria are commonly used as indicator organisms) and plant nutrients (principally nitrogen and phosphorus salts), although, of course, some removal of BOD occurs in maturation ponds and pathogens and plant nutrients are removed to some extent in anaerobic and facultative ponds.

1.2 Waste stabilization in ponds

Waste stabilization in ponds is in one sense a very simple treatment process: wastewater enters and flows through a series of ponds by gravity, and after a few weeks a highly purified effluent is produced. However, in

Fig. 1. Aerial view of waste stabilization ponds serving Sesimbra, Portugal
(the series comprises an anaerobic pond, a baffled secondary pond and a single maturation pond)



another sense, they are far from simple: their microbial ecology is much more complex than those of activated sludge and trickling filters and is not yet fully understood. This section contains a very brief description of ponds and their processes of waste stabilization. For a more detailed discussion, reference should be made to Gloyna, Hawkes and Mara & Pearson (1-3).

1.2.1 Anaerobic ponds

Anaerobic ponds receive such a high organic loading (>100 g BOD_5 per m^3 per day) that they are devoid of dissolved oxygen. They function essentially as open septic tanks. Indeed, in very small treatment works, septic tanks are often used in place of anaerobic ponds. The settleable solids in the raw wastewater settle to form a sludge layer, where they are digested anaerobically by acidogenic and methanogenic bacteria at temperatures above 15 °C. Total BOD removal is high, ranging from around 40% at 10 °C or below to over 60% at 20 °C and above. A scum layer often forms on the surface, and this need not be removed, although fly breeding may be a nuisance in some instances in summer and require remedial action, such as spraying with clean water or final effluent or, in exceptional cases, with a suitable biodegradable insecticide.

Odour release (mainly hydrogen sulfide) is commonly thought of as a major disadvantage of anaerobic ponds. Yet if designed to receive a volumetric loading <400 g BOD per m^3 per day (4) (see section 3.4), odour nuisance does not occur with domestic wastewaters containing <500 mg SO_4/l. Anaerobic ponds sometimes appear dark red or purple. This is due to the presence of species of anaerobic sulfide-oxidizing photosynthetic bacteria whose growth is beneficial in preventing hydrogen sulfide release.

Anaerobic ponds usually have a depth of 2-5 m. The depth chosen for any particular anaerobic pond should minimize land area requirements and construction costs (the cost of excavation generally increases with depth), and keep hydraulic short-circuiting to an acceptable minimum (see section 4.5).

1.2.2 Facultative ponds

In primary facultative ponds (those that receive raw wastewater), there are two main mechanisms for BOD removal (Fig. 2):

- sedimentation and subsequent anaerobic digestion of settleable solids; up to 30% of the influent BOD may leave the pond as methane gas (5);

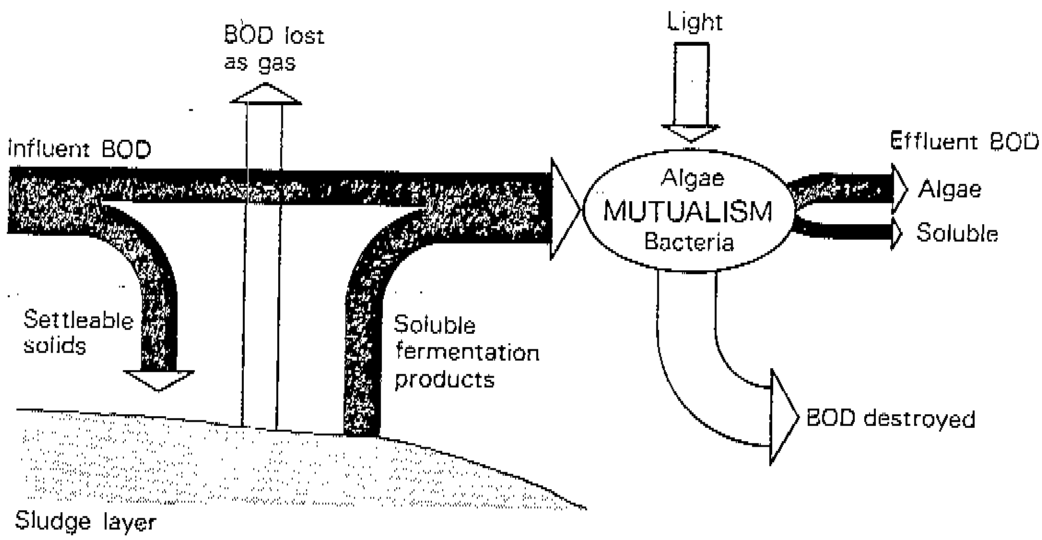
- aerobic bacterial oxidation of the non-settleable organic compounds, together with the solubilized products of anaerobic digestion; the oxygen needed for this comes partly from the air through surface re-aeration, but it is provided mainly by the photosynthetic activities of the microalgae, which grow profusely in the pond and colour it dark green; the algae in return receive most of their carbon dioxide from the end product of bacterial metabolism, so there exists a mutualistic relationship between the heterotrophic bacteria and the predominantly autotrophic algae in the pond (Fig. 3).

In secondary facultative ponds (those that receive anaerobic pond effluent), the first of these two mechanisms does not occur to any significant extent. BOD removal in both types of facultative pond is in the range 60-80%.

The depth of facultative ponds is usually 1.5 m, although depths between 1 m and 2 m are used. Depths less than 0.9 m are not recommended, as rooted plants may grow in the pond and provide a shaded habitat suitable for mosquito breeding.

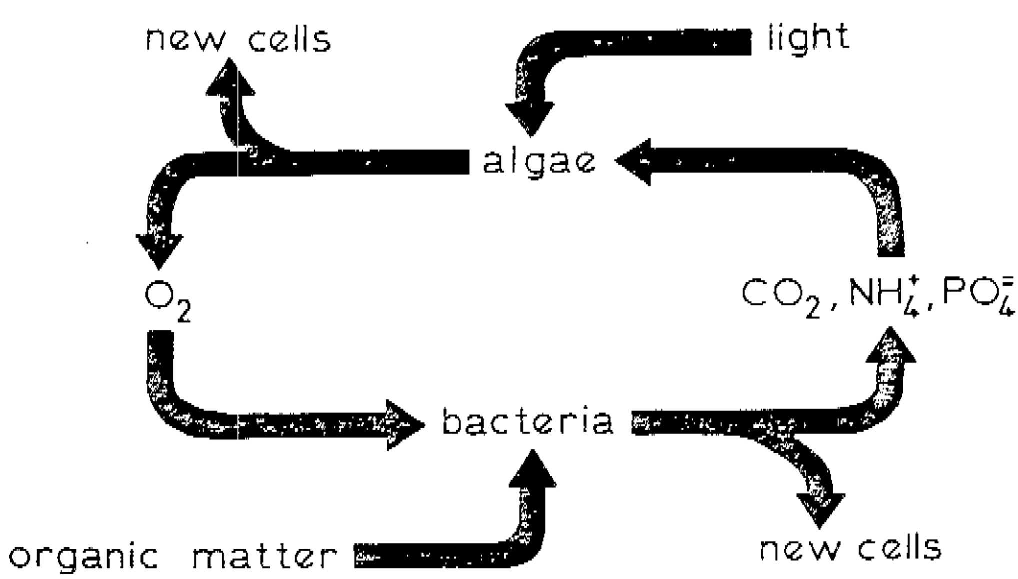
As a result of the photosynthetic activities of the pond algae, there is a diurnal variation in the concentration of dissolved oxygen. After sunrise, the dissolved oxygen level gradually rises to a maximum in the mid-afternoon, after which it falls to a minimum at night. The position of the oxypause (the depth at which the dissolved oxygen concentration reaches zero) similarly changes, as does the pH since at peak algal activity bicarbonate ions dissociate to provide more carbon dioxide for the algae, so leaving an excess of hydroxyl ions with the result that the pH can rise to above 10.

Fig. 2. Pathways of BOD removal in primary facultative ponds



Source: Marais (5).

Fig. 3. Mutualistic relationship between algae and bacteria in facultative waste stabilization ponds



The wind has an important effect on the behaviour of facultative ponds, as it induces vertical mixing of the pond liquid. Good mixing ensures a more uniform distribution of BOD, dissolved oxygen, bacteria and algae and hence a better degree of waste stabilization. In the absence of wind-induced mixing, the algal population tends to stratify in a narrow band, some 20 cm thick, during daylight hours. This concentrated band of algae moves up and down through the top 50 cm of the pond in response to changes in incident light intensity, and causes large fluctuations in effluent quality (BOD, chemical oxygen demand (COD), suspended solids) if the effluent take-off point is within this zone (see section 4.5).

1.2.3 Maturation ponds

A series of maturation ponds receives the effluent from a facultative pond, and the size and number of maturation ponds is governed mainly by the required bacteriological quality of the final effluent (see sections 3.1 and 3.6). Maturation ponds usually show less vertical biological and physicochemical stratification and are well oxygenated throughout the day. Depths of up to 3 m have been used, but more commonly depths are the same as in facultative ponds (1-2 m).

The principal parameters that affect the removal of faecal bacteria in ponds are temperature, retention time and organic loading. Faecal bacterial removal increases with increasing temperature and retention time, but decreases with increasing organic load. However, there are too few data to predict with confidence the effect of organic loading, and as a result design procedures are currently based only on temperature and retention time (see section 3.6).

Little is known about the removal of excreted viruses in ponds. Adsorption on to settleable solids is generally considered to be the principal removal mechanism, but this is an area that requires further research. Excreted protozoan cysts and helminth eggs are removed by sedimentation, and a series of ponds with an overall retention time of 11 days or more will produce an effluent free of cysts and eggs (6).

1.2.4 Major microbial groups

Bacteria

Most aquatic bacterial groups are represented and implicated directly or indirectly in the overall treatment process occurring in ponds. This heterotrophic bacterial population is in a continuous state of flux exhibiting dynamic changes, both temporally and spatially, and is controlled by the pond chemistry. In general, the size of the total heterotrophic bacterial population decreases along a pond series as the quantities of organic substrates diminish.

Algae

Although the key role of the algal population in facultative and maturation ponds is generally considered to be the generation of oxygen, it is becoming increasingly clear that their ability to raise the pH of maturation ponds above 9 during daylight hours, as a consequence of their photosynthetic activity, is an important mechanism in destroying faecal bacteria.

A knowledge of the types of algal species present and their biomass concentration provides a useful indication of pond status and wastewater treatment efficiency. The dominant algal genera are usually members of the Chlorophyta and Euglenophyta and, to a lesser extent, the Chrysophyta and Cyanophyta; examples of typical algal genera found in stabilization ponds are listed in Table 1. In general, species diversity in ponds decreases as the organic loading increases, and consequently fewer species are found in facultative ponds than in maturation ponds. Motile, flagellate genera such as Euglena, Pyrobotrys and Chlamydomonas tend to dominate in the more turbid conditions of facultative ponds, where their ability to move towards surface light gives them a competitive advantage over non-motile forms such as Scenedesmus, Chlorella and Miractinium, which abound in the more transparent waters of maturation ponds. Speciation will change, however, in response to changes in environmental conditions and wastewater quality.

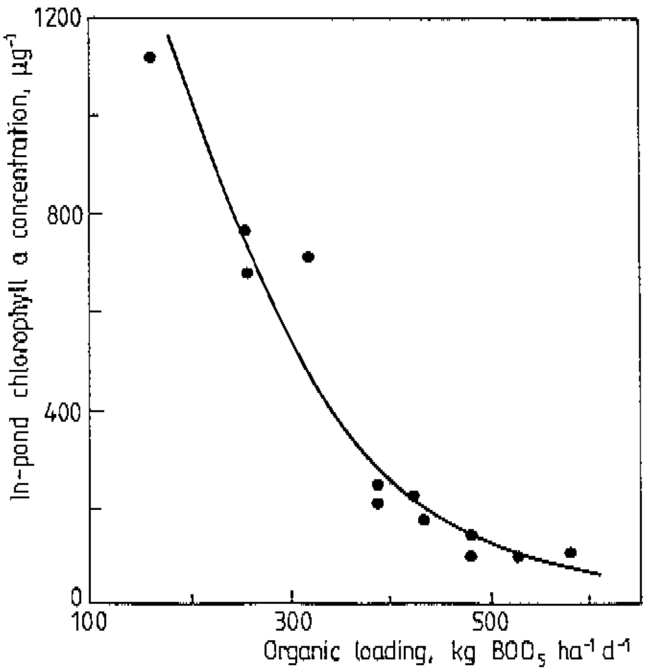
Table 1. Examples of algal genera present in waste stabilization ponds[a]

Algal genus	Facultative	Maturation
Euglena	+	+
Phacus	+	+
Chlamydomonas	+	+
Chlorogonium	+	+
Pyrobotrys	+	+
Eudorina	+	+
Pandorina	+	+
Scenedesmus	–	+
Volvox	+	+
Dictyosphaerium	–	+
Oocystis	–	+
Cyclotella	–	+
Ankistrodesmus	–	+
Chlorella	+	+
Micractinium	–	+
Rhodomonas	–	+
Coelastrum	–	+
Navicula	–	+
Cryptomonas	+	+
Oscillatoria	+	+
Anabaena	–	+
Spirulina	–	+

[a] + = present
– = absent

The algal standing crop in efficiently operating facultative ponds is frequently in the range 1000-3000 µg/l chlorophyll a, but it depends on the BOD_5 surface loading (Fig. 4) and fluctuates with environmental changes associated with the seasons and also due to such factors as zooplankton

Fig. 4. Variation of algal biomass with organic loading in primary facultative waste stabilization ponds at 25 °C



Source: Mara & Silva (unpublished data).

grazing, transient chemical toxicity and attack by phycopathogenic organisms. The standing crop is lower in maturation ponds (BOD_5 loading <50 kg per ha per day) and decreases as subsequent ponds in a series become more lightly loaded.

1.2.5 Nitrogen and phosphorus removal

Nitrogen removal in ponds may reach 80% or more and appears to be related to pH, temperature and retention time. The principal mechanisms involved are volatilization of ammonia and sedimentation of organic nitrogen as microbial biomass (7,8). Nitrification and denitrification do not appear to occur to any significant extent (9). None of the current models for nitrogen removal can yet be confidently used for design, and further studies are necessary if a fuller understanding of nitrogen cycling in ponds is to be obtained and ponds designed specifically for nitrogen removal.

The efficiency of phosphorus removal in ponds depends on the balance between phosphorus sedimentation and precipitation (as microbial biomass and insoluble phosphates respectively) and its return to the pond liquid via mineralization and resolubilization. Algae comprise the largest component of organic phosphorus fraction in the pond liquid, as they incorporate large quantities of orthophosphate. Houng & Gloyna (10) developed a first-order model for phosphorus removal and cycling in ponds, and they showed that total phosphorus removal would be around 45% in facultative ponds in which the BOD removal was 90%. They suggested that increasing the number of maturation ponds increases phosphorus removal, as progressively more phosphorus becomes immobilized in the oxidized surface layers of the sediment in these ponds, thus preventing the release of phosphorus back into the pond liquid. However, as with nitrogen, further work is needed to develop design equations for phosphorus removal in ponds.

1.2.6 Toxicity factors

Since the performance of a pond system depends on the activities of its constituent algal and bacterial populations, any toxic substance that affects their metabolism will reduce its treatment efficiency. The algae, and in particular their photosynthetic apparatus, are more easily inhibited than the bacteria. In ponds treating domestic wastewater, the major potential toxicants are ammonia and sulfide. Heavy metals are not normally a problem with domestic wastes, since ponds can withstand up to at least 30 mg/l of heavy metals without any reduction in treatment efficiency (11).

Ammonia concentrations above 28 mg N/l are likely to be toxic to algae within the pH range experienced during daylight hours in ponds (12). Ammonia becomes exponentially more toxic above pH 8, since a larger proportion is then in the unionized NH_3 state, which rapidly penetrates the algal cell. Inhibition of photosynthesis by high ammonia concentrations can cause facultative ponds to become completely anaerobic, even when the BOD surface loading is low. Ammonia inhibition is reversible in the short term, i.e. hours rather than days, and the toxicity of sub-lethal concentrations of ammonia may be self-regulating since inhibition of photosynthetic activity reduces the pH and hence the toxicity of the ammonia.

Sulfide is toxic to algae in its undissociated H_2S state; thus, in contrast to ammonia, its toxicity increases with decreasing pH. In the range of pH found in ponds, sulfide concentrations of 8 mg/l seriously inhibit photosynthesis, but the effect is reversible in the short term (13). Sulfide also inhibits the activities of anaerobic heterotrophic bacteria, and concentrations of 50-150 mg/l inhibit methanogenesis in anaerobic ponds (14).

1.3 Advantages and disadvantages

Waste stabilization ponds have many advantages in Mediterranean Europe over other types of wastewater treatment. These include:

- low capital and operational costs, including a zero requirement for energy other than solar energy;
- extremely simple maintenance requirements (see section 5.2);
- very high removals of excreted pathogens: up to 99.9999% (i.e. 6 log_{10} units or from 10^8 to 10^2 per 100 ml) reduction of faecal coliforms and complete removal of excreted protozoa and helminths;
- the ability to cope with increased (tourist) populations in summer (see section 3.5) and to withstand hydraulic and organic overloads;
- the ability to treat a wide variety of biodegradable industrial and agricultural wastewater, including a relatively low sensitivity to heavy metals.

The principal disadvantages of pond systems are that they require much larger areas of land than other forms of sewage treatment and that they have specific soil requirements (see section 4.2). Thus, design engineers must consider local land prices and soil suitability in selecting the least cost method of wastewater treatment. In many cases, ponds will be the treatment system of choice, as suitable land is often available at relatively low cost. Other disadvantages of ponds are that the final effluent may contain too high a concentration of suspended algal solids and that evaporative losses in hot, dry climates may significantly reduce the amount of treated wastewater available for agricultural reuse.

2. Current pond usage in Mediterranean Europe

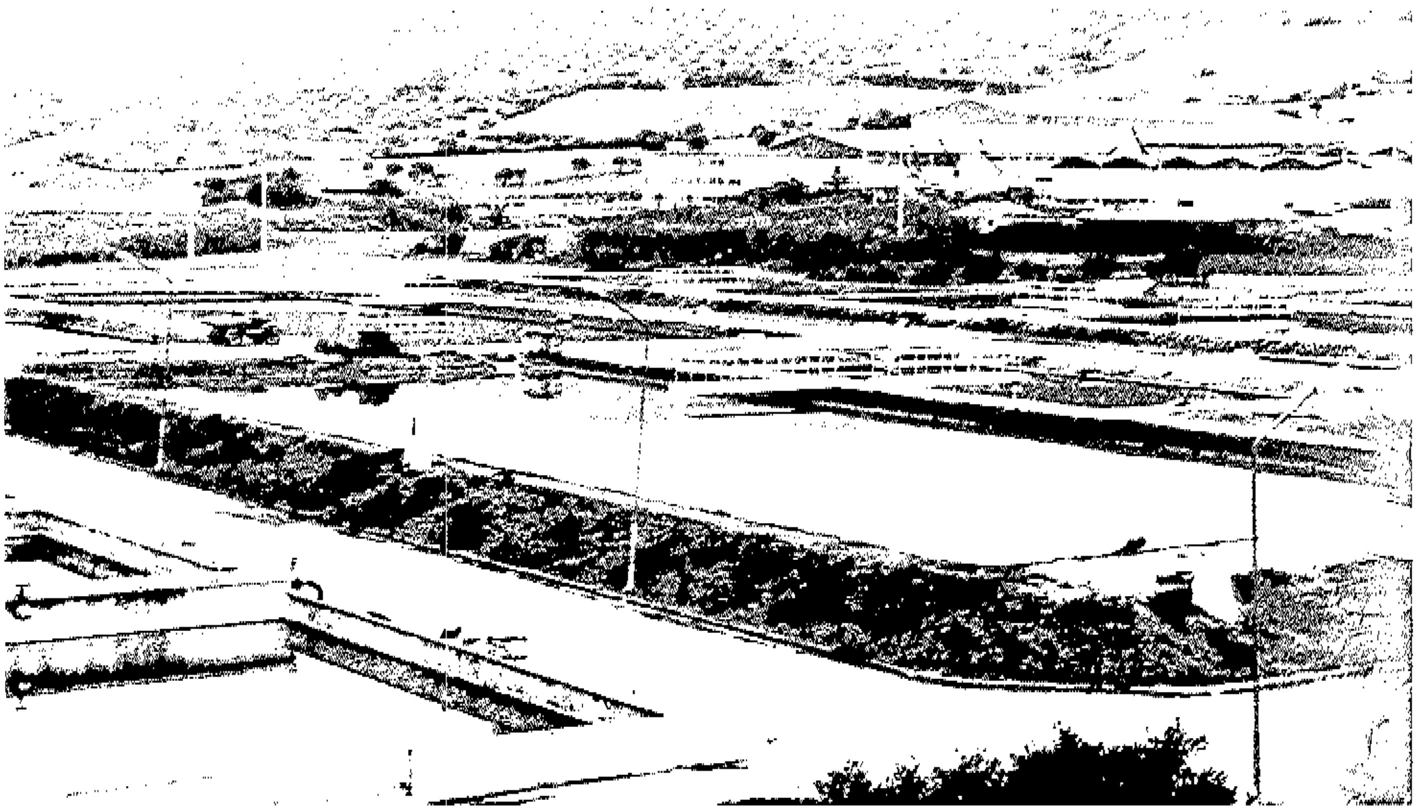
Waste stabilization ponds are widely used in France and Portugal, but not at present in other countries in Mediterranean Europe, although there are a few pond systems in use or under construction in Greece, Italy and Spain. Ponds are also used in some other European countries, especially, for example, the Federal Republic of Germany.

In France, there are approximately 1500 pond systems that mainly serve small rural communities of less than 1000 population (15,16), but they are also used for larger communities on the Mediterranean coastline, especially where there are both important shellfisheries and major centres of summer tourism (17,18). At present, ponds comprise one in eight of all wastewater treatment plants in France. Usually, pond systems consist of a single primary facultative pond followed by two maturation ponds, each half the size of the facultative pond; a total surface area of 10 m^2 per person is usually adopted as the design criterion (this is equivalent to an organic loading of 100 kg BOD_5 per ha per day on the facultative pond) (19). Anaerobic ponds are not used; a few systems have Imhoff tanks instead, but this is now becoming less common. Some pond systems include a rooted macrophyte pond (see Annex 1), but this option is no longer favoured due to the increased maintenance involved.

In Portugal, there are at present 17 pond systems in operation, mainly in the south of the country; the design population varies from 300 to 18 000. Anaerobic ponds are used at nearly half the systems, and most include one maturation pond. The increasing use of ponds in Portugal, combined with a lack of knowledge of their local performance, led the Direcção Geral do Saneamento Básico to initiate a major research programme on ponds, which is the first of its kind in Europe. In 1982, an experimental pond complex was constructed at the Frielas wastewater treatment works in Greater Lisbon (Fig. 5). These facilities, which have been in full operation since 1984, comprise two anaerobic ponds, one primary and two secondary facultative ponds and four maturation ponds, arranged as shown in Fig. 6. Their performance has been evaluated generally in accordance with the recommendations given in section 6. A preliminary examination of the results obtained to date indicate that higher loadings than hitherto considered feasible can be safely used in Portugal (Gomes de Silva, personal communication, 1986).[a]

[a] A detailed analysis of the results obtained during the first operational phase of the experimental pond complex will be presented at the IAWPRC Specialized Conference on Waste Stabilization Ponds to be held in Lisbon during the period 29 June-2 July 1987. The conference proceedings will be published in Water science and technology in December 1987.

Fig. 5. The experimental waste stabilization pond complex at Frielas, Greater Lisbon



3. Process design guidelines

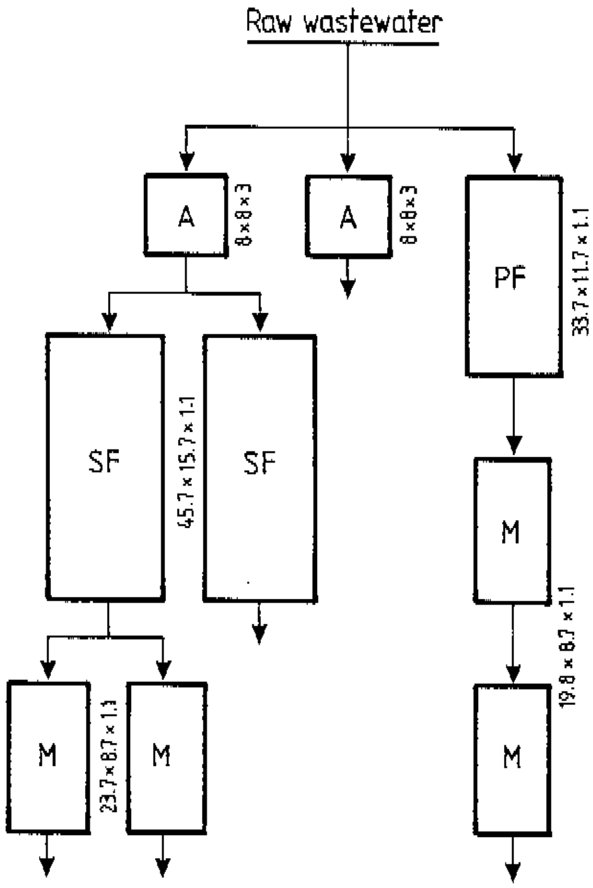
Despite the number and growing popularity of waste stabilization ponds in Europe, there exist few reliable field data on pond performance in most countries in Mediterranean Europe. Evaluation of existing pond performance is essential if ponds are to be designed as economically as possible; recommendations for pond monitoring and evaluation are given in section 6. The construction and operation of well designed experimental ponds, such as those in Lisbon described in section 2, are also very effective ways in which reliable pond design criteria can be developed.

Due to this current paucity of field data, the design recommendations given below for anaerobic, facultative and maturation ponds must be regarded as tentative. It is expected that, as more data become available, these recommendations will be refined and a second edition of this manual produced. A microcomputer-based procedure for pond design incorporating these recommendations is available (20).

3.1 Effluent standards

Effluent standards are usually expressed by regulatory agencies in terms of organic matter (usually as BOD_5 but increasingly also as COD), suspended solids, nitrogen (as ammonia, oxidized nitrogen or both) and faecal coliform organisms. The maximum permissible concentration of each constituent should be decided on the basis of what is to be done with the effluent. For example, if it is to be discharged into a river, the upstream river water quality and the available dilution are important. If the effluent is to be reused for

Fig. 6. Schematic diagram of the experimental waste stabilization pond at Frielas, Greater Lisbon



Legend: A = anaerobic pond
PF = primary facultative pond
SF = secondary facultative pond
M = maturation pond
Mid-depth pond dimensions are given in metres

irrigation, the maximum permissible faecal coliform concentration depends on the type of crop to be irrigated (it should be less than 1000 per 100 ml if unrestricted irrigation is to be allowed; see section 7); or if the effluent is to be discharged into shellfish growing areas, the available dilution must be taken into account in order than the shellfish do not grown in water containing more than 10 faecal coliforms per 100 ml (17,21). If the effluent is to be used for irrigation, the count of intestinal nematode eggs should be <1 per litre (see section 7), and this is readily achievable in a series of ponds having an overall retention time of at least 11 days (6).

In the absence of official standards, design engineers should ensure that the final effluent from a series of ponds does not, except in exceptional and justifiable circumstances, contravene the following recommended minimum quality requirements:

- unfiltered COD, <150 mg/l;
- unfiltered BOD_5, <30 mg/l;
- suspended solids, <50 mg/l;
- faecal coliforms, <10 000 per 100 ml.

Frequently, however, as noted above, much more stringent requirements need to be met, even in the absence of official standards. These guidelines are expressed in terms of unfiltered BOD and COD, i.e. including the oxygen demand of the algae in the effluent. It is a moot point whether the effects of the algae should be included or not (22), but their inclusion results in a value that is generally a better estimate of the oxygen demand of the effluent in the receiving watercourse, especially during critical conditions in summer. In contrast, French guidelines for pond effluent quality are based on filtered values (23), as follows:

- filtered COD, <120 mg/l;
- filtered BOD_5, <40 mg/l;
- suspended solids, <120 mg/l.

3.2 Number of ponds

In normal circumstances, it is recommended that pond systems comprise at least three ponds in series. Thus, acceptable designs are either an anaerobic pond followed by a secondary facultative pond and one or more maturation ponds or a primary facultative pond followed by at least two maturation ponds. For small communities (<1000 population), three ponds in series usually suffice (see section 3.7), but large communities may require a greater number, especially if a high degree of pathogen removal is required (see section 3.6). Only exceptionally should a system with less than three ponds in series be considered. This might be appropriate in certain circumstances, e.g. discharge into coastal or estuarine waters or into a river with large dilution, but each case should be carefully justified.

3.3 Design parameters

The four most important design parameters are temperature, the BOD_5 and faecal coliform concentrations of the raw wastewater and its flow.

3.3.1 Temperature

In winter, the mean daily pond temperature is warmer by 2-3 °C than the mean daily air temperature, and in summer the reverse is true. Thus, to provide a small margin of safety, the winter design temperature should be taken as the mean monthly air temperature in the coldest month, and the summer design temperature as the mean monthly air temperature, less 3 °C, in the coolest month in the peak population season (see Annex 3).

3.3.2 BOD_5

If the wastewater exists, its BOD_5 may be measured using 24-hour flow-weighted composite samples (see section 6.1). If it does not, it may be estimated from the following equation:

$$L_i = 1000\ B/q \qquad [1]$$

where: L_i = wastewater BOD_5, mg/l
B = BOD_5 contribution, g/caput/day
q = wastewater flow, litre/caput/day

Values of B vary between 30 and 70 g per caput per day, and a suitable design value is 50 g per caput per day.

3.3.3 Faecal coliforms

Grab samples of the wastewater may be used to measure the faecal coliform concentration if the wastewater exists. The usual range is 10^7-10^9 faecal coliforms per 100 ml, and a suitable design value is 1×10^8 per 100 ml.

3.3.4 Flow

The mean daily flow should be measured if the wastewater exists. If it does not, it must be estimated very carefully since the size of the pond installation, and hence its cost, is directly proportional to the flow. The wastewater flow should not be based on the design water consumption per caput, as this is unduly high since it contains an allowance for losses in the distribution system. A suitable design value is 85% of the in-house water consumption, and this can be readily determined from records of water meter readings. If these do not exist, the design wastewater flow should be based on local experience in sewered communities of similar socioeconomic status and water use practice.

3.4 Anaerobic ponds

There is little experience of anaerobic ponds in Mediterranean Europe. They are, however, used in Bavaria, Federal Republic of Germany, where they work well, even in winter, if designed on the basis of at least 0.5 m^3 per person (24). Assuming a BOD contribution of 50 g per caput per day, this is equivalent to a maximum permissible volumetric BOD loading of 100 g per m^3 per day. This recommendation is consistent with Israeli practice (25), and also with the general recommendation made by Meiring et al. (4) that volumetric loadings on anaerobic ponds should be between 100 and 400 g/m^3 so as to maintain anaerobic conditions and avoid odour nuisance.

The volumetric loading (λ_v, g/m^3/day) is given by:

$$\lambda_v = L_i Q / V_a \qquad [2]$$

where: L_i = influent BOD, mg/l (= g/m^3)
Q = flow, m^3/day
V_a = anaerobic pond volume, m^3

Since winter temperatures in Mediterranean Europe are less than 15 °C, below which the activity of methanogenic bacteria essentially ceases and anaerobic ponds act merely as sludge storage basins (5), it is recommended that the Bavarian loading of 100 g per m^3 per day be adopted for the winter design of anaerobic ponds. Higher loadings (up to 300 g per m^3 per day) may be used in summer provided that there is local experience of their satisfactory operation. Otherwise, a loading of 100 g per m^3 per day should be used. Solution of equation 2 then yields the required pond volume, which is translated into a physical design as explained in section 4.

The removal of BOD in anaerobic ponds is a function principally of temperature (26), but too few data exist to quantify the relationship. However, a winter removal of 40% can be used as a conservative basis for design. A higher removal (up to 60%) may be assumed for summer operation provided that there is local experience of this level of performance. Otherwise, a removal of 40% should be used.

3.5 Facultative ponds

There are several ways in which facultative ponds may be designed (1,27). The two most commonly used methods are those based on first-order kinetics and maximum permissible surface loading. The former is not currently recommended for design purposes in Mediterranean Europe, since there are too few reliable data on which to base design values for the various kinetic constants. Pond design procedures based on BOD surface loading are empirical, and local experience of pond performance may be used to establish a recommended design value, e.g. in France, a loading of 100 kg per ha per day is commonly used (19). Climatic factors influence the permissible loading, and the effect of temperature can be taken into account by the method of McGarry & Pescod (26). Their original equation, which describes the envelope of failure for primary facultative ponds, is:

$$\lambda_{s(max)} = 60.3\ (1.099)^{T-20} \qquad [3]$$

where: $\lambda_{s(max)}$ = maximum BOD_5 loading, kg/ha/day
T = mean air temperature, °C

Equation 3 was modified by Mara (27) to give the following linear design equation:

$$\lambda_s = 20T-120 \qquad [4]$$

where: λ_s = design BOD_5 loading, kg/ha/day
T = design temperature, °C

Arthur (28) changed equation 4 to:

$$\lambda_s = 20T-60 \qquad [5]$$

Experience in Israel (25) suggests that both equations 4 and 5, which are based on pond experience in the tropics, give values that are too high for use in Mediterranean Europe, for which a more appropriate equation is:

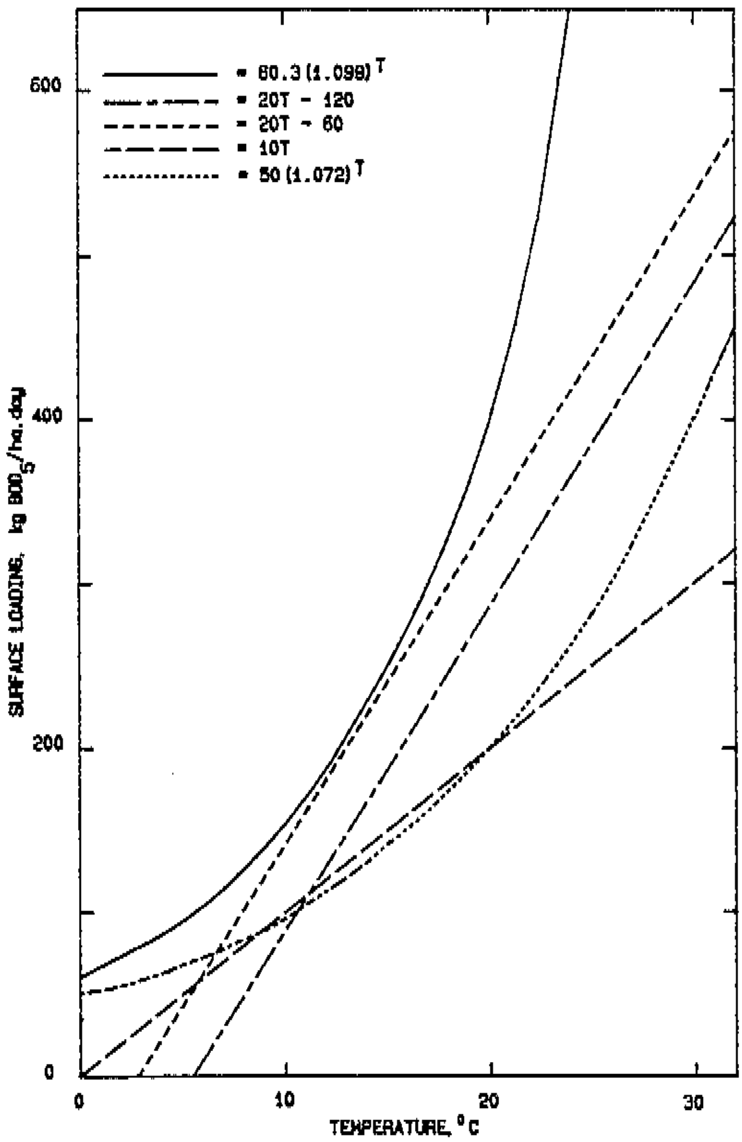
$$\lambda_s = 10T \qquad [6]$$

Equation 6 is satisfactory at temperatures up to 20 °C, but is probably rather too conservative at higher temperatures, for which the following equation, which is based on a doubling of the design load for every 10 °C rise in temperature, is more appropriate:

$$\lambda_s = 50(1.072)^T \qquad [7]$$

Equations 3-7 are shown graphically in Fig. 7.

Fig. 7. Variation of permissible organic loading with temperature according to equations 3-7



Experience in France and the Federal Republic of Germany indicates that a loading of 100 kg/ha per day is satisfactory in winter, and this value, which corresponds to a temperature of 10 °C in equations 6 and 7, is recommended for design temperatures of 10 °C and below. At higher temperatures, the design loading should be calculated from equation 6, although equation 7 may be used at design temperatures above 20 °C. The same design loading may be used for both primary and secondary facultative ponds, although if a pond series comprises only an anaerobic and a secondary facultative pond, i.e. if there are no maturation ponds, the design loading on the secondary facultative pond should be reduced by 30%.

Surface loading is related to the flow (Q, m^3/d) and the BOD (L_i, mg/l) of the wastewater and the pond area (A_f, m^2) as follows:

$$\lambda_s = 10 L_i Q / A_f \qquad [8]$$

Thus, combining equations 6 and 8:

$$A_F = L_i Q/T \qquad [9]$$

The area calculated from equation 8 is then translated into physical dimensions and the depth selected, as explained in section 4.

The removal of BOD in both primary and secondary facultative ponds is often related to the BOD loading, e.g. by an equation of the general kind:

$$\lambda_r = a\lambda_s \qquad [10]$$

where: λ_r = areal BOD_5 removal, kg/ha/day
a = efficiency of BOD removal

Values of a range from 0.7 to 0.8 (26,29,30) in tropical climates, but few data exist from Mediterranean Europe. Provided that the facultative pond effluent has an unfiltered BOD_5 between 50 and 100 mg/1, it may be considered as functioning properly (31) and the subsequent maturation ponds will not be overloaded.

In summer when the temperature rises, the pond is able to accept a higher load and so is able to treat the wastewater from a larger population (18). This is very useful, as summer tourism can increase the resident (winter) population by a factor of 2-20. For example, if the summer design temperature were 25 °C, the maximum permissible summer loading would be 250 kg per ha per day, so a pond designed for a winter loading of 100 kg per ha per day would be able to treat the wastewater from a summer population of 2.5 times the winter population. Summer conditions control the design of facultative ponds if the "seasonal population factor" (defined as the average summer population divided by the winter population) is greater than the ratio of the permissible summer to winter loadings, i.e. when, from equation 6:

$$\text{seasonal population factor} > T_s/T_W \qquad [11]$$

where: T_s = summer temperature, °C
T_W = winter temperature, °C

Winter conditions control the design if the seasonal population factor is less than this ratio. The use of the seasonal population factor in facultative pond design is illustrated in Annex 3.

3.6 Maturation ponds

3.6.1 Pathogen removal

Maturation ponds are usually designed primarily to remove excreted pathogens. Although less than ideal for the purpose, faecal coliform bacteria are commonly used as indicators of excreted pathogens (32,33), so maturation ponds are usually designed to achieve a given removal of faecal coliforms. Recent research at the Ecole national de la santé publique in Rennes, France (34), has confirmed that the design procedure developed by Marais (35), which was developed from data from American ponds operating in the temperature range 2-21 °C, is applicable to maturation ponds in northern France, at least in terms of the removal of faecal coliforms and bacterial pathogens but not for the removal of excreted viruses which can be highly variable. The method assumes that faecal coliform removal follows first-order kinetics and that the ponds are completely mixed. Thus, the resulting equation for a single maturation pond is:

$$N_e = N_i/(1 + k_T\theta_m) \qquad [12]$$

where: N_e = number of faecal coliforms per 100 ml effluent
N_i = number of faecal coliforms per 100 ml influent
k_T = first order rate constant for faecal coliform removal at T°C, d^{-1}
θ_m = maturation pond retention time, day 5

The value of k_T at various temperatures is given by the equation (see Table 2):

$$k_T = 2.6(1.19)^{T-20} \qquad [13]$$

Table 2. Values of the first order rate constant for faecal coliform removal at various design temperatures (calculated from equation 13)

T(°C)	$k_T(day^{-1})$	T(°C)	$k_T(day^{-1})$
1	0.10	13	0.77
2	0.11	14	0.92
3	0.14	15	1.09
4	0.16	16	1.30
5	0.19	17	1.54
6	0.23	18	1.84
7	0.27	19	2.18
8	0.32	20	2.60
9	0.38	21	3.09
10	0.46	22	3.68
11	0.54	23	4.38
12	0.65	24	5.21

For a series of anaerobic, facultative and maturation ponds, equation 12 becomes:

$$N_e = N_i/[(1+k_T\theta_a)(1+k_T\theta_f)(1+k_T\theta_m)^n] \qquad [14]$$

where N_e and N_i now refer to the final effluent and raw wastewater respectively and n is the number of maturation ponds, which are assumed to be all of the same size (this is desirable as it optimizes removal efficiency (35) but may not always be possible due to topographical constraints[a]).

[a] For unequally sized maturation ponds, the term $(1+k_T\theta_m)^n$ in equation 14 is replaced by $[(1+k_T\theta_{m1})(1+k_T\theta_{m2})(1+k_T\theta_{mn})]$.

In order to use equation 14 for design, it is necessary to know the values of N_e and N_i and the retention times in the anaerobic pond (if there is one) and the facultative pond. The value of N_e is often stipulated as a required effluent standard (see section 3.1), and N_i can be measured if the wastewater exists, or else a design value of 1×10^8 per 100 can be assumed. The retention times in the anaerobic and facultative ponds are usually taken as the volume divided by the flow, but if there is significant evaporation it is more accurate to use the equation:

$$\theta = 2V/(2Q_i - 0.001Ae) \qquad [15]$$

where: V = pond volume, m^3
Q_i = inflow, m^3/day
A = pond area, m^2
e = evaporation, mm/day

Equation 13 contains two unknowns, θ_m and n, and is therefore solved by trial and error. For example, one might try two ponds at seven days or three ponds at five days, and so on, until trial solutions give an acceptable value of N_e. However, examination of equation 14 shows that it is better to have a large number of small ponds rather than a small number of large ponds of the same overall retention time. Marais (35) recommends that the minimum retention time in maturation ponds (θ_m^{min}) should be around three days so as to minimize short-circuiting. Thus, it is better to solve equation 14 for N = 1, 2, 3 ... and to consider the combination of θ_m and n, which has the highest value of n subject to the constraints that:

$$\theta_m^{min} \leq \theta_m \leq \theta_f$$

and:

$$\lambda_{m1} < \lambda_f$$

where: θ_f = retention time in facultative pond, day
λ_{m1} = BOD_5 loading on first maturation pond, kg/ha/day[a]
λ_f = BOD_5 loading on facultative pond, kg/ha/day

The combination of θ_m^{min} and the next highest value of n (i.e. the first value of n for which $\theta_m < \theta_m^{min}$) is then considered. This combination is selected as the design solution provided that it satisfies the second constraint given above. If it does not, the first combination considered is adopted. This design procedure ensures the solution with the least land area requirement; its use is illustrated in Annex 3.

3.6.2 BOD removal

Maturation ponds, although designed primarily for faecal coliform removal, do achieve some degree of BOD removal. Insufficient data are available to develop a precise design equation for BOD removal in maturation ponds in Mediterranean Europe, but it may be safely assumed that a series of maturation ponds, which has a total retention time at least equal to that in the preceding facultative pond (as recommended in France, for example), or one that has been designed to produce an effluent containing less than 1000 faecal coliforms per 100 ml will usually produce an effluent with a filtered BOD_5 of <25 mg/l.

[a] To calculate λ_{m1} an overall BOD reduction of 60% in the anaerobic and facultative ponds may be assumed at all design temperatures.

If maturation ponds are to be designed solely for BOD removal, it is suggested that they are designed on the basis of equation 6 with 70% removal of filtered BOD in the preceding facultative pond (or anaerobic and facultative ponds) and 25% removal of filtered BOD in each of the maturation ponds. The presence of algae in the final effluent often precludes the achievement of low concentrations of suspended solids and unfiltered BOD, and it may be necessary to include some simple algal removal system (36) to meet strict effluent discharge standards.

3.6.3 Nitrogen and phosphorus removal

The use of maturation ponds specifically for the removal of nitrogen and phosphorus is not recommended since, although removal does occur (see section 1.2), the amounts are variable and cannot at present be predicted with any degree of certainty.

3.7 Small communities

For small communities (<1000 population), the design procedure given above may be too detailed, especially if the effluent is not required to meet strict discharge standards. For such communities, it is suggested that the following equation be used for a three-pond system comprising a primary facultative and two maturation ponds:

$$A_T = 100\ P/T \qquad [16]$$

where:
- A_T = total pond area, m^2
- P = contributing population
- T = design temperature, °C (for temperatures below 10 °C, T should be taken as 10)

This equation is based on equation 6 and a BOD_5 contribution of 50 g per caput per day. The total area should be divided in the ratio $A_T/2:A_T/4:A_T/4$ for the facultative and the two maturation ponds respectively. The pond depths should be 1.5 m.

For a pond system comprising an anaerobic pond followed by a secondary facultative pond and one maturation pond, the following equations should be used:

$$V_a = 0.5\ P \qquad [17]$$
$$A_f = 30\ P/T \qquad [18]$$
$$A_m = A_f \qquad [19]$$

where:
- V_a = anaerobic pond volume, m^3
- A_f = facultative pond area, m^2
- A_m = maturation pond area, m^2

These equations are based on a volumetric loading of 100 g per m^3 per day on the anaerobic pond, which is assumed to achieve 40% BOD removal, and equation 6. The pond depths should be 3 m for the anaerobic pond and 1.5 m for the facultative and maturation ponds.

4. Physical design guidelines

The process design prepared as described in section 3 must be translated into a physical design. Actual pond dimensions, consistent with the available site, must be calculated; embankments and pond inlet and outlet structures must be designed and decisions taken regarding preliminary treatment, parallel pond systems and whether or not to line the ponds. By-pass pipes, security fencing and notices are generally required, and facilities for pond operators must be provided.

The physical design of pond systems is as important as their process design and can greatly influence their efficiency. The geotechnical aspects of pond design are very important indeed. In Europe, around half the number of malfunctioning ponds malfunction due to geotechnical problems that could have been obviated at the design stage.

4.1 Pond location

Ponds should be located at least 200 m downwind from the community they serve and away from any likely area of future expansion. This is mainly to discourage people visiting the ponds (see section 4.6). Odour release, even from anaerobic ponds, is most likely to be a problem in a well designed system, but the public may need assurance about this at the planning stage, and a minimum distance of 200 m normally allays any fears.

There should be vehicle access to the ponds and, so as to minimize earthworks, the site should be flat or gently sloping. The soil must also be suitable (see section 4.4). Ponds should not be located within 2 km of airports, as the birdlife, especially seagulls, attracted to the ponds may constitute a risk to air navigation.

4.2 Geotechnical considerations

The principal objectives of a geotechnical investigation are to ensure correct embankment design and to determine whether the soil is sufficiently permeable to require lining. The maximum height of the groundwater table should be determined, and the following properties of the soil at the proposed pond location must be measured:

- particle size distribution;
- maximum dry density and optimum moisture content (modified Proctor test);
- Atterberg limits;
- organic content;
- coefficient of permeability.

At least four soil samples should be taken per hectare, and they should be as undisturbed as possible. The samples should be representative of the soil profile to a depth 1 m greater than the envisaged pond depth.

Organic, e.g. peaty, and plastic soils and medium-to-coarse sands are not suitable for embankment construction. If there is no suitable local soil with which at least a stable and impermeable embankment core can be formed, it must be brought to the site at extra cost and the local soil, if suitable, used for the embankment slopes. If the local soil is totally unsuitable, construction costs will be very high and ponds may not be the most economic treatment system.

Ideally, embankments should be constructed from the soil excavated from the site, and there should be a balance between cut and fill, although it is worth noting that ponds constructed completely in cut may be a cheaper alternative, especially if embankment construction costs are high. The soil used for embankment construction should be compacted in 150–250 mm layers to 90% of the maximum dry density determined by the modified Proctor test. Shrinkage of the soil occurs during compaction (10–30%) and excavation estimates must take this into account. After compaction, the soil should have a coefficient of permeability, as determined _in situ_, of $<10^{-7}$ m/s (see section 4.3). Wherever possible, and particularly at large pond installations, embankment design should allow for vehicle access to facilitate maintenance.

Embankment slopes are commonly 1 to 3 internally and 1 to 1.5–2 externally. Steeper slopes may be used if the soil is suitable. Slope stability should be ascertained according to standard soil mechanics procedures for small earth dams. Embankments should be planted with grass to increase stability: slow-growing rhizomatous species such as _Cynodon dactylon_ (Bermuda grass) should be used to minimize maintenance (see section 5.2).

External embankments should be protected from stormwater erosion by providing adequate drainage. Internally, embankments require protection against erosion by wave action, and this is best achieved by precast concrete slabs (Fig. 8) or stone rip-rap (Fig. 9) at top water level. Alternatively, plastic floats (Fig. 10) may be used. Such protection also prevents vegetation from growing down the embankment into the pond, so providing a suitably shaded habitat for mosquito breeding.

4.3 Hydraulic balance

To maintain the liquid level in the ponds, the inflow must be at least greater than net evaporation and seepage at all times. Thus:

$$Q_i \geq 0.001A(E + S) \qquad [20]$$

where:
- Q_i = inflow to first pond, m^3/day
- A = total area of pond series, m^2
- E = net evaporation (i.e. evaporation less rainfall), mm/day
- S = seepage, mm/day

Seepage losses must be at least smaller than the inflow less net evaporation so as to maintain the water level in the pond. The maximum permissible permeability of the soil layer making up the pond base can be determined from d'Arcy's law:

$$k = [Q/(86{,}400A)][\Delta l/\Delta h] \qquad [21]$$

where:
- k = maximum permissible permeability, m/s
- Q_s = maximum permissible seepage flow (= Q_i-0.001AE), m^3/day
- A = base area of pond, m^2
- Δl = depth of soil layer below pond base to aquifer or more permeable stratum, m
- Δh = hydraulic head (= pond depth + Δl), m

Fig. 8. Embankment protection by precast concrete slabs set at top water level

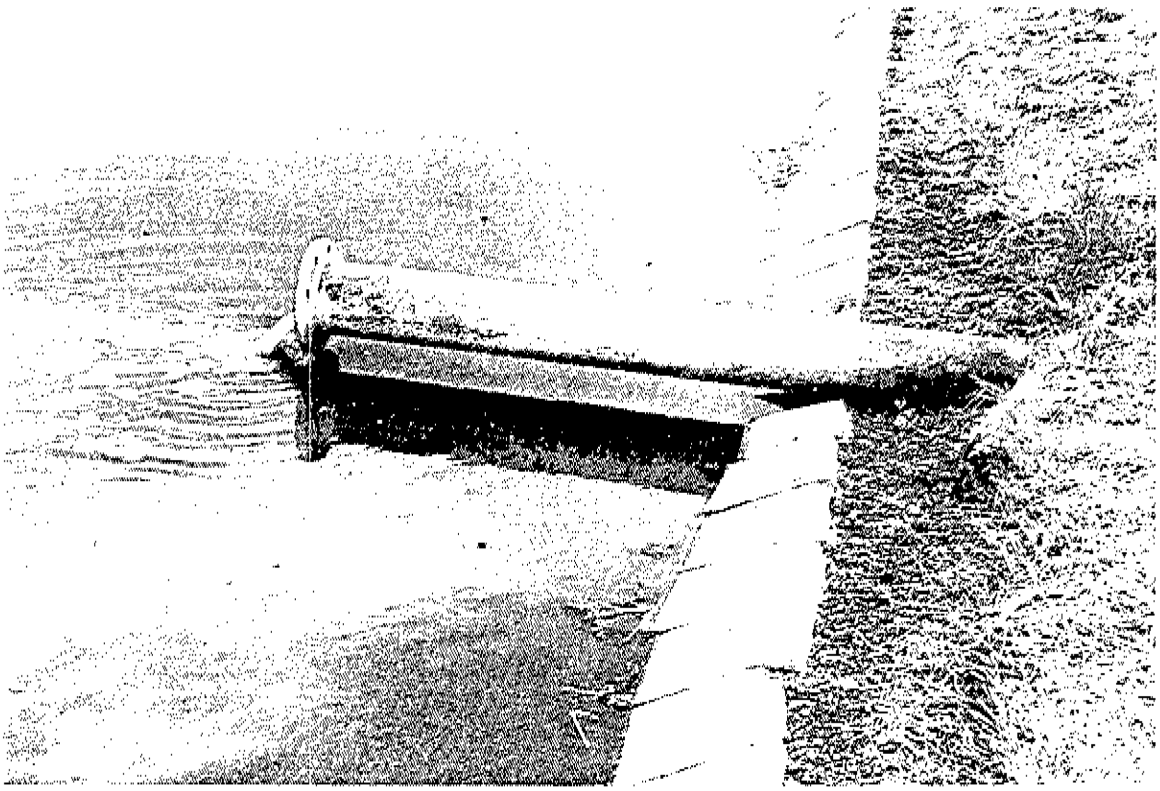
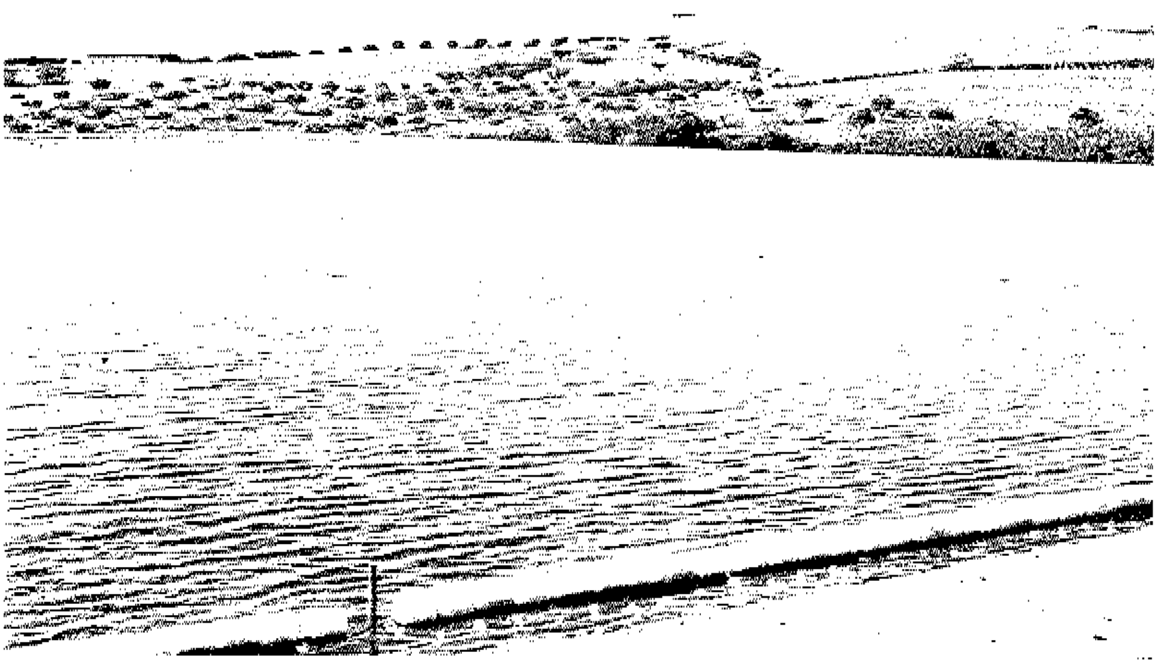


Fig. 9. Embankment protection by stone rip-rap extending to embankment base

Fig. 10. Embankment protection by plastic floats



If the permeability of the soil is more than the maximum permissible, the pond must be lined. A variety of lining materials is available and local costs dictate which should be used. Satisfactory lining has been achieved with ordinary portland cement (8 kg/m^2), plastic membranes and 150 mm layers of low-permeability soil. As a general guide, the following interpretations may be placed on values obtained for the in situ coefficient of permeability:

- $>10^{-6}$ m/s: the soil is too permeable and the ponds must be lined;
- $>10^{-7}$ m/s: some seepage may occur but not sufficiently to prevent the ponds from filling;
- $<10^{-8}$ m/s: the ponds will seal naturally;
- $<10^{-9}$ m/s: there is no risk of groundwater contamination (if $k > 10^{-9}$ m/s and the groundwater is used for potable supplies, further detailed hydrogeological studies may be required).

4.4 Preliminary treatment

For small pond systems, i.e. those serving less than 1000 people, it is generally unnecessary to provide any form of preliminary wastewater treatment, such as screening and grit removal, prior to treatment in ponds. However, the provision of a 50 mm bar screen to remove large solids is a sensible precaution. In coastal areas, where the wastewater generally contains a large quantity of sand, the need for grit removal facilities should be carefully assessed. Normally, manually cleaned twin grit removal (constant velocity) channels are sufficient. For larger populations, mechanically raked screens and mechanical grit separators may be considered. The design of such preliminary treatment facilities should follow conventional recommended practice, and adequate provision should be made for the disposal of screenings and grit. As an alternative to grit removal facilities, primary facultative ponds may be designed with a deeper section near the inlet to contain the incoming grit and other settleable solids and so permit their easier removal (see section 5.2).

Immediately after preliminary treatment, there should be a stormwater overflow set at six times the dry weather flow, if the sewer system is not of the separate kind, and a Parshall or Venturi flume to measure the wastewater flow. Automatic flow recorders are advisable at large flows, but they are generally too troublesome at small installations. A flow measurement facility is essential, since pond performance cannot otherwise be assessed (see section 6).

4.5 Pond geometry

There has been little rigorous work done on determining optimal pond shapes. Ponds in France, for example, vary considerably in their geometry. The most common shape is rectangular, although there is much variation in the length-to-breadth ratio. Clearly, the optimal pond geometry, which includes not only the shape of the pond but also the relative positions of its inlet and outlet, is that which minimizes hydraulic short-circuiting.

In general, anaerobic and primary facultative ponds should be rectangular, with length-to-breadth ratios of less than 3, so as to avoid sludge banks forming near the inlet. Secondary facultative and maturation ponds should, wherever possible, have higher length-to-breadth ratios (up to 10, or even 20, to 1) so that they better approximate plug flow conditions. High length-to-breadth ratios may also be achieved by placing baffles in the pond (Fig. 1). Ponds do not need to be strictly rectangular but may be gently curved if necessary or if desired for aesthetic reasons (Fig. 11). A single inlet and outlet are usually sufficient, and these should be located in diagonally opposite corners of the pond. The use of complicated multi-inlet and multi-outlet designs is unnecessary and not recommended.

To facilitate wind-induced mixing, the pond should be located so that its longest dimension (diagonal) lies in the direction of the prevailing wind. If this is seasonally variable, the summer wind direction should be used as this is when thermal stratification is potentially maximal. To minimize hydraulic short-circuiting, the inlet should be located such that the wastewater flows in the pond against the wind.

The areas calculated by the design procedure described in section 3 are mid-depth areas, and the dimensions calculated from them are thus mid-depth dimensions. These need to be corrected for the slope of the embankment, as shown in Fig. 12. The dimensions and levels that the contractor needs to know are those of the base and the top of the embankment; the latter includes the effect of the freeboard.

The minimum freeboard that should be provided is decided on the basis of preventing waves, induced by the wind, from overtopping the embankment. For small ponds (under 1 ha in area) 0.5 m freeboard should be provided; for ponds between 1 ha and 3 ha, the freeboard should be 0.5-1 m, depending on site considerations. For larger ponds, the freeboard may be calculated from the equation (37):

Fig. 11. Waste stabilization ponds with high length-to-breadth ratios at Mèze, southern France

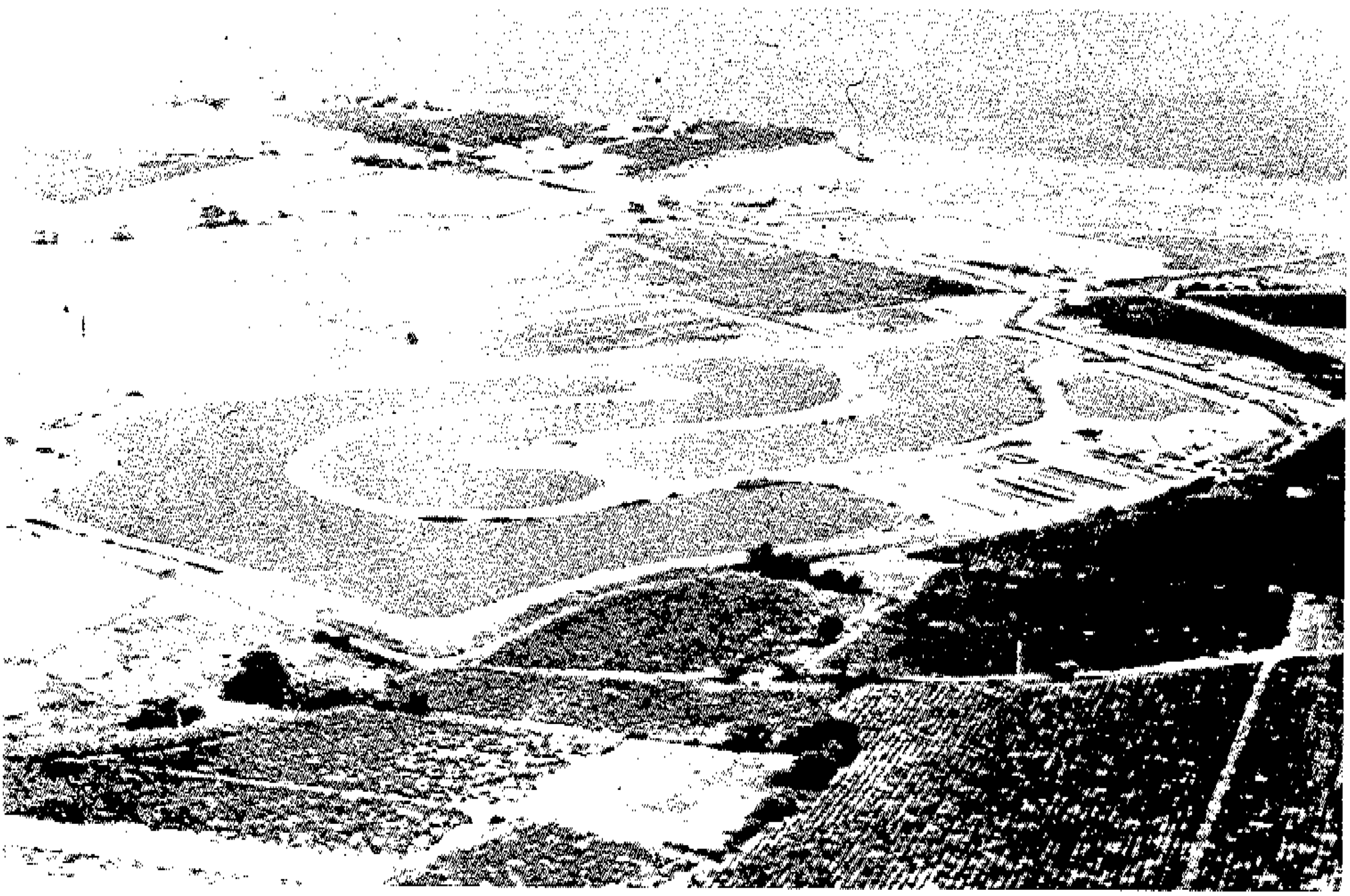
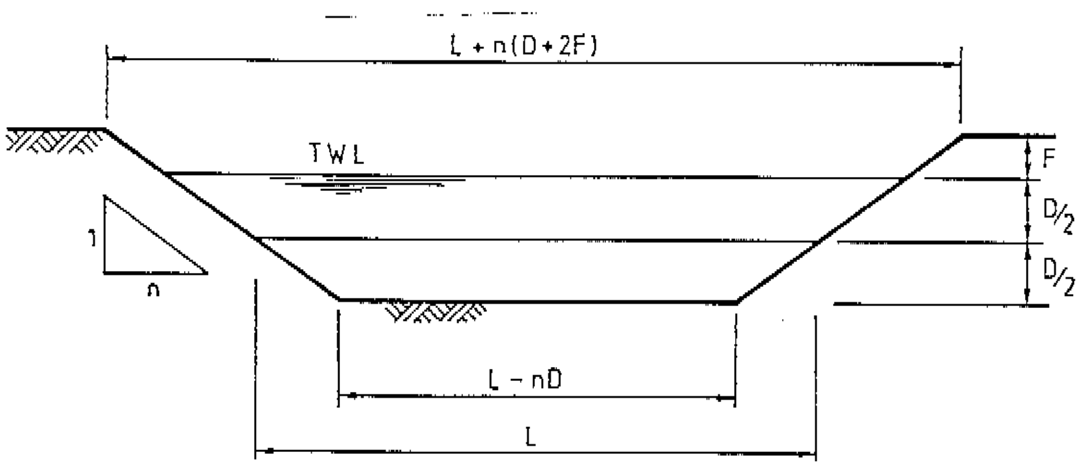


Fig. 12. Calculation of dimensions of pond base and embankment top from those derived from the mid-depth area



$$F = (\log A)^{1/2} - 1 \qquad [22]$$

where: F = freeboard, m
A = pond area, m^2

Pond liquid depths are commonly in the following ranges:

- anaerobic ponds, 2-5 m;
- facultative ponds, 1-2 m;
- maturation ponds, 1-1.5 m.

The depth chosen for any particular pond depends on site considerations (presence of shallow rock, minimization of earthworks). In primary facultative ponds, especially those with high length-to-breadth ratios, it is often advantageous to provide a deeper zone (2-5 m) near the inlet for sludge settlement and digestion. This is especially useful in coastal areas for small pond systems treating wastewater with a high grit load when no grit removal facilities are included.

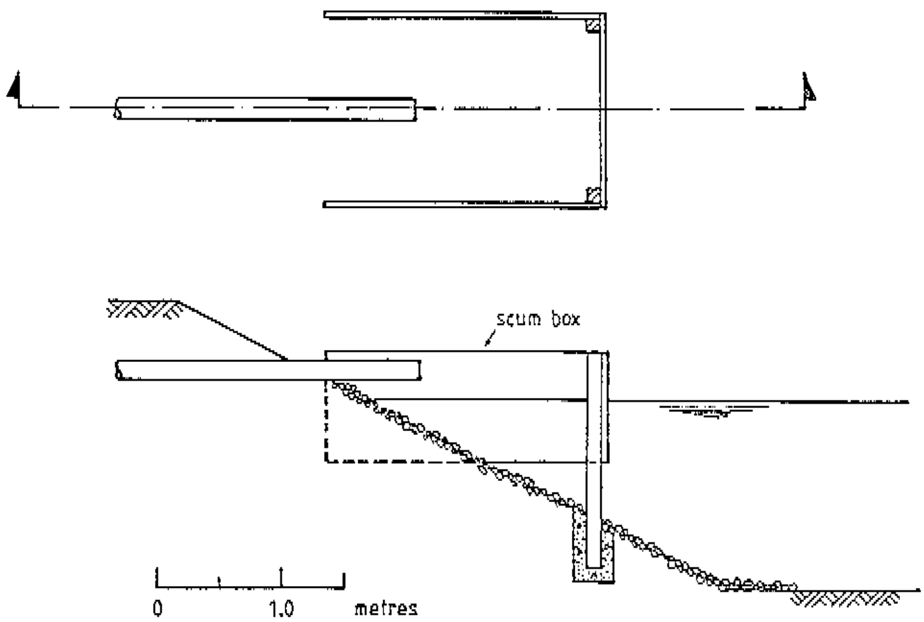
At pond systems serving more than 10 000 people, it is often sensible (so as to increase operational flexibility) to have two or more series of ponds in parallel. The available site topography may in any case necessitate such a subdivision, even for smaller pond systems. Usually the series are equal, that is to say they receive the same flow, and arrangements for splitting the raw wastewater flow into equal parts after preliminary treatment must be made. This is best done by providing penstock-controlled flumes ahead of each series.

4.6 Inlet and outlet structures

There is a wide variety of designs for inlet and outlet structures, and provided they follow certain basic concepts their precise design is relatively unimportant. Firstly, they should be simple and inexpensive; while this should be self-evident, it is all too common to see unnecessarily complex and expensive structures. Secondly, they should permit samples of the pond effluent to be taken with ease. The inlet to anaerobic and primary facultative ponds should discharge below the liquid level so as to minimize short-circuiting (especially in deep anaerobic ponds) and reduce the quantity of scum (which is important in facultative ponds). Inlets to secondary facultative and maturation ponds can discharge either above or below the liquid level, although discharge at mid-depth is preferable as it reduces the possibility of short-circuiting. Some simple inlet designs are shown in Fig. 13 and 14. For small pond systems provided with a 50 mm screen (see section 4.4), the simple "scum box" shown in Fig. 13 should be used.

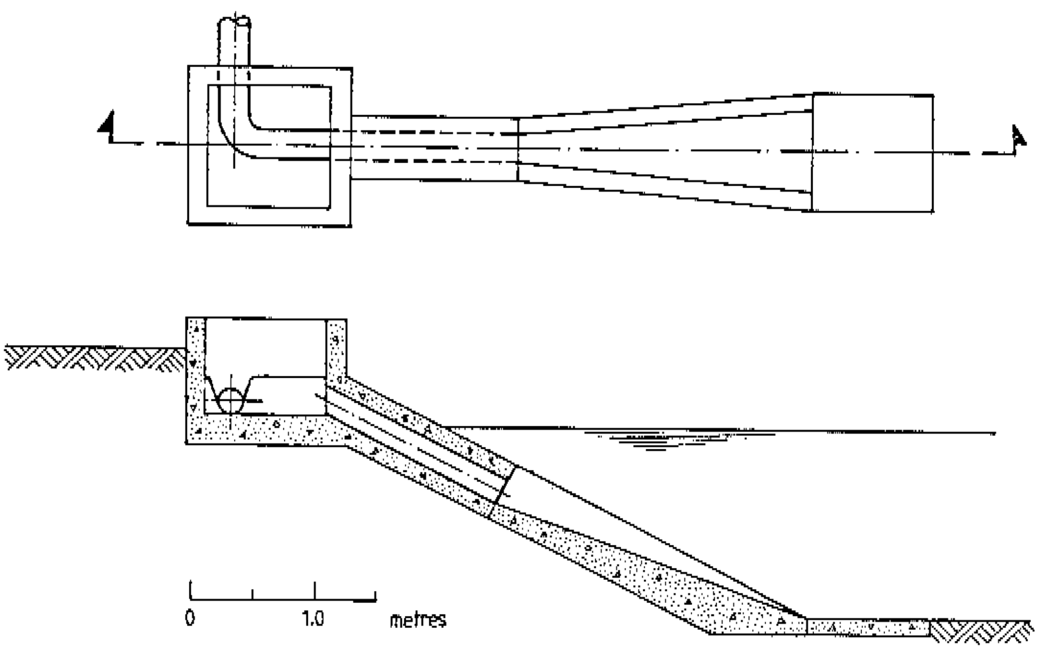
The outlet of all ponds should be protected against the discharge of scum by the provision of a scum guard. The take-off level for the effluent, which is controlled by the scum guard depth, is important as it can have a significant influence on effluent quality. In facultative ponds, the scum guard should extend just below the maximum depth of the algal band when the pond is stratified so as to minimize the quantity of algae, and hence BOD, leaving the pond. In anaerobic and maturation ponds, where algal banding is irrelevant, the take-off should be nearer the surface: in anaerobic ponds it should be well above the maximum depth of sludge but below any surface crust, and in maturation ponds it should be at the level that gives the best possible microbiological quality. The following effluent take-off levels are recommended:

Fig. 13. Inlet structure for anaerobic and primary facultative ponds



Source: Agence de Bassin Loire-Bretagne and Centre technique du genie rural, des eaux et fôrets (19).

Fig. 14. Inlet structure for secondary facultative and maturation ponds



Source: Mara, D.D. (27).

- anaerobic ponds, 30 cm;
- facultative ponds, 60 cm;
- maturation ponds, 5 cm.

The installation of a variable height scum guard is recommended, since it permits the optimal take-off level to be set once the pond is operating.

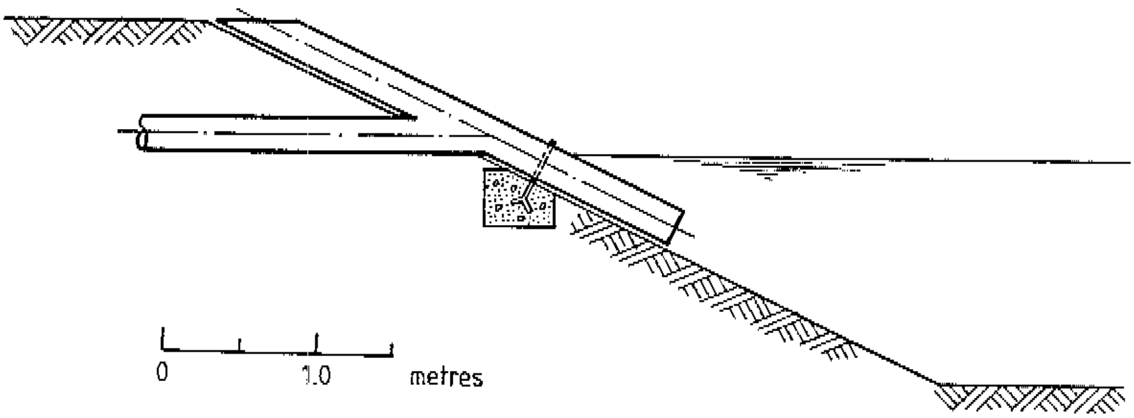
Some simple designs for outlet structures are shown in Fig. 15 and 16. If a weir is used in the outlet structure, the following formula should be used to determine the head over the weir and so, knowing the pond depth, calculate the weir's required height:

$$q = 0.0567\ h^{3/2}$$

where: q = flow per metre length of weir, l/s
h = head of water above weir, mm

The weir need not necessarily be strictly linear. Often a U-shaped structure is more economical, especially at high flow rates.

Fig. 15. Pond outlet structure

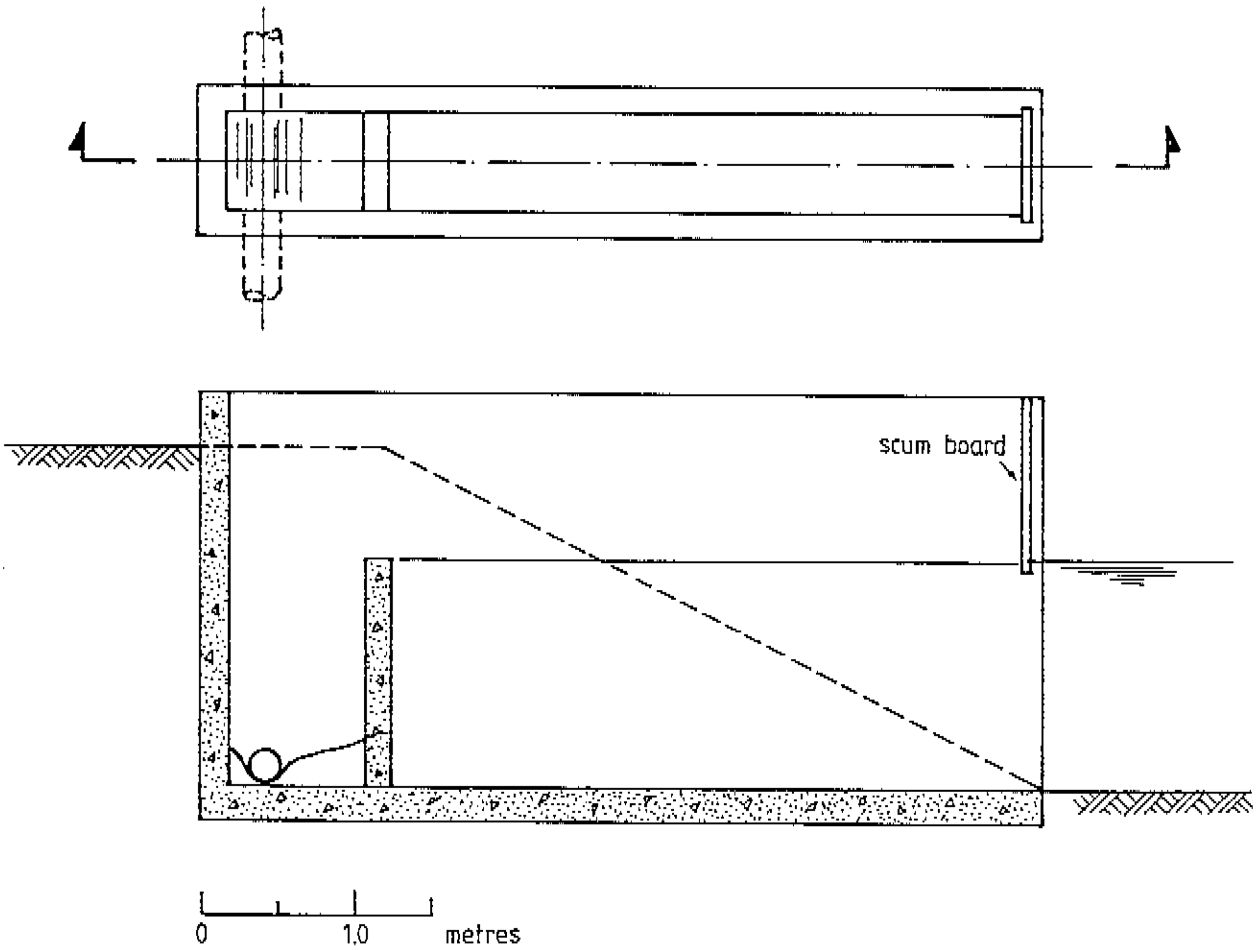


Source: Agence de Bassin Loire-Bretagne and Centre technique du génie rural, des eaux et forêts (19).

The outlet from the final pond in a series should discharge into a simple flow-measuring device such as a triangular or rectangular notch. Since the flow into the first pond is also measured, this permits the rate of evaporation and seepage to be calculated or, if evaporation is measured separately, the rate of seepage.

It is often advantageous, especially at large pond systems, to be able to by-pass anaerobic or primary facultative ponds to facilitate maintenance, particularly desludging. This results in a temporary overload on the secondary facultative or first maturation pond, but this is not usually too serious if it is restricted to the time of year when there is some spare capacity, e.g. in summer for ponds designed for winter conditions or in late spring for ponds designed for summer conditions. The pond layout should be such that the length of by-pass pipework is as short as possible.

Fig. 16. Outlet weir structure



Source: Mara, D.D. (27)

4.7 Security

Ponds (other than very remote installations) should be surrounded by a chain-link fence and gates should be kept padlocked. Warning notices, in several languages in tourist areas, attached to the fence and advising that the ponds are a wastewater treatment facility, and therefore potentially hazardous to health, are essential to discourage people visiting the ponds, which if properly maintained (see section 5) should appear as pleasant, inviting bodies of water. Children are especially at risk, as they may be tempted to swim in the ponds. Birdwatchers and hunters are also attracted to ponds by the often rich variety of wildlife, and they may not be aware that the ponds are treating wastewaters.

4.8 Operator facilities

The facilities to be provided for the team of pond operators depend partly on their number (see section 5.3), but would normally include the following:

- first-aid kit;
- strategically placed lifebuoys;
- wash-basin and toilet;
- storage space for protective clothing, grass-cutting and scum-removal equipment, screen rake and other tools, sampling boat (if provided) and life-jackets.

With the exception of the lifebuoys, these can be accommodated in a simple, e.g. wooden, building. This can also house, if required, sample bottles and a refrigerator for sample storage. For small systems, such facilities are generally unnecessary, but they should be available in the service vehicle. Simple laboratory facilities and a telephone may be provided at larger installations. Adequate space for car parking is also required.

5. Operation and maintenance

5.1 Start-up procedures

Pond systems should be commissioned in Mediterranean Europe in late spring or summer so as to establish as quickly as possible the necessary microbial populations to effect waste stabilization. Prior to commissioning, all ponds must be free from vegetation. Anaerobic ponds should be filled with raw sewage and seeded with digesting sludge from, for example, an anaerobic digester at a conventional sewage treatment works or with seepage from local septic tanks. The ponds should then be gradually loaded up to the design loading rate over the following week (or month if the ponds are not seeded). Care should be taken to maintain the pond pH above 7 to permit the development of methanogenic bacteria, and it may be necessary during the first month or so to dose the pond with lime or soda ash. If due to an initially low rate of sewer connections in newly sewered towns the sewage is weak or its flow low, it is best to by-pass the anaerobic pond until the sewage strength and flow is such that a loading of at least 100 g per m^3 per day can be applied to it.

It is preferable to fill facultative and maturation ponds with freshwater (from a river, lake or well; mains water is not necessary) so as to permit the gradual development of the algal and heterotrophic bacterial populations. Primary facultative ponds may advantageously be seeded in the same way as anaerobic ponds. If freshwater is unavailable, primary facultative ponds should be filled with raw sewage and left for three to four weeks to allow the microbial population to develop; some odour release is inevitable during the period.

5.2 Routine maintenance

The maintenance requirements of ponds are very simple, but they must be carried out regularly. Otherwise, there will be serious odour, fly and mosquito nuisance. Maintenance requirements and responsibilities must therefore be clearly defined at the design stage so as to avoid problems later. Routine maintenance tasks are as follows:

- removal of screenings and grit from the preliminary works;

- cutting the grass on the embankments and removing it so that it does not fall into the pond (this is necessary to prevent the formation of mosquito-breeding habitats; the use of slow-growing grasses minimizes this task - see section 4.2);

- removal of floating scum and floating macrophytes, e.g. Lemna, from the surface of facultative and maturation ponds (this is required to maximize photosynthesis and surface re-aeration and obviate fly breeding);

- spraying the scum on anaerobic ponds (which should not be removed as it aids the treatment process), as necessary, with clean water or pond effluent to prevent fly breeding;

- removal of any accumulated solids in the inlets and outlets;

- repair of any damage to the embankments caused by rodents, rabbits or other animals;

- repair of any damage to external fences and gates.

The operators must be given precise instructions on the frequency at which these tasks should be done, and their work must be regularly inspected. In this regard, it is very helpful if the operators are provided with a local pond maintenance manual, examples of which are those produced by the Centre national du Machinisme agricole, du génie rural, des eaux et des forêts (38) for France and Marecos do Monte (39) for Portugal. The operators should be required to complete at weekly, or at least fortnightly, intervals a pond maintenance record sheet, an example of which is given in Fig. 17. The operators may also be required to take samples and some routine measurements (see section 6).

Anaerobic ponds require desludging when they are half full of sludge. This occurs every n years:

$$n = V_a/2Ps$$

where: V_a = volume of anaerobic pond, m^3
P = population served
s = sludge accumulation rate, m^3/person/year

Very few sludge accumulation data for Mediterranean Europe exist. A suitable design value is probably around 0.1 m^3 per person per year. Thus, at a design loading of 100 g BOD per m^3 per day and assuming a BOD contribution of 50 g per person per day, desludging would be required every 2.5 years. In Bavaria, anaerobic ponds are desludged every one to three years by local farmers (using their own equipment) who spread the sludge on to ploughed fields (not pasture) in the autumn. In this case, the ponds are desludged long before the level of sludge accumulation would make its removal an operational necessity. In France, the rate of sludge accumulation in primary facultative ponds is some 2-2.5 cm per year (Demillac et al., personal communication, 1986), and desludging is required approximately every ten years.

Sludge removal can be readily achieved by using a raft-mounted sludge pump, which discharges into either an adjacent sludge lagoon or tankers that transport it to a landfill site, central sludge treatment facility or other suitable disposal location. Although the microbiological quality of pond

Fig. 17. Example of routine maintenance record sheet, to be completed by pond operators

POND MAINTENANCE RECORD SHEET

Pond location: ....

Date and Time: .... Air temperature: .... °C

Weather conditions: ....

Pumping station (if there is one):

- elapsed time meter reading: No. 1 .... No. 2 ....
- electricity meter reading: ....
- observations: (flooding) ....

....

Access road: state (vegetation, damage); maintenance carried out ....
....
....

Pond site: state; maintenance carried out ....
....
....

Pretreatment works: state; maintenance carried out
- screen (s): ....
- other (grit, grease removal): ....

VISUAL INSPECTION OF PONDS

POND NUMBER	1	2	3	OBSERVATIONS
Colour of water (green, brown/grey, pink/red, milky/clear)				
Odour				
Scum, foam				
Floating macrophytes				
Rooted macrophytes				
State of embankments (erosion, rodent damage, vegetation)				
Inlet and outlet (blockage)				
Water level (high, normal, low)				

GENERAL OBSERVATIONS, other maintenance carried out: ....
....

Source: Centre national du Machinisme agricole, du génie rural, des eaux et des forêts (38).

sludge is better than that from conventional sewage treatment works and its toxic chemical composition no worse, its disposal must still be carried out in accordance with the relevant local or regional regulations governing sludge disposal (40).

5.3 Operator requirements

The number of operational staff required for pond systems is a matter for local decision, but is small in comparison with conventional sewage treatment works and depends on the size of the system, the type of preliminary treatment (manually or mechanically operated), and the local cost and quality of labour. In general, for systems serving up to 10 000 people, a full-time operator is not required, and a part-time operator working for around two to ten hours per week is normally sufficient provided that grass cutting, embankment repairs and other major maintenance work are done by a visiting service crew. For larger pond systems, a full-time operator is required. As a rough guide, one operator is required for every 10 000 people served, although local circumstances may suggest a greater or smaller number.

6. Monitoring and evaluation

Once a waste stabilization pond system has been commissioned, a routine monitoring and evaluation programme should be established so that its real, as opposed to design, performance can be determined and the quality of its effluent known.

Routine monitoring of the final effluent quality of a pond system permits a regular assessment to be made of whether the effluent is complying with the local discharge or reuse standards, and this information may be required by the local regulatory river or health authority. Moreover, should a pond system suddenly fail or its effluent start to deteriorate, the results of such a monitoring programme often give some insight into the cause of the problem and may indicate what remedial action is required.

The evaluation of pond performance and behaviour, although a much more complex procedure than the routine monitoring of effluent quality, is none the less extremely useful as it provides information on how underloaded or overloaded the system is, and thus by how much, if any, the loading on the system can be safely increased as the community it serves expands, or whether further ponds (either in parallel or in series) are required. It also indicates how the design of future pond installations in the region might be improved to take account of local conditions.

6.1 Effluent quality monitoring

Effluent quality monitoring programmes should be simple, but should none the less provide reliable data. Two levels of effluent monitoring are recommended (reference should also be made to the routine pond maintenance record sheets completed by the pond operators - see section 5.2 and Fig. 17):

- level 1: representative samples of the final effluent should be taken at least monthly, although for small installations quarterly samples usually suffice; these samples should be analysed in a local or regional laboratory for those parameters for which effluent discharge or reuse standards exist;

- level 2: when level 1 assessment shows that a pond effluent is failing to meet its required discharge or reuse quality, a more detailed study is necessary before any alteration to the pond system is attempted; Table 3 gives a list of parameters whose values are required, together with directions on how they should be obtained.

Table 3. Parameters to be determined in a "level 2" effluent quality monitoring programme

Parameter	Type of sample[a]	Remarks
Flow	–	Measure both raw wastewater and final effluent flows
BOD_5	C	Unfiltered samples[b]
COD	C	Unfiltered samples[b]
Suspended solids	C	
Ammonia	C	
Faecal coliforms	G	Take sample between 0800 and 1000 h
pH	G)	Take two samples, one at 0800-1000 h and the other at 1400-1600 h
Temperature	G)	
Total nitrogen	C)	Only when effluent being used (or being assessed for use) for crop irrigation. Ca, Mg and Na are required for SAR
Total phosphorus	C)	
Chloride	C)	
Electrical conductivity	C)	
Ca, Mg, Na	C)	
Boron	C)	
Geohelminths[c]	C)	

[a] C = 24-hour flow-weighted composite sample; G = grab sample.

[b] Also on filtered samples if the discharge standards are so expressed.

[c] *Ascaris lumbricoides*, *Trichuris trichiura*, *Ancylostoma duodenale* and *Necator americanus*.

Since pond effluent quality shows a significant diurnal variation (although this is less pronounced in maturation ponds than in facultative ponds), 24-hour flow-weighted composite samples are preferable for most parameters, although grab samples are necessary for some (pH, temperature and faecal coliforms). Composite samples should be collected in one of the following ways:

- in an automatic sampler, which takes grab samples every one to two hours, with subsequent manual flow weighting if this is not done automatically by the sampler;

- by taking grab samples every one to three hours (depending on labour availability), with subsequent manual flow weighting.

If neither of these options is feasible, grab samples should be taken every two to three hours for as long a part of the day as possible and manually flow weighted. The subsamples used to make the composite sample should be properly preserved after collection. Usually storage below 4 °C for a maximum of 30 hours is sufficient (if a nonrefrigerated automatic sampler is used, the sample bottle container section should be packed with ice during warm weather). If feasible, similar samples may be taken of the raw wastewater so that percentage reductions of the parameters may be determined and an estimate of the performance of the pond system obtained.

6.2 Evaluation of pond performance

The evaluation of the performance and behaviour of a series of ponds is a time-consuming and expensive process, and it requires experienced personnel to interpret the data obtained. It is in many ways akin to research, but it is the only means by which pond design can be adapted to local conditions. It is often therefore a highly cost-effective exercise. The recommendations given below constitute a level 3 monitoring programme, and they are based on the guidelines for the minimum evaluation of pond performance given in Pearson et al. (41) which should be consulted for further details.

It is not intended that all pond installations be studied in this way, but only one or two representative systems in each major climatic region of a country. This level of investigation is most likely to be beyond the capabilities of local organizations, and it would need to be carried out by a regional or national body, or by a university under contract to such a body. This type of study is also required when it is essential to know how much additional loading a particular system can receive before it is necessary to extend it.

Samples should be taken and analysed on at least five days over a five-week period at both the hottest and coldest times of the year. Samples are required of the raw wastewater and of the effluent of each pond in the series and, so as to take into account most of the weekly variation in influent and effluent quality, samples should be collected on Monday in the first week, Tuesday in the second week and so on (local factors, such as a high influx of visitors at weekends, may influence the choice of days on which samples are collected). Table 4 lists the parameters whose values are required.

Composite samples, collected as described in section 6.1, are necessary for most parameters; grab samples are required for pH and faecal coliforms; and samples of the entire pond water column should be taken for algological analyses (chlorophyll a and algal genera determination), using the pond column sampler shown in Fig. 18 and 19. Pond column samples should be taken from a boat or from a simple sampling platform (Fig. 20). Data on at least maximum and minimum air temperatures, rainfall and evaporation should be obtained from the nearest meteorological station.

Table 4. Parameters to be determined for minimum evaluation of pond performance

Parameter	To be determined for[a]	Type of sample[b]	Remarks
Flow	RW, Fe	-	
BOD_5	RW, all pond effluents[c]	C	Unfiltered and filtered samples
COD	RW, all pond effluents	C	Unfiltered and filtered samples
Suspended solids	RW, all pond effluents[c]	C	
Faecal coliforms	RW, all pond effluents	G	
Chlorophyll a	All F and M pond contents	P	
Algal genera	All F and M pond contents	P	
Ammonia	RW, all pond effluents[c]	C	
Nitrate	RW, FE	C	
Total phosphorus	RW, FE	C	
Sulfide	RW, A pond effluents, F pond contents or depth profile	G,P	Only if odour nuisance present or facultative pond effluent quality poor. A depth profile is preferable
pH	RW, all pond effluents	G	
Temperature (mean daily)	RW, all pond effluents	-	Use maximum-minimum thermometers suspended in RW flow and at mid-depth in ponds
Dissolved oxygen[d]	Depth profile in all F and M ponds	-	Measure at 0800, 1200 and 1600 h on at least three occasions
Sludge depth	A and F ponds	-	Use "white towel" test (42)
Electrical conductivity	FE	C)	Only if effluent used or to be used for crop irrigation. Ca, Mg and Na required for SAR
Chloride	RW, FE	C)	
Ca, Mg and Na	FE	C)	
Boron	FE	C)	
Geohelminths[e]	RW, all pond effluents	C)	

[a] RW = raw wastewater; FE = final effluent of pond series; A = anaerobic; F = facultative; M = maturation.

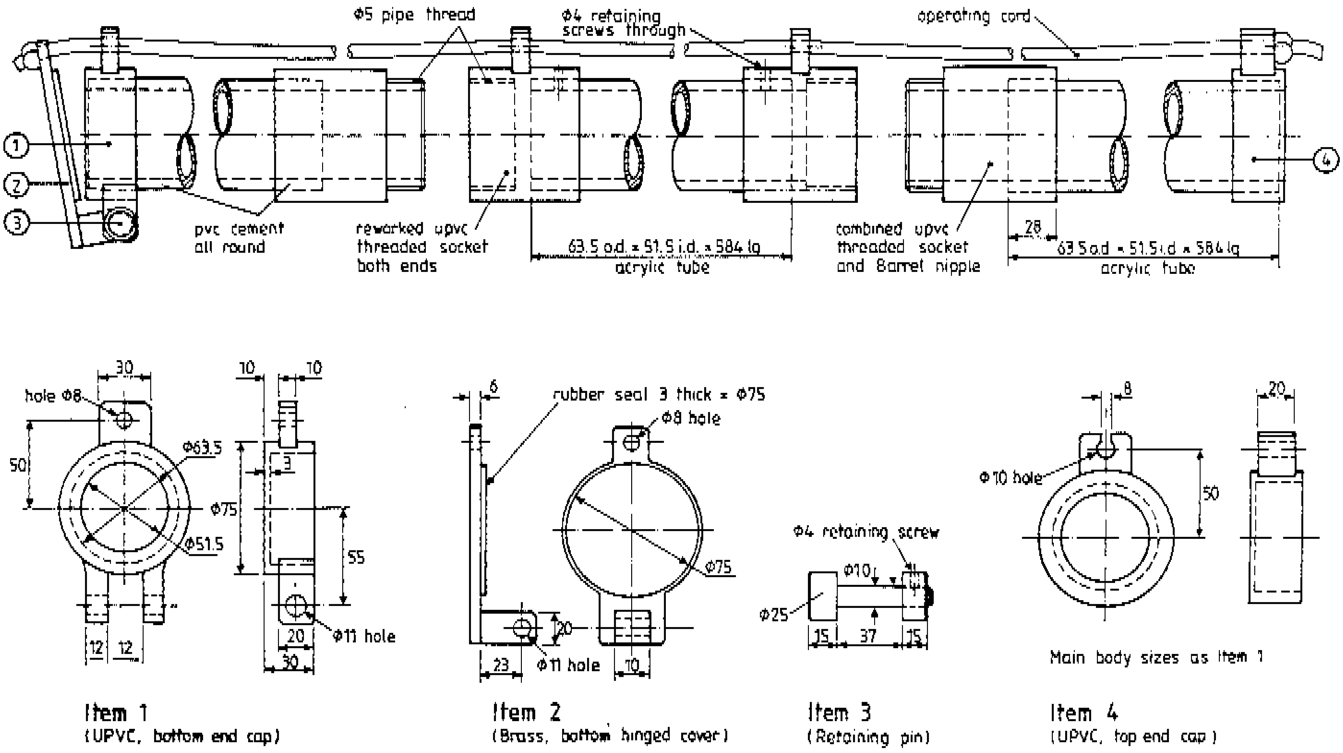
[b] C = 24-hour flow-weighted composite sample; G = grab sample taken when pond contents most homogeneous; P = pond column sample.

[c] Alternatively RW, A, F and final M pond effluents only, if more than two maturation ponds.

[d] Measure depth profiles of pH and temperature at same times, if possible.

[e] Ascaris lumbricoides, Trichuris trichiura, Ancylostoma duodenale and Necator americanus.

Fig. 18. Details of pond column sampler



Note: The overall length of the sampler (here 1.7 m) may be increased as necessary, and its diameter (here 50 mm) may be altered to 75 mm if required. The design shown here is a three-piece sampler for ease of transportation, but this feature may be omitted. Alternative materials may be used.

On each day that samples are taken, the mean mid-depth temperature of each pond, which closely approximates the mean daily pond temperature, should be determined by suspending a maximum-and-minimum thermometer at mid-depth of the pond at 0800-0900 h and reading it 24 hours later.

On one day during each sampling period, the depth of sludge in the anaerobic (if any) and facultative ponds should be determined, using the "white towel" test of Malan (42). White towelling material is wrapped along one third of a sufficiently long pole, which is then lowered vertically into the pond until it reaches the pond bottom; it is then slowly withdrawn. The depth of the sludge layer is clearly visible, since some sludge particles will have been entrapped in the towelling material (Fig. 21). The sludge depth should be measured at five points in the pond, away from the embankment base, and the mean depth calculated.

It is also useful to measure on at least three occasions during each sampling season the diurnal variation in the vertical distribution of pH, dissolved oxygen and temperature. Profiles should be obtained at 0800, 1200 and 1600 h. If submersible electrodes are not available, samples should be taken manually every 20 cm.

Fig. 19. A pond column sampler in use on a facultative pond

7. Reuse of pond effluents

The effluent from a properly designed and well maintained series of ponds is normally very suitable for reuse for crop irrigation and for watering sports fields and golf courses. Provided that it meets the microbiological quality criteria given in Table 5, which are based on an epidemiological appraisal of the actual health risks resulting from the agricultural reuse of raw and treated wastewater (43,44), there will be no risk to public health. Pond systems are readily designed (see section 3.6) to produce an effluent with less than the recommended maximum concentration of faecal coliforms for unrestricted irrigation (1000 per 100 ml), and recent research has shown that a three-pond system with an overall hydraulic retention time of at least 11 days is able to produce an effluent free from intestinal meatode eggs (6).

Fig. 20. A simple pond sampling platform

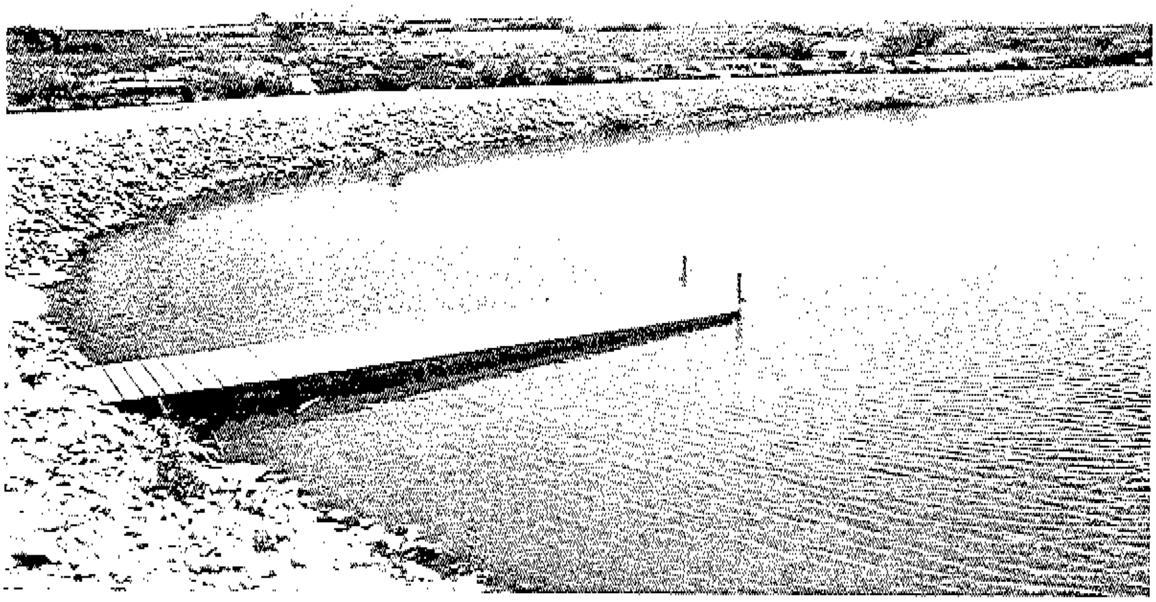


Fig. 21. Determination of the sludge depth by the "white towel" test

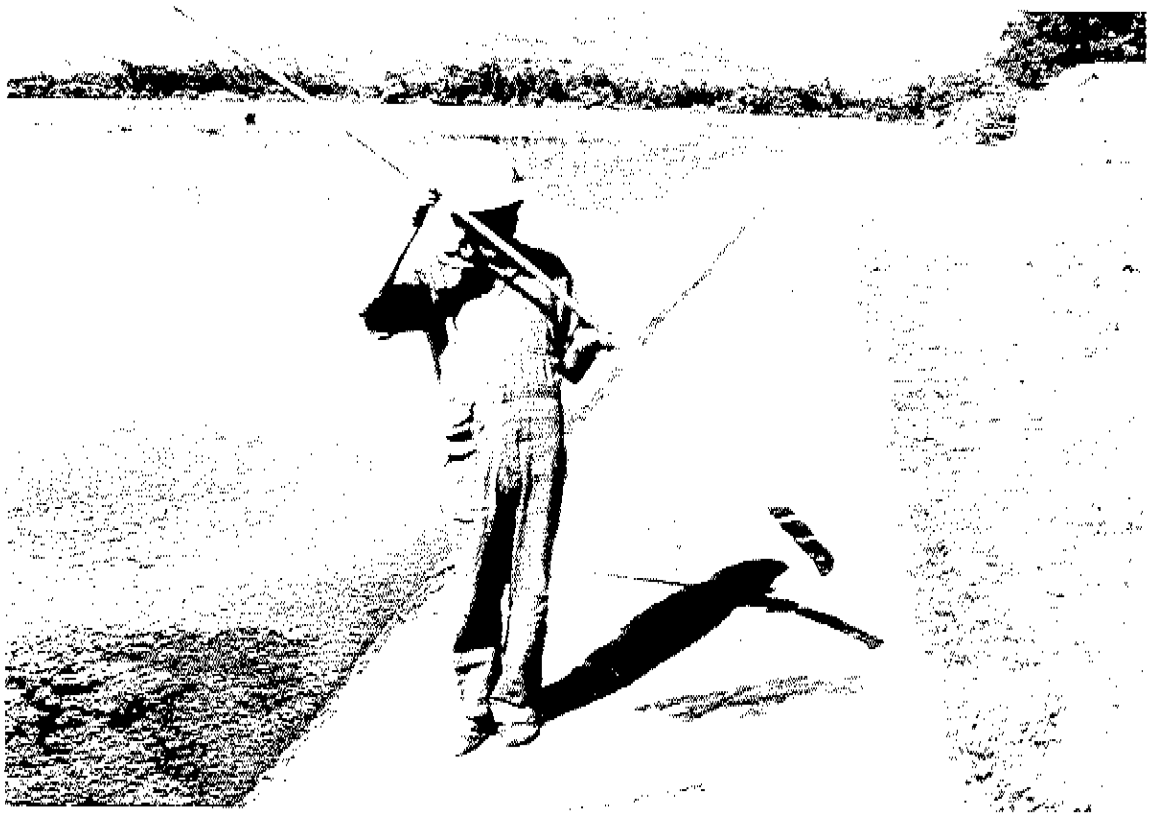


Table 5. Microbiological quality guidelines for agricultural and municipal reuse of treated wastewater[a]

Reuse process	Intestinal nematodes[b] (arithmetic mean number of eggs per litre)	Faecal coliform bacteria (geometric mean number per 100 ml)
Restricted irrigation		
Irrigation of trees, industrial crops, fruit trees[c] and pasture[d]	≤ 1	$\leq 100\ 000$
Unrestricted irrigation		
Irrigation of edible crops, sports fields	≤ 1	$\leq 1\ 000$
Public parks, lawns	≤ 1	≤ 100

[a] Adapted from IRCWD (43).

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

[c] Irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground.

[d] Irrigation should cease two weeks before animals are allowed to graze.

The physicochemical quality of pond effluents, especially with regard to their electrical conductivity and sodium absorption ratio, is normally within the recommended limits for irrigation waters (45), and it is only if the ponds are treating a significant proportion of industrial wastewater that is necessary to check this and also to ensure that the final effluent does not contain harmful concentrations of phytotoxins, especially boron and heavy metals. Algal removal is not necessary (in the soil, algae act as slow release fertilizers), except when trickle irrigation is practised as they may exacerbate problems of emitter clogging.

7.1 Effluent storage reservoirs

Pond effluent can be advantageously stored in deep reservoirs during winter when it is not required for irrigation (44). In Israel, where this practice was developed, these storage reservoirs are 6-15 m deep and the effluent, which is used primarily for the irrigation of cotton and fodder crops, is stored for four to six months. A more recent development is the use of these reservoirs for the treatment of raw wastewater: this works satisfactorily if the surface loading rate is restricted to 60 kg BOD_5 per ha per day, and if the maximum draw-off level is at least 80 cm above the reservoir base (25).

REFERENCES

1. Gloyna, E.F. Waste stabilization ponds. Geneva, World Health Organization, 1971.
2. Hawkes, H.A. Stabilization ponds. In: Curds, C.R. & Hawkes, H.A., ed. Ecological aspects of used water treatment. Volume 2. Biological activities and treatment processes. London, Academic Press, 1983, pp. 163–217.
3. Mara, D.D. & Pearson, H.W. Artificial freshwater environments: waste stabilization ponds. In: Schoenborn, W., ed. Biotechnology. Weinheim, VCH Verlagsgesellschaft, 1986, Vol. 8, pp. 117-206.
4. Meiring, P.G. et al. A guide to the use of pond systems in South Africa for the purification of raw and partially treated sewage. Pretoria, National Institute for Water Research, 1968 (CSIR Special Report WAT 34).
5. Marais, G.v.R. Dynamic behaviour of oxidation ponds. In: McKinney, R.E., ed. Proceedings of the Second International Symposium on Waste Treatment Lagoons. Laurence, KS, University of Kansas, 1970, pp. 15–46.
6. Mara, D.D. & Silva, S.A. Removal of intestinal nematode eggs in tropical waste stabilization ponds. Journal of tropical medicine and hygiene, 89: 71-74 (1986).
7. Ferrara, R.A. & Avci, C.B. Nitrogen dynamics in waste stabilization ponds. Journal of the Water Pollution Control Federation, 54: 361–369 (1982).
8. Pano, A. & Middlebrooks, E.J. Ammonia nitrogen removal in facultative wastewater stabilization ponds. Journal of the Water Pollution Control Federation, 54(4): 344-351 (1982).
9. Reed, S.C. Nitrogen removal in wastewater stabilization ponds. Journal of the Water Pollution Control Federation, 57(1): 39–45 (1985).
10. Houng, H.J.S. & Gloyna, E.F. Phosphorus models for waste stabilization ponds. Journal of the Environmental Engineering Division, American Society of Civil Engineers, 110: 550–561 (1984).
11. Moshe, M. et al. Effect of industrial wastes on oxidation pond performance. Water research, 6: 1165–1171 (1972).
12. Abeliovich, A. & Azov, Y. Toxicity of ammonia to algae in sewage oxidation ponds. Applied and environmental microbiology, 31: 801–806 (1976).
13. Pearson, H.W. & Howsley, R. Concomitant photoautotrophic growth and nitrogenase activity by cyanobacterium Plectonema boryanum in continuous culture. Nature, 288: 263–265 (1980).
14. Pfeffer, J.T. Anaerobic lagoons: theoretical considerations. In: McKinney, R.E., ed. Proceedings of the Second International Symposium on Waste Treatment Lagoons. Laurence, KS, University of Kansas, 1970, pp. 310–320.
15. Boutin, P. & Racault, Y. Le lagunage naturel: situation actuelle d'une technique d'épuration en France. Techniques et sciences municipales eau, 6: 273–284 (1986).
16. Boutin, P. Le lagunage naturel en France: compléments d'information sur la situation actuelle. Bordeaux, Centre national du machinisme agricole, du génie rural, des eaux et des forêts, 1986.
17. Ringuelet, R. Un bel exemple d'épuration des eaux domestiques poussé jusqu'à la décontamination fécale avec des méthodes naturelles douces et rustiques: le bassin versant de l'étang de Salces-Leucate. Techniques et sciences municipales eau, 4: 187-201 (1983).
18. Drakides, M. & Calignon, M. Lagunes à charge estivale. Pierre-Bénite, Agence de Bassin Rhône-Méditerranée-Corse, 1983.

19. Lagunage naturel et lagunage aéré: procédés d'épuration des petites collectivités. Orléans, Agence de Bassin Loire-Bretagne et Centre technique du génie rural, des eaux et forêts, 1979.
20. Gambrill, M.P. et al. Microcomputer-aided design of waste stabilization ponds in tourist areas of Mediterranean Europe. Public health engineer, 14(2): 39-41 (1986).
21. Council of the European Communities. On the quality required of shell-fish waters (79/923/EEC). Official journal of the European Communities, L281: 47-52 (1979).
22. Cosser, P.R. Lagoon algae and the BOD test. Effluent and water treatment journal, 22: 357-361 (1982).
23. Conditions de détermination de la qualité minimale d'un rejet d'effluents urbain (circulaire interministérielle). Journal officiel de la République Française (1980) (N.C. 10395).
24. Bucksteeg, K. Expérience des étangs de stabilisation non aérés en Bavarie: domaine d'utilisation, dimensionnement, traitement des eaux usées diluées, construction. La tribune du Cebedeau, 36(481): 533-540 (1983).
25. Zohar, Y. Wastewater treatment by stabilization ponds in Israel. Jerusalem, Ministry of Health, 1986 (Progress Report, No. 1).
26. McGarry, M.G. & Pescod, M.B. Stabilization pond design criteria for tropical Asia. In: McKinney, R.E., ed. Proceedings of the Second International Symposium for Waste Treatment Lagoons, Laurence, KS, University of Kansas, 1970, pp. 114-132.
27. Mara, D.D. Sewage treatment in hot climates. Chichester, John Wiley, 1976.
28. Arthur, J.P. Notes on the design and operation of waste stabilization ponds in warm climates of developing countries. Washington, DC, World Bank, 1983 (Technical Paper, No. 7).
29. Mara, D.D. & Silva, S.A. Sewage treatment in waste stabilization ponds: recent research in northeast Brazil. Progress in water technology, 11(1/2): 341-344 (1979).
30. Arthur, J.P. The development of design equations for facultative waste stabilization ponds in semi-arid areas. Proceedings of the Institution of Civil Engineers (Part 2), 71: 197-213 (1981).
31. Marais, G.v.R. & Shaw, V.A. A rational theory for the design of sewage stabilization ponds in central and south Africa. Transactions of the South African Institution of Civil Engineers, 3: 205-227 (1961).
32. Mara, D.D. & Feachem, R.G. A reappraisal of the role of faecal indicator organisms in tropical waste treatment processes. Public health engineer, 7(1): 31-33 (1979).
33. Feachem, R.G. et al. Sanitation and disease: health aspects of excreta and wastewater management. Chichester, John Wiley, 1983.
34. Demillac, R. & Baron, D. Inactivation comparée des virus hydriques et des bactéries indicatrices de contamination fécale en bassins de lagunage. Rennes, Ecole nationale de la santé publique, 1982.
35. Marais, G.v.R. Faecal bacterial kinetics in waste stabilization ponds. Journal of the Environmental Engineering Division, American Society of Civil Engineers, 100(EE1): 119-139 (1974).
36. Ellis, K.V. Stabilization ponds: design and operation. Critical reviews in environmental control, 13(2): 69-102 (1983).
37. Oswald, W.J. Waste pond fundamentals. Washington, DC, World Bank, 1975 (unpublished document).
38. L'exploitation des lagunages naturels. Lyon, Centre national du machinisme agricole du génie rural, des eaux et des forêts, 1985 (Documentation technique FNDAE, No. 1).

39. Marecos do Monte, M.H. Manual de operacao e manutençao de sistemas de lagunagem. Lisbon, Laboratório nacional de engenharia civil, 1987.

40. Council of the European Communities. On the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (86/278/EEC). Official journal of the European Communities, L181: 6-12 (1986) (L181 (86.7.4)).

41. Pearson, H.W. et al. Guidelines for the minimum evaluation of the performance of full-scale waste stabilization pond systems. Water research, 1987 (in press).

42. Malan, W.M. A guide to the use of septic tanks systems in South Africa. Pretoria, National Institute for Water Research, 1964 (CSIR Research Report, No. 219).

43. IRCWD. Health aspects of wastewater and excreta use in agriculture and aquaculture: the Engelberg report. IRCWD news, 23: 11-18 (1985).

44. Shuval, H.I. et al. Wastewater irrigation in developing countries: health effects and technical solutions. Washington, DC, World Bank, 1986 (Technical Paper No. 51).

45. Ayers, R.S. & Westcot, D.W. Water quality for agriculture. Rome, Food and Agriculture Organization of the United Nations, 1985 (Irrigation and Drainage Paper, No. 29, Rev. 1.).

Annex 1

MACROPHYTE PONDS

Although algae are vital to the efficient operation of both facultative and maturation ponds, their removal from the final effluent would significantly reduce its BOD_5 and suspended solids concentrations. High algal concentrations also degrade the quality of the receiving water body by releasing considerable quantities of phosphorus and nitrogen into the water as they decay, so accelerating the process of eutrophication. The use of macrophyte ponds has been based on the idea that, by growing large water plants in the final pond in a series, the dense leaf canopy formed at or above the pond surface will shade out the algae, so reducing their concentration in the final effluent and thus improving its quality. This relatively simple technique, if successfully applied, eliminates the need to use expensive and more complicated mechanical and chemical algal removal techniques. The macrophytes also remove inorganic nutrients (N,P) from the pond liquid as a consequence of their own metabolism and that of the microbial flora attached to their roots and submerged stems and leaf bases.

Rooted macrophyte ponds

In rooted macrophyte ponds, young plants or cuttings are embedded into the bottom of the empty final maturation pond at appropriate spacings for the species being used. The pond is then slowly filled with effluent from the preceding pond at a rate which ensures that the developing plants are not totally submerged and thus destroyed. Once fully established, the emergent macrophytes form a dense cover across the pond surface and provide a surface for the development of a submerged epiphytic community of algae and bacteria, which aids the wastewater treatment process. In Europe, suitable species include Phragmites communis and Scirpes lacustris (1,2), but it is likely that any local rhizomatous species capable of growth in nutrient-rich water could be used, and these would benefit from being already adapted to local conditions. Current practice suggests that rooted macrophyte ponds should be shallow (around 0.5 m deep) and should ideally receive the effluent from primary maturation ponds, but in fact they frequently receive facultative pond effluent.

The macrophytes require annual harvesting to prevent large amounts of decaying vegetation falling into the pond, which would otherwise increase the BOD_5 and suspended solids in the effluent and, in the long term, cause the pond to silt up. To prevent plant debris leaving the pond, the effluent is frequently passed through a metal screen or series of screens of decreasing mesh size. However, maintenance costs are increased because the screens require frequent cleaning as they rapidly become clogged with plant debris and attached microbial growth.

Rooted macrophyte ponds attract animals and birds, which can, via their faeces, re-introduce pathogens late into the treatment system. They also provide suitably shaded habitats for the breeding of mosquitoes, especially Mansonia spp, and this has proved so intense that it has been advocated that the use of rooted macrophyte ponds should be discontinued, solely for this reason (3).

Although pond systems incorporating rooted macrophyte ponds exist in, for example, France, the Federal Republic of Germany and the Netherlands, their popularity is declining with use for several reasons. These not only include increased maintenance costs and mosquito nuisance but also the finding that, although the algal population does decrease in macrophyte ponds, the reduction is frequently only partial because shade-adapted algae develop instead.

Floating macrophyte ponds

Floating macrophyte ponds, as their name implies, contain plants that float on the water with their aerial rosette of leaves close to the surface and their fibrous root systems hanging down into the pond water column to absorb nutrients. Several genera have been evaluated in pilot schemes, including *Salvinia*, *Spirodella*, *Lemma* and *Eichhornia* (4). Most shade out algae efficiently, but the larger species with their correspondingly larger root systems are considerably more efficient at nutrient stripping. *Eichhornia crassipes* (water hyacinth) has been studied in most detail, particularly in the United States (5,6). It would seem that *Eichhornia* ponds receiving effluent from a facultative pond can be loaded at rates of up to 40 kg BOD per ha per day; at higher loadings, odours develop at night.

Since water hyacinth will not grow at water temperatures below 10 °C, its application even in warm European climates may be limited. In contrast, *Lemma* spp. (duckweed) will survive freezing conditions and also grow rapidly at 30 °C. The main problems with duckweed are that it is less efficient than water hyacinth at nutrient stripping and its small size makes it susceptible to being blown across the pond surface to pile up as a thick odorous scum in one corner.

Mosquito breeding is also a problem in floating macrophyte ponds, but since the mosquitoes concerned are *Culex* spp., rather than *Mansonia* spp., this can be controlled by the introduction of larva-eating fish such as *Gumbusia* and *Peocelia*. Macrophytes such as water hyacinth, which trap clean water in their shaded leaf axils above the pond water surface, also encourage the breeding of clean water mosquitoes, and in this case the larvae are safe from fish predation.

There are other factors that require careful consideration when using either rooted or floating macrophyte ponds. Water loss via evapotranspiration from the leaf surfaces can be several times greater than evaporation from the free surface of an ordinary pond. Dissolved oxygen concentrations in the pond water column during the day are also very much lower than in conventional ponds, because the photosynthetic oxygen produced by the macrophyte leaves is lost directly to the atmosphere. Furthermore, the use of nonindigenous macrophytes is totally unacceptable because, if they escape from the ponds, as has happened with *Eichhornia*, they may have a highly deleterious effect on the ecology and quality of the local environment.

In conclusion, it can be said that none of the proposed designs for macrophyte ponds, either rooted or floating, has been evaluated sufficiently to confirm its long-term efficiency of operation. Information to date suggests that both types of macrophyte pond require considerably more maintenance than conventional ponds; otherwise, effluent quality is poor. In particular, pathogen removal, due to the lower pH in macrophyte ponds, is very much less than in algal maturation ponds. Thus, macrophyte ponds should only be considered for use as an additional treatment process subsequent to conventional maturation ponds, and then only when a high degree of algal or nutrient removal is necessitated by the ecology of the receiving watercourse.

REFERENCES

1. De Jong, J. The purification of wastewater with the aid of rush or reed ponds. In: Tourbier, J. & Pierson, R.W., ed. Biological control of water pollution. Pittsburgh, PA, University of Pennsylvania Press, 1976, pp. 133-137.
2. Vaucouloux, M. Les procédés extensifs d'épuration biologique des eaux usées domestiques : les lits à macrophytes. Paris, Ministère de l'agriculture, 1980.
3. Ringuelet, R. Comment concévoir un lagunage sous climat méditerranéen et en zone littorale à forté variation de population: le fruit de quinze annèes d'expérience. Colloque Franco-Espagnol, Montpellier, 22-23 May 1984.
4. O'Brien, W.J. Use of aquatic macrophytes for wastewater treatment. Journal of the Environmental Engineering Division, American Society of Civil Engineers, 107(EE4): 681-698 (1981).
5. Wooten, J.W. & Dodd, J.D. Growth of water hyacinths in treated sewage effluent. Economic botany, 30: 29-37 (1976).
6. Hauser, J.R. Use of water hyacinth aquatic treatment systems for ammonia control and effluent polishing. Journal of water pollution control federation, 56(3): 219-225 (1984).

Annex 2

HIGH-RATE ALGAL PONDS

High rate algal ponds are highly specialized waste stabilization ponds that are primarily designed to maximize the production of algae. Yields of up to 160 000 kg of algae (dry weight) per ha per year have been reported. This is equivalent to 80 000 kg of protein per ha per year, which is far in excess of that achieved by conventional agriculture; this is the reason for the economic attractiveness of these ponds. The current state-of-the-art stems from the pioneering work of Oswald et al. (1,2) in California and, more recently, from studies in south-east Asia (3), South Africa (4) and Israel (5,6). Most of the information has come from small-scale pilot installations and, even after more than 20 years of research, few full-scale systems are yet in operation.

A high-rate algal pond usually takes the form of a shallow channel 2-3 m wide with a water depth of 20-60 cm and arranged in a "race track" configuration. To prevent the algae settling out, the pond is mixed by stirring, either continuously or at regular intervals, with paddles located along its length. Detention times are between two and six days and are therefore much shorter than those in conventional pond systems. The shallow depths of high-rate algal ponds and their short retention times make them very sensitive to changes in environmental conditions and shock loads. Their short retention time may appear to offer a significant reduction in land area requirements, but this is offset by their shallow depth and low removal of excreted pathogens, which may require the use of maturation ponds to produce a satisfactory effluent.

The influent wastewater is pretreated by primary sedimentation or pretreated in an anaerobic pond to remove settleable solids (if removed by primary sedimentation, these solids can be digested anaerobically and the methane thus produced used as an energy source for sterilization and drying of the final algal product). High-rate algal ponds can be heavily loaded with wastewater, up to 350 kg BOD per ha per day in the tropics and subtropics and still, so it is claimed, produce an effluent with <20 mg/l of filtered BOD_5. Since these ponds are designed to maximize algal biomass production, it follows that efficient harvesting of the algae is crucial to the economic viability of the system. Harvesting techniques that have been used include centrifugation, mechanical filtration, autoflocculation and chemical flocculation, followed by forced air flotation (7).

In warm temperate climates, reduced operational efficiency during the winter months has been countered by increasing the retention time. This has been achieved by increasing the pond liquid depth as ambient temperatures fall. For example, in Israel, Azov and Shelef (6) increased the depth from 0.3 m in July to a maximum of 0.60 m in January. Such a strategy can also reduce dilution and washout of the algae from ponds during periods of heavy rainfall.

Reduced algal yields have been associated with predation by zooplankton, such as Daphnia and Moinia, and as a consequence of fungal infections. Correction of such problems is possible but requires a very high degree of microbiological competence. Careful manipulation of the performance of high-rate algal ponds may also be necessary in an attempt to control algal speciation in instances where the reuse strategy requires a particular type of algal product. However, this sort of quality control is extremely difficult. Even when these ponds are being skilfully operated, the microbial quality of the effluent is not usually as good or reliable as that from conventional pond systems.

In conclusion, it should be emphasized that high-rate algal ponds are highly sensitive biological reactors that require very careful control and maintenance by highly skilled personnel. They are much more complicated to operate than activated sludge systems, and they cannot be considered as a simple alternative to conventional pond systems. Their use should only be contemplated when the necessarily highly trained and experienced technical staff are routinely available and when the algal product can be economically used.

REFERENCES

1. Oswald, W.J. et al. Algae in waste treatment. Sewage and industrial wastes, 29: 437-457 (1957).
2. Oswald, W.J. Current status of microalgae from wastes. Chemical Engineering Progress Symposium, series 65, 93: 87-92 (1969).
3. McGarry, M.G. & Tongkasame, C. Water reclamation and algae harvesting. Journal of the Water Pollution Control Federation, 5: 824-835 (1971).
4. Buhr, H.O. & Miller, S.B. A dynamic model of the high-rate algal bacterial wastewater treatment pond. Water research, 17: 29-37 (1980).
5. Azov, Y. et al. Alternative operating strategies for high-rate sewage oxidation ponds. In: Shelef, G. & Soeder, C.J., ed. Algae biomass. Amsterdam, Elsevier/North-Holland Biomedical Press, 1980, pp. 523-529.
6. Azov, Y. & Shelef, G. Operation of high-rate oxidation ponds; theory and experiments. Water research, 16: 1153-1160 (1982).
7. Ellis, K.V. Stabilization ponds: design and operation. Critical reviews in environmental control, 13(2): 69-102 (1983).

Annex 3

DESIGN EXAMPLES

Design a series of ponds to treat the wastewater from a community with winter and summer (July-September) populations of 2000 and 10 000 whose BOD and wastewater flow are 50 g per caput per day and 150 litres per caput per day respectively. The mean monthly air temperatures are given in Table 1, and net evaporation (evaporation less rainfall) is 0 mm per day in winter and 7 mm per day in summer. The final effluent is to contain $\leq$10 000 faecal coliforms in winter and $\leq$1000 in summer.

Table 1. Mean monthly air temperature (°C) at proposed pond location

Month	Temperature	Month	Temperature
January	7.0	July	23.2
February	8.3	August	25.6
March	9.6	September	23.0
April	12.9	October	17.2
May	16.0	November	11.3
June	18.4	December	7.6

Solution

Two designs are presented: one with and one without anaerobic ponds.

The following calculations are common to both designs:

(a) From equation 1, the influent BOD $= 50 \times 1000/150$
$= 333$ mg/l

(b) The winter wastewater flow $= 2000 \times 150 \times 10^{-3}$
$= 300\ m^3/day$

(c) The summer wastewater flow $= 1500\ m^3/day$

(d) From Table 1, the winter design temperature is 7 °C (January), and the summer design temperature (that of the coolest month in the peak population season less 3 °C) is 20 °C (September).

(e) Thus, from equation 12, the values of the first rate constant for faecal coliform removal are given by:

$$k_T = 2.6\ (1.19)^{T-20}$$
$$= 0.27\ d^{-1} \text{ in winter}$$
$$= 2.60\ d^{-1} \text{ in summer}$$

Design A (without anaerobic pond)

Since the winter design temperature in <10 °C, the permissible winter loading on the primary facultative pond is 100 kg per ha per day, and the summer loading is given by equation 6 as:

$$\lambda_s = 10T$$
$$= 10 \times 20$$
$$= 200 \text{ kg/ha/day}$$

Summer conditions control the design of the facultative pond since the seasonal population factor (= 5) is greater than the ratio of the permissible summer to winter loadings (= 2). The design procedure is as follows.

(a) Calculate the facultative pond area (A_f) from equation 9:

$$A_f = LiQ/T$$
$$= 333 \times 1500/20$$
$$= 25\ 000\ m^2$$

(b) Calculate the facultative pond retention time (θ_f) from equation 15 on the assumption that a pond depth (D) of 1.5 m is acceptable:

$$\theta_f = 2A_fD/(2Q - 0.001A_fe)$$
$$= 2 \times 25\ 000 \times 1.5/[(2 \times 1500) - (0.001 \times 25\ 000 \times 7)]$$
$$= 26.5 \text{ days}$$

(c) Calculate θ_m from equation 14 for n = 1,2,3 ... for faecal coliform removal in summer (N_e = 1000 per 100 ml), assuming $N_i = 1 \times 10^8$ per 100 ml and noting that $\theta_a = 0$:

$$N_e = N_i/[(1 + k_T\theta_f)(1 + k_T\theta_m)^n]$$
$$\theta_m = \{[N_i/N_e(1 + k_T\theta_f)]^{1/n} - 1\}/k_T$$
$$= \{[10^8/1000\ (1 + (2.6 \times 26.5))]^{1/n} - 1\}/2.6$$
$$= 550 \text{ days for } n = 1$$
$$= 14.2 \text{ days for } n = 2$$
$$= 3.9 \text{ days for } n = 3$$
$$= 2.0 \text{ days for } n = 4$$

Further values of n are not considered as the last is less than θ_m^{min} (3 days). The first combination of θ_m and n is rejected as $\theta_m^{min} > \theta_f$, and the fourth combination is also rejected since $\theta_m < \theta^{min}$. The combination of $\theta_m = \theta_m^{min}$ and n = 4 requires more land than the third combination, which is therefore chosen. For this combination, the BOD_5 loading on the first maturation pond is calculated from the equation:

$$\lambda_{m1} = 10\ L_iQ/A_m$$

or, since $A_mD = Q\theta_m$:

$$\lambda_{m1} = 10\ L_iD/\theta_m$$

Assuming a depth of 1.5 m and a 60% BOD reduction in the facultative pond:

$$\lambda_m = 10 \times 0.4 \times 333 \times 1.5/3.9$$
$$= 512 \text{ kg/ha/day}$$

This value is higher than the loading on the facultative pond (200 kg per ha per day) and therefore unacceptable. Thus, λ_{m1} should be taken as 200 kg per ha per day and θ_{m1} calculated from:

$$\theta_{m1} = 10\ L_i D/\lambda_{m1}$$
$$= 10 \times 0.4 \times 333 \times 1.5/200$$
$$= 10 \text{ days}$$

The retention time in the subsequent maturation ponds is now calculated from:

$$\theta_m = \{[N_i/N_e(1 + k_T\theta_f)(1 + k_T\theta_{m1})]^{1/n} - 1\}/k_T$$
$$= \{[10^8/1000(1 + (2.6 \times 26.5))(1 + (2.6 \times 10))]^{1/n} - 1\}/2.6$$
$$= 20 \text{ days for } n = 1$$
$$= 2.4 \text{ d for } n = 2$$

Thus, a combination of $n = 2$ and $\theta_m = 3$ days is chosen.

(d) Check conditions in winter when flows are five times less and retention times five times greater:

(1) $$\lambda_s = 10\ L_i Q/A$$
$$= 10 \times 333 \times 300/25\,000$$
$$= 40 \text{ kg/ha/day, which is satisfactory}$$

(2) $$\theta_f = A_f D/Q$$
$$= 25\,000 \times 1.5/300$$
$$= 125 \text{ days}$$
$$N_e = N_i/[(1 + k_T\theta_f)(1 + k_T\theta_{m1})(1 + k_T\theta_m)^2]$$
$$= 10^8/\{[1 + (0.27 \times 125)][1 + (0.27 \times 50)][1 + (0.27 \times 15)]^2\}$$
$$= 7800 \text{ per 100 ml, which is also satisfactory}$$ [a]

(e) To calculate the areas of the maturation ponds, the effluent flow from the facultative pond in summer is calculated:

$$Q_e = Q_i - 0.001 A_f e$$
$$= 1500 - (0.001 \times 25\,000 \times 7)$$
$$= 1325 \text{ m}^3\text{/day}$$

Thus, the area of the first maturation pond is given by:

$$A_{m1} = Q_e\theta_{m1}/D$$
$$= 1325 \times 10/1.5$$
$$= 8833 \text{ m}^2$$

[a] If N_e were required to be 1000 per 100 ml in winter as well as in summer, the design would be unsatisfactory. In this case, all the calculations would be repeated for winter conditions and the resulting design checked for conditions in summer.

Allowing for the evaporation losses in the first maturation pond, the area of the second maturation pond is similarly calculated as 2526 m^2, and that of the third as 2490 m^2.

Design B (with anaerobic ponds)

The permissible loading on the anaerobic pond is 100 g per m^3 per day in both winter and summer. Assuming that summer conditions control the design, the design procedure is as follows.

(a) Calculate the anaerobic pond volume (V_a) from equation 2:

$$V_a = L_i Q/\lambda_v = 333 \times 1500/100 = 4995\ m^3$$

Assuming a depth of 3 m, the required area is 1665 m^2. The retention time is 3.3 days.

(b) Assuming a 40% reduction in BOD removal in the anaerobic pond, calculate the secondary facultative pond area from equation 9:

$$A_f = L_i Q/T = 0.4 \times 333 \times 1500/20 = 10\ 000\ m^2$$

Assuming a depth of 1.5 m and ignoring evaporative losses from the anaerobic pond (due to scum formation these are negligible), the retention time is given by equation 15:

$$\theta_f = 2A_f D/(2Q - 0.001 A_f e) = 2 \times 10\ 000 \times 1.5/[(2 \times 1500) - (0.001 \times 10\ 000 \times 7)] = 10.2 \text{ days}$$

(c) Calculate θ_m from equation 14 for n = 1,2,3 ... for faecal coliform removal in summer (N_e = 1000 per 100 ml), assuming $N_i = 1 \times 10^8$ per 100 ml:

$$\theta_m = \{[N_i/N_e(1 + k_T\theta_a)(1 + k_T\theta_f)]^{1/n} - 1\}/k_T$$
$$= \{[10^8/1000(1 +(2.6 \times 3.3))((1 + 2.6 \times 10.2))]^{1/n} - 1\}/2.6$$
$$= 145 \text{ days for } n = 1$$
$$= 7.1 \text{ days for } n = 2$$
$$= 2.3 \text{ days for } n = 3$$

Since for the third combination θ_m is less than θ_m^{min} (3 days), consider the combination of n = 3 and θ_m = 3. This results in a value of λ_{m1} of 512 kg per ha per day, as in design A, which is higher than the permissible loading on the facultative pond (200). Thus, λ_{m1} is taken as 200 and θ_m calculated from:

$$\theta_m = 10 L_i D/\lambda_{m1} = 10 \times 0.4 \times 333 \times 1.5/200 = 10 \text{ days}$$

Using this value of θ_m for the first maturation pond and 3 days for the second and third, calculate N_e:

$N_e = N_i/(1 + k_T\theta_a)(1 + k_T\theta_f)(1 + k_T\theta_{m1})(1 + k_T\theta_{m2})$

$= 10^8/[1 + (2.6 \times 3.3)] \times [1 + (2.6 \times 10.2))] \times [1 + (2.6 \times 10)] \times [1 + (2.6 \times 3)^2]$

= 520 per 100 ml, which is satisfactory

(d) Check conditions in winter:

(1) $\lambda_v = L_iQ/V_a$

$= 333 \times 300/4995$

$= 20$ g/m^3/day, which is satisfactory

(2) $\lambda_s = 10\ L_iQ/A_f$

$= 10 \times 0.6 \times 333 \times 300/10\ 000$

$= 60$ kg/ha/day, which is satisfactory

(3) $\theta_f = A_fD/Q$

$= 10\ 000 \times 1.5/300$

$= 50$ days

$N_e = 10^8/\{[1 + (0.27 \times 16.5)] \times [1 + (0.27 \times 50)] \times [1 + (0.27 \times 50] \times [1 + (0.27 \times 15)]^2\}$

= 3420 per 100 ml, which is also satisfactory

(e) Following the procedure in design A(e), the areas of the first, second and third maturation ponds are calculated as 9535 m^2, 2727 m^2 and 2688 m^2 respectively.

Comparison of designs

The pond areas required for the two designs are summarized in Table 2. The total area for design A is 39 ha and, for design B, 27 ha. Design A therefore requires 46% more land than design B. Design engineers should thus always consider the inclusion of anaerobic ponds as they result in significant economies, although for small schemes the extra maintenance required (desludging every two to three years, see section 5.2) may outweigh this advantage.

Table 2. Comparison of mid-depth areas required for designs A and B

Pond	Area (m^2)	
	Design A	Design B
Anaerobic	–	1 665
Facultative	25 000	10 000
First maturation	8 833	9 535
Second maturation	2 526	2 727
Third maturation	2 490	2 688
Total area	38 849	26 615