

WASTEWATER STABILIZATION PONDS

PRINCIPLES OF PLANNING & PRACTICE



WORLD HEALTH ORGANIZATION
REGIONAL OFFICE FOR THE EASTERN MEDITERRANEAN
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**WASTEWATER
STABILIZATION PONDS**

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PLANNING & PRACTICE



WORLD HEALTH ORGANIZATION
Regional Office For The Eastern Mediterranean
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In the name of God, the compassionate, the Merciful

FOREWORD

by

Hussein A. Gezairy, MD, FRCS

Regional Director for the
Eastern Mediterranean Region of
the World Health Organization

It is my firm belief that health cannot be the responsibility of the health sector alone. For example, no amount of treatment by medical staff can counteract the effects of contaminated drinking water supplies and inadequate sanitation.

The impetus given to improving these services by the United Nations International Drinking Water Supply and Sanitation Decade has brought marked advances world-wide. It is a programme in which the World Health Organization has a major role. But the magnitude of the task, that of providing potable water and adequate sanitation to all people, is formidable. In the countries of the Eastern Mediterranean Region, studies have shown that, as elsewhere, the distribution of services tends to be inequitable: urban communities are consistently better served than rural ones, and provision of sanitation lags markedly behind the provision of safe water.

It is for this reason that the Regional Office is publishing this book on wastewater stabilization ponds. They can treat the sewage from both large and small communities, and the effluent of a well-designed pond system can be discharged to local water bodies without polluting them. Furthermore, the effluent can also serve as a valuable resource, since it can be used directly for irrigation or for fish culture.

Wastewater stabilization pond systems have been used for some 75 years, and in many parts of the world. If inexpensive land is available, they are the cheapest and most effective means of treating communal wastewaters. While the land area they require has restricted their use in densely populated countries, shortage of land is not usually a problem in countries of the Eastern Mediterranean Region. This adds to the attractiveness of this form of wastewater treatment.

Pond systems make use of the forces of nature – sunlight, wind, temperature, and bacterial and algal growth – to achieve a re-usable effluent. The task of the designer is to optimize the interaction of these factors.

Of particular interest to developing countries is that operation and maintenance require a minimum of operator skills and running costs, for example for energy supplies. Furthermore, nearly all materials and equipment can be obtained within the country, with little recourse to items requiring foreign currency. Finally, construction can easily be undertaken with local labour under local supervision.

The book has been divided into two parts. Part A is intended for national and local administrators and decision-makers, whatever their field of work, who are faced with making a choice between competing systems for wastewater treatment. It provides a comprehensive summary concerning the various aspects of constructing, operating and maintaining pond systems. It also considers aspects such as management and safety. While it would not be possible for it to be non-technical, for then decisions would have no sound basis, this part has been written in understandable language, and it is believed that the educated layman will be able to grasp the concepts and advantages with little real difficulty.

Part B is intended for persons making the preliminary designs on which cost estimates and, hence, choices can be made. It is expected that architects or engineers with only little experience in the field could use the book for this purpose. In particular, the appendix and annex provide a worked example and a simple methodology to help the designer in preparing adequately detailed designs.

The book will also have another important use, namely that of serving students and their lecturers at engineering faculties as a basic yet detailed introduction to the topic. Above all, it considers a number of management factors that receive scant attention in textbooks, but which nevertheless affect the viability of the technology in practice – for example, the effect of gaining the support of the local community.

I believe that the publication will do much to raise awareness of this highly appropriate technology in Member States of the Eastern Mediterranean Region – and elsewhere.

A handwritten signature in black ink, appearing to be 'C. J. B.' followed by a flourish.

PREFACE

The preparation of a book on the topic of wastewater stabilization ponds was recommended by an intercountry seminar on this topic held at the turn of the decade, following the participants' identification of the need for such a publication in the Region. Mr Max Lothar Hess was engaged as a WHO short-term consultant to prepare a first draft. It was sent for review and comment to a number of experts, and their views were appropriately incorporated into the second draft by the consultant for consideration at an expert group meeting held in Lahore, Pakistan, in December 1984.

The Regional Office's Publication Proposals Review Committee, after studying the manuscript, suggested that the chapters of a more general nature be grouped together in a first part, ahead of the chapters intended specifically for designers. It was believed that the book would, in this way, better address a target readership that included senior decision-makers and administrators in national and local government — those that require sound management information on a subject which may be outside their normal sphere of activity. It is well known that final decisions on, for example, the type of technology to be chosen, while reflecting the assessments of experts, usually lie with officials and civic leaders who are not in themselves experts in the field, and who are often in need of unbiased general information. Especially in developing countries, considerations of foreign exchange required, both to obtain and run the technology in question, ability of local expertise to build and operate it, and the question of having end- and by-products that will increase "local wealth" by providing employment, are factors that may outweigh simple cost calculations. The Committee's suggestion was very much in line with the new WHO policy for publications.

The Editors, Dr M.I. Sheikh and Mr E.R.A. Beck of the Regional Office, thereupon reorganized the manual, revising the text so as to ensure that it was better suited to the new target readership. Also following the Committee's decision, colour photographs were included to provide a better impression of scale and practical features. Mr Beck also rewrote the appendix and provided an annex giving a calculational methodology that was suitable for use with a pocket calculator.

The revised manual was finally assessed by staff of the Environmental Health Division at WHO, Geneva, Professor M.B. Pescod of the University of Newcastle-upon-Tyne and Professor E.F. Gloyna of the University of Texas at Austin. Their comments and suggestions were incorporated appropriately.

It is believed by WHO that the value of the manual has been improved by broadening its target readership, and that it will also find a place as a teaching/learning aid for engineering students in the Region.

ACKNOWLEDGEMENTS

The Editors acknowledge with gratitude the work undertaken by Mr Max Lothar Hess, who prepared the first and second drafts of the manual. The names of the experts who reviewed the first draft are listed below, as are the names of those who served on the expert group meeting held in 1984, and their support is also gratefully acknowledged.

Special thanks are owed to Professor E.F. Gloyna and Professor M.B. Pescod, who also read subsequent drafts and provided unstinting encouragement to the Editors, and to colleagues on the staff of the Environmental Health Division, WHO, Geneva, for their review of the text and their efforts in obtaining reference material and many of the colour photographs included herein.

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ILLUSTRATIONS

The WHO regional Office for the Eastern Mediterranean acknowledge with thanks permission to reproduce the illustrations:

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Figs. 1, 2, 9, 12B, 14B (and front cover), 17, rear cover	Professor M.B. Pescod
Figs. 6B, 8	Water Authority of Jordan
Figs. 11A, 11B, 15	Mr. Lothar Hess
Figs. 12C, 18	Dr. R.C. Ballance

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Part A
BASIC CONSIDERATIONS IN
THE PLANNING AND OPERATION
OF WASTEWATER STABILIZATION PONDS



Wastewater stabilization ponds at Lahore, Pakistan. They were built in 1967, served 30 000 people in the city and supported research into operational characteristics. The final effluent was used for fish culture and irrigation (some of the crops can be seen in the foreground). The project was so successful that the ponds were extended with assistance from the Pakistan National Science Foundation, World Bank and USAID.

Chapter I

THE CHALLENGE

In 1978, the Member States of the World Health Organization, as part of the strategy for achieving the goal of "health for all", approved the concept of primary health care as the comprehensive approach to that goal. This approach views health as a part of socio-economic development and includes among its eight essential elements provision of an adequate supply of safe water and basic sanitation, for it was realized that all efforts to promote health must fail without these. This period also marked the inception of the United Nation's International Drinking Water Supply and Sanitation Decade (1981 – 1990), which marked an important initiative to raise awareness among governments of the links between water, sanitation, health and national development. The Organization's activities in this field have been closely integrated with the efforts of governments and other UN agencies in support of Decade activities throughout the world.

In the course of the Decade, experience has shown that provision of safe water alone is not an adequate response, since the increased use of water requires a matching system for water collection and disposal. For example, in some situations, stagnant pools of unclean water formed that brought their own health risks.

In 1985, on a world basis, only three out of five persons in developing countries had access to safe drinking water, while only about one in four had any kind of adequate sanitary facility. However, this figure hides the fact that people in rural communities are far worse off than their urban fellows. In the Eastern Mediterranean Region alone, with urban and rural populations of 134 million and 196 million, respectively, some 21 million (16%) urban dwellers and 119 million (61%) in rural areas were without safe water, some 37.5 million (28%) and 170 million (87%) were without adequate sanitary facilities.

Drinking water and sanitation for all means providing more than 3000 million people with new and improved services world wide. If the same standards of service, methods and technologies for implementation as have been used in the recent past continue to be employed, the targets may never be achieved. While this situation is critical in the area of drinking water supplies, it is even more so in the case of wastewater treatment. There is thus a real challenge for the planning, construction

CHAPTER I. THE CHALLENGE

and financing institutions involved; if it is to be met, suitable low-cost techniques must be employed. Much research has been and is being carried out on wastewater treatment by means of stabilization ponds in both developed and developing countries, and operational experience has been accumulated over a period exceeding 50 years. A properly designed pond system can now be considered a reliable, efficient, economical and simple process for treating sewage and industrial wastewaters.

Stabilization pond systems are known to have advantages over other types of wastewater treatment processes. One major advantage is their ability to provide enhanced removal of pathogens, which is of great benefit to health. The effluent is safer than that from many other processes, allowing it to be reused in agriculture and aquaculture.

Furthermore, the pond process is appropriate for both large and small populations; for example, some of the world's largest pond installations treat wastewater from more than a million people.

Indeed, the role of stabilization ponds in solving the problems of wastewater disposal in developing countries should not be underestimated by national planners, health authorities, engineers and economists. With low construction and operating costs, this form of wastewater treatment is not only competitive with other, more complex treatment processes, but is much less capital-intensive wherever inexpensive land is available. Moreover, the technology required is well suited to the needs of a developing economy, placing no undue strain on technical and manpower resources, while the design of such installations can easily be modified to suit a large variety of climatological and other local conditions.

Chapter II

OBJECTIVES AND SCOPE

II-1. OBJECTIVES

The purpose of Part A of this manual is to provide information about wastewater stabilization ponds for all concerned with design, construction and operation, including national and civic decision-makers who ultimately have to choose and finance the wastewater system to be used by a given community. Part B and Appendix I add more specific information about design for the use of technical personnel. The manual will, it is believed, be of particular value in developing countries, where the necessary national experience has often not yet been built up. Furthermore, it will be of value as a "teaching, training and learning aid" as well as being invaluable for operations managers whose task it is to supervise operators and other workers employed at such installations.

The manual reviews the most commonly used techniques and draws on practical experience from all parts of the world, from both industrialized and non-industrialized countries. Two installations greatly differing in scale are illustrated in Figs 1 and 2, reflecting the ability of wastewater stabilization ponds to serve large and small communities.

Up to now, the mathematical models developed for ponds have been simplistic and do not reflect the many factors influencing a stabilization pond environment, such as stratification, the outbreaks of algal predators (rotifers and *daphnia*) in facultative ponds (see below), or the predominance of blue-green algae. Consequently, a complex modelling approach has no advantage over less sophisticated design methods at the present time. In temperate and cold regions, many of these phenomena may be of little importance but, in this manual, an attempt is made to take into account both the unfavourable and the beneficial impacts of high ambient temperature on pond performance.

The manual deals with only three types of wastewater stabilization pond, viz:

- anaerobic ponds;
- facultative ponds;
- maturation ponds.

CHAPTER II. OBJECTIVES AND SCOPE

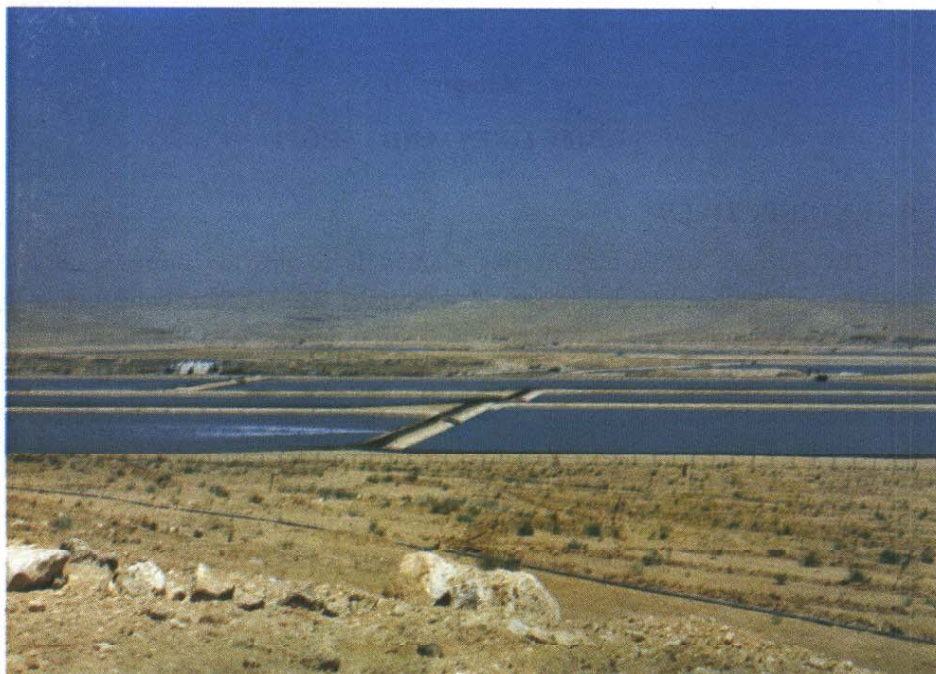


FIG.1. Looking across the IRP wastewater stabilization ponds at Khirbet Samra near Amman, Jordan.



FIG.2. Pond installation at Khon Khan, Thailand.

WASTEWATER STABILIZATION PONDS

Mechanically-aerated ponds are not considered in this manual, since such installations require greater investment and since operation and maintenance are more complex.

II-2. SCOPE

The following topics are covered in the manual:

- the purpose of treatment;
- basic information about the treatment processes;
- design criteria;
- abnormalities, malfunctions and operational disorders;
- procedures for operation, maintenance, sampling and safety; and
- trouble-shooting in the event of operational problems.

It is expected that, through use of this manual, the pond designer and the plant operating staff will be well informed about the design, operation and maintenance of a pond installation and its associated equipment, and about the control of "controllable" features.

Some simple forms for recording data are included, and instructions for sample collection and for estimating the need for maintenance and repair are given. The forms are only presented as examples, for it is recognized that they will have to be adapted to suit each installation, according to its special characteristics and the qualifications of the staff employed.

Chapter III

DEFINITIONS

It is perhaps helpful to define some of the terms used in the manual as an aid to the reader.

Wastewater This may be domestic sewage, industrial effluent or a combination of the two, as in the case of municipal sewage from industrial areas. In this manual, the term 'wastewater' will be used wherever the text applies equally to sewage and to industrial effluents.

Sewage As used in this manual is domestic or municipal sewage not containing industrial effluent.

Pond A body of water contained in an excavation in the ground or in a reservoir formed above ground with the aid of earthen embankments, or in a combination of the two. (The term 'lagoon' is often used synonymously with 'pond' but, for the purposes of this manual, 'pond' is preferred.)

Wastewater stabilization pond A man-made pond (treatment unit) in which wastewater is allowed to stand for a time, under the influence of microorganisms and the forces of nature, so that it is converted into an effluent that meets the quality standards established for final disposal or reuse.

Anaerobic pond A wastewater stabilization pond devoid of dissolved oxygen and where anaerobic bacteria break down the complex organic matter.

Facultative pond A wastewater stabilization pond that supports a significant upper layer containing dissolved oxygen (aerobic layer) and a lower layer devoid of oxygen (anaerobic layer). An intermediate layer is also recognized. In the upper layer, algae and both facultative and aerobic bacteria coexist.

Maturation (or polishing) pond An *aerobic* secondary or tertiary wastewater stabilization pond whose prime function is to remove further pathogenic agents from a treated effluent. It also removes some suspended matter and some nutrients, and further reduces the concentration of biodegradable organic matter.

WASTEWATER STABILIZATION PONDS

When pathogen removal is the primary objective, the term 'maturation' pond is preferred, and this is the term used throughout this manual.

Primary pond A single wastewater stabilization pond, or the first such pond in a combination of two or more ponds connected in series. It receives raw wastewater and may be an anaerobic or a facultative pond.

Secondary pond A wastewater stabilization pond preceded by a primary pond. It may be an anaerobic, a facultative or a maturation pond.

Tertiary or quaternary pond Extensions of this nomenclature.

Aerobic process With reference to wastewater stabilization ponds, a biological process requiring oxygen.

Anaerobic process A biological process that proceeds in the absence of oxygen.

Oxygen demand is an important parameter when considering wastewater treatment and represents the amount of oxygen needed to break down the organic material (an end product of once-living plant or animal material) in the wastewater. The demand can be considered as the oxygen needed to oxidize (i) all the carbon, (ii) the oxidizable nitrogen and (iii) certain other oxidizable compounds. The importance of removing oxidizable organic matter in wastewater is that the end products are no longer pathogenic (i.e. no longer capable of causing disease) and will no longer burden the environment with degradable biological material when the wastewater is discharged after treatment.

Chemical oxygen demand (COD) expresses the total amount of oxygen required to oxidize the organic material in wastewater.

Biochemical oxygen demand (BOD) measures the total amount of oxygen required for the biological breakdown of (i) carbon-containing and (ii) oxidizable-nitrogen-containing material, i.e. the amount of oxygen required to sustain biological activity in an aerobic pond.

5-day biochemical oxygen demand (BOD_5) measures the amount of oxygen required to sustain biological activity over a period of 5 days at 20°C. It has been chosen as a standard reference so that wastewater BODs can be compared.

CHAPTER III. DEFINITIONS

The anaerobic process in an anaerobic pond also breaks down organic matter (see §V-2). The difference between the BOD of the wastewater entering the anaerobic pond and the BOD of the wastewater leaving it is used as a measure of the usefulness of the anaerobic pond treatment.

Chapter IV

GENERAL CONSIDERATIONS

The selection of a wastewater treatment process depends upon many factors, only some of which are quantifiable in monetary terms. Capital costs and operating costs are relatively easy to estimate. Other factors, such as process reliability and stability or robustness, are very difficult to assess in economic terms but are often much more important. The principal considerations in process selection are:

- adequate protection of public health (removal of pathogens);
- level of operator skills available;
- minimization of operating costs (energy, maintenance, spare parts);
- maximization of the use of local resources (labour, materials, equipment);
- capital cost.

A short question which provides much guidance in wastewater treatment process selection is: "Is it simple, and does it work?".

In the case of wastewater stabilization ponds, the answer is clearly: "Yes". They represent the simplest process by which man attempts to stabilize the biodegradable matter contained in wastewater, by creating conditions favourable for the natural processes of purification. The forces of nature (sunshine, wind, temperature and spontaneous plant and animal life) are allowed to act upon the wastewater. There is only a limited amount that the designer can do to facilitate stabilization pond operation and even less that the operator can do to steer or modify the conditions in the pond if they are not as predicted. For these reasons, stabilization ponds should function with little more than maintenance and supervision.

Stabilization ponds employ the most rudimentary process of biological wastewater treatment. They have been developed to produce an effluent suitable for discharge to most receiving waters and for water reclamation at low cost and with unskilled labour. They do not provide the most complete treatment, but a series of such ponds will provide a much greater removal of disease-causing organisms than other conventional wastewater treatment processes.

CHAPTER IV. GENERAL CONSIDERATIONS

Operator skill requirements are low and, while there is need for some training, it is not of an advanced nature.

Energy consumption and maintenance requirements are minimal, as is the need for spare parts. Strictly speaking, "operation" of a pond installation is only required where pumps, screens, grit chambers or other devices have been installed, and even in such cases the technical "know-how" is easily mastered.

Construction is relatively simple and is suited to the use of local materials and labour.

Thus wastewater stabilization ponds will normally be the first choice in process selection for developing countries under most circumstances. Some useful information relating to pond design, construction and operation, as applicable in India, are given by Arceivala [1].

However, there will be locations where they cannot be justified because land is unavailable or too costly, although in the latter case the following points should be considered in the decision-making process before a final choice is made;

- (a) The success rate of activated sludge systems in many developing countries has been poor;
- (b) There is a continuous production of sludge from 'conventional' processes which has to be treated and disposed of safely;
- (c) The effluent from a series of stabilization ponds may be reused safely without disinfection, for example in agriculture, provided an evaluation is made of soil – effluent interactions and of suitable crop types;
- (d) Pond systems provide a solution which offers some flexibility for upgrading to meet future loads from both small and large communities;
- (e) Most pond systems require very little heavy electrical or mechanical equipment, small ones often none;
- (f) The foreign exchange component of the total cost of treatment will be much lower for pond systems than for other processes.

Chapter V

BASIC CONSIDERATIONS

V-1. PURPOSE OF WASTEWATER TREATMENT

Typical domestic sewage is composed of some 99.9% water and 0.1% impurities, mainly suspended, colloidal and dissolved solids. There are also gases, microorganisms and other materials present.

Wastewater treatment involves the separation of the solid fraction from the liquid phase, treating the solids and the liquid arising from this separation to reduce, as far as possible, the organic pollutants. This allows final disposal of the stabilized wastewater constituents into the environment without detrimental effects. Stabilization ponds provide suitable treatment and are, in addition, very effective in removing pathogens.

In other types of wastewater treatment plant, separation of the solid and liquid fractions is achieved using capital-intensive units, often mechanically aided, in concrete channels, tanks and other devices. These include screens, grit chambers, settling tanks, thickeners, aeration tanks, digesters and other unit processes. These forms of treatment are less efficient than ponds in the removal of pathogens.

In wastewater stabilization ponds, all unit processes and unit operations may be carried out together in the same unit, or a combination of similar units may be used. If only one stage of treatment is used, the pond will normally be anaerobic or facultative. However, an anaerobic pond should, in most cases, be followed by a secondary pond for additional aerobic biological treatment.

V-2. TREATMENT IN AN ANAEROBIC STABILIZATION POND

When anaerobic ponds are compared with other conventional treatment plants, they take the place of the following units:

- primary settling tanks;
- sludge thickeners;
- anaerobic sludge digesters;
- gas pipes and burners;
- sludge drying facilities;
- pumps, motors and equipment involved in primary treatment;
- sometimes, screens and grit chambers.

CHAPTER V. BASIC CONSIDERATIONS

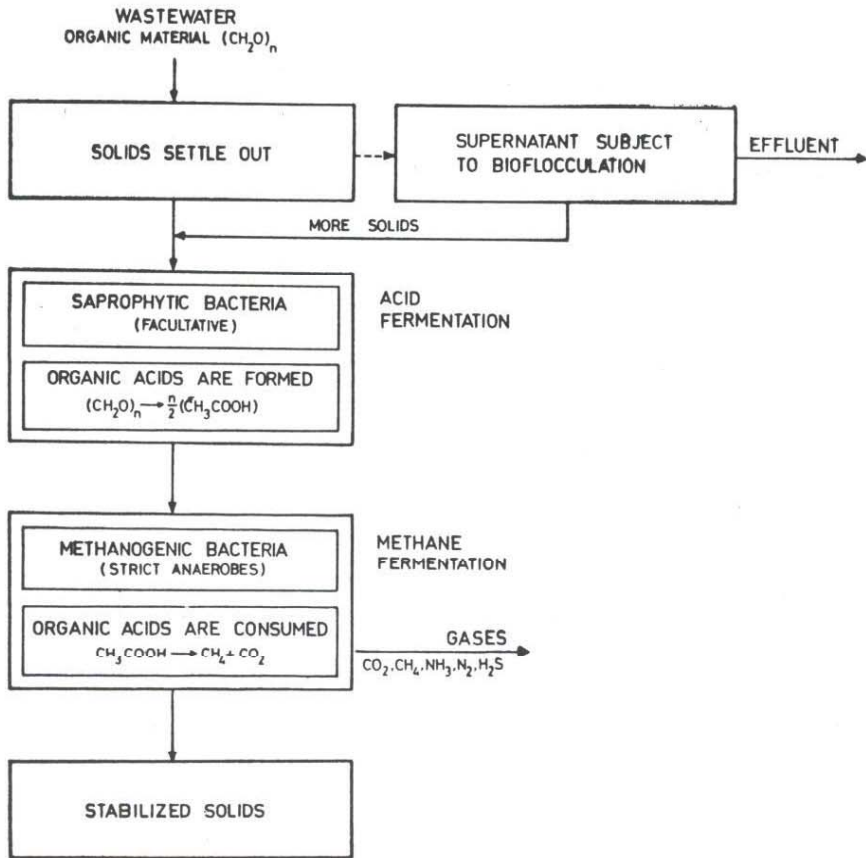


FIG.3. The stabilization process in an anaerobic pond.

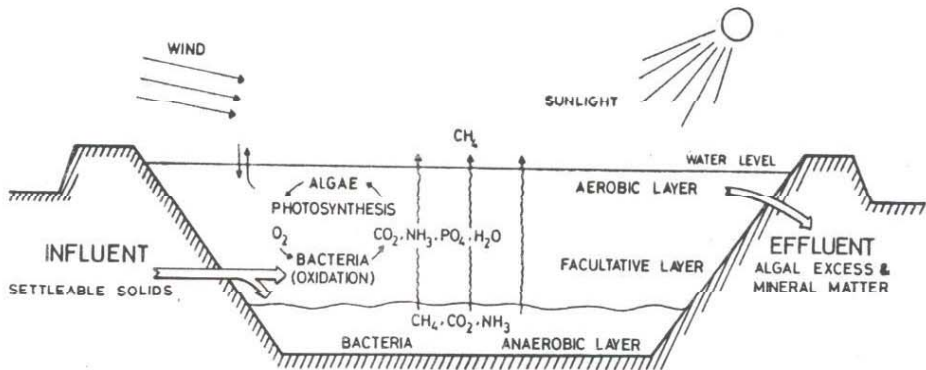


FIG.4. The stabilization process in a facultative pond.

WASTEWATER STABILIZATION PONDS

During slow passage of the wastewater through the pond, and after some time has elapsed, the following changes will have taken place:

- (a) Most of the suspended solids will have settled to the bottom of the pond;
- (b) Some removal of pathogenic agents will have been achieved;
- (c) Floating material, including oil, grease, corks, cigarette filters, plastics and other items, will have been carried to the surface, where they will build up in a scum layer. Scum baffles or similar devices will subsequently prevent this scum from leaving the pond with the effluent;
- (d) Part of the suspended solids, including worm eggs, parasites and bacteria, settle to the bottom of the pond. Here they undergo anaerobic decomposition, concentration and part mineralization. The organic material is broken down by anaerobic bacteria. Through the metabolism (respiration and growth) of these bacteria, part of the organic matter is converted into mineral matter. During this phase, gases are generated, primarily CO_2 , CH_4 and H_2S ; these gases are dispersed into the atmosphere through the liquid surface (Fig.3). A portion of the sludge resulting from the settling of solids will be transformed into gas. This reaction, together with sludge thickening, accounts for the very slow build-up of solids in an anaerobic pond. As a result, the accumulated sludge may be estimated at only 40 litres per person per year [2].

The liquid effluent from the anaerobic pond is nearly always transferred to a facultative pond; this effluent will have low levels of suspended and settleable solids and worm eggs. In terms of BOD_5 (5-day biochemical oxygen demand, see Ch.III), the effluent will often have a 40–60% reduction in concentration from that in the raw influent to the primary, anaerobic pond, depending on temperature and retention time.

V-3. TREATMENT IN A FACULTATIVE POND

A facultative pond is built with a smaller depth and with a larger surface area than an anaerobic pond of the same volume. The designer attempts to maintain an aerobic upper layer "floating" upon an anaerobic lower one. The aerobic condition in the upper layer is produced by dissolved oxygen; this is primarily generated as a result of photosynthesis caused by the incidence of solar radiation upon the algal population of the pond (Fig.4).

Aerobic and facultative bacteria in the upper and middle layers metabolize the dissolved, colloidal and suspended organic matter, consuming dissolved oxygen and producing CO_2 ; this is transformed into algal cell material (organic carbon).

CHAPTER V. BASIC CONSIDERATIONS

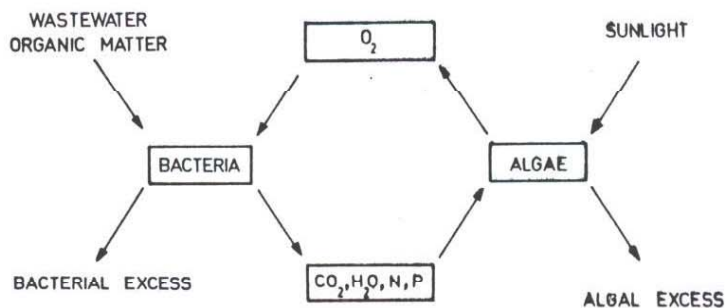


FIG.5. Synergistic relationship between algae and bacteria in a facultative pond.

Facultative bacteria also consume combined oxygen from nitrates and sulphates when free oxygen is exhausted.

During the passage of wastewater through a facultative pond, the following changes may be observed:

- Most of the remaining suspended solids settle to the bottom of the pond, where they develop a layer that works like an anaerobic sludge digester. This is the anaerobic zone of a facultative pond (Fig.4). If the pond is a primary one, worm eggs, parasites and some bacteria will be reduced as in an anaerobic pond;
- Above the anaerobic sludge layer, an intermediate zone exists in which dissolved oxygen is present some of the time, fed from the upper layer. The intermediate zone is greenish in colour due to the presence of algae;
- The upper layer is a natural culture medium for algae and operates as an aeration system, producing oxygen for the aerobic and intermediate zones. The oxygen concentration varies with depth and with the time of day. At night, there is no oxygen production, but some surface diffusion of atmospheric oxygen occurs;
- The algae in the upper layer coexist with bacteria in a synergistic relationship;
- During the stabilization process, much of the biodegradable organic matter is transformed, mainly into living organic matter – in the form of algae, bacteria, protozoa, etc. (Living or dead algae generate a biochemical oxygen demand, and for this reason a few authors consider facultative ponds to be poor treatment devices, since one type of organic material is simply converted into another. However it should be noted that algal biochemical oxygen demand in the effluent is not necessarily detrimental to the environment).

WASTEWATER STABILIZATION PONDS

- (f) The effluent of a facultative stabilization pond taken from the surface layer is strongly green-coloured because of the presence of algae. It also contains other living organisms, such as microcrustaceans, bacteria and rotifers, and it has a high content of dissolved oxygen. However, there are practically no suspended solids that will settle.

Bacteria consume oxygen in respiration and multiplication and, at the same time, they break down organic matter present in the wastewater. As a by-product of their metabolism, they release into the liquid mass carbon dioxide as well as nitrates, sulphates, phosphates and other mineral salts. Algae in turn use these by-products when they absorb light to synthesize their own cellular material, releasing oxygen. Some of this oxygen is then consumed by aerobic bacteria, continuing the cycle. Figure 5 depicts the synergistic relationship between algae and bacteria in a facultative wastewater stabilization pond.

Part of the oxygen generated by algae during photosynthesis remains dissolved in the liquid mass, often giving rise to supersaturated conditions in the upper layer, while a part is dissipated to the atmosphere. It should be noted that, in addition to bacteria, microcrustaceans, larvae, protozoa and other aerobic and facultative microorganisms make use of dissolved oxygen, as do algae during darkness.

A facultative pond used as a secondary pond (i.e. following an anaerobic pond) in climates where the average "coldest month" air and water temperatures do not go below around 10°C and 15°C, respectively, should have a minimum retention time of 5 days for typical domestic wastes. The upper limit is determined by design parameters and the area of land available, and can extend to tens of days. When facultative ponds are used as primary ponds at the temperatures quoted above, the retention times will be tens of days.

V-4. TREATMENT IN A MATURATION POND

Maturation ponds are used mainly for reduction of pathogenic organisms. Besides removing a very high percentage of faecal bacteria, viruses, protozoa and other pathogens, maturation ponds may also remove some algae and some nutrients. Occasionally, however, algal blooms do occur in maturation ponds.

The bactericidal effect of maturation ponds is due to several natural factors, including sedimentation, lack of food and nutrients, solar ultra-violet radiation, high temperatures, high pH-value, predators, the toxins and antibiotics excreted by some organisms, as well as natural die-off.

CHAPTER V. BASIC CONSIDERATIONS

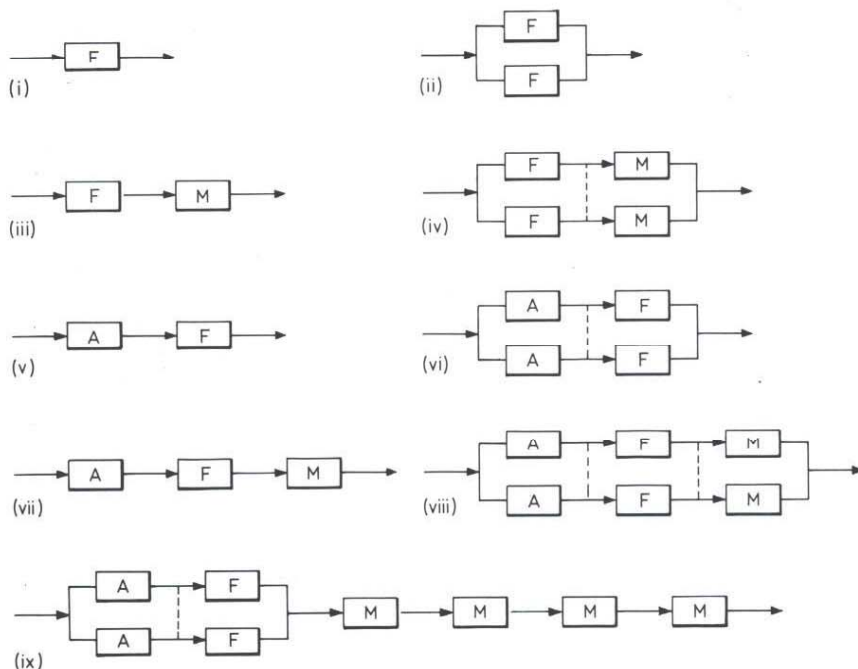


FIG.6A. A selection of possible pond arrangements in parallel and series (A = anaerobic; F = facultative; M = maturation). The preliminary design calculation for a train of ponds corresponding to arrangement (ix) is given in Appendix I.

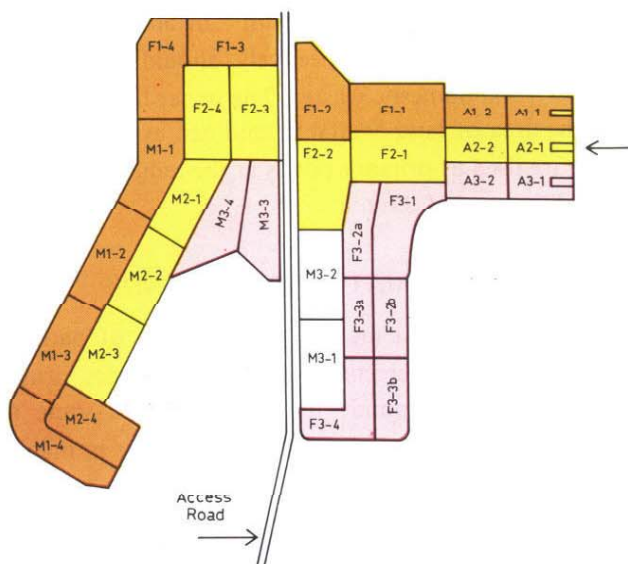


FIG.6B. Layout of the three parallel trains of wastewater stabilization ponds of the IRP plant at Khirbet Samra, near Amman, Jordan (A = anaerobic; F = facultative; M = maturation).

WASTEWATER STABILIZATION PONDS

TABLE I. COMPARISON OF ANAEROBIC AND FACULTATIVE PONDS AS PRIMARY UNITS

Main Characteristics	Primary anaerobic pond	Primary facultative pond
Influent wastewater	domestic, normal	domestic, normal
Effluent	grey, few settleable solids, 50-70% BOD ₅ reduction, septic odour	green, few settleable solids, 60-90% BOD ₅ reduction, odourless
Dissolved oxygen	absent	present
Retention time	1 to 5 days	7 to 50 days
Water depth	2.5 to 5.0 m	1.5 to 2.0 m
Effluent pH	6.5 to 7.5	7.0 to 10.0
Algae in effluent	absent	present
Coliforms in effluent	many	considerable

These ponds should only be used to upgrade the effluent from a facultative pond, from another maturation pond (or from another type of wastewater treatment plant). They should not receive raw wastewaters nor anaerobic-pond effluents. Although they are not designed specifically for upgrading poor effluents from other ponds, they achieve this objective to a certain, though limited, extent, having the effect of "polishing" the effluents from preceding stages of treatment.

Maturation ponds are normally designed for a retention time from 3 to 10 days per pond when two or more are in series (a minimum of 5 days when only one is used), while typical depths range between 1.0 and 1.5 metres.

V-5. CONFIGURATIONS OF POND SYSTEMS

Anaerobic, facultative and maturation ponds are often used in series. Each stage in a series may be broken down into two or more ponds operated in parallel.

Anaerobic ponds are frequently used ahead of facultative ponds in order to reduce the land area required. A comparison of the main characteristics of anaerobic and facultative ponds is given in Table I. Facultative ponds followed by one or more maturation ponds are used where a high-grade effluent is necessary, especially with regard to pathogenic organisms. This is the case when effluent is reused for agricultural purposes and for aquaculture.

Some typical pond configurations in parallel and in series are shown in Fig.6.

CHAPTER V. BASIC CONSIDERATIONS

V-6. POND LOCATION AND ORIENTATION

The site for stabilization ponds must be carefully chosen so as to minimize the likelihood of complaints and to take advantage of any beneficial natural and local features. Thus, the location and accessibility of alternative sites with respect to the community or industry being served must be considered, while allowance must be made for sewerage expansion plans and urban master plans. Both the topographical and geological features of sites must be taken into consideration. For example, steeply sloping sites should be avoided wherever possible because of the need for high embankments.

Anaerobic ponds should be located at least 1000 metres from the nearest dwelling, while facultative ponds should preferably be at least 500 metres away. Wherever feasible, stabilization ponds should be located so that the direction of the prevailing wind is **away** from the nearest community and, if possible, the ponds should be oriented so that their longest dimension is parallel to that direction. The water level in the final pond discharging to a receiving water body must be chosen to allow gravity flow even under flood conditions.

The aim is to have the discharge water level in the first stabilization pond below the invert level of the final manhole in the incoming sewer, so as to eliminate the need for pumping.

Chapter VI

FACTORS AFFECTING TREATMENT IN PONDS

There are several factors which may, advantageously or adversely, affect the hydraulic and biological conditions of wastewater stabilization ponds. Some of these factors can be taken into account at the design stage, whereas others, as already stated, are beyond the designer's and the operator's influence. These factors must be understood so that detrimental effects may be minimized. Care in site selection and design can reduce the impacts of some factors.

VI-1. NATURAL FACTORS

Natural factors are not controllable by man. They are mainly the meteorological phenomena: wind, temperature, rainfall, sunshine and evaporation.

VI-1.1. Wind action

Stabilization ponds should be designed in a manner that favours wind friction upon the water surface and hence induces mixing. A long "fetch" in the direction of the prevailing wind is beneficial. However, whenever possible, ponds should be located at a site where the prevailing wind is not in a direction towards the community, in case odour problems arise.

Wind action is useful as it mixes the pond's contents, thus conveying oxygen from the surface to the deeper layers, dispersing influent and microorganisms throughout the entire liquid mass. In addition, if photosynthesis is not sufficient and there is an oxygen deficiency, wind may contribute to the transfer and diffusion of atmospheric oxygen into the liquid mass. If the site where the ponds are located is subject to strong winds, high waves may result. These can cause erosion of the embankment slopes, and slope lining or some other protection may be required at the water level (see §XII - 3.2).

VI-1.2. Temperature

Wastewater stabilization in ponds is achieved by means of physical, chemical and biochemical reactions which are significantly influenced by temperature. Thus, the rate of photosynthesis and the cellular metabolism of microorganisms are enhanced by high temperatures and retarded by low temperatures. Stabilization pond design should take account of the most adverse temperature conditions.

CHAPTER VI. FACTORS AFFECTING TREATMENT IN PONDS

Temperature is an uncontrollable factor, yet it is of paramount importance to the satisfactory performance of a wastewater stabilization pond. At lower temperatures, dissolved oxygen present in the ponds has a tendency to remain in the pond longer than at higher temperatures. If the temperature rises, dissolved oxygen is likely to be partly liberated to the atmosphere, especially under supersaturated conditions. On the other hand, since algal oxygen production is directly related to photosynthesis, which is also temperature-dependent, in colder waters oxygen production is lower than in warmer waters. The biological activity of microorganisms decreases by about 57% when temperature drops by 10°C. The best efficiency obtained in anaerobic, facultative and maturation ponds occurs on days with good solar radiation (sunny, cloudless weather), at an air temperature in excess of 20°C and in the presence of a mild wind. However, above 35°C the rate of photosynthesis declines rapidly, so as to be practically negligible when the temperature is in excess of 45°C for some time.

High temperatures stimulate blue-green algae (*Cyanophyceae*) to grow more intensively, replacing to a certain extent the more efficient green algae (*Chlorophyceae*). At the same time, aerobic bacteria consume oxygen at a higher rate, creating conditions which are likely to result in the appearance of anaerobic patches at different points in the pond.

A sudden increase in temperature may adversely affect facultative pond efficiency in the following way: bacterial activity is quickly stimulated, growth is also enhanced and the oxygen uptake rate increases. If this higher uptake is not compensated by a higher oxygen production, anaerobic conditions may arise, the effluent may become turbid and objectionable anaerobic odours are likely to be released.

A sudden drop in temperature may slow down algal activity, with a lowering of oxygen production. Part of the algal mass is then likely to settle to the lower layers, the green colour will be greatly reduced and pond efficiency will decrease. It has also been reported that in the colder months there is an increase in phosphorus and ammonia nitrogen in the effluent from facultative ponds.

At very high temperatures, heavy algal blooms are likely to occur. Thick green mats may appear on the water surface, causing the lower layers to be darkened by their shadow, with a consequent reduction in oxygen production. Oswald [3] considers this condition a "pond failure". However, it is often possible to remove the greater part of the floating green mats with a long-handled skimmer, restoring the light transparency and hence the photosynthesis in deeper layers.

Some design criteria consider the minimum monthly mean water temperature that might occur during the year. The McGarry and Pescod [4] formula considers the minimum monthly average air temperature, which is a parameter more easily found in meteorological records and tables than water temperature. There are formulae for converting air temperature to water temperature but they are not widely applicable and can lead to illusory results. They may be used as an approximation in the absence of better local data. One example of such a formula is given by Eckenfelder [5] :

$$(T_0 - T_p) = \frac{(T_p - T_a) f A_p}{Q} \quad (1)$$

where: T_0 = influent temperature ($^{\circ}\text{C}$);
 T_p = pond temperature ($^{\circ}\text{C}$);
 T_a = ambient air temperature ($^{\circ}\text{C}$);
 f = proportionality factor (-0.489 for the central region of USA);
 A_p = pond surface area (m^2);
 Q = wastewater flow rate (m^3/d).

The proportionality factor, f , incorporates the heat transfer coefficients, the surface area increase due to agitation, and wind and humidity effects. Its approximate value quoted by Eckenfelder [5] for the central portion of USA and by Metcalf and Eddy [6] for eastern USA for temperature, area and flow rate measured in units of $^{\circ}\text{F}$, ft^2 and $10^6 \text{ gal (US)}/\text{d}$, respectively, is 12×10^{-6} , which transforms to 0.489 for the units given above.

VI-1.3. Rainfall

The mean and maximum rainfall will have some influence on pond performance and reliability. Retention time in ponds will be reduced during periods of rainfall. Heavy showers may dilute the contents of shallow ponds, affecting the food available to the biomass. The sudden increase in flow may carry over large amounts of solids in the effluent. On a very hot day, rain may cool the surface layer of the pond and create an inversion layer, with the appearance of floating anaerobic sludge, which spoils the effluent. It is not unusual to see algal mats on the surface of a pond driven to the bottom by a cool shower. Rainfall will also serve to add oxygen to a pond through its own dissolved oxygen content and by increasing surface turbulence.

Storm water entering a sewer system may carry considerable amounts of sand into the ponds and, especially if it is a combined system, will dilute the influent.

Overflow weirs must be provided if the wet-weather flow exceeds three times the dry-weather flow. A knowledge of stormwater flows will be essential for the design of the necessary works to protect earth embankments against damage and erosion.

VI – 1.4. Solar radiation

The intensity of solar radiation is an important factor in the satisfactory operation of facultative ponds, as it indirectly generates oxygen through algal photosynthesis. Nevertheless, the belief that the rate of photosynthesis increases without limit as solar radiation increases is a fallacy. In fact, beyond a certain radiation intensity, the **rate** of increase of photosynthesis declines until oxygen production reaches a constant level, a kind of saturation limit. From this point on, photosynthetic oxygen production will not increase, regardless of any further increase in solar radiation. Thus, for low light intensities, light is the limiting factor in oxygen production, whereas for high light intensities (several hours of warm sunshine on a clear day), temperature is the factor fostering (or limiting, see §VI – 1.2) oxygen production.

Facultative ponds rely on solar radiation, and this parameter varies mainly with latitude. However, another significant factor is atmospheric transparency. Clouds and haziness reduce the available light to some extent but, as has already been pointed out, direct sunlight is not absolutely essential. There are regions in the world where a blue sky is rather uncommon, yet stabilization ponds operate under completely normal photosynthetic conditions. A good example is the complex of 21 ponds at Lima, Peru, which were surveyed in 1979 under a collaborative arrangement between WHO, CEPIS (Pan-American Center for Sanitary Engineering and Environmental Sciences), IDRC (International Development Research Centre, Canada) and the Peruvian Ministry of Health [7]. There is also some evidence that too much solar radiation may either directly (possibly, by ultraviolet radiation) or indirectly (through shadow caused by algal blooms) have an adverse effect on photosynthesis, but this is still the subject of discussion.

VI – 1.5. Evaporation

Evaporation is a factor which, in combination with percolation through a pervious pond bottom, determines the expected reduction of the incoming flow and, in extreme cases, whether the pond will yield an effluent or not.

Intense evaporation may upset the ecological balance in stabilization ponds through the increase in the concentration of solids. It may also cause an undesirable reduction in the depth of water and affect retention time.

An evaporation rate of 5 mm depth per day amounts to 50 m³ per hectare per day of water loss and, up to this limit, the effect of evaporation may be disregarded [8]. However, in hot arid regions, evaporation may exceed 15 mm/d. Such intense water evaporation can concentrate the contents of a pond to some degree, with the possibility of increasing the salinity and the concentration of organic matter to a point at which the osmotic balance of the cells of the aquatic microorganisms is disturbed. Under these conditions their normal development, and thus the biological equilibrium of the biomass, is impaired. Furthermore, evaporation may drastically reduce effluent discharge and, in extreme cases, reduce water depth to a troublesome level, which may cause waterweeds to emerge near the embankments.

VI-1.6. Seepage

A survey of soil characteristics, particularly those connected with the permeability of the ground at the proposed pond site, is of great importance at the planning stage. This will provide information regarding the need for bottom lining. A knowledge of the depth to the groundwater aquifer and of aquifer use is also of assistance in deciding about lining. Soil sampling and testing will indicate whether the excavated earth is suitable for embankment construction and a simple infiltration test will indicate if percolation is likely to cause problems.

Ponds built on permeable soils should be lined in order to attain the maximum discharge possible, especially if the pond effluent is to be used for agricultural purposes. Lining with an impervious material is also important in cases where the groundwater needs to be protected from pollution. Lining techniques are dealt with in §XII-3.

VI-2. PHYSICAL FACTORS

Physical factors are generally related to design and the designer is able to be selective in deciding among alternatives.

VI-2.1. Surface area

The surface area of a stabilization pond is determined as a function of an organic loading (usually expressed in terms of BOD₅) applied per day, especially for facultative ponds. In warmer climates, surface (or areal) loadings from 150 to 400 kg BOD₅/ha·d have been used successfully for facultative ponds. The lower loadings apply to ambient air temperatures around 20°C and the higher ones to temperatures of about 30°C. Surface loadings in excess of 200 to 250 kg BOD₅/ha·d have been claimed to result in occasional odour problems, while

CHAPTER VI. FACTORS AFFECTING TREATMENT IN PONDS

loadings much in excess of 400 kg BOD₅/ha·d are likely to lead to anaerobiosis (absence of dissolved oxygen) and/or to a drop in the overall efficiency of the plant.

VI-2.2. Water depth

Stabilization ponds are normally operated at constant depth. Nevertheless, as a consequence of intense seepage and evaporation, or of some emergency withdrawal of pond contents, the water level might drop on occasions, causing problems. If the depth drops to as little as 0.6 m, aquatic plants are likely to have their growth stimulated and a large fraction of the surface may become covered with weeds extending above the water level. Thus, penetration of sunlight will be impaired and pond efficiency may drop to an unacceptable level. In such a case, mosquito breeding may also occur. The same nuisances might develop during the first few months of filling the pond, when the level is still low. For this reason, it is advisable to fill the pond as quickly as possible to the normal operating level before loading it with wastewater, for instance by pumping in water from a nearby water body, perhaps with the help of a mobile pump of the local fire brigade or using a portable pump for small installations.

If, on the other hand, the water depth is made greater than 2 m, sunlight will hardly reach the lower layers and photosynthesis will be reduced to a point where a large anaerobic layer develops, which could eventually disturb the process. A typical design depth for facultative ponds is 1.5 m, with 1 m being the absolute minimum depth for any of the three types of pond considered.

VI-2.3. Short-circuiting

Short-circuiting in ponds is the cause of several problems, such as the appearance of dead or stagnant zones that reduce the effective volume and surface area of the pond, with the possibility of odour problems in the overloaded areas. An inevitable consequence is the reduction of pond efficiency.

The wastewater to be treated should be introduced into the pond below the surface at a location some distance from the edge. It is advisable to locate inlets and outlets in carefully chosen positions, for instance splitting the inlet into two or more pipes and placing the outlet as far as possible from the nearest inlet. A relative location of inlet and outlet favouring the transport of incoming wastewater directly to the outlet through the action of the prevailing wind should be avoided. Water currents induced by wind are likely to be more important as a short-circuiting factor than the relative positions of inlet and outlet. A poorly-shaped pond may

also contribute to short-circuiting; other factors are weed growth, silting and stratification (§VIII – 2).

VI – 3. CHEMICAL FACTORS

The main chemical factors affecting pond performance are:

- pH – value;
- toxic materials;
- oxygen.

VI – 3.1. pH – value

Both anaerobic and facultative ponds operate most efficiently under slightly alkaline conditions. Industrial wastewaters which are likely to cause extremes of pH – value in ponds should be controlled at source rather than introducing the complexity of pH adjustment at the influent to ponds.

In warm climates, anaerobic ponds with hydraulic retention times of 3 – 5 days are unlikely to produce any serious problems in treating sewage and will automatically maintain a pH – value that is slightly alkaline. Under these conditions, methane fermentation will be in balance with acid production.

In the case of facultative ponds, if the pond colour is deep green, the pH – value is likely to be in the alkaline range whereas, if the pond is yellowish-green or milky, the chances are that acidification has taken place. There is, however, a natural diurnal variation in facultative pond pH – value; in the morning hours it will be somewhat low, due to the presence of excess CO₂ produced by aerobic bacterial respiration during the night, whereas at the end of the afternoon, it will increase as a result of algae absorbing the major part of the CO₂ in solution.

VI – 3.2. Toxic materials

The presence of toxic materials is a problem that cannot be overcome in the operation of pond systems. Heavy metals, pesticides, disinfectants, sulphides, wastes from antibiotic-producing industries, and other industrial wastewaters received by the collection system should be controlled at source. Limits on discharges to sewers must be applied.

Stabilization ponds are generally less sensitive to the presence of toxic substances than other treatment processes. The long retention time permits a

CHAPTER VI. FACTORS AFFECTING TREATMENT IN PONDS

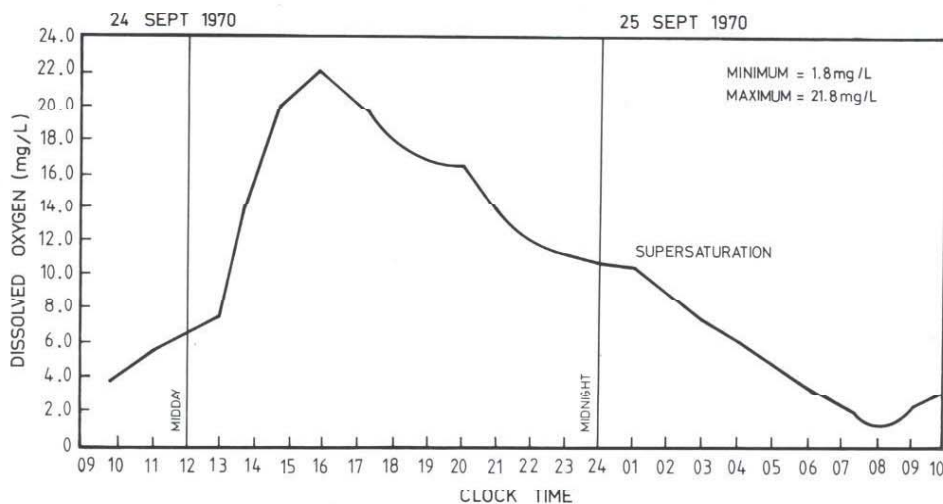


FIG.7. Variation of dissolved oxygen measured at one-hourly intervals over a 24-hour period in a facultative pond in Brasilia, Brazil [27].

gradual adaptation of the biomass to inhibiting substances by natural selection; the most resistant strains of each species survive and multiply whilst the most sensitive ones die off. This applies particularly when there are no shock loads. Tests carried out in warm countries have shown that ponds can resist relatively high concentrations of heavy metals. Concentrations up to 6 mg/L each of cadmium, chromium, copper, nickel and zinc are claimed not to have disturbed the treatment efficiency of facultative ponds. A United States Environmental Protection Agency manual indicates that the first signs of efficiency impairment are felt only when the overall concentration is in excess of 60 mg/L (12 mg/L of each of the five above-mentioned metals) [9].

VI-3.3. Oxygen

Dissolved oxygen is the best indicator of satisfactory operation of a facultative or maturation pond. The contents of normally-functioning facultative ponds will have a supersaturation of free dissolved oxygen at the surface and in the subsurface layers during the afternoon. However, the dissolved oxygen concentration may drop to less than 1.0 mg/L at dawn and sometimes, after an exceptionally clear and sunny day, complete depletion of oxygen may occur during the night due to an exceptional algal bloom.

The aerobic surface layer serves to strip out malodorous gases which may be released from the anaerobic layer. Nevertheless, odour problems still occur from

time to time in facultative ponds, in spite of the presence of dissolved oxygen in the surface layer. This may happen when blue-green algae develop as a consequence of high water temperature or when anaerobic patches appear on the surface of a pond because the bottom temperature has increased rapidly above 22°C and a vigorous release of gas has taken place.

Figure 7 shows a typical variation of dissolved oxygen concentration near the surface of a facultative pond over a 24 – hour period.

VI-4. WASTEWATER AND RECEIVING WATER CHARACTERISTICS

VI-4.1. Wastewater flow

Stabilization ponds are sometimes designed on the basis of hydraulic retention time, a parameter directly related to wastewater flow. Since the hydraulic retention time in ponds is normally several days or weeks, the average flow rate is an adequate basis for design. Due to the relatively large volume of pond systems, maximum and minimum flows in the collection system are damped out and only average flow needs to be considered.

If there are no measured data on sewage flow, it can be estimated from the number of inhabitants contributing to the sewer system, the per caput wastewater contribution and the amount of groundwater infiltration.

VI-4.2. Wastewater composition

The design of stabilization ponds is directly related to wastewater characteristics, which vary from country to country. Wastewater composition is influenced by the type of sewerage system and the contributing industries. Combined sewers convey a more dilute wastewater on rainy days whereas separate sewers are much less sensitive to rainfall, although some stormwater always enters the system. In addition, infiltration contributions, industrial and institutional discharges, the legal or illicit dumping of septic tank sludge into the sewers and other unusual circumstances often seriously affect the characteristics of domestic sewage. Under such conditions, a sampling and analysis programme should be carried out and flow should be measured.

Organic loading is the most fundamental parameter used in the design of any biological treatment process. This loading may be determined in terms of BOD₅ (5 – day biochemical oxygen demand) or COD (chemical oxygen demand) or,

CHAPTER VI. FACTORS AFFECTING TREATMENT IN PONDS

ideally, both. There is a movement towards replacing (or at least supplementing) BOD_5 and COD by TOC (total organic carbon) but, because of the need for fairly sophisticated laboratory equipment to measure TOC and the scant data available, following this trend is not recommended. Only after sufficient data have been gathered to enable a true assessment to be made of the practical advantages of using TOC, if any, should one consider using TOC for routine analysis.

Some parameters other than organic loading may be important where industrial wastewaters are to be treated, or are present in the sewage, since the designer will need to know if some pre-treatment has to be provided to protect the biomass in the pond system.

If the wastewater is expected to be a typical domestic sewage but is not available for analysis, an organic load per caput of the population connected to the system may be assumed. Wagner and Lanoix [10] suggested a per caput BOD_5 contribution of about 40 g per person per day for developing countries. In India, the per caput BOD_5 has been found to vary between 31 and 45 g per person per day (Mara [11]), while in Brazil, the environmental protection agency of Sao Paulo (CETESB), after surveying seven inland towns, obtained on average 44 g BOD_5 per person per day [12]. A figure of 45 g BOD_5 per person per day now seems to be reasonable.

Where a sample of sewage cannot be obtained for analysis, it is advisable to obtain a representative analysis of the water supplied to the sewered community to check on such characteristics as total dissolved solids (TDS), sulphates, etc.

VI-4.3. Characteristics of receiving waters

If the pond effluent is not to be reclaimed for further use, it will have to be disposed of somewhere, most often into a stream or a lake. The self-cleansing and dilution capacity of a receiving water under conditions of critical flow should be known in order to determine the degree of treatment to be provided. Sometimes a heavily-loaded primary pond may be sufficient, while in other cases several ponds in series or an upgrading of effluent quality by other means are required.

If the receiving body is a non-eutrophic lake, the nutrient content of the pond effluent is often the most critical factor which needs to be taken into account to prevent eutrophication. Should a wastewater stabilization pond effluent have to be discharged into an estuary or into the sea, it is worthwhile making a series of algal survival tests in the saline water. If the algae in the pond effluent do not remain

WASTEWATER STABILIZATION PONDS

alive, they will constitute a new organic load on the receiving water and this will have to be taken into consideration in deciding the feasibility of stabilization pond treatment.

The highest level of the receiving water under flood conditions must be known so as to locate the pond at an adequate elevation to allow gravity discharge of the effluent at all times.

Chapter VIII

FAVOURABLE AND UNFAVOURABLE FACTORS RELATED TO FACULTATIVE PONDS IN WARM REGIONS

VIII-1. FAVOURABLE FACTORS

If pond temperature is about 30°C, important beneficial effects may be expected in stabilization ponds. The main parameter positively influenced by high temperature is the biodegradation rate constant, K , because organic matter is broken down more rapidly as temperature increases. Under normal conditions at 30°C, biodegradable substances are stabilized at a rate 2.3 times faster than they are at 20°C, assuming a temperature reaction coefficient of 1.085. As has already been pointed out, above 30°C even though biodegradation is stimulated, secondary effects may impair the final result.

Photosynthesis, the major oxygen-producing phenomenon in ponds, is also fostered by higher temperatures, though the presence of solar radiation is indispensable. Green plants absorb a fraction of the incident solar energy in order to convert inorganic carbon (CO_2) into organic matter. To a certain extent, an increase in solar radiation speeds up photosynthesis, though direct sunlight is not essential.

Wind-induced currents are beneficial in pond installations. Unfortunately, windless days and nights are frequent in warm regions. However, there are some rules to follow if maximum advantage is to be taken of wind action; these will be discussed in later sections. Warm air temperature combined with reasonable sunshine and a mild wind constitute an ideal combination of favourable conditions for producing good results from a wastewater stabilization pond system.

VIII-2. UNFAVOURABLE FACTORS

Studies on factors influencing facultative wastewater stabilization pond performance were carried out at the experimental wastewater stabilization ponds of IPHER (Institute of Public Health Engineering and Research) at Lahore, Pakistan, under conditions of high temperatures (up to 35°C) and high light levels (up to 77 000 lux*) [14]. It was shown that facultative ponds were most efficient when the

* The lux is a unit of "illuminance", being the light flux incident per square metre of surface area.

WASTEWATER STABILIZATION PONDS

light levels ranged from 49 000 to 63 000 lux. As the light level increased further; efficiency decreased.

During the corresponding period, the pond temperature increased beyond 30°C, at which time the green algae were replaced by blue-green species and algal mats started to appear on the pond surface, obstructing the penetration of light to lower depths, hindering photosynthesis and reducing pond efficiency. Similar phenomena were observed at the Mairiporã wastewater stabilization pond system (Sao Paulo, Brazil), where the mats had to be removed with a long-handled skimmer in order to restore pond efficiency [13]. This kind of mat often emits detectable odours.

Algal blooms occur very often in warm ponds. They quickly absorb dissolved carbon dioxide and bicarbonates, with a resulting increase in pH – value, which may rise to more than 10 [15]. Such a high pH – value inhibits bacterial oxidation and thereby produces an effluent that eventually does not meet established standards. However, a high pH – value will assist pathogen die-off.

Another negative factor is the occurrence of stratification, with the concurrent appearance of a thermocline. Stratification in a facultative pond can justly be considered an enemy of efficient operation [16]. During periods of high temperature and intense solar radiation, the upper layers of the pond become appreciably warmer than the lower levels. As a result, two distinct layers of water may develop in the pond: the epilimnion above and the hypolimnion below, separated by the thermocline. Thus it is not uncommon to have a temperature difference of 10°C or more between the surface layer and a layer at a depth of 0.5 m [2].

The hypolimnion is frequently devoid of dissolved oxygen while, at the same time, intense sunshine fosters algal proliferation in the upper layer. As a consequence, water turbidity increases and light penetration is severely impaired, inhibiting photosynthesis in the lower layers. This relatively opaque blanket reinforces the stratification already achieved and only a small fraction of the total water volume is aerobic. The major fraction is anoxic and very little, if any, diffusion occurs between the layers. Unless a reasonably strong wind is able to destroy the stratification by mixing, it may continue unbroken for weeks or months during hot periods [16].

An additional disadvantage of stratification is that short-circuiting occurs, with the incoming wastewater spreading underneath the warmer layer. It passes out of

CHAPTER VIII. FACULTATIVE PONDS IN WARM REGIONS

the pond having utilized only a small fraction of the pond volume and having been subject to a much reduced retention time. Short-circuiting across the top is also possible if the influent is appreciably warmer than the upper layer, as might be the case with an industrial wastewater.

It should be noted that some authors consider that stratification is beneficial, with mixing occurring only in the top layer, because the presence of an anoxic zone near the bottom of a facultative pond is vital to methane fermentation, this accounting for much of the treatment efficiency. As in all things, this is a question of degree and should not impair the overall performance of the pond.

A falling ambient temperature on a calm night, especially after a clear and warm day, creates the worst meteorological conditions from the point of view of pond failure through oxygen depletion.

Chapter IX

WASTEWATER TREATMENT IN HOT AND ARID REGIONS

Many of the hotter regions of the world are areas where water is scarce, hence wastewater reuse is important. A great many creeks, streams and rivers exist intermittently and, for some months in the year, there is no water to serve as receiving body. Thus, in both cases (water reuse and absence of receiving water), there need be little concern about BOD removal. However, there are other factors to be taken into account, such as, for instance, pathogen removal in order to protect farm workers, crops and animals. Another effluent requirement might be low suspended solids which, under certain conditions, could clog the soil pores or, in the case of suspended algae, could generate objectionable odours when they decay. For agricultural use, the treated effluent should not contain more than about 2500 mg/L of total dissolved solids: thus evaporation could be an important limiting factor when considering stabilization pond treatment. The interaction of effluent and the soil (a function of effluent quality and soil chemistry) as it relates to permeability of the soil profile is of paramount importance. In this respect the sodium adsorption ratio is an important quality parameter.

The solubility of dissolved oxygen decreases at higher temperatures, and continual evaporation from ponds tends to increase the concentration of minerals. This in turn further decreases the solubility of dissolved oxygen.

Although many authors consider stabilization ponds to be efficient BOD removers, others do not, because of the relatively high suspended organic solids content frequently carried over with the effluent. Effluent BOD is often determined on filtered samples, and efficiency calculations are significantly affected by the analytical method adopted. Nevertheless, if ponds are properly designed and suitably operated in series (see part B), high-grade effluents can be produced consistently. Such combinations of ponds used for treating sewage are reported to discharge effluents meeting water reclamation and reuse standards for agricultural purposes. They may be expected to yield effluents with as little as 300 faecal coliforms per 100 mL, a soluble BOD less than 10 mg/L (although 60 mg/L is acceptable for irrigation reuse) [17], and very low suspended solids (in the range 10–30 mg/L [18]).

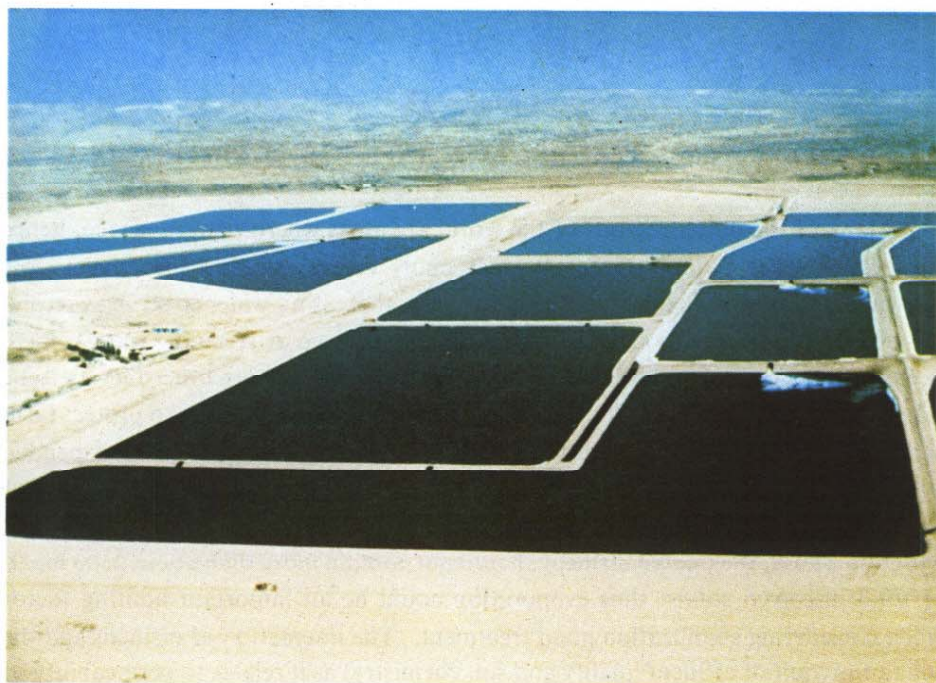


FIG.8. An aerial view of the IRP wastewater stabilization pond system. Pond F3-4 (see Fig.6B) is in the foreground. The No.1 train seen in the background is empty (i.e. only trains 2 and 3 are operating). The pipeline connecting the plant with Amman is 39 km long. The BOD_5 removal under summer conditions using two trains is expected to give the same quality of effluent as do three trains under winter conditions. The final effluent is to be used for irrigation; the 18 million cubic metres of water per year is enough for 4000 hectares (40 square kilometres). Residual sludges are removed every few years and applied as fertilizer to the planted areas in the immediate vicinity of the ponds. 10000 apple, 30000 olive and 260000 poplar, eucalyptus and acacia trees were planted by the end of 1985, a further 300000 forest trees during 1986.

While, especially in hot climates, consistently good results should not be expected from heavily-loaded stabilization ponds, well-designed and properly operated and maintained ponds will provide effective wastewater treatment (Fig.8) and should always be the treatment of first choice in developing countries. More sophisticated wastewater treatment techniques should be used only if there are most convincing reasons for not employing ponds.

IX-1. POND DESIGN FOR HOT AND ARID REGIONS

Designing a wastewater stabilization pond for hot regions is not unlike designing a biological reactor, including the "art" of creating habitats for the many living species that nature is constantly feeding into different parts of the pond environment. Ecological niches must be provided for the intended specific fauna and flora which are expected to perform the tasks assigned to them.

WASTEWATER STABILIZATION PONDS

Stabilization ponds are shallow and cover large areas of land. They are the simplest treatment by which man attempts to foster the natural processes of purification, but this does not mean that the chemical, physical and biological processes occurring in a pond are simple. It does, however, imply that there is only a limited amount that the designer can do to facilitate operation and, once the pond is constructed, even less that the operator can do to modify the process.

In hot climates, mathematical models based on biochemical kinetics and dispersion processes are of limited assistance in designing stabilization ponds because of the considerable importance of secondary phenomena that cannot be taken into account. Initially, the designer must recognize that it is not yet possible to quantify more than a fraction of the parameters affecting the process, i.e. it must be appreciated that all existing design approaches are approximations. Designers should resist the temptation to adopt a highly complicated method of design and should remember that often the best assistance that can be obtained is to study the results of operation of existing ponds somewhere in the same region. Frequently, an empirical design based on the operation of existing ponds will not only be the simplest but also the "safest" and most effective approach.

Maturation ponds will, to a large extent, correct the malfunctions that may occur in primary facultative ponds, but should not be designed for that purpose. The very good bacterial removal efficiency of a combination of facultative and maturation ponds is not equalled by any other process of wastewater treatment, unless disinfectants are used. Normally, secondary or tertiary treatment in maturation ponds will dispense with the need to disinfect effluents intended for agricultural reuse.

For environmental, financial, safety and technical reasons, as well as for reuse considerations in fish rearing and irrigation, use of chlorine on stabilization pond effluents should be avoided. Chlorination will also raise the effluent BOD by killing the algae and releasing their organic content for bacterial degradation. While living algae do not exert a very large BOD when young, as they grow older in long-detention ponds, or are deprived of CO_2 at high concentration, they excrete biodegradable organic substances, which then cause secondary growths of oxygen-consuming bacteria. Thus, algae appear to exert a BOD, even though live algae will consume less than 15% of their dry weight in oxygen daily.

Single facultative ponds may not provide satisfactory coliform removal for reuse purposes. Particularly in heavily-loaded units, the concentration of organic

CHAPTER IX. WASTEWATER TREATMENT IN HOT AND ARID REGIONS

matter may be such as to allow coliform bacteria to reproduce, thus affecting the net die-off [19]. For efficient pathogen removal, it is necessary to use one or more maturation ponds in series with a facultative pond (§XXI-2).

On the one hand, ammonia-nitrogen in the effluent from ponds is beneficial for crop growing. On the other hand, if the effluent is to be discharged to a receiving water, ammonia at concentrations in excess of 0.5 mg/L may be harmful to fish; it also creates an oxygen demand. Nevertheless, although nitrification of ammonia-nitrogen may take place in ponds, it is an uncontrollable reaction, as are all the others.

Nitrification does not occur consistently in facultative stabilization ponds, although the bacteria for ammonia oxidation are present and the necessary oxygen is made available by algal photosynthesis and natural re-aeration. It is not clear, however, why nitrification occurs in ponds at certain times and does not occur at others, under apparently similar conditions [20].

Nitrates are very rarely found in established facultative ponds. Probably any nitrate that forms is quickly converted to N_2 by denitrifying bacteria in the lower layers. Nitrate is only likely to occur in shallow, well-mixed, aerobic ponds, or in ponds which follow trickling filter, activated sludge or aerated lagoon treatments. Higher concentrations can also result from carry-over of high concentrations of nitrate in the water supply.

Nitrification generates hydrogen ions, destroying part of the alkalinity of the pond, i.e. reducing the pH-value. For each 1 mg/L of ammonia that is oxidized, 7.1 mg/L of alkalinity are neutralized. Since nitrification is stimulated at high temperatures, a beneficial effect may be expected from reducing the high pH-values caused by algal blooms. However, high pH-values result in high coliform and pathogen removal.

IX-2. BASIC DESIGN CONSIDERATIONS

There are many considerations to be taken into account before or during the design of a pond. Some of the factors mentioned in §§VI-1 to 4 are considered here but, in addition, the designer is expected to take account of other types of information, such as standards and regulations, treatment requirements, population growth estimates, etc. General design considerations are discussed, for example, by Gloyne [8] and Lumber [21].

WASTEWATER STABILIZATION PONDS

As a guide, the following data may be needed when designing a pond system:

- standards, regulations, and which are the regulatory agencies;
- period of design, target date for start of operation;
- present and future populations to be served (estimates of population growth);
- industrial wastewaters (population equivalents, acceptability of industrial wastes, recommended pre-treatment);
- analysis of sewage;
- flows for design;
- loadings for design;
- treatment requirements;
- final disposal or reuse of the treated effluent;
- insolation conditions;
- temperature conditions;
- direction of prevailing wind(s);
- groundwater infiltration into the sewer system;
- stormwater intrusion;
- suitability of pond treatment, combinations of ponds;
- possible sites (distance from nearest dwellings, communities etc.) with selection of the best alternative;
- possibility of contaminating groundwater;
- shape and orientation of the ponds, positions of inlets and outlets;
- constructional details;
- area requirements, net and gross;
- sludge accumulation and removal.

There are several ways of tackling the design of wastewater stabilization ponds used singly or in combination, and different modelling systems have been developed by individual design teams. For example, some designers consider ponds to be completely-mixed systems and develop their models on the basis of first-order reaction kinetics. Much evidence supports the hypothesis that temperature and insolation are the factors of paramount importance to pond functioning, and most design approaches take these two factors into particular account. Nevertheless, the statement made in §IX – 1 generally holds true, that “an empirical design based on the operation of existing ponds will not only be the simplest but also the “safest” and most effective approach.”

Chapter X

UPGRADING POND EFFLUENT

X-1. EFFLUENT STANDARDS FOR REUSE

The design of facultative and maturation wastewater ponds must ensure that the characteristics of the effluent are those required for reuse. The most important uses of reclaimed effluent are:

- agricultural irrigation; (Fig.9);
- fish rearing (aquaculture);
- groundwater recharge.

Proposed standards for these uses are summarized in Table II [17]. Pond effluents will more often than not fail to meet these stringent standards and would require upgrading before reuse. However, it should be noted that, for many places,



FIG.9. Reuse of pond water that meets bacterial and other standards for irrigation of cash crops can provide communities with additional jobs and a source of income that raises living standards.

these standards will be unnecessarily restrictive and they should be relaxed wherever feasible. Moreover, many effluent quality improvement methods are not appropriate for use in developing countries and are too costly. Examples of such technologies are: microstraining, rapid sand filtration, chlorination (which is strongly opposed), flotation, and treatment with activated carbon. There are, however, some forms of natural post-treatment that are feasible.

X-2. UPGRADING BY WATER HYACINTH

Water hyacinth has been used successfully to upgrade treatment plant effluents, particularly for the removal of algac. Even though the water hyacinth is the most feared waterweed, and should never be introduced into a country where it does not already exist, when control is properly mastered, good results can be obtained.

Water hyacinth is able to take up large amounts of nutrients, i.e. nitrogen and phosphorus, and heavy metals. At the same time its roots provide support for a gelatinous biomass which further stabilizes organic matter, producing carbon dioxide, inorganic substances and other materials, most of which are concentrated by the plants. Bacteria and other organisms adhere to the gelatine-covered parts. When the hyacinth is harvested, all these substances are removed from the water [22].

TABLE II. EFFLUENT REUSE STANDARDS [17]

Parameter	Agricultural irrigation	Fish rearing	Recharge
BOD ₅	No limit	< 10 mg/L	< 5 mg/L
Suspended solids	< 30 mg/L	Low	< 30 mg/L
Total dissolved solids	2500 mg/L	< 2000 mg/L	Low
Solubles in N-hexane	< 50 mg/L	No limit	Virtually none
Total Kjeldahl nitrogen	No limit	See ammonia	Low
Ammonia nitrogen	No limit	< 0.5 mg/L	Virtually none
Nitrate nitrogen	No limit	No limit	< 50 mg/L
Total phosphorus	No limit	No limit	< 10 mg/L
MPN ^a faecal coliforms	< 1000/100 ml	< 1000/100 ml	< 1000/100 ml
Cd, Hg and other heavy metals	Virtually none	Virtually none	Virtually none
Phenols	< 1 mg/L	< 0.001 mg/L	< 0.001 mg/L

a Most probable number (of).

CHAPTER X. UPGRADING POND EFFLUENT

Hyacinth grows very rapidly in hot climates, doubling its mass in about 6 days. One hectare of a hyacinth-covered pond can produce more than 4 tonnes wet-weight of plants or 200 kg of dry solids per day; more than 290 kg/ha·d have been reported [23]. Reductions of 80% nitrogen and 44% total phosphorus have been achieved by 0.55 ha of a hyacinth pond 0.60 m deep, with a retention time of 24–48 hours and fed with 1000 m³/d of facultative pond effluent [24]. Very low concentrations of ammonia nitrogen are present in water hyacinth ponds, which is important for fish rearing, and clear, low-BOD effluents are produced.

In order to facilitate hyacinth harvesting, it is convenient to use long channels, less than 10 metres in width, operated in parallel [22]. Harvested hyacinth may be disposed of by using the green mass as organic fertilizer, for feeding to cattle, setting up methane fermentation to produce fuel, composting for agricultural use, or in sanitary landfill.

Indeed, the rapidly growing experience with water hyacinths for removal of algae, residual suspended materials, dissolved organic substances and even microbial entities brings considerable confidence that their use for conditioning pond effluents, including nutrient removal, gives tangible advantages.

Other macrophytes have also been used for upgrading effluents, but less information on their performance is available.

* Gloyna, E.F., private communication, 1987.

Chapter XI

POND GEOMETRY

XI-1. FACTORS INFLUENCING POND SHAPE

Irregular contours in stabilization ponds must be avoided because they are likely to cause dead spaces, short-circuiting and wave amplification, thereby disturbing the normal functioning of the units. Most frequently, the shape of a pond results from the topographical relief of the site and is chosen to minimize earthmoving; the importance of reducing earthmoving effort and cost should, however, not be exaggerated.

XI-2. POND SHAPES

Square

The square is often a convenient shape for a stabilization pond. It normally necessitates less earthmoving than other shapes of equal surface area or volume. Several types of inlet and outlet may be used (see §XII-4).

Rectangular

The ratio of length to width should not be greater than 2:1 in rectangular-shaped ponds. If, however, a greater ratio is unavoidable, multiple inlets should be used. Some authors favour very long rectangular ponds (ratio length:width 3:1 or more) to foster wind action, but this idea should not be over-emphasized. Inlets and outlets are dealt with in §XII-4.

Irregular

Sometimes the available area of level or only slightly sloping land is limited, and thus square or rectangular ponds may be uneconomical because of loss of useful pond area at the edges. In such cases irregular-shaped ponds which fit into the available land may be used, but no peninsular or re-entrant angles or curves should exist (see §XI-1).

XI-3. POND CORNERS

No sharp corners should exist at the intersection of embankment slopes. Vertices should be rounded off and smoothed out to foster water movement and to avoid dead spaces.

Chapter XII

POND CONSTRUCTION, LINING AND APPURTENANCES

Pond design consists not only of determining surface area and depth but also of working out a number of constructional details and specifications which will assure proper performance of the unit throughout its life. Many reports on existing ponds indicate a series of disorders of a functional nature, failure of structures, as well as nuisances resulting from poor engineering. A sound design definitely minimizes such malfunctions as, for example, totally anaerobic zones in a facultative pond, absence of effluent due to seepage through the pond bottom, eroded embankments, excessive waterweed growth, mosquito breeding, insufficient wind-induced mixing, or silting around inlets. Furthermore, good design and engineering nearly always result in savings by minimizing lining requirements and optimizing excavation and fill, as well as by keeping maintenance costs low and precluding expensive civil engineering interventions needed to adjust design errors once the ponds are in operation.

XII – 1. EARTHMOVING

XII – 1.1. Bottom elevation for minimum earthmoving volume

On a level site, it is enough to dig out a shallow excavation to obtain the material required for construction of the embankments. The following two conditions are mandatory: (i) the operating water level in the pond should be situated below the invert of the last section of the incoming gravity sewer and above the highest groundwater table, and (ii) the soil withdrawn should be suitable for compaction and should maintain its cohesion when immersed.

Though surface organic soils and sand may not be suitable for embankment construction, satisfactory material is often found below the surface layer. This material may then be used to form a relatively impervious and stable core, while the surface soil can be used as a filler and for shaping the slopes of the embankments. Should no suitable soil be available at the site, it must be transported from elsewhere at extra cost. In this case, the bearing capacity of the in situ soils should be carefully considered to avoid subsequent embankment failure. Compressible or plastic soils may considerably increase the cost of embankment construction and raise doubts about the economy of the choice of stabilization ponds as mode of treatment.

WASTEWATER STABILIZATION PONDS

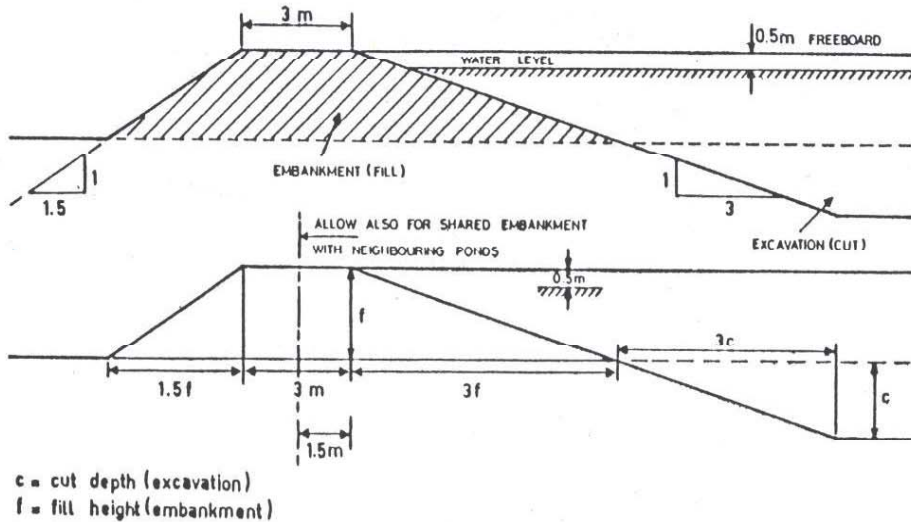


FIG.10. Embankment construction showing cut and fill. The broken line indicates the original ground level.

If suitable soil is available for embankment construction, the excavated material is compacted in layers, usually not more than 15 cm thick. The most economical condition arises when all the earth required to build the embankments can be excavated from the bottom of the ponds. On a geometrical basis, the excavated volume should equal the fill volume, but in practice some allowance must be made for shrinkage during compaction. Depending on the soil compressibility, moisture content and other factors, excavation should be increased by 10% to 30%. It is essential to take samples from soil borings made at the projected site to determine the shrinkage factor after compaction. If the site is sloping, the aim should still be the same – to balance the embankment fill with the excavation.

Thus, it is always advisable to seek the advice of a geotechnical engineer before proceeding with embankment design. Site borings will usually be necessary to identify available soils and to estimate construction costs.

An example of an optimization calculation is to be found in Appendix I and its associated Annex I.

XII – 2. EMBANKMENT GEOMETRY

To minimize erosion caused by wind-induced waves, the slope of the embankment on the wet side should be gentle: not more than about 1/3 or 1/4 (33% to 25%). Steeper slopes may be adopted when the characteristics of the soil allow or if protective lining is used. On the dry side of the embankment, the slope is often 1/1.5 (67%) or steeper (Fig.10). The dry slope and the strip above water level on the wet

CHAPTER XII. POND CONSTRUCTION, LINING AND APPURTENANCES

side should be grassed as protection against erosion. The species of grass chosen for this purpose will have a marked influence on maintenance costs. Furthermore, if the grass reaches below the pond water level, it will create a habitat for larvae, snails and other pests, and hence a narrow bare strip of about 0.3 m should be maintained between the grass and the water level (Fig.11A).

The top of the pond embankment should be made wide enough to allow the passage of vehicles at large installations; at small plants a 1.5 metre wide footpath is adequate. Access for vehicles calls for a crest width of not less than 2.5 m. After rough earthmoving, embankment slopes should be formed and finished by hand or with a blade scraper before grassing.

XII – 3. LINING

Lining should be the exception rather than the rule. It adds considerably to the cost of a pond installation and, for this reason, it should not be resorted to unless unavoidable.

XII – 3.1. Bottom lining

If the soil is too pervious, the pond might never fill to the design level because of seepage through the bottom, and the pond level will stabilize at a level where the static head above the pond bottom is sufficient to allow all of the inlet flow to percolate into the ground. If the static head approaches the predetermined water depth in the pond, it will do no harm for, as time goes by, the pervious pond bottom will progressively become clogged with settled sludge, leading to normal operation. Should the actual pond depth stabilize well below the desired level, it implies that a bottom lining should have been used. If water reclamation is important, pond bottom lining would be necessary to ensure an effluent.

It is important to determine the need for bottom lining before construction, since subsequent repairs are costly. Soil analyses and infiltration tests will help to avoid problems, but sometimes the results are misleading and failures can sometimes only be detected when the ponds are being filled. If it is decided to build a pond on fairly pervious soil, the bottom of the unit can be made watertight by laying a 10 cm thick layer of compacted clayey earth transported from a nearby site. One hectare will require 1000 cubic metres of lining clay. Some designers have accepted thinner clay layers, down to 5 cm, to save transport costs, but such a reduced lining is difficult to lay uniformly and gives poor adhesion to the original ground; subsequently, it is likely to fail at crevices, wash-outs, piping, etc.

WASTEWATER STABILIZATION PONDS

FIG.11A. View of strip on the embankment above water level that is kept free of grass and plant growth to avoid creating a habitat for pests. The operator is cutting the grass.

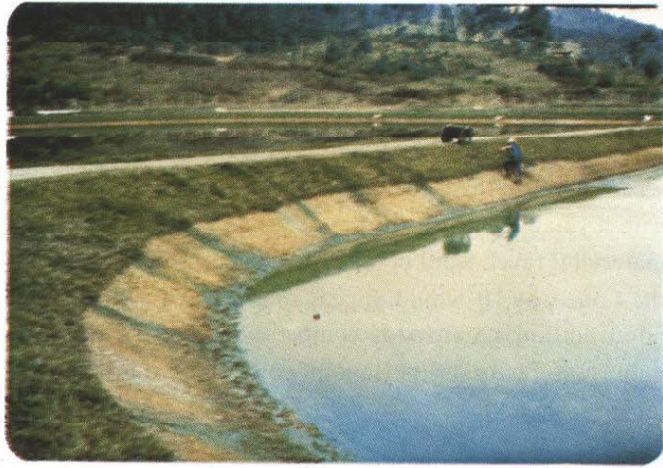


FIG.11B. Plastic sheeting used as pond lining to ensure that the pond operates at design water level, for seepage would be excessive in this porous, sandy soil.



Polyethylene and vinyl sheetings have been used in some instances, but their cost is likely to be high in developing countries. If this kind of waterproofing is employed, usually both the pond bottom and slopes are lined, with the edges of the liner extending to the crest of the embankment, to which it is fastened by some suitable means (Fig.11B). Plastic sheeting has been used to line only relatively small ponds, mostly mechanically-aerated lagoons. Low-cost lining films made of reclaimed scrap plastics are now being manufactured.

Another possible lining material is soil-cement, but there is a lack of information on its use in stabilization ponds. Soil-cement can be prepared manually using the in-situ soil, mixing it with 8% to 11% (based on dry solids) of Portland cement.

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The soil is first loosened by hand with a rake to a depth of about 5 cm and allowed to dry out somewhat. (If the soil has been allowed to dry out so much that it loses its cohesion, a minimum of water should be added carefully to restore the correct moisture content.) The correct amount of cement is placed on the ground in small, equal portions, say 30 kg per 4 m²; it is then uniformly distributed and thoroughly mixed with the loosened soil to achieve an even layer. After that, it is compacted with a small roller. In the case of soils with more than 70% by weight of granular material (gravel, sand or silt) soil-cement is most similar to concrete and is cured in the same way. It would appear that 8 kg of Portland cement per square metre of pond bottom stabilized is competitive in cost with any other means of lining; an important factor is the labour cost, since this form of bottom lining is labour intensive.

XII – 3.2. Slope lining

Generally speaking, lining of a gentle slope (say 1/3 (33%) or less) is unnecessary because waves resulting from wind friction will break on the slope and dissipate their energy gently, as on a beach, doing no harm to the embankment. Lining may be essential for steeper slopes, but the decision to line should not be taken without careful evaluation of alternatives. Rip-rap* seems to have been the most used lining for pond embankments, above and below the water level, where rock has been available at low cost. In this form of lining, rocks of different size and shape are placed together by hand without jointing them with mortar. Rip-rap is effective against erosion and weed growth. Rip rap should be about 15 cm thick and 1 m wide, 0.5 m above and 0.5 m below normal water level in the pond. Rip-rap is likely to entrap grease and other floating materials and, for this reason, some designers prefer to use concrete slab or brick lining, even at higher cost. A simple method of installing a concrete lining is to lay rolls of chickenwire in place and cover them with a 5 cm thick layer of cement mortar (ferro-cement).

XII – 3.3. Pond lining and groundwater pollution

There is general concern about groundwater pollution through seepage from stabilization ponds. Much of this apprehension arises from a lack of understanding about the ability of the soil to remove pollutants. Literature on the subject permits the following conclusions:

- In nearly all cases, bacterial contamination disappears completely after about 2 metres of passage through the soil from the point of wastewater infiltration;
- Organic and mineral colloidal matter is completely eliminated;

*Small broken rock of assorted sizes, often a by-product of quarrying operations.

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- Organic soluble matter passes through practically unchanged, even when long periods of time are involved, though some denitrification may occur in lower anaerobic layers;
- Nitrates that escape denitrification suffer no marked change (indeed, they can be used as tracers for groundwater movement);
- Phosphates are almost completely eliminated.

This evidence suggests that aquifer pollution should only be of concern where groundwater is abstracted for water supply close to a stabilization pond installation. Even then, the pollution would only be of a chemical nature and health problems would not normally arise. Only in very special cases, which will certainly be evident to the designer, will pollution be a major risk, for example with highly permeable strata or fissured bedrock.

XII – 4. APPURTENANCES

XII – 4.1. Pipes

Pipes going through the embankment should be installed prior to construction to avoid cutting and filling newly constructed work, with the risk of creating weak points.

XII – 4.2. Inlets

There is some disagreement about whether an inlet pipe to a pond should be submerged or located above water level (Fig.12). Arguments in favour of inlets at the bottom are their low cost and simple construction, while arguments against are the possibilities of obstruction by silting and setting of sludge at low flows and accumulation of settled material around the exits. It is claimed that elevated inlets are free from obstruction at low flows because the necessary minimum velocities are ensured even under partial-flow conditions, whereas inlets at the bottom always run full. Better mixing and dispersion conditions of the influent are attributed to elevated inlets, resulting from the turbulence the in-flow creates. Furthermore, visual observation of approximate flow patterns is possible from any point on the crest of the embankment with this type of inlet. The disadvantages of elevated inlets are higher costs, due to pipe supports (e.g. masonry pillars), exposure to vandalism and silting around the support columns.

Inlets, both submerged and elevated, should reach a point some distance from the edge of the pond. In square-shaped ponds, the inlet usually ends at the centre. In

CHAPTER XII. POND CONSTRUCTION, LINING AND APPURTENANCES

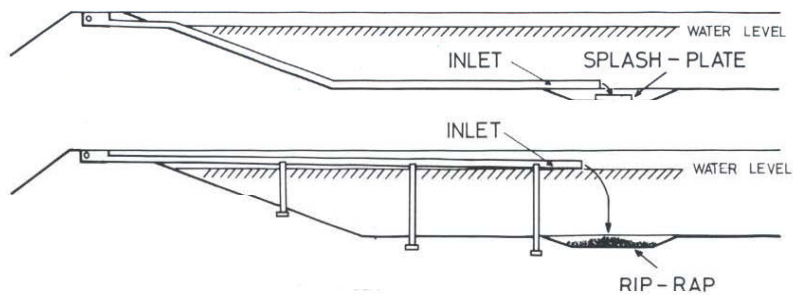


FIG.12A. Submerged and elevated inlets.



FIG.12B. Elevated inlet at the IRP ponds at Khirbet Samra, Jordan.

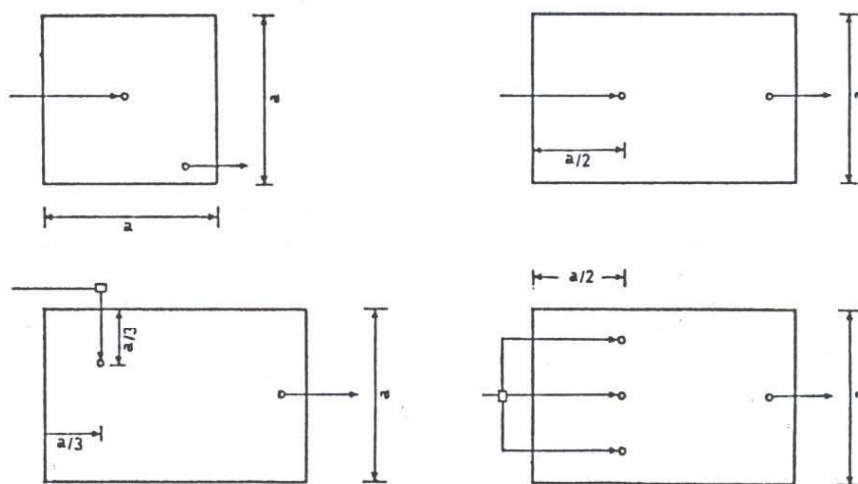


FIG.12C. Typical placement of inlets in square and rectangular ponds.

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rectangular ponds the inlet is frequently located as shown in Fig.12C, which prevents raw sewage from reaching the edges of the pond.

Inlets are not necessarily located as far as possible from outlets; short-circuiting is rarely caused by the relative position of inlet and outlet alone, since the upper layer of a pond is an almost completely-mixed system. More often, short-circuits are the result of the shape of a pond and of the fact that the wind blows for a long period in a direction from inlet to outlet [25]. However, if thermal stratification occurs, short-circuiting along the bottom may result.

Some authors recommend that a submerged inlet pipe should end with a short vertical section pointing upwards to keep the mouth clear of settled material. This practice, however, leads to a greater risk of obstruction in the inlet pipe. It is better to set the pipe horizontal and suspend it about 2 m above and in from the edge of a circular depression in the pond bottom about 0.5 m deep and some 10 m or more in diameter. This stores grit and settled material for many years, keeping it away from the mouth of the inlet; the depression also serves to protect the methane fermentation in the bottom layer.

Most frequently, however, submerged inlet pipes are bedded directly upon an even pond bottom, ending at a concrete splash pad of about 1 m diameter to prevent local erosion. For elevated inlets, the recommendation is to install a rip-rap lining of about 1 m x 2 m underneath the end of the pipe to prevent erosion of the pond bottom during the filling phase (Fig.12A).

XII - 4.3. Outlets

The outlet of a pond may be placed at any point on its edge, but is normally located at the base (toe) of the embankment at the opposite end to the inlet. There are many types of outlet, but many of them are attached to a discharge pipe at bottom level going through the embankment. This permits complete emptying of the pond, if necessary.

It should be kept in mind that the water level in the pond is controlled by the outlet device. The simplest form of outlet is a vertical pipe with its upper end at a level where the desired pond surface is to be; the lower end is connected to the discharge pipe. Most convenient, however, are outlets with devices allowing the pond level to be varied for operational purposes. Lowering the pond surface by 0.5 m will facilitate the cutting of weeds and the repair of slopes after erosion. Such an outlet may simply consist of a vertical square box with its base resting on the

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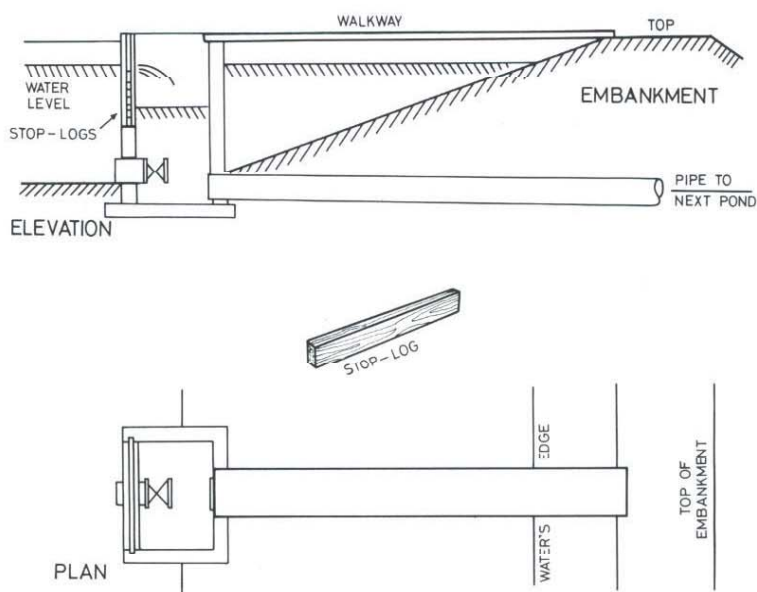


FIG. 13. Variable level outlet that serves as a weir.

pond bottom, at the toe of the embankment, its upper end emerging above the water level. One of the faces of this box is built partly of stop-logs which can be added or taken out, and the box then acts as a weir of variable height (Fig.13).

Some designers recommend the installation of a baffle around the outlet to prevent scum and floating matter from passing over with the effluent. In a well-maintained pond, where the operator removes floating matter as soon as the wind blows it into one of the corners, such a device is unnecessary.

XII – 4.4. Flow measurement

At least two flowmeters should be installed in each pond, one on the inlet and the other on the outlet (see also §XIII – 3). The inlet flowmeter may best be installed on the top of the embankment, just above the upper end of the inlet pipe. The outlet flowmeter may be the outlet control device itself if it is designed as a rectangular weir. Otherwise, a suitable flowmeter can be installed on the discharge pipe where it emerges from the outer side of the embankment. Comparison of inlet and outlet flows will give an indication of the magnitude of evaporation, seepage or infiltration, as well as of the diluting effect of rainfall. This comparison also serves a purpose in the evaluation of pond performance.

XII – 4.5. Interconnecting pipes between ponds

Interconnecting pipes are used to convey the effluent from one pond to another where two or more units are operated in series. In many cases, a pipe laid through the embankment below water level will serve as a suitable inter-connection, and the difference in water levels between the ponds will, at least, equal the head loss in the interconnecting pipe. If it is intended that the two ponds should have specific water levels, the outlet from the first pond must be fitted with a device which assures the required level in that pond (e.g. Fig.13), and so on.

If the interconnecting pipe is under water at both ends, say 30 cm or more, no special protection is needed to keep floating material on the surface of the first pond from entering the second. Some designers add, at the inlet end, an elbow-shaped bend, turned down so as to draw from a deeper layer. This device may be designed to be used as a variable level draw-off to transfer the contents of the first pond from the most advantageous layer to the second.

Frequently, the inlet pipe to the second pond is extended down along the slope until it reaches the toe of the embankment. Sometimes a flowmeter is installed on the transfer pipe. Its best location is on the inlet side, placed in a box penetrating slightly into the embankment.

Interconnecting pipes between successive ponds, for example an anaerobic and a facultative pond or a facultative and a maturation pond, must always be protected against floating matter entering the interconnecting pipe. Whenever possible, interconnecting pipes should enable individual ponds to be isolated. To accomplish this while continuing to operate the pond installation requires a by-pass system for each isolated pond.

XII – 5. REVISING THE DESIGN OF THE INCOMING SEWER

It was shown in the section on earthmoving (§XII – 1) that the most economical design will balance the fill against the excavation, allowing for compaction. If the elevation of the pond bottom so designed is at a level below that of the influent sewer, though the surface of the pond is above, it is possible that the incoming sewer could be relaid rather than resorting to pumping. This situation often arises when the sewer has been designed by a different designer, responsible only for the collection system. In this case, it might be feasible to reduce the slope of a length of the sewer so that it arrives at the pond embankment at an elevation above the pond surface level. For gently sloping terrain, this is frequently possible. If not, the cost of deepening the excavation for the pond must be compared with the capital and operating costs of a pumping unit.

Chapter XIII

POND INSTALLATION AND EQUIPMENT

XIII-1. MINIMIZING COMPLEXITY

Stabilization ponds involve the most rudimentary processes of biological wastewater treatment. They have been developed to produce an effluent suitable for discharge to most receiving waters. Once the designer has created a habitat for a balanced ecosystem in the ponds, the wastewater is practically abandoned to the forces of nature. Little can be done but to keep the pond and its surroundings in good condition. Consequently, one can hardly talk about *operation* of stabilization ponds because *maintenance* is almost all that can and needs to be done.

For this reason, pond facilities, utilities and equipment should be kept to a minimum so as not to interfere with the simplicity of the system. It should always be kept in mind that a major reason for adopting stabilization ponds is their economy; therefore including expensive appliances in a pond installation only adds, often unnecessarily, to the cost. Should pumping be absolutely essential, operational attention becomes necessary and maintenance increases. Under these circumstances,

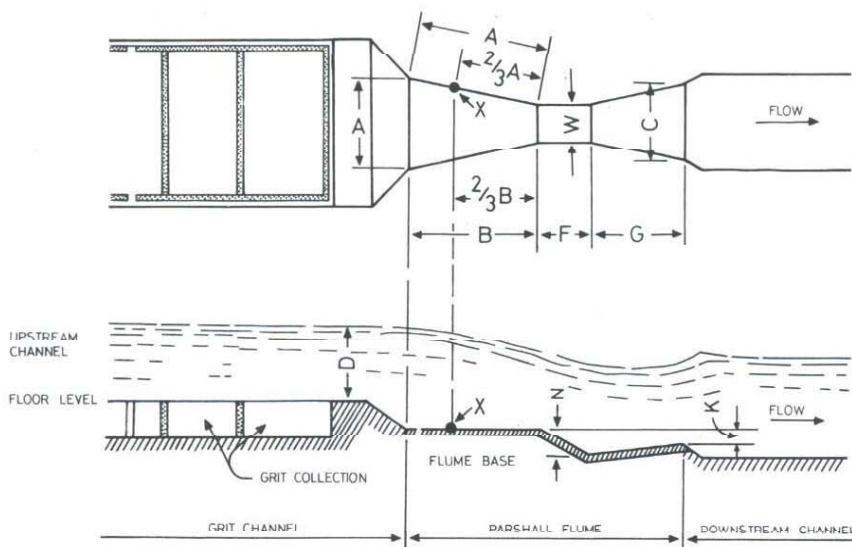


FIG.14A. Characteristic shape and principal calibration dimensions of a Parshall flume flow-metering device in plan and elevation.

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advantage may be taken of some form of pre-treatment, because an operator with some skill will have to be present at all times.

Pre-treatment may consist of only the removal of grit and coarse and floating materials, together with some difficult industrial wastewaters; pH-adjustment and nutrient addition might be considered but, if this is required, the task of operation is likely to be more than one man can handle. Generally speaking, pre-treatment is not recommended; wastewater stabilization ponds should perform satisfactorily with little more than careful maintenance.

XIII-2. PUMPING STATIONS

If it is impossible to deliver wastewater to the pond by gravity, a pumping station has to be installed. However, if pumping is avoidable, every effort should be made to choose an alternative, one possibility being to change the slope of the incoming sewer (§XII-5). Not only should attempts be made to avoid pumping from the incoming sewer, with the attendant problems of pumping solids, but also pumping stations between ponds should be avoided. If a choice has to be made, the latter are simpler.



FIG.14B. View of a Parshall flume in operation. The letters A, W and X refer to characteristic dimensions specified in Fig.14A.

CHAPTER XIII. POND INSTALLATION AND EQUIPMENT

A pumping station is a source of operational and maintenance problems as well as of considerable expense. Pumping stations require energy supplies (e.g. electricity or diesel fuel) and constant attention by a trained operator. Pumps are subject to clogging, to wear, to leakage and, even when running smoothly, potential trouble must always be anticipated.

Centrifugal pumps break down flocs present in the influent, thus hindering their settling to the pond bottom. Archimedean-screw pumps have fewer negative aspects and are self-adjusting, variable flow units; the incoming flow is equal to the downstream flow. Screw pumps cost more than centrifugal pumps, but less than centrifugal variable-speed pumps, and they do not need a wet sump. Coarse material retaining screens can also usually be dispensed with.

XIII – 3. FLOW METERING

As pointed out in §XII – 4.4, pond installations are best equipped with at least two flowmeters, one on the inlet and another on the outlet. The most used types of flowmeter are the rectangular weir, the V-notch weir and the standing-wave flume. Suitable, inexpensive flow measuring devices are the Thompson weir, the Parshall flume, the Venturi-flume and the Palmer-Bowlus flume.

The Parshall flume (Fig.14) is widely used to meter from very low to very high flows [26]. This type of flume will not clog nor retain grit, fibres or other materials which are found to adhere to the edges of, or to settle behind, other types of meter. A simple scale marked in litres per second, fastened to a suitable point in a float chamber, allows direct reading of the flow. Automatic recording meters are too expensive to be used in pond installations, where low cost is of great importance. Meter reading and recording supply valuable data and serve to keep the pond operator busy.

XIII – 4. THE CASE FOR AND AGAINST SCREENS

If a pumping station is essential, a bar screen should be installed ahead of the pumps in order to protect them against clogging. In the absence of a pumping station, opinions on whether to install a screen or not are divided; some designers are in favour of equipping an inlet with such a device to eliminate large items and floating debris, while others are against screens because they call for continuous attention. Furthermore, screenings (i.e. the material collected by screens) are composed of coarse material, regardless of whether it will float or settle; it would be better to leave the heavier material in the influent to settle in the primary pond.

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In any case, floating material can easily be removed by means of a long-handled skimmer as soon as it is blown by the wind to a corner of the pond. Concrete-lined scum ramps may be located at the corners of the pond where floating material can be expected to accumulate, and from there the material may be removed for burial. Screenings should be burnt and/or buried with 40 cm of soil cover.

Screens are composed of parallel, straight or curved bars and may be mechanically cleaned, or manually cleaned by means of rakes. Manually cleaned screens are appropriate for smaller installations, say up to 50 litres per second (20 000 population equivalent). Above 150 L/s (50 000 population equivalent), mechanically cleaned devices are often preferred. Between 50 and 150 L/s a choice has to be made, balancing the arguments for and against mechanical screens. The general recommendation is that only in the largest stabilization pond installations, where maintenance can be assured, should mechanically raked screens be considered. In view of the ability of ponds to accommodate the material which would be screened out, the majority of designers prefer to eliminate screens from stabilization pond plants.

XIII - 5. THE CASE FOR AND AGAINST GRIT CHAMBERS

Some designers prescribe grit chambers as a means of minimizing pond silting. There are some instances reported where severe cases of sand accumulation have created islands in the middle of shallow stabilization ponds. Such cases are exceptional and grit is not the only cause, because the build-up of all kinds of sludge contributes to the problem.

If the sewerage system is of the separated type, i.e. carrying sewage and stormwater separately, very little grit may be expected, only about 1 to 3 litres per caput per year. In a pond system with 2 m² of bottom area per person served, this would mean a sludge layer of about 1 millimetre per year if it were uniformly deposited. Even if this value were underestimated one hundredfold, it would still take 20 years to fill a pond two metres deep completely. In fact, grit accounts for only about 5% by weight of the settled material and therefore there is very little advantage in removing grit. A primary anaerobic pond can be substituted for a grit chamber and this function might well help to justify the inclusion of the anaerobic pond in the overall pond system design.

This situation may change if the sewerage system is of the combined type, and where the stormwater may carry a considerable amount of sand and grit. In this case the provision of a grit chamber might be advantageous.

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Some industrial wastewaters also contain grit in appreciable quantities; examples are the effluents from root and tuber washing, and from glass and marble polishing. These wastewaters may cause detrimental deposits in ponds and a grit chamber might be necessary to remove the detritus. With these exceptions, grit chambers should be avoided because they will unnecessarily increase the number of man-hours required to operate and maintain a stabilization pond installation.

There are many types of grit chamber, but the most suitable for use in developing countries are manually cleaned ones. The simplest unit consists of a straight long channel with a cross-section selected so that the wastewater passes along it at a constant velocity of about 0.3 m/s, regardless of the flow, when it is associated with a suitable control weir or flume. A widely used combination is a trapezoidal channel associated with a standing wave flume. The grit removed in such a channel will usually contain some organic putrescible matter and it should therefore be buried.

Grit chambers may be replaced by a depression excavated in the bottom of the primary pond below the end of the inlet pipe. This excavation should have a volume large enough to store settled grit for about two years.

XIII – 6. AERATORS

Aerators are used only in mechanically aerated ponds and are therefore beyond the scope of this manual.

XIII – 7. OPERATOR'S ACCOMMODATION

It is recommended that the operator reside at the pond site to encourage him to be concerned about the pond installation operating smoothly and without nuisance. However, his dwelling should be located in the least objectionable position, which will normally be upwind of the prevailing wind. It is expected that only one man will be required to handle all the work involved in operating and maintaining a medium-sized stabilization pond installation (serving a population of approximately 20 000 to 60 000). There is very little routine work, and frequently this man will have spare time to undertake tasks outside the pond site, such as removing obstructions in sewers and generally assisting the sewer system maintenance staff.

In any case, some form of sheltered accommodation for the operator must be provided, preferably lockable to enable records, files and working clothes to be kept safely.

XIII – 8. WATER SUPPLY

A supply of water should be installed at the pond site, especially if there is an operator's house. In any case, the operator needs to wash his hands and tools with

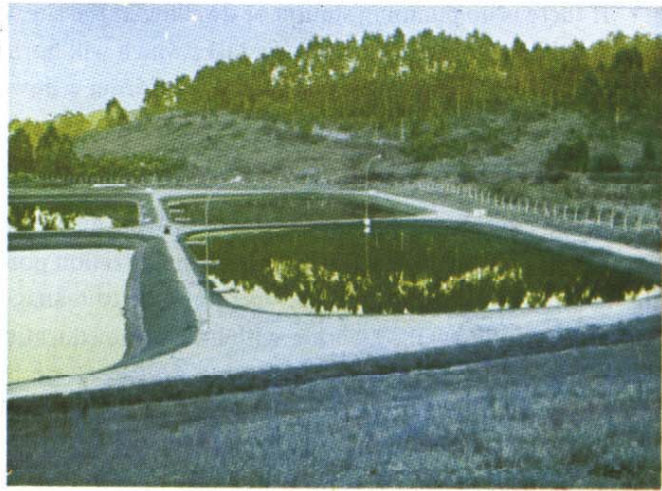


FIG. 15. Well-kept stabilization pond site showing walkway and road illumination.

uncontaminated clean water. In addition, running water should be available if a scum ramp or septage dump is used, in order to clean it down after use. The best solution is to provide a connection from the public water distribution system but, if this is not possible for economic or technical reasons, a local supply may be provided, similar to those in use in remote farms and small communities. Groundwater will provide the simplest source, but at least a hand pump or a simple windmill should be supplied with the protected well.

If no piped water supply is available, a small motor-driven pump (portable or on wheels) could be provided for maintenance, washing-down, and lawn and plant watering purposes, taking water from a well or even from the final maturation pond if appropriate pathogen removal etc. is assured.

XIII-9. SANITARY FACILITIES

A toilet should be provided on site.

XIII-10. ELECTRICAL INSTALLATION

If a pumping station is to be installed or an operator's dwelling is to be provided, electric power must normally be available. Generally, there is no difficulty in bringing an electric power line to a site; if that proves impossible, a diesel-generator should be installed. From a safety point of view also, it is advisable to illuminate some parts of the site, such as buildings, walkways, sampling and metering points, inlets and outlets, fences, gates, etc. (Fig. 15).

CHAPTER XIII. POND INSTALLATION AND EQUIPMENT

If there is no pumping station or dwelling at the site, providing electrical power is of much less importance. The few tasks which will normally be carried out by the operator should not involve instruments requiring a power supply.

XIII – 11. LABORATORY

When considering whether or not to provide an outside laboratory, it should be recognized that, in developing countries, stabilization pond installations, except for the very largest, will not have an operator able to manage delicate instruments. He will often be an unskilled worker with little or no education, whereas even a modest laboratory requires a qualified technician. Unless research work is being carried out, it is not worthwhile having expensive personnel working at pond installations. The responsible agency's central laboratory will be able to carry out the analyses that might be called for during occasional monitoring exercises or for routine intermittent monitoring.

Nevertheless, there are very simple and basic tests which can be performed by an unskilled man after a little training, such as reading a thermometer, a flow meter or an Imhoff cone, using pH indicator paper, and identifying odours and pond colours in a rudimentary way. This work will help to keep the operator occupied and give him a feeling of importance; it is necessary also to avoid him doing nothing most of the time and getting bored with the monotony of the job. Any laboratory at a pond site should be limited to basic testing, as already mentioned. There may also be a need to provide for the collection, preservation and storage of samples if some analyses are to be performed at a central laboratory. The operator should be trained to collect and label such samples.

XIII – 12. METEOROLOGICAL STATION

Here again, there is no need for complex instrumental measurement of meteorological conditions as a routine operational tool. Some simple meteorological instruments may be installed to provide basic information of interest in evaluating the influence of local weather conditions on pond performance. The only equipment which is justifiable is an anemometer, simple thermometers and an evaporation pan. Additional instruments, such as a hygrometer, a rain-gauge, devices for measuring solar radiation intensity, a water-turbidity meter and a seismograph, would only be installed if detailed research were to be conducted and in such a case the pond operator would not normally be involved in making these measurements.

XIII – 13. EMERGENCY EQUIPMENT

Accidents may happen at a pond site. Operators and others may be hurt, fall into the water or even drown. To minimize risks, some emergency equipment should be supplied, especially as ponds are usually located at some distance from urban areas and little help may be available on the spot.

A telephone is a cheap and most effective aid for calling the right assistance. An alarm with a siren may be used to attract the attention of nearby residents or passers-by when the operator is alone and needs assistance, either for himself or for others.

Life-buoys and first-aid kits should always be at hand. Special medications, such as snake-bite sera, should also be available to match local conditions.

XIII – 14. FENCING

Stabilization pond sites should be surrounded by a strong, open-mesh fence, having a lockable gate as the only access, in order to keep out intruders and stray animals. Warning displays should be placed at locations most likely to be either inadvertently or intentionally trespassed upon.

Fences may be combined with vegetation, for example, to discourage children from crawling under them: however, no form of fencing should be used that prevents wind access to the pond surfaces (see Fig.18).

XIII – 15. OTHER FACILITIES

Other facilities may include roads, walks, parking areas, toilets, implement and tool storage cabinets, etc. as necessary and as permitted by cost considerations. Open areas should be covered with lawns and flowers. Trees, ornamental plants and bushes should be selected from those species which do not shed too many leaves nor require too much maintenance. Hedges and tall trees which would cut down wind access to the pond should be avoided.

There are grass species which minimize the need for lawn conservation and mowing and such species should be selected. Studies have indicated that a drastic reduction in maintenance costs can be achieved by judiciously selecting grass species which are slow-growing and self-trimming; such varieties might not, of course, be easily available in some countries or may be costly. Furthermore, in small installations, there is operator time available for such tasks as mowing and gardening.

In any case, local climatic conditions will dictate the type of vegetation that can be supported. However, it must be remembered that the water deriving from the final maturation pond should be of a quality suited to watering.

Chapter XIV

OPERATIONAL CONTROL OF WASTE STABILIZATION PONDS

XIV-1. THE NEED

It should be emphasized once more that it is meaningless to provide for complex data measuring and recording in a pond installation unless a full-time operator is necessary, which might be the case if a pumping station exists or an evaluation is being carried out. Otherwise, occasional inspections and repair of damage that might occur, for example after heavy rainfall, should suffice. A pond operator should be kept busy at all times and simple data recording will provide a routine which not only boost his morale but may also be very useful in establishing local parameters for future pond design.

XIV-2. MANPOWER REQUIREMENTS

The number of operators required for a pond installation depends mainly upon the size of the occupied area and whether or not a pumping station or other mechanical equipment is installed. If the wastewater enters the ponds by gravity, one man is usually sufficient to carry out the tasks mentioned in the following sections, provided that the total area of the installation is less than 8 ha. This figure corresponds to a population served of about 20 000 inhabitants. A second operator is required for an area of between 8 and 20 ha or for a population up to about 50 000. Operator training courses are essential in all situations.

If it is necessary to pump wastewater to the ponds, at least one additional man must be considered where the pumps are started and stopped automatically. If the operation of the pumps is manual, four men are required as a minimum. In this case, at least one of them must be an experienced pump operator and should have some skill in minor mechanical and electrical repairs. It is, however, advisable to set up regional mechanical workshops and laboratories which are intended to provide the necessary technical support to a number of wastewater treatment plants, because it is uneconomical for each plant to have its own facilities.

XIV-3. DAILY ROUTINE

Several agencies have produced operating manuals for wastewater stabilization ponds [9, 27]. Basically, to detect any abnormality the operator should walk around

WASTEWATER STABILIZATION PONDS

each pond at least once every day and a system should be devised to ensure this. Time-punch clocks might be useful in this context.

The observed information, together with any meteorological data and physical details on the ponds, should be recorded on appropriate forms. Figure 16A gives examples of suitable record forms, but there will be many instances where the operator is illiterate and symbols will have to be used in place of words on such documents.

XIV – 3.1. Meteorological measurements

Stabilization ponds depend on certain natural factors to yield good results. The recording of meteorological factors will assist in assessing the behaviour of ponds and will sometimes allow remedial adjustments to be made to overcome problems, provided the means exist to do this. Only the simplest measurements should be contemplated for normal stabilization pond installations.

Temperature

The temperature of both the ambient air and the water in the pond should be determined every day at the same point at the same time. Without continuous recording of temperature, this discipline is necessary to allow a realistic mean monthly temperature to be calculated and its variation determined.

Solar radiation

This parameter may be recorded very simply as:

- bright sunlight (blue sky, no clouds, intense sunshine);
- sunshine (some occasional clouds);
- cloudy (no sunshine).

Rainfall

This parameter may be recorded without a rain gauge as:

- no rain (dry);
- fine rain (drizzle);
- moderate rain;
- heavy rain or storm.

Often this will be on a daily basis, but sometimes the day will be divided into two to four periods to give some indication of when the rainfall occurred.

CHAPTER XIV. OPERATIONAL CONTROL

Pond No.	Date	Operator's name :			
1. EVENTS				YES	NO
<ul style="list-style-type: none"> - Bottom sludge floating somewhere in the pond - Green patches on the pond's surface: <ul style="list-style-type: none"> • anaerobic • facultative - Black or dark-grey patches on the facultative pond - Black or dark grey patches on the maturation pond - Plant and weed growth: <ul style="list-style-type: none"> • within the lagoon • on the slopes - Erosion of the embankment slopes - Visible infiltration - Fences in good shape - Presence of insects - Presence of birds and water-fowl - Storm water ditches: clean - Flow meter - Objectionable odour : <ul style="list-style-type: none"> • in the anaerobic pond • in the facultative pond • in the maturation pond - Oily spots 					
2. PHYSICAL PARAMETERS					
Parameter		Time			Remarks
		07:00	12:00	17:00	
<ul style="list-style-type: none"> - Flow (L/s) inlet <li style="padding-left: 40px;">outlet - Air temperature (°C) - Water temperature (°C) .. - Water depth (m) - Sludge layer thickness (m) 					
3. METEOROLOGICAL DATA					
Parameter		Time		Remarks	
		07:00-12:00	12:00-17:00		
Sunshine	Bright sunlight Sunshine, some clouds Cloudy, no sunshine				
Rainfall	Dry, no rain Fine rain (drizzle) Moderate rain Storm occurrence				
Wind	Calm, no wind Breeze (gentle wind) Moderate wind Strong wind Hurricane				

* Sludge thickness is to be determined once a week for research purposes only.

FIG. 16A Reproduction of a typical daily record form.

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(i) Without nitrogen and phosphorus determination.

Parameter	Unit	Influent	Effluent	Frequency
pH		x	x	W
BOD ₅	mg/L	x	x	W
COD	mg/L	x	x	W
Settleable solids	mL/L	x	x	W
Total solids	mg/L	x	x	F
Fixed solids	mg/L	x	x	F
Volatile solids	mg/L	x	x	F
Faecal coliforms	MPN/100mL	x	x	M

W = weekly; F = fortnightly; M = monthly. MPN = mean probable number.

(ii) With nitrogen and phosphorus determination.

Parameter	Unit	Influent	Effluent	Frequency
pH		x	x	W
BOD ₅	mg/L	x	x	W
COD	mg/L	x	x	W
Settleable solids	mL/L	x	x	W
Total solids	mg/L	x	x	F
Fixed solids	mg/L	x	x	F
Total Kjeldahl nitrogen (TKN)	mg/L		x	O
Nitrate nitrogen	mg/L		x	O
Total phosphorus	mg/L		x	O
Faecal coliforms	MPN/100mL	x	x	M

W = weekly; F = fortnightly; M = monthly; O = occasionally. MPN = mean probable number.

FIG.16B. Reproduction of charts indicating to the operator the pattern and frequency of sampling required for assessing the efficiency of pond operation (used in conjunction with data from the daily record form of Fig.16A). The operator needs training to ensure that samples are appropriately taken and prepared for transmission to the laboratory.

Wind

Wind may be recorded without an anemometer as:

- calm (no detectable air movement);
- breeze (gentle wind);
- moderate wind;
- strong wind;
- violent wind (hurricane).

Evaporation

If a simple evaporation pan is installed, the operator can often be instructed to take readings and record the data.

CHAPTER XIV. OPERATIONAL CONTROL

Physical Aspects

Ideally, the following data should be recorded:

- influent flow;
- effluent flow;
- water level (normal, depressed);
- visible sludge accumulation, floating sludge mats;
- colour (grey, green, discoloured patches, pink, milky, brownish, etc.).

Other aspects

- odour production;
- rodent activity;
- insect infestation.

XIV – 3.2. Physico-chemical and biological data

Sampling, but not analysis, should be carried out by the operator according to instructions furnished by the central laboratory responsible for the monitoring or research. Typical sampling frequencies are included in Fig.16B.

Chapter XV

POND OPERATION AND MAINTENANCE

XV – 1. OPERATION AND MAINTENANCE OF ANAEROBIC PONDS

The indicators of proper functioning of an anaerobic stabilization pond are:

- no plants or weeds on the inner (wet) slope (grass and weeds must be cut periodically in order to control insect breeding);
- the surface is partly or completely covered by a scum layer which contains oils, greases and various floating matter: this floating scum layer helps to maintain anaerobic conditions in the pond, isolates the contents of the pond from atmospheric oxygen, insulates the wastewater against heat loss and hinders the liberation of offensive odours.

The operator must check every day to see that there is:

- no seepage through the embankments;
- no clogging of the inlet pipe, especially if it is submerged;
- no floating scum being carried over to the secondary facultative pond;
- uniform flow distribution, where two or more inlets exist. With time, the operator will learn to recognize flow uniformity by sight.

If there is an interest in knowing the sludge layer thickness in an anaerobic pond, determinations should be carried out periodically at several points across the bottom of the pond. Several simple devices allow this measurement to be accomplished easily.

XV – 2. OPERATION AND MAINTENANCE OF FACULTATIVE AND MATURATION PONDS

The visual signs of proper functioning of facultative and maturation ponds are:

An intensely green-coloured effluent (paler in the case of maturation pond effluents), practically devoid of settleable suspended solids. If the effluent has a very light and somewhat transparent green colour, or even a yellowish colour, this indicates that predators are present and that some forms of zooplankton are feeding on the algae ;

CHAPTER XV. POND OPERATION AND MAINTENANCE

- Absence of weeds and water-plants inside the pond. Water-weeds foster insect-breeding. If there is a protective lawn on the inside slope of the pond embankment, it must be kept at least 10 cm above the highest water level. Seeding must be limited to the area above this bald protection ribbon ;
- Absence of bluish-green coloured appearance. A bluish-green appearance indicates an objectionable bloom of blue-green algae (*Cyanophyceae*). Such an outbreak has a detrimental effect on sunlight penetration, thus reducing the oxygen concentration in the pond ;
- With some warm wastewaters, the precipitation of magnesium hydroxide and calcium phosphate may occur as a consequence of an increase in the pH – value in a facultative pond. This reaction is called self-flocculation and causes the pond to display a milky-green appearance. It may result in pond failure (see Chapter VII).

Figure 16 reproduces the main observations and analytical results which may assist in assessing the efficiency of a facultative or maturation pond.

Chapter XVI

OPERATIONAL PROBLEMS AND SOLUTIONS

XVI-1. THE NEED FOR MAINTENANCE

Owing to the fact that stabilization ponds comprise an extremely simple treatment system, the need for maintenance and the admittedly minimal requirements for correct operation are often overlooked. Although it is true that ponds do not need to be "operated", at least in small installations with a single pond, or two in series, maintenance is of paramount importance. The various constructional materials deteriorate; therefore earthen embankments, rip-rap linings, grassed areas, etc. require regular attention. A well-maintained pond (and a well-operated pond system, if there are pumping stations and/or pre-treatment units) will yield a good effluent at all times with little labour.

XVI-2. PROBLEMS WITH ANAEROBIC PONDS

Anaerobic ponds may develop objectionable odours, may serve as breeding sites for mosquitoes and may encourage weed growth; these nuisances are discussed below.

XVI – 2.1. Objectionable odours

Malodorous conditions may be caused by one of the following factors:

- too great a throughput with consequent reduction in retention time;
- presence of toxic substances and inhibitors in the influent;
- sudden temperature drop;
- low influent pH – value.

Possible remedies for odour problems include:

- If there is a facultative pond in series with the primary (anaerobic) pond, the secondary pond effluent may be recirculated to the anaerobic pond, creating an upper layer of oxygen-containing water. (This technique is, however, not recommended in view of the need for pumping and the high cost involved);
- Stop removing scum to allow a natural floating cover to form;
- Reduce the influent flow, by-passing a part without treatment until a new unit is built.

CHAPTER XVI. OPERATIONAL PROBLEMS AND SOLUTIONS

Adding chemicals is of doubtful value and the cost is hard to justify. Chlorination is capable of deodorizing an ill-smelling anaerobic pond, but chlorine addition to the influent should never be adopted because it will inhibit biological activity in the pond. Another important deficiency of this technique is that chlorine is a very dangerous gas for an unskilled operator to handle.

XVI – 2.2. Mosquitoes and other insects

The appearance of mosquitoes, flies and other insects may be due to one or more of the following factors:

- Screening and/or grit (where screens and grit chambers are installed) that have been removed have been left lying about without being buried;
- Weeds and grass have been allowed to grow on the inside slope of the pond so as to touch or penetrate the liquid mass;
- There is no floating scum layer, (this should be left in place to control odours);

Possible remedies for insect control include:

- Any screenings and/or grit should be buried immediately and covered with at least 40 cm of earth;
- Grass, water-weeds and aquatic plants should be promptly cleared as soon as they appear and, after removal, should not be allowed to fall into the pond;
- A pesticide may be sprayed on to the scum layer; however great care should be taken to prevent pesticides getting into the liquid mass;
- The floating scum may be stirred up with a long-handled rake in order to cause larvae to sink (water jets may also be used for this purpose, using a small portable pump if there is no piped supply).

XVI – 2.3. Weed growth

Two kinds of weeds must be considered in pond installations: aquatic-weeds and terrestrial weeds. Aquatic plants have roots and stem partly or completely immersed in water and ordinarily appear only on the wet side of the inner slope. Terrestrial weeds can be found anywhere on the dry area of the site.

Water-weeds are involved in a sequence of nuisance problems, namely: weeds attract insects and larvae; these attract frogs; they, in turn, attract rodents, which then attract snakes. If water-weeds are not periodically removed, they may even



FIG.17. Algal mats, floating scum and other floating material must be removed regularly to ensure free access of sunlight to a facultative pond.

affect the safety of the embankments, because rats are reported to dig tunnels through which leakage may occur; as a consequence, embankments are likely to collapse.

Aquatic plants must be removed periodically, preventing them from dying in the pond. They may conveniently be uprooted with a hoe, and then raked out of the pond.

XVI – 3. PROBLEMS WITH FACULTATIVE AND MATURATION PONDS

The most annoying problems in facultative ponds are scum formation, objectionable odours, short-circuiting, weed growth, and serving as a breeding site for mosquitoes and other insects. The last three mentioned problems also apply to maturation ponds.

XVI – 3.1. Scum

The surface of a facultative pond should be free of floating matter, such as scum, paper, plastics, oils, greases and all other materials which could obstruct the passage of sunlight (Fig.17). Sometimes algal mats accumulate upon the pond's surface as a consequence of a bloom*, producing a dark-green scum. If algal mats are not removed, they are likely to produce odour problems as they decay, apart from restricting light access.

*A sudden and rapid increase in the algal population.

CHAPTER XVI. OPERATIONAL PROBLEMS AND SOLUTIONS

Possible remedies for scum accumulation include:

- Algal mats may be sprayed with a jet of water from a hose directed by the operator on to the floating material. The mat will sink to the bottom of the pond. Alternatively, after it has drifted across the pond's surface impelled by wind action to a corner, the algal mat may also be broken down with a long-handed rake;
- If there is a skimmer available, it may be used to remove the floating mats, which should be buried.

In shallow facultative ponds, another type of scum may be produced during very warm days; some parts of the anaerobic bottom layer may float to the surface due to an increase in gas production; these parts form a crust. They should be made to sink by spraying with water.

XVI – 3.2. Objectionable odours

Objectionable odours emanating from a facultative pond are likely to be caused by one of the following:

- organic overloading;
- long periods without sunshine, with clouds and low temperatures;
- occurrence of toxic matter in the influent;
- short-circuiting;
- reduction of wind-induced mixing resulting from tree screening or solid fencing (which should never be used).

Overloading in a facultative pond always occurs simultaneously with a drop in the pH – value and a reduction in dissolved oxygen concentration. The effluent colour changes from green to yellowish-green and, on the green surface, grey patches appear in the neighbourhood of the inlet. Under these conditions odour problems will arise.

Long periods of low temperature and a cloudy sky will reduce photosynthetic oxygen production, and sometimes dissolved oxygen will be absent even during the day. Possible remedies against reduced photosynthesis include recirculating the effluent or installing surface aerators at the inlet, to temporarily supplement deficient oxygen production [9].

Toxic material in the influent will cause a properly functioning pond to fall suddenly in efficiency without a visible reason. If this happens, the operator should

WASTEWATER STABILIZATION PONDS

immediately notify the central laboratory so that samples can be analysed to detect the possible presence of heavy metals or some other inhibitor of biological action. These may come from industrial wastewater discharges into the collection system.

The only possible remedy against biological inhibitors is to identify the source of pollution and prevent future discharges to the sewer. Regulations will be essential to limit the amount of toxic material which may be released into the sewer system [27].

Possible remedies against objectionable odours include:

- If there are two or more facultative ponds operated in parallel and only one of them is affected by the problem, the affected one should be taken out of operation until it recovers its normal performance. In the meantime the influent should be diverted to the next unit or units;
- As a last resort or if there is only one facultative pond, part of the effluent may be recirculated to the inlet by means of a portable pump and a long hose;
- Under extreme conditions, portable floating aerators, if available, may be installed temporarily to overcome the overloading problem;
- If the trouble stems from a lack of wind-induced mixing caused by trees or tall vegetation, the obstacle should be removed. Should the obstacle be a structure which cannot be removed, provision may have to be made to provide artificial mixing on a more permanent basis. This is costly, and the related equipment requires attention.

XVI – 3.3. Short-circuiting

Short-circuiting in a facultative pond can be caused by: (i) poor design of the inlet, unsuitable relative positioning of the inlet and outlet, or badly located inlet or inlets with respect to the shape of the pond, reinforced by the action of wind; (ii) the presence of aquatic weeds inside the pond; or (iii) silting.

The existence of short-circuits may be detected by making an analysis for dissolved oxygen on several samples taken at different points in the pond. If there are substantial differences in values, a short-circuit is likely to exist and poor mixing can be expected.

Possible remedies against short-circuiting include:

- Adjusting multiple inlets, if they exist, so as to obtain a better flow distribution;

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- Changing the inlet structure, if there is only one, so that it becomes a multiple inlet in an attempt to improve the flow pattern;
- Removing aquatic weeds or silt if they are the cause.

XVI – 3.4. Mosquitoes and other insects

Insect breeding in facultative ponds is mostly associated with aquatic plants emerging from the water surface. *Culex* and *Anopheles* mosquito larvae are common in many regions and the presence of gnats is not uncommon in ponds with emerging aquatic plants.

Possible remedies include:

- The outlet of a pond should be of a type that allows the operator to vary the water level. The water depth may then be decreased to a level which will expose to sunlight those parts of the plants to which larvae stick and so cause them to dry up and die. Varying the level of the water surface is a very effective prophylactic against larval development;
- Scum destruction also helps to control insects;
- Depending upon the availability of dissolved oxygen, larvivorous fish may be reared in facultative or maturation ponds. Suitable types of fish are *Gambusia*, *Lebistes*, *Tilapia* and Chinese grass carp.
- If a considerable infestation with flies occurs, pesticides sprayed on to the inner slope of the embankments are effective as a means of insect control, but are not recommended for general application. Great care should be taken to avoid pesticides entering the liquid mass.

XVI – 3.5. Weed growth

Vegetation may literally cover the whole surface of the pond it is operated with too shallow water (say 60 cm). Such shallowness often occurs as a consequence of excessive seepage through the pond bottom, or may be caused by insufficient flow as compared with infiltration and evaporation. If the normal operating depth of a pond is in excess of 90 cm, weed growth will be limited to a narrow strip at the water's edge.

Possible remedies against water-weed growth include:

- Frequent weeding of the shallow edges of the pond: this will suffice in most cases. The vegetation removed should not be allowed to drop into the water;

- Removal of aquatic plants, should they emerge from the water at points distant from the pond's edge; this will have to be done by the operator working from a boat or a raft. Dropping the water level some 30 to 50 cm will allow the plants to be cut at a point conveniently low on the stalk;
- Lining the inner slopes of the embankment, or parts of them, with a suitable material, such as rip-rap or concrete slabs; this will prevent aquatic plants developing in the shallow water. Lining is also useful for minimizing embankment erosion.

XVI – 4. POND DESLUDGING

The design of a primary pond should provide a sufficient extra volume for accumulating for a reasonable period of time (5 – 10 years) the sludge that will result. Accumulated sludge must then be removed, and this can be achieved using wet or dry sludge removal techniques. In some cases, during the desludging period, the pond sequence is temporarily modified using a by-pass, or a stand-by pond is operated.

XVI – 4.1. Wet desludging

Wet desludging may be carried out without emptying the unit. A self-priming sludge pump can be mounted on a raft for this purpose. There are also dredgers, similar to the equipment normally used to dredge ports, canals and river bottoms.

An alternative is to empty the pond down to the top of the sludge layer and have it taken out with a dragline or clam-shell machine.

Wet desludging produces a liquid sludge requiring suitable final disposal, such as land application or sludge lagoons.

This is the process of choice for small pond installations, or where space or cost restrictions make the use of a stand-by pond impracticable.

XVI – 4.2. Dry desludging

Using this technique, the liquid layer on the top of the sludge is removed and the sludge allowed to dry by natural evaporation. The drying process takes months or even one or two years to be completed. Therefore, a stand by pond must be available.

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If this technique is adopted, the sludge build-up must be limited to a maximum sludge layer depth of about one metre, otherwise it will take too long to dry. The dried sludge will occupy only about one tenth of the volume of the original wet sludge. It is easily stored and may be used in agriculture.

Chapter XVII

MAINTENANCE AND SAFETY

XVII – 1. THE IMPORTANCE OF MAINTENANCE AND SAFETY

A stabilization pond installation must be kept in good condition with the same care that a more complex wastewater treatment plant deserves. Unfortunately, because of the simplicity of pond operation and maintenance, there is often a tendency to neglect “good housekeeping” at the plant. If this is the case, the ponds deteriorate with time and lose their usefulness.

Those who are aware of the importance of keeping a good civic image will realize that a wastewater stabilization pond installation must look good as well as work well. There are characteristics common to any maintenance and safety programme. Adequate resources must be provided to achieve this.

XVII – 2. DEALING WITH THE PUBLIC

Waste stabilization ponds should not be open to the public as a recreational area. It is not uncommon for birds and wildlife to be attracted to the large water surface of stabilization ponds and this awakens the interest of people and encourages them to walk in the surroundings.

An operator should be instructed how to explain to visitors the purpose, functions and usefulness of the ponds. Furthermore, he must make them aware of the risks that exist because of the inevitable presence of disease-causing micro-organisms, and they should be warned against touching plants or the water in the enclosed areas of the site.

Signs should be placed at convenient points around the site indicating that the installation is a wastewater treatment system, and wording should be used that discourages trespassing.

The involvement of local communities in the planning, building and operation of the installation should be actively sought (see §XVIII – 3).



FIG.18. Open wire-mesh fencing serving to keep out trespassers and animals, with signs to discourage entry, at a pond at Village, USA.

XVII – 3. SECURITY FENCING

The wastewater stabilization pond site must be surrounded by a secure but open fence (Fig.18), that keeps out intruders and straying animals but does not prevent wind access to the pond surface. The operator should inspect the fence periodically, walking around the perimeter and looking for damage to the wire or posts. Once such damage is detected, the operator should carry out the required repairs immediately.

Where crocodiles or other forms of reptilian water life exist, they should be prevented from gaining access to stabilization ponds.

XVII – 4. EMBANKMENTS AND GRASSED AREAS

Earth embankments should be inspected for the existence of signs of erosion, crevices, vegetation and holes dug by animals. Suggested corrective measures are as follows:

- Crevices may be filled with clay, smoothed over and compacted;
- Aquatic plants should be removed;
- Grass should be mown as required, using the normal local technique; grass should stop short of the water surface by some 30 cm (see Fig.11A);

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- Stormwater drainage ditches and trenches should be kept free of sand and obstructions, and should be inspected after heavy rainfall;
- Trees should not be allowed to grow within 150 m of wastewater stabilization ponds, hedges not at all.

XVII – 5. APPURTENANCES

- Pond inlets and outlets should be kept clean and free from obstructions ;
- Weirs should be brushed and cleared periodically to rid them of trapped algal mats, crusts, rags, plastics, leaves, etc;
- Grooves for stop-log operation should be cleaned periodically so as to facilitate water depth adjustment as required;
- If there is a gate operated by means of worm-and-wheel or other machinery, the the mechanism should be regularly lubricated with a suitable grease, to prevent it from rusting and seizing up.

XVII – 6. SOLID WASTE DISPOSAL

- Screenings and grit removed by screens and grit chambers (if they are included) should be buried promptly to prevent problems with flies and odour ;
- Mats, scum and floating sludge must be removed or sunk as soon as possible after they form and are accessible. If they are removed (with a skimmer), they must be buried immediately;
- Rocks, gravel, pieces of wood and other debris that might have fallen into effluent chambers should be removed.

XVII – 7. OPERATOR SAFETY

For his own sake, the operator should be instructed in some simple safety rules, given below:

- Before eating any food or drinking, or even lighting a cigarette, the hands must be washed;
- Working garments, helmet, gloves, boots and waterproof coat, should remain at the working place when he leaves;
- Tools (shovels, hoes, rakes, skimmers, etc.) should be washed with clean water before being stored;
- Cuts, scratches and abrasions must be cleaned and disinfected immediately;
- When working near electrical switch-gear, he must be sure that his hands, garments and boots are dry. If he has to carry out maintenance work on electrical equipment, in addition to ensuring that he is dry, suitable gloves and insulated tools must be used;

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- The operator should not encourage friends to visit him because, if somebody falls into the water, a fatal accident may result. The sludge deposit on the bottom of the pond is often sticky and may hinder the victim's attempts to save his life. Furthermore the risks for infection due to microorganisms mentioned above are serious;
- At the pond site, a boat, rope and lifebuoy should be available for rescue purposes;
- The operator should be vaccinated against tetanus, typhoid fever, and, if necessary, against yellow fever and cholera, as suggested by the national health authorities. A regular medical examination should be carried out;
- The operator should pay strict attention to personal hygiene. For example, he should keep his finger-nails clean and trimmed, because dirty nails are disease-transmitting media;
- A first-aid box should be available in a visible and accessible place. Appropriate sera (snake-bite, scorpion sting, etc.) and discardable syringes should be included;
- The operator should be properly instructed on how to give first-aid treatment to himself and others, including the use of the sera on himself or on others, because other medical assistance may arrive too late.

Chapter XVIII

MANAGEMENT

Though a wastewater stabilization pond is a simple installation which does not require skilled manpower on the site during operation, some technical, financial and administrative support is necessary.

XVIII – 1. TRAINING

The operator must receive training in the routines he is supposed to perform. If he has sufficient education, or the capacity to learn more advanced subjects, he could take an elementary short course on the pond treatment process. He should be informed of his responsibilities, particularly regarding public health, so that he will feel that he is playing an important role and will approach his job with care and attention.

XVIII – 2. FINANCIAL ASPECTS

Pond operation and maintenance are very important. This implies that a budget must be made available to cover regular expenses, such as tools, protective garments, repair materials, flashlight batteries, printed matter, toilet paper, medicines, insect repellants and other minor items, as well as for paying the operator, energy costs, etc. The salary paid to the operator should definitely be more than that of a normal manual worker in view of the responsibilities he is expected to assume.

Although the running costs will be low, the success of the whole operation depends on the responsible agency providing the resources on a continuing basis. Once the capital investment in a wastewater stabilization pond system has been made, it is folly to risk project failure through lack of operating funds.

XVIII – 3. ADMINISTRATIVE ASPECTS

On the governmental side, the agency concerned should establish a department to be responsible for the administration of wastewater collection, transport and treatment facilities. Operator supervision is an essential function of such a department, for the operator cannot be expected to work in a vacuum.

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Pond performance evaluations should also be carried out by the department, so that future designs will take advantage of findings. This department should organize the operator's training courses and activities and, in time, set up a control or research laboratory. Without effective administrative and technical back-up, the wastewater stabilization pond installation is likely to become less and less efficient until it ceases to be effective. This deterioration can happen in a short time.

The community served should be required to pay towards the service, and community self-help should be encouraged, from the time of planning, during building, and as part of maintenance and operation. Community involvement, following appropriate education of the public, is beneficial in every way, and can markedly reduce running costs, as well as public nuisance, like trespassing, since the dangers are understood.

Part B

**DETAILED CONSIDERATIONS OF
WASTEWATER STABILIZATION POND DESIGN**

Chapter XIX

DESIGN OF ANAEROBIC PONDS

Anaerobic ponds are able to accept high organic loadings and are particularly useful for treating strong organic wastewaters. Dissolved oxygen is absent and no photosynthesis takes place, as a result of the high turbidity and the dark colour of the pond contents and floating material. Sometimes, insignificant concentrations of dissolved oxygen and some incipient photosynthesis may be detected in the surface layer, but this rather uncommon effect is not a characteristic of the anaerobic nature of the pond.

XIX – 1. DESIGN CRITERIA

Anaerobic ponds are akin to septic tanks and unheated anaerobic digesters. The size of septic tanks is often recommended to be around 0.5 m^3 per person: the BOD loading, at 45 grams per person per day, will then be $90 \text{ g/m}^3 \cdot \text{d}$, which is in the range of loadings for anaerobic ponds.

Up to now, there has been no agreement on a standard design for anaerobic stabilization ponds. The scatter of performance data, range of criteria and the number of recommendations are enormous. For example, Eckenfelder [28] refers to a retention time of between 5 and 50 days, whereas Gloyna [8] recommends that this time should not exceed 5 days “because the ponds then act as facultative ponds” and “longer detention may cause the upper layers of the pond to become aerobic and reduce the obligate anaerobic conditions necessary for maximum efficiency”.

From the available literature, all existing design procedures adopt one of the following three criteria as a basis:

- (a) surface loading rate (in terms of $\text{kg BOD}_5/\text{ha} \cdot \text{d}$);
- (b) volumetric loading rate (in terms of BOD_5 or volatile solids as $\text{g/m}^3 \cdot \text{d}$);
- (c) hydraulic retention time (d).

XIX – 2. SURFACE LOADING RATE

According to Gloyna [8], it is incorrect to refer to an anaerobic pond in terms of surface loading. However, this is a practice that has been adopted by many

CHAPTER XIX. DESIGN OF ANAEROBIC PONDS

designers, drawing on facultative pond practice, and it will take years for this parameter to be abandoned. Nevertheless, although surface loading is inadequate for sizing an anaerobic pond, it is useful to assess land requirements and to check whether there is a risk of the pond becoming facultative at some time in the year.

As a result of research work carried out in Lima, Peru [7], it is believed that, in tropical regions, a pond expected to be anaerobic all the time should have a surface loading in excess of 1000 kg BOD₅/ha·d. On the basis of ammonia measurements, it was found in this location that, above a surface loading of 357 kg BOD₅/ha·d, the anaerobic process prevailed. This is considered the upper limit for facultative pond loading in Lima [19]. Between these two limits, the pond should be considered as operating part of the time in a facultative and part of the time in an anaerobic mode. At Campina Grande, in north-east Brazil, the upper limit of surface loading for facultative ponds is considered to be in excess of 400 kg BOD₅/ha·d for water temperatures of 25–27°C [2].

Many authors consider that the surface area of an anaerobic pond does not influence its performance, whereas the volume does. This is a logical rationalization unless the sludge/liquid interface (if it exists) is the site of significant anaerobic activity in the liquid phase. Nowadays, the depth of anaerobic ponds is made as large as practically feasible, sometimes as deep as five metres, keeping the surface area as small as possible in order to lose less heat and absorb less oxygen from the atmosphere. The validity of this approach to anaerobic pond design has yet to be established. Eckenfelder [28] has reported data on anaerobic ponds with loadings ranging from 280 to 4500 kg BOD₅/ha·d, resulting in BOD removals of between 50% and 80%. Pond depths varied from 2.5 to 5 m.

In view of the erratic data available on anaerobic ponds, the designer is faced with a very high degree of uncertainty.

XIX–3. VOLUMETRIC LOADING

Volumetric loading is expressed in terms of grams BOD₅ per cubic metre per day (g BOD₅/m³·d).^{*} This design criterion is akin to the basis of design for anaerobic sludge digesters and anaerobic dispersed-growth processes. Designs based on this criterion are still uncommon, although it appears with present knowledge to be more logical and sounder because it is based indirectly on solids retention time.

^{*} The following identities hold true: 1 g BOD₅/m³·d = 1 kg BOD₅/1000 m³·d = 1 kg BOD₅/dam³·d. (1 cubic decametre is 1000 m³.)

TABLE III. BOD₅ REDUCTION AS A FUNCTION OF RETENTION TIME (T > 20°C) [30]

Retention time (days)	BOD ₅ reduction (%)
1	50
2.5	60
5	70

TABLE IV. RELATIONSHIP BETWEEN ANAEROBIC POND TEMPERATURE, RETENTION TIME AND BOD₅ REDUCTION [32]

Temperature of anaerobic pond (°C)	Retention time (days)	Expected BOD ₅ reduction (%)
10	5	0 – 10
10 – 15	4 – 5	30 – 40
15 – 20	2 – 3	40 – 50
20 – 25	1 – 2	40 – 60
25 – 30	1 – 2	60 – 80

Bradley and Senra [29] refer to the volumetric organic loadings adopted in six States of the USA, ranging from 40 to 250 g BOD₅/m³·d, with a predominance of the higher values. Gloyna [8] mentions the volumetric loading recommended by the Ministry of Health of Israel as being 125 g BOD₅/m³·d. Mara [30] recommends loadings not in excess of 400 g BOD₅/m³·d, supposedly to avoid objectionable odours. Senra [27] suggests an upper limit of 70 g BOD₅/m³·d in order to avoid odour problems. Fisher et al. [31] report loadings between 42 and 283 g BOD₅/m³·d for anaerobic ponds in Alberta State, Canada. These loadings are essentially in the range of those usually recommended for septic tanks in cool climates.

XIX – 4. RETENTION TIME

Retention time is the most commonly used parameter in anaerobic pond design. However, it is the one that varies over the broadest range from author to author. Gloyna [8] reports retention times as low as 18 hours (African Housing Board, Lusaka) and recommends a maximum of 5 days in tropical areas. Eckenfelder [28] makes reference to retention times between 5 and 50 days, but the high values should be attributed to cold climates (it is generally accepted that there is practically no anaerobic activity under 10°C).

An intimate relationship between retention time, temperature and efficiency is favoured by the majority of authors. For temperatures above 20°C, Mara [30] suggests the values given in Table III for sewage treatment, while Arceivala [32] provides the data given in Table IV.

In Melbourne, Australia, the sewage retention time in anaerobic ponds is 1.25 days during the summer and 5 to 7 days in winter; the corresponding BOD₅

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TABLE V. THEORETICAL BOD₅ REDUCTION AT 22°C [33]

Retention time (d)	BOD ₅ reduction (%)
0.12	20
0.40	30
0.71	35
1.3	40
2.4	45
4.7	50
9.4	55

removal efficiencies are 65 – 80% and 46 – 60%, respectively. Gloyna [8], referring to Vincent and Marais [33], indicates as theoretical reductions of BOD₅ at 22°C the values given in Table V.

Very high percentages for BOD₅ reduction are sometimes achieved in anaerobic ponds. Senra [13] reports that, during the first six months of 1977, one of the two anaerobic ponds in Mairiporan, State of Sao Paulo, Brazil, subject to a load of 1557 kg BOD₅/ha·d and a retention time of 5 days, yielded an effluent with 79% BOD₅ reduction. It is likely that this pond had good methane fermentation under way.

XIX – 5. CRITIQUE OF DESIGN CRITERIA

From the foregoing discussion it is evident that a considerable amount of investigation has yet to be carried out before general agreement can be reached on a rational design procedure for anaerobic ponds. Mixing induced by the rising gas/sludge mixture is never complete, kinetics are probably not of the first order, the complex biota are of different composition and efficiency from place to place (some species and strains are believed to metabolize organic matter more slowly than others), predators may be present, temperature varies with depth, and so on. None of these significant factors are taken into account in present design approaches.

Design criteria based on areal or volumetric organic loading do not consider the influent flow, and hence the retention time. Those design criteria based on hydraulic retention time imply that not only the BOD of the solids, but also some soluble BOD, is removed. If this were not so, reductions in influent sewage BOD₅ of the order of 60% or more could not be achieved. Temperature is one of the most important factors influencing BOD removal efficiency, hence retention time requirements are closely linked with ambient temperature. An increase in temperature of 5°C speeds up the anaerobic biodegradation four-fold, when measured in terms of gas (carbon dioxide and methane) generated per unit time [8].

XIX – 6. RECOMMENDED DESIGN APPROACH

The only fundamental design condition for an anaerobic pond is to make certain that methane fermentation becomes established.

For sewage treatment temperatures in excess of 22°C, the designer is on the safe side if the following design criteria are adopted:

- volumetric loading up to 300 g BOD₅/m³·d and/or
- hydraulic retention time of about 5 days;
- assumed BOD₅ removal of 50%;
- depth between 2.5 and 5 metres.

The occurrence of a few successive days with temperatures under 20°C will probably not have any detrimental effect on the overall efficiency of the pond. These recommended values are conservative and depict a situation where there is a low probability of nuisances arising. High sulphate levels in a wastewater will create odour problems at high pond loadings. If odour is not of concern, volumetric loadings up to 400 g BOD₅/m³·d, or higher in the case of industrial wastewaters, may be applied and retention times below 5 days (minimum 1 day) may be adopted.

It should be emphasized that odour problems are always likely to occur in anaerobic ponds as a result of unforeseen circumstances (for instance a rapid fall in temperature). They should only be used for sewage treatment where sufficient relatively flat and inexpensive land is not available for primary facultative ponds. In other words, anaerobic ponds should be used primarily as a means of reducing the area required for pond construction. This becomes especially significant in the case of high-strength industrial effluents.

Anaerobic pond installations should comprise at least two units, operated in parallel, in order to permit sludge removal from one of them while the other is still in operation. Since anaerobic ponds are relatively small in volume, the sludge layer builds up quickly. The volume of digested sludge accumulated in an anaerobic pond may be assumed to be 40 litres per person per year [2].

An anaerobic pond should always be followed by a facultative pond or, better still in the case of sewage treatment, by a facultative pond and one or more maturation ponds. More than one anaerobic pond operated in series is not uncommon in the treatment of high-strength industrial wastewaters [4]. Scum, mats and other

CHAPTER XIX. DESIGN OF ANAEROBIC PONDS

floating material should not be removed from anaerobic ponds, even if they become unsightly, because this floating cover keeps the pond contents warmer and isolates the surface from air contact, thus minimizing objectionable odours evolving from the surface.

A specimen calculation and preliminary design are given in Appendix I.

Chapter XX

DESIGN OF FACULTATIVE PONDS

There are many models for the design of facultative stabilization ponds. The multiplicity of models indicates that none of them is unrestrictedly applicable. Some are complex and rely on data difficult to obtain in practice, for instance the solar radiation model of Oswald and Gotaas [34] and the axial dispersion model of Wehner and Wilhelm [35]. The most widely used models in practice are those of Gloyna [36], Marais and Shaw [37], and McGarry and Pescod [4].

Considering the strict definition of a facultative wastewater stabilization pond given in Chapter III, care should be taken to ensure that an aerobic layer of significant depth is maintained throughout the day at all times of the year. With this conservative approach to design, it is clear that there can be only one truly facultative pond in a series of three ponds or more that include an anaerobic stage; preceding ponds to the truly facultative one will be anaerobic, and succeeding ones will be maturation; a facultative pond efficiency of about 80% would be expected. However, if a long series of ponds is adopted in the system design, as might be the case when dealing with high-strength industrial effluents or when a steeply-sloping site makes large-pond construction uneconomical, there will be several ponds which operate in the grey area between anaerobic and strictly facultative conditions. Though these anaerobic/facultative ponds will be facultative for most or only part of the time during the diurnal and annual cycles, depending on their position within the series of ponds, they will nevertheless remove BOD. The stage at which truly anaerobic pond action ceases and strictly facultative pond action commences will vary throughout the year, depending upon changes in ambient temperature and solar radiation, while the efficiency of BOD removal in each stage will also vary.

All pond systems should be designed with due allowance for future expansion, but it is generally prudent to construct only a sufficient number of ponds to serve the short-term requirements – responding to five-year projections perhaps.

XX-1. THE SURFACE LOADING APPROACH

The adoption of a figure for pond surface (or areal) organic loading based on local experience is an empirical approach to design. Nevertheless, it is the most frequently used method and is the one still preferred by the majority of designers.

CHAPTER XX. DESIGN OF FACULTATIVE PONDS

There is considerable evidence that surface loading is a useful and appropriate parameter for application to the design of facultative ponds. The problem in adopting this approach is to decide what this loading should be in the absence of local data.

Investigations by Silva and Mara [2] in north-east Brazil have proved the feasibility of applying facultative pond loadings up to and even in excess of 400 kg BOD₅/ha·d. Yanez [7] reported very high loadings at the San Juan pond complex at Lima, Peru, from 400 kg BOD₅/ha·d up to 1158 kg BOD₅/ha·d, at which loading high algal counts (from 10⁴ to 10⁵ cells of *Chlamydomonas* per millilitre) were still maintained. Although the ponds did not go completely anaerobic at these high loadings, several objectionable characteristics resulted, such as a milky-green, brown or pink colour most of the time, some scum production and very frequent strong odour release. The San Juan experience suggests that loadings between 200 and 400 kg BOD₅/ha·d may result in occasional slight odour problems; between 400 and 700 kg BOD₅/ha·d there would be frequent light odours and occasional strong ones and, at higher loadings, light or strong odours would always be present. Pond temperature during the survey varied between 19 and 27.5°C, and there was almost no rainfall (between 1.0 and 1.9 mm per month).

On the basis of these data, it would appear that a suitable areal loading for warm climates lies between 200 and 400 kg BOD₅/ha·d. Pond temperatures of the order of 30°C favour loadings around 300 to 400 kg BOD₅/ha·d, whereas at lower temperatures, in the range 20–25°C, lower loadings would be needed (from 200 to 250 kg BOD₅/ha·d should be satisfactory).

Pilot plant studies are sometimes carried out to establish appropriate surface loadings for facultative ponds but, unless the pilot-scale ponds are large enough to allow the full effects of wind-mixing to be established, they might give misleading results.

XX–2. EMPIRICAL MODELS

XX–2.1. Arceivala equation

Arceivala [32] proposed, for India, the following relationship between admissible surface load $L_{s,0}$ and local latitude (lat) between 8°N and 36°N:

$$L_{s,0} \text{ (kg BOD}_5\text{/ha·d)} = 375 - 6.25 \text{ (lat)} \quad (2)$$

Thus, for India, the extreme values of $L_{s,0}$ work out to be 325 and 150 kg BOD₅/ha·d at the southernmost point and in the north, respectively. This approach implies an indirect dependence of $L_{s,0}$ upon the local climatic conditions, especially upon sunlight and temperature, that vary with latitude.

XX-2.2. McGarry and Pescod regression equation

McGarry and Pescod [4] found that, under the normal operating range of loadings for facultative ponds, hydraulic retention time, influent BOD₅ concentration and pond depth had little influence on percentage or areal BOD₅ removal. The effect of temperature on percentage BOD₅ removal also appeared to be minimal, but it was noted that temperatures were not evenly distributed over the range of loadings, higher ambient temperatures being associated with higher loadings.

These authors performed regression analyses on a wide range of performance data and found a high correlation between maximum applied areal or surface loading, $L_{s,0}$, and the minimum ambient mean monthly air temperature, T_a (°C). The relationship is:

$$L_{s,0} (\text{kg BOD}_5/\text{ha}\cdot\text{d}) = 60.3 \times 1.0993^{T_a} \quad (3)$$

Above the loadings derived from Eq.(3), a facultative pond can be expected to operate completely anaerobically at certain periods.

Mara [38] later suggested a linear approximation of this equation:

$$L_{s,0} (\text{kg BOD}_5/\text{ha}\cdot\text{d}) = 20T_a - 120 \quad (4)$$

but this is now considered unnecessarily conservative for use in design. More recently, Arthur [39] presented an adjustment of the linear approximation of McGarry and Pescod's equation, recommending the following form for design:

$$L_{s,0} (\text{kg BOD}_5/\text{ha}\cdot\text{d}) = 20T_a - 60 \quad (5)$$

Mara's north-eastern Brazil data suggest that this is an appropriate modification.

Recent studies sponsored by the United States Environmental Protection Agency (USEPA) and reported by Finney and Middlebrooks [40] have indicated that the McGarry and Pescod formula does not apply to loadings below 112 kg BOD₅/ha·d. They suggested that none of the most-used models are of use for ponds with low loadings. The USEPA survey was carried out on four multiple-pond systems in different climatic areas of the United States of America, with loadings varying from 14.1 to 27.2 kg BOD₅/ha·d; these loadings are about one tenth of the

CHAPTER XX. DESIGN OF FACULTATIVE PONDS

levels usually applied in warm climates. For such climates, several investigators have supported the McGarry and Pescod formulation: Mara and Silva [2] for north-east Brazil, Yanez [7] for Lima, Peru, and Kawai et al. [12] for the south of Brazil.

Application of the McGarry and Pescod equation will result in a BOD₅ removal of about 80% for an influent wastewater BOD₅ concentration of the order of 500mg/L. Unfiltered effluent BOD₅ can be expected to be between 50 and 80 mg/L, reflecting the algal content.

XX – 2.3. Gloyna equation

Gloyna's approach to stabilization pond design is to provide a broad margin of safety in the model, not only to achieve a predetermined BOD removal, but also to prevent aesthetic nuisances, particularly objectionable odours. The design formula suggested by Gloyna [36] was developed after numerous pond systems had been studied and after laboratory and pilot-scale studies had been conducted. It represents an empirical approach which includes an ultimate BOD (or COD) load, because he believes that the relatively long retention times in facultative ponds require the consideration of long-term BOD. In the case of domestic wastewaters, the ultimate demand may be attained after some 20 days of incubation at 20°C. After only 5 days of incubation at this temperature, about 60–90% of the ultimate demand is satisfied [8]. Thus the ultimate demand varies between 1/0.9 and 1/0.6 times the 5-day demand, i.e. between 1.1 BOD₅ and 1.7 BOD₅. Gloyna suggests that BOD₅ might be substituted if the pond receives settled sewage or only soluble BOD. His formula [36] presumes a BOD removal of the order of 80–90% and has the following form:

$$V = 3.5 \times 10^{-5} Q L_u \theta^{(35-T)} f f' \quad (6)$$

In equation (6):

- V = pond volume (m³);
- Q = wastewater flow (L/d);
- L_u = ultimate influent BOD (or COD) (mg/L) «termed L_a in Refs [8, 36]»;
- θ = temperature reaction coefficient (assumed to be 1.085 for facultative ponds treating sewage comprising domestic and industrial wastewaters);
- T = pond water temperature (°C);
- f = algal inhibition factor (f=1 for sewage and many industrial wastewaters);
- f' = sulphide or other immediate chemical oxygen demand (f'=1 for SO₄ equivalent ion concentration of less than 500 mg/L).

Once the pond volume has been calculated using this formula, a decision has to be made regarding pond depth. This judgement will depend on the type of wastewater, solids deposition, temperature, and variability of climatic factors.

XX – 3. KINETIC AND DISPERSION MODELS

XX – 3.1. Marais and Shaw first-order reaction equation

Marais and Shaw [37] applied completely-mixed reactor kinetics to facultative ponds and assumed first-order reaction rates. The basic equation is:

$$L_p = \frac{L_0}{K_T R_T + 1} \quad (7)$$

where: L_p = pond and effluent BOD_5 (mg/L);
 L_0 = influent BOD_5 (mg/L);
 K_T = breakdown rate at temperature $T^\circ C$ (d^{-1});
 R_T = retention time at temperature $T^\circ C$ (d).

The breakdown rate, K_T , depends on pond temperature as follows:

$$\frac{K_{35}}{K_T} = \theta^{(35-T)} \quad (7')$$

where: T = pond operating temperature ($^\circ C$);
 θ = temperature reaction coefficient (= 1.085);
 K_{35} = breakdown rate at $35^\circ C$.

A value for K_{35} must be obtained by experimentation or assumed.

Marais also used an equation relating effluent BOD_5 and pond depth that was developed for South African conditions; this has ultimately taken the form:

$$L_p = \frac{600}{2d + 8} \quad (8)$$

Where d is the depth of the pond (m).

Applying both equations for effluent BOD_5 , it is possible to determine surface organic loading, but strictly this will only apply in South Africa or in regions where the climate is similar.

CHAPTER XX. DESIGN OF FACULTATIVE PONDS

The Marais approach is not widely accepted because the assumption of complete mixing in a facultative pond is not normally valid. Also, the concept of a reaction rate constant similar to that of chemical reactions (Silva and Mara [2]) is being questioned because, with time, the substrate is becoming less and less biodegradable. The biodegradation constant, K_T , considered at 20°C to be 0.17 d^{-1} , actually decreases to 0.07 d^{-1} for treated effluents. Second-order reaction kinetics have been claimed to be more representative [2].

XX – 3.2. Thirumurthi dispersed flow equation

The basis of Thirumurthi's approach [41] is different from previous models in that it considers the hydraulic state of dispersion in the pond. His model has been developed for conditions intermediate between plug-flow and completely-mixed systems. This model is only suitable for research and field studies because of the need for a local determination of the diffusion and dispersion coefficients. From the point of view of practical design, it can be disregarded.

XX – 4. FACULTATIVE POND DEPTH

Nowadays, the recommended depth for facultative stabilization ponds in hot climates is at least 1.5 metres. In heavily-loaded ponds, the settled sludge accumulates quite rapidly in comparison with that in lightly-loaded ponds (e.g. seldom above $50 \text{ kg BOD}_5/\text{ha}\cdot\text{d}$ in the USA). Oswald [3] has indicated that the rate of sludge build-up has been measured to be as low as 30 litres per caput per year when methane fermentation is proceeding satisfactorily. In order to lengthen the period between successive desludgings, it is recommended that deeper facultative ponds be designed. Another reason for making ponds deeper is to protect the anaerobic methane fermentation in the bottom layer from surface dissolved oxygen, which is toxic to methanobacteria.

Some authors discourage the adoption of depths much in excess of 2 metres, because of the great predominance of the anaerobic bottom layer over the upper aerobic layer, with the additional risk of stratification and occasional overturn, spoiling the effluent and killing algae. In addition, the deeper the pond, the colder the bottom, retarding anaerobic biodegradation. It seems reasonable to suggest that the depth of a facultative pond should be varied in the range 1.5 to 2.0 m, only going to 3.0 m when there are very good reasons for doing so, for instance when long retention times are indicated (which might be the case with poorly-degradable industrial wastewaters).

XX – 5. RECOMMENDED DESIGN APPROACHES

XX – 5.1. Primary facultative ponds

Where local data on the performance of a facultative pond exist, then such information should form the principal basis for the design of a new pond, provided that:

- the data were systematically collected and reliably analysed;
- the proposed pond is to treat similar wastewater;
- allowance is made for whether the existing pond is to be preceded by an anaerobic pond.

If there are no local or other appropriate data available, it is suggested that the empirical relationships derived by McGarry and Pescod [4] and by Gloyna [36] offer two reasonable bases for design.

The McGarry and Pescod relationship shown in Eq.(3) does not include a safety factor, and Mara's suggestion that a factor of 1.5 might be appropriate for design should be considered, i.e. the value of $L_{s,0}$ derived from Eq.(3) should be divided by 1.5.* The choice will depend on the environmental "sensitivity" in the vicinity of the pond and the nature of the incoming wastewater. For example, some designers use no safety coefficient if only negligible loading with industrial wastes can reasonably be forecast, i.e. the COD/BOD ratio will always be less than 2.5. The decision should be left to the judgement of the designer.

Where environmental problems cannot be tolerated at any time, Eq.(6), the empirical equation of Gloyna [36], provides a more conservative approach to design. If, for example, a water temperature of 19°C is allowed to be associated with a mean air temperature of 15°C in the coldest month, together with a depth of 1.6 m and a ratio of ultimate BOD to 5 – day BOD of 1.3 (= 1/0.75, i.e. with 5 days retention, the BOD removal is 75% of the ultimate BOD), then a loading rate of 95 kg BOD₅/ha·d is obtained using this equation. It can be seen from these simple calculations that the Gloyna approach will in shallow ponds require a much larger facultative pond area than the McGarry and Pescod approach (see Appendix I). It should, however, be noted that, since the McGarry and Pescod equation defines surface area and the Gloyna equation the volume, as the depth chosen increases, the two approaches give convergent results.

* If a safety factor of 1.5 is applied, the suggested loading rate at 15°C would be 166.3 kg BOD₅/ha·d, to be compared with the 249 kg BOD₅/ha·d calculated using the original equation.

CHAPTER XX. DESIGN OF FACULTATIVE PONDS

XX – 5.2. Secondary facultative ponds

A question that sometimes arises is: “Should secondary facultative ponds be designed on the same basis as primary ones?”

It is logical to assume that the more-easily degradable material will have been removed in the primary unit (whether anaerobic or facultative) and that the primary stage effluent is less-biodegradable than the raw wastewater. Thus, the stabilization of organic material in the secondary pond is likely to take place at a lower reaction rate.

Studies carried out by CETESB [12] comparing single facultative ponds with anaerobic/facultative pond systems in southern Brazil indicate that the admissible loading that could be applied to a secondary facultative pond was about 20% less than that which could be applied to a primary pond for the same effluent BOD. Nevertheless, CEPIS studies in Lima [19] relating surface loading and BOD removed did not produce evidence of any significant difference between the performance of primary and secondary facultative ponds under the same loading conditions. It is clear that this subject is still open to discussion and that more research is required.

Since the empirical equations presented in this chapter were mainly derived from primary facultative pond treatment data based on installations treating both domestic and industrial wastewaters, and since no special allowance was made for less-biodegradable effluents, it seems reasonable for the present to consider these equations as being suitable for application in the treatment of all but the most biologically-resistant wastes, in secondary as well as primary facultative ponds. Only if a very high-grade effluent is essential should the loading of the secondary facultative pond be reduced, perhaps by 20%, as the research at CETESB has indicated.

XX – 5.3. Retention time

Secondary facultative ponds (i.e. those preceded by one or more anaerobic ponds) operated in climates where the average “coldest month” air and water temperatures are, respectively, around 10°C and 15°C or higher would have a minimum retention time of 5 days, extending to some tens of days, depending on design parameters. Increasing the retention time increases the land area required. For primary ponds operated at these temperatures, the retention times are reckoned in tens of days. On sites with low relative air humidity, strong breezes and higher air temperatures, long retention times can involve very significant water loss resulting from evaporation (§VI – 1.5).

A specimen calculation and preliminary design are given in Appendix I.

Chapter XXI

DESIGN OF MATURATION PONDS

XXI – 1. FUNCTION OF MATURATION PONDS

Maturation ponds are widely used for the additional removal of pathogenic agents, such as some species of bacteria, fungi, protozoa and viruses. They normally have a low efficiency for BOD removal because they receive an influent of low soluble BOD, but they can remove soluble BOD that has been carried over from the preceding facultative pond. For example, a facultative pond effluent with a soluble BOD_5 of 50 to 70 mg/L can be reduced to a soluble BOD_5 of 25 mg/L or less by treatment in one or more maturation ponds. Specifically, when agricultural reuse of the effluent is planned, maturation ponds are often considered indispensable. However, they can only be justified in regions where land cost is low and sufficient area is available.

Maturation ponds are never primary treatment units. They are always preceded by a facultative pond, which may be a primary or secondary unit. A combination commonly met with is an anaerobic pond followed by a facultative pond placed ahead of one or more maturation ponds.

The design of maturation ponds is based on bacterial decay, although the intention is to eliminate all pathogenic organisms. Faecal bacteria, protozoa and viruses die off with time because of the unfavourable environment in a treatment unit. The main factors causing bacterial decay are sedimentation, scarcity of food (organic carbon and nutrients), ultra-violet light, predators (bacteriophages, microcrustaceans, protozoa and rotifers), the antibiotics and toxins produced and introduced into the environment by some species, high water temperatures and high pH – values. The main parameter to be considered in bacterial die-off in ponds is retention time. Experimental work and practical experience have shown that a minimum retention period of 5 days in a single maturation pond or 3 days per pond in a series of two or more ponds following a facultative pond is usually adequate. Retention times can extend to 10 days or more.

Maturation ponds are usually 1.0 to 1.5 metres in depth. However, the effluent structure should allow the depth to be varied in order to control mosquito breeding and to prevent the bottom layer from going anaerobic.

CHAPTER XXI. DESIGN OF MATURATION PONDS

XXI - 2. BACTERIAL REDUCTION MODELS

If a bacterial effluent standard is to be met using ponds without final disinfection, this will usually determine the required retention time and number of ponds in series. According to Marais [42], the disappearance of faecal bacteria (*Escherichia coli*, *Streptococcus faecalis* and others) in a stabilization pond may be estimated using the following equation:

$$\frac{N_R}{N_0} = \frac{1}{K'R + 1} \quad (10)$$

In equation (10):

- N_0 = bacterial population in the influent;
- N_R = bacterial population after R days;
- K' = die-off constant (d^{-1}). This varies from micro-organism to micro-organism and between different strains of the same one;
- R = retention time (d).

If *Escherichia coli* is used as an indicator organism, $K' = 2.0$ per day [8]. Yanez [19] has compiled the data shown in Table VI for faecal coliform bacteria and salmonella.

If there are two or more ponds in series, the corresponding equation is:

$$\frac{N_R}{N_0} = \frac{1}{(K'R_1 + 1)(K'R_2 + 1) \dots (K'R_n + 1)} \quad (11)$$

where R_1, R_2 to R_n are the retention times in the first, second to nth ponds, in a series of n ponds.

When all the ponds have the same volume and therefore the same retention time, as is often the case, Eq.(11) becomes:

$$\frac{N_R}{N_0} = \frac{1}{(K'R + 1)^n} \quad (12)$$

As already mentioned, the retention time R in each pond should be kept between 3 and 10 days, or not less than 5 days if there is only one such pond.

It should be emphasized that K' is temperature-dependent. K' at temperature T is related to K' at 20°C by:

$$\frac{K'_T}{K'_{20}} = \theta^{(T - 20)} \quad (13)$$

TABLE VI. VALUES OF DIE-OFF CONSTANT FOR DIFFERENT BACTERIAL SPECIES [19]

Organism	K' (d-l)	Temperature (°C)	Reference
Faecal coliforms	0.552	11-15	Wright [43]
Faecal coliforms	0.664	16-29	Wright [43]
Faecal coliforms	2.0	Not recorded	Marais and Shaw [37]
Faecal coliforms	2.6	20	Slanetz et al. [44]
Salmonella	0.8	Not recorded	Marais and Shaw [37]

Various authors have suggested a value of 1.07 for θ' , the temperature coefficient.

It must be kept in mind that the value of the constant $K' = 2 \text{ d}^{-1}$ for *E. coli* does not apply to other pathogens; in the case of *salmonella typhi*, for example, it has been found to be only 0.8 d^{-1} .

It should be noted that faecal coliform bacteria are not necessarily pathogenic and are considered only as an indicator of the risk of infection. It is, therefore, incorrect to generalize too much when considering a K - value, and the application to other organisms should be exercised with caution, even when the phenomena involved are understood. Nevertheless, the equations given are useful for estimating maturation pond dimensions.

More recent work has been done by Polprasert et al. [45], who have attempted to take into account the complex physical and biochemical reactions taking place in ponds to assess bacterial die-off. A multiple-regression equation involving parameters such as retention time, organic loading, algae concentration and ultra-violet light exposure has been suggested. The Wehner and Wilhelm non-ideal flow equation [35] including the pond dispersion number was proposed for predicting bacterial survival, in preference to the first-order rate equation.

A specimen calculation and preliminary design, using the Marais approach, are given in Appendix I.

Appendix I

DESIGN OF A WASTEWATER STABILIZATION POND SYSTEM

Water is to be supplied to 80% of the inhabitants of a town of unknown population and 80% of the people so supplied are to be sewerred. A direct count of the houses gives a total of 3840 dwellings. There is no major industry in the sewerred areas, but there is some home industry in the community. The designer has selected four blocks which he considers as representative of the population density and has counted the dwellings and the number of inhabitants. He has found 616 people living in 112 dwellings. The population growth is estimated to be 4% per year during the next ten years. At that time, the collected wastewater is to be treated in a series of wastewater stabilization ponds whose first stage comprises two anaerobic ponds in parallel, the second two facultative ones in parallel; these are to be followed by as many maturation ponds in series as necessary to achieve the required coliform count. In the case considered, the river into which the ponds will discharge is used for irrigation and watering animals; there is some family fishing and the children play there. Having determined the prevailing wind, a site has been chosen to be as nearly downwind of the town as possible. The measured and assumed parameters are shown in Table A-1.

SPECIMEN CALCULATION

A. POPULATION TO BE SEWERED

The first step is to determine the population to be sewerred in ten years time.

Estimated present population: $3840 \times \frac{616}{112} = 21\,120$ inhabitants

Estimated population in 10 years: $21\,120 \times (1.04)^{10} = 31\,263$ inhabitants

Population to be sewerred: $31\,263 \times 0.8 \times 0.8 = 20\,008$ inhabitants

This number is rounded to 20 000 inhabitants.

B. ANAEROBIC PONDS

The next step is to calculate the design details of the anaerobic ponds (cf. Chapter XIX). The various parameters are taken from Table A-1.

The influent load in terms of BOD₅ per day is:

$$\text{Inhabitants} \times \text{BOD}_5/\text{person-day} = 20\,000 \times 45 = 900\,000 \text{ g BOD}_5/\text{d} \quad (\text{A-1})$$

WASTEWATER STABILIZATION PONDS

TABLE A-1. MEASURED AND ASSUMED PARAMETERS

Population in 10 years	20 000
Water supply per inhabitant (per caput)	150 L/d
Percentage of water supplied that is collected by the sewer system	85%
Volume of influent to pond system per day ($20\,000 \times 150 \times 0.85/1000$)	$2550\text{ m}^3/\text{d}$
Mean probable number (MPN) of coliforms in the influent	$4.2 \times 10^8/100\text{ mL}$
Anaerobic ponds	
BOD ₅ per caput	45 g/d
BOD ₅ of sewage [= $45/(150 \times 0.85)$] per caput	0.353 g/L (= 353 mg/L)
Volumetric loading of anaerobic ponds	$100\text{ g BOD}_5/\text{m}^3\cdot\text{d}$
Digested anaerobic sludge production per caput per year	0.04 m^3
Anaerobic pond depth chosen to be	4 m
BOD ₅ reduction in the anaerobic ponds	50%
Percentage removal of coliform in the anaerobic ponds	disregard
Facultative ponds	
Ultimate BOD (BOD _u), [see text]	1.4 BOD_5
Mean air temperature during the coldest month	15°C
Mean water temperature during the coldest month	18°C
Digested sludge production per caput per year	0.03 m^3
Facultative pond depth chosen to be	1.70 m
Percentage removal of coliform in the facultative ponds	99%
Maturation ponds	
Coliform count permissible in the final effluent of the maturation ponds	$\text{MPN} < 2 \times 10^3/100\text{ m}$
Bacterial removal rate, K'	2.0 d^{-1}
Maturation pond depth chosen to be	1.0 m
Civil engineering parameters	
Embankment slope, pond side	1/3 (= 33%)
land side	1/1.5 (= 67%)
Freeboard, all ponds	0.5 m
Compaction test on soil sample (compacted soil vol./original vol.) x 100	90%

Therefore the volume of the pond (without sludge accumulation) is given by:

$$\text{Influent load/volumetric loading} = 900\,000/100 = 9000\text{ m}^3 \quad (\text{A-2})$$

Allowance for a five-year accumulation of sludge at 0.04 m^3 per person per year gives:

$$20\,000 \times 0.04 \times 5 = 4000\text{ m}^3 \quad (\text{A-3})$$

Hence total volume (liquid plus sludge) is:

$$9000 + 4000 = 13\,000\text{ m}^3 \quad (\text{A-4})$$

APPENDIX I. DESIGN OF A WASTEWATER STABILIZATION POND SYSTEM

The resulting liquid retention time (do not include sludge volume!) is calculated based on the volume of influent to the pond system per day (Table A-1):

$$\frac{9000}{2550} = 3.529 = 3.5 \text{ days (rounded)} \quad (\text{A-5})$$

As the depth is to be 4 m and the pond cross-section is a trapezium (see Fig.A-1), the area at half-depth (now considering both liquid and sludge) would be:

$$\text{Volume/depth} = 13\,000/4 = 3250 \text{ m}^2 = 0.325 \text{ ha} \quad (\text{A-6})$$

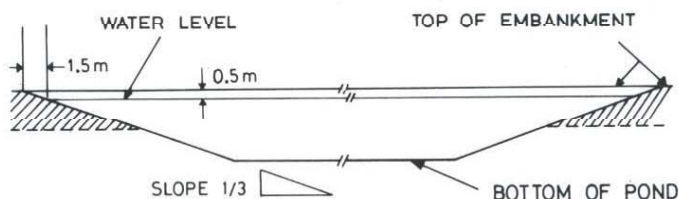


FIG.A-1. Sketch of the trapezoidal cross-section of a pond.

Pond shape

There are to be two equal ponds, operated in parallel, each of 6500 m^3 and hence of area at half-depth 1625 m^2 each. The ponds are to be square, having an embankment slope of 1/3 (33%) as shown in Fig.A-1. Hence, the side of the square at half-depth is:

$$\sqrt{\text{Area}} = \sqrt{1625} = 40.3 \text{ m side length} = 40 \text{ m (rounded)} \quad (\text{A-7})$$

The side of the square at the bottom is, by simple geometry:

$$40 - 2 \times (\text{half liquid-plus-sludge depth}) \times \text{inverse slope} \\ = 40 - (2 \times 2 \times 3) = 28 \text{ m} \quad (\text{A-8})$$

Similarly, the side of the square at the liquid surface is:

$$40 + (2 \times 2 \times 3) = 52 \text{ m} \quad (\text{A-9})$$

If a freeboard of 0.5 m is chosen, the side length at the top of each embankment is:

$$52 + (2 \times 0.5 \times 3) = 55 \text{ m} \quad (\text{A-10})$$

The corners would be rounded, with a radius of 10 m at the top and 4 m at the bottom.

Inlets and outlets

The inlet to each pond would be located at the centre and the outlet near a corner (see Fig.A-2).

WASTEWATER STABILIZATION PONDS

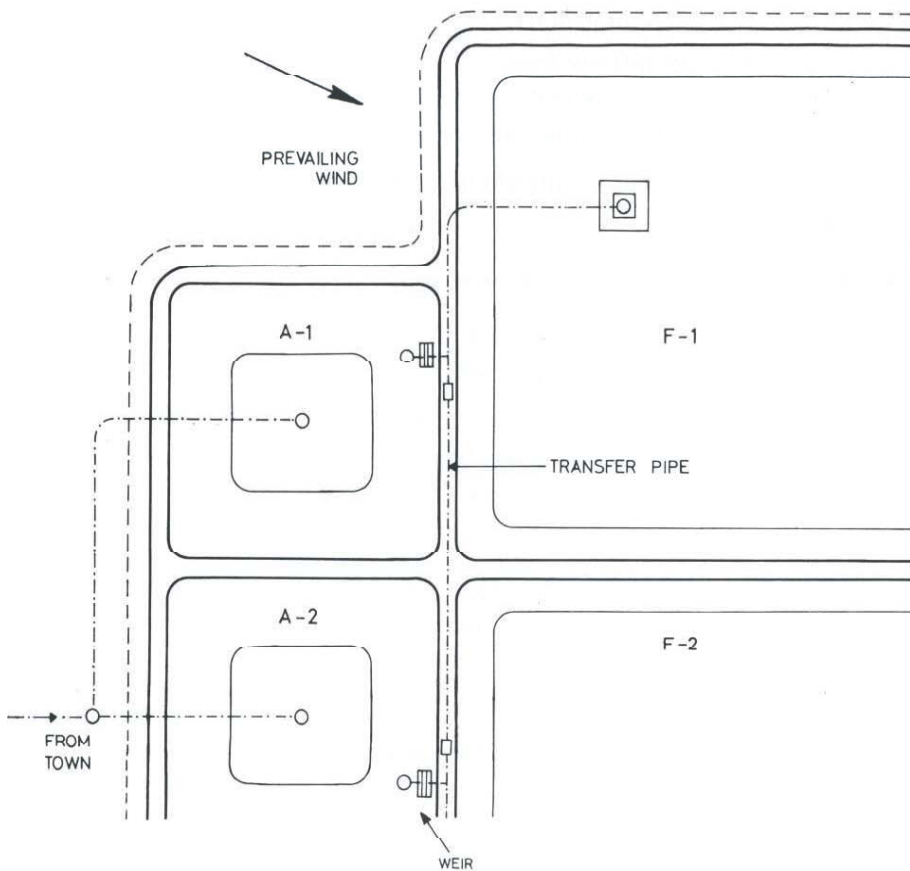


FIG.A-2. Layout of the anaerobic ponds showing inlets and outlets.

For the inlet, the pipe would be laid on the slope and the bottom of the pond, ending at its centre, in this case with a splash-plate in the depression (cf. Fig. 12A in the main text).

For the outlet, a baffled elbow ending in a measuring box near the top of the embankment would be provided. Each pond empties into its neighbouring facultative pond, but a transfer pipe with appropriate control valves is provided between the two sets of parallel ponds.

C. FACULTATIVE PONDS

For comparison purposes, the facultative ponds will be designed using both the McGarry and Pescod and the Gloyne equations. The design principles are as discussed in Chapter XX.

APPENDIX I. DESIGN OF A WASTEWATER STABILIZATION POND SYSTEM

With a 50% reduction in BOD_5 in the anaerobic pond, the facultative pond load will be 50% of the influent load given by Eq.(A-1), namely $(0.5 \times 900\,000) = 450\,000$ g BOD_5 /d. If it is conservatively assumed that some 70% of the biochemical oxygen demand is satisfied during the retention period (based on the temperature conditions given in Table A-1), the ultimate BOD is $BOD_5/0.7$ $(450\,000 \times 1.4) = 630\,000$ g BOD_5 /d.

Design based on the McGarry and Pescod equation

The McGarry and Pescod regression equation (§XX – 2.2, Eq.(3)) is:

$$L_{s,0} \text{ (kg } BOD_5/\text{ha}\cdot\text{d)} = 60.3 \times 1.0993^{T_a}$$

where $L_{s,0}$ is the applied areal or surface loading and T_a ($^{\circ}\text{C}$) is the minimum ambient mean monthly air temperature. Meteorological data show that the mean air temperature during the coldest month of the year is 15°C . Hence:

$$L_{s,0} = 60.3 \times 1.0993^{15} = 249.5 \text{ kg } BOD_5/\text{ha}\cdot\text{d} \quad (\text{A-11})$$

As stated in Chapter XX, above these loadings a facultative pond might be expected to operate anaerobically at certain periods. It is therefore convenient to apply a safety factor of 1.5 (see §XX – 5.1). Thus the design loading will be taken as:

$$249.5/1.5 = 166.3 \text{ kg } BOD_5/\text{ha}\cdot\text{d} \quad (\text{A-12})$$

Hence the total surface area of the facultative ponds is determined from the facultative pond load expressed in terms of ultimate BOD (kg BOD/d) divided by the design loading:

$$630/166.3 = 3.79 \text{ ha} = 38\,000 \text{ m}^2 \text{ (rounded)} \quad (\text{A-13})$$

Design based on the Gloyna equation

The Gloyna equation (§XX – 2.3, Eq.(6)) is:

$$V = 3.5 \times 10^{-5} Q L_u \theta^{(35-T)} f f'$$

Here V = pond volume (m^3);

Q = wastewater flow (L/d);

L_u = ultimate influent BOD (or COD) (mg/L);

θ = temperature reaction coefficient;

T = pond water temperature ($^{\circ}\text{C}$);

f = algal inhibition factor;

f' = sulphide or other immediate chemical oxygen demand.

The composite term QL_u is the facultative pond load expressed in terms of ultimate BOD (mg BOD/d this time), and for our purposes f and f' are both equal

WASTEWATER STABILIZATION PONDS

to unity. Thus, since the mean water temperature during the coldest month is 18°C and θ can be taken as 1.085 for this type of sewage:

$$V = 3.5 \times 10^{-5} (630 \times 10^6) 1.085^{(35-18)} = 88\,250 \text{ m}^3 \quad (\text{A-14})$$

Choice of pond depth and comparison of the two results

At this stage, a decision has to be made regarding the depth of the facultative ponds (see §XX – 4). This judgement will depend on the type of wastewater, solids deposition, temperature, and variability of climatic factors. For primarily domestic wastewaters, a liquid depth of 1.6 m is a value that gives good aeration. Ignoring the sloping sides at this stage, a first estimate of the surface area may be derived from the Gloyna equation by dividing the volume by the depth:

$$88\,250 / 1.6 = 55\,200 \text{ m}^2 = 5.52 \text{ ha (rounded)} \quad (\text{A-15})$$

The Gloyna equation has resulted in an area some 45% larger than the area ($38\,000 \text{ m}^2$) derived from the McGarry and Pescod equation **for the given depth**. As the latter already includes a safety factor, it is reasonable to choose the smaller surface area for, as was pointed out in Chapter XX, the Gloyna equation gives conservative values. Hence a surface area of $38\,000 \text{ m}^2$ will be chosen.

With a depth of 1.6 m and an embankment slope of 1/3, the volume of the McGarry and Pescod pond would be of the order of $55\,000 \text{ m}^3$ (area at half-depth for a square pond multiplied by the depth). With a daily wastewater flow of 2550 m^3 , a retention time of around 21.5 days is obtained. This is satisfactory. Indeed, the ultimate BOD under these circumstances would be nearer $\text{BOD}_5 / 0.85 = 1.2 \text{ BOD}_5$; this increases the margin of safety.

It will be assumed that the evaporation loss for this retention time is 10% of the volume of the facultative ponds, equivalent to about 7 mm/d. This has a bearing on the concentration of the bacteria in the effluent passing to the maturation ponds.

The accumulation of sludge can be estimated to be 30 litres (0.03 m^3) per person per year (§XX – 4). Taking the sludge accumulation over a five-year period, as for the anaerobic ponds, the volume of sludge is:

$$20\,000 \times 0.03 \times 5 = 3000 \text{ m}^3 \quad (\text{A-16})$$

As can be seen, the sludge volume will have a smaller impact on pond depth than is the case for the anaerobic ponds.

Pond shape

There are to be two rectangular facultative ponds of equal surface area, namely $19\,000 \text{ m}^2$ each. With a length-to-width ratio of 1.5:1, the longer side being in the

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prevailing wind direction, the side lengths at water level will be 168.8 m and 112.5 m respectively, to be rounded to 170 m and 110 m. The ponds will be of trapezoidal cross-section with an embankment slope on the pond side of 1/3.

The area at the bottom of the pond will be of the order of 160 m x 100 m by simple calculation. The sludge per pond will be 1500 m³, and its depth will be $1500/16\ 000 = 0.094$ m. This will be rounded to 0.1 m (10 cm). Hence the liquid-plus-sludge depth, i.e. the pond depth, will be 1.7 m.

The sides of the rectangle at the bottom are, by simple geometry:

side – 2 x (liquid + sludge depth) x inverse slope, i.e.

$$170 - (2 \times 1.7 \times 3) = 159.8 \text{ m and } 110 - (2 \times 1.7 \times 3) = 99.8 \text{ m} \quad (\text{A-17})$$

These side lengths are rounded to 160 m and 100 m respectively.

With a freeboard of 0.5 m, the side lengths at the top of each embankment are:

$$170 + (2 \times 0.5 \times 3) = 173 \text{ m and } 110 + (2 \times 0.5 \times 3) = 113 \text{ m} \quad (\text{A-18})$$

The corners would be rounded, with a radius of 10 m at the top and 7 m at the bottom (rate of change of radius as for anaerobic ponds).

Water level, inlets and outlets

The water level in the facultative ponds should be set at least 0.30 m below that of the anaerobic ponds. The top of the embankments would be lower by the same amount. The positions suggested for the inlets is shown in Fig.A-2. The inlets are of the type shown in the lower diagram of Fig.12A of the main text; the outlets use stop-log weirs as shown in Fig.13. The effluents from the two facultative ponds are combined and flow into the first maturation pond.

D. MATURATION PONDS

The design principles are discussed in Chapter XXI. The mean probable number of coliforms in the influent to the pond system are estimated to be $4.2 \times 10^8/100$ mL. With a negligible removal of coliforms in the anaerobic ponds, 99% removal in the facultative ponds, and a 10% by volume evaporation of water from the facultative ponds (i.e. 90% remains), the coliform input to the first maturation pond will be:

$$4.2 \times 10^8 \times \frac{(1 - 0.99)}{0.90} = 4.7 \times 10^6 \text{ coliforms/100 mL} \quad (\text{A-19})$$

The bacterial effluent standard to be met using maturation ponds will usually determine the required retention time and hence the number of ponds in series.

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TABLE A-2. MATURATION PONDS: VARIATION OF RETENTION TIME AND POND AREA WITH NUMBER OF PONDS FOR THE CHOSEN BACTERIAL REDUCTION

Number of ponds, n	1	2	3	4	5
Retention time per pond, R (days)	1175	23.7	6.15	2.98	1.86
Pond area at half-depth ^a (m ²)	3.0×10^6	60×10^3	16×10^3	7.6×10^3	4.8×10^3
Total area (m ²)	3.0×10^6	120×10^3	48×10^3	30×10^3	24×10^3

a (R x wastewater flow/day) divided by pond depth = 2550R for a depth of 1 m. Mid-depth is used to avoid allowance for sloping sides at this stage. Volume data are rounded.

When all the ponds have the same volume and therefore the same retention time, the equation to be used is Eq.(12) of the main text:

$$\frac{N_R}{N_0} = \frac{1}{(K'R + 1)^n}$$

where N_0 is the bacterial population in the effluent from the facultative pond (= 4.7×10^6 coliforms/100 mL), N_R is the bacterial population after R days, K' is the die-off constant (d^{-1}), and R is the retention time (d).

The die-off constant K' varies from micro-organism to micro-organism and between different strains of the same one. If *Escherichia coli* is used as the indicator organism, $K' = 2.0 d^{-1}$. The bacterial population N_R at the outflow from the wastewater stabilization pond system is to have a mean probable number of less than 2×10^3 /100 mL. Thus:

$$\frac{2 \times 10^3}{4.7 \times 10^6} = \frac{1}{(2R + 1)^n} \quad (A-20)$$

Reforming, the equation becomes:

$$\log (2R + 1) = \frac{\log 2350}{n} \quad (A-20')$$

The equation is solved to obtain the retention time, R, for different numbers of ponds, n, from 1 to 5, and the results are presented in Table A-2. Clearly, as the number of ponds increases, the retention time and, hence, the surface area per pond decrease rapidly, the total surface area less so. Since it was stated that the minimum retention time per pond for two or more ponds should not be less than 3 days, and since the surface areas for 1 and 2 ponds are unrealistic, the choice falls on either 3 ponds with retention times of 6 days each, or 4 ponds with retention times of 3 days each. The lower total area for 4 ponds still brings a significant economic advantage over that for 3 ponds.

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Using Eq.(A-20), the value of N_R can be checked for the retention time and number of ponds chosen, giving $4.2 \times 10^6/7^4 = 1.95 \times 10^3/100 \text{ mL}$, which is within the prescribed limit. The individual pond volumes are 7650 m^3 .

Since the depth is to be 1 m, the area of each pond at half-depth is 7650 m^2 . To suit the land available, it is in this case practical to have an arrangement whereby the maturation ponds have one side equal to the width of the facultative ponds, i.e. 113 m at the top of the embankment. Since the freeboard and slopes are the same as for the other ponds, the side in question will be 107 m at half depth. Hence the other dimension at half-depth will be $7650/107 = 71.5 \text{ m}$, rounded to 72 m. Hence the dimensions of the maturation ponds are:

At the bottom: $104 \text{ m} \times 69 \text{ m}$ (A-21)

At water level: $110 \text{ m} \times 75 \text{ m}$ (A-22)

At the top of the embankment: $113 \text{ m} \times 78 \text{ m}$ (A-23)

The corners would be rounded, with a radius of 10 m at the top and 8 m at the bottom.

The length-to-width ratio is nearly 1:1.5, but it should be noted that the long side is now parallel to the short side of the facultative ponds, and no longer in the prevailing wind direction. With the given side ratio, this is acceptable.

(It would also have been possible to have four ponds next to each other, 55 m wide at the embankment level, each 150 m long. The length-to-width ratio would have been 1:2.67 at water level, and flow conditions would have approached those of plug flow.)

Water level, inlets and outlets

Because of the loss of head, the maturation ponds should be set with their water levels at least 1 m below that of the facultative ponds. The top of the embankments should be lower by the same amount.

As stated, the four maturation ponds are connected in series. The interconnections between them can be made simply by means of horizontal pipe systems placed within the embankments beneath water level. With the suggested configuration, it is best to use multiple inlets and outlets, say, three each per pond. The final effluent flows into a river through a Parshall flume (see §XIII – 3 and Fig.14) to provide final effluent flow monitoring.

E. EARTHMOVING

The general configuration of the ponds will be as shown in Fig.A.3. The elevation shown in the upper portion has an expanded vertical scale in order to show the height and level differences clearly.

To allow the influent from the town to flow into the anaerobic ponds without pumping, it has been determined that the water level in these ponds must not be more than 2 m above the site ground level. The water body, a small river into which the maturation ponds discharge, has a level of 0.6 m below the site ground level. The river has no history of flooding.

Because of the loss of head, the facultative ponds must be set with their water level not less than 0.3 m below that of the anaerobic ponds, the maturation ponds with their water level not less than 1 m below that of the facultative ponds. The tops of the embankments will be lower by matching amounts. Pumping facilities would have to be provided for the effluent from the maturation ponds if the water level in those ponds is less than about 1 m above the level of the receiving water body.

Principle of minimum excavation

It will be assumed that the site is practically level (sloping less than 0.5% in any perpendicular plane). It is economically optimal to ensure that cut and fill are balanced, i.e. cut equals fill including allowance for volume after compaction. Practically, it is better to ensure that there is a slight excess excavated than to have to bring in additional material from elsewhere. A small excess can always be disposed of on the embankments.

The volume of the fill derived from the cut is almost always less after compaction than its original volume, i.e. compacted volume is less than the original "in-place" volume [46]. It is assumed that, at this particular site, soil borings have shown that the material of the ground is suitable for embankment construction and that the volume of a sample after compaction was 90% of its original volume. Thus:

$$\text{Volume available for embankments} = 0.90 \times \text{excavated volume} \quad (\text{A-24})$$

For the calculation, as a first approximation, the difference in water levels between anaerobic and facultative ponds is taken to be 0.5 m, and that between facultative and maturation ponds to be 1.0 m. The cut depths are c_a , c_f and c_m , the fill heights (to the top of the embankments) f_a , f_f and f_m , and the water levels w_a , w_f and w_m for the three types of pond respectively.

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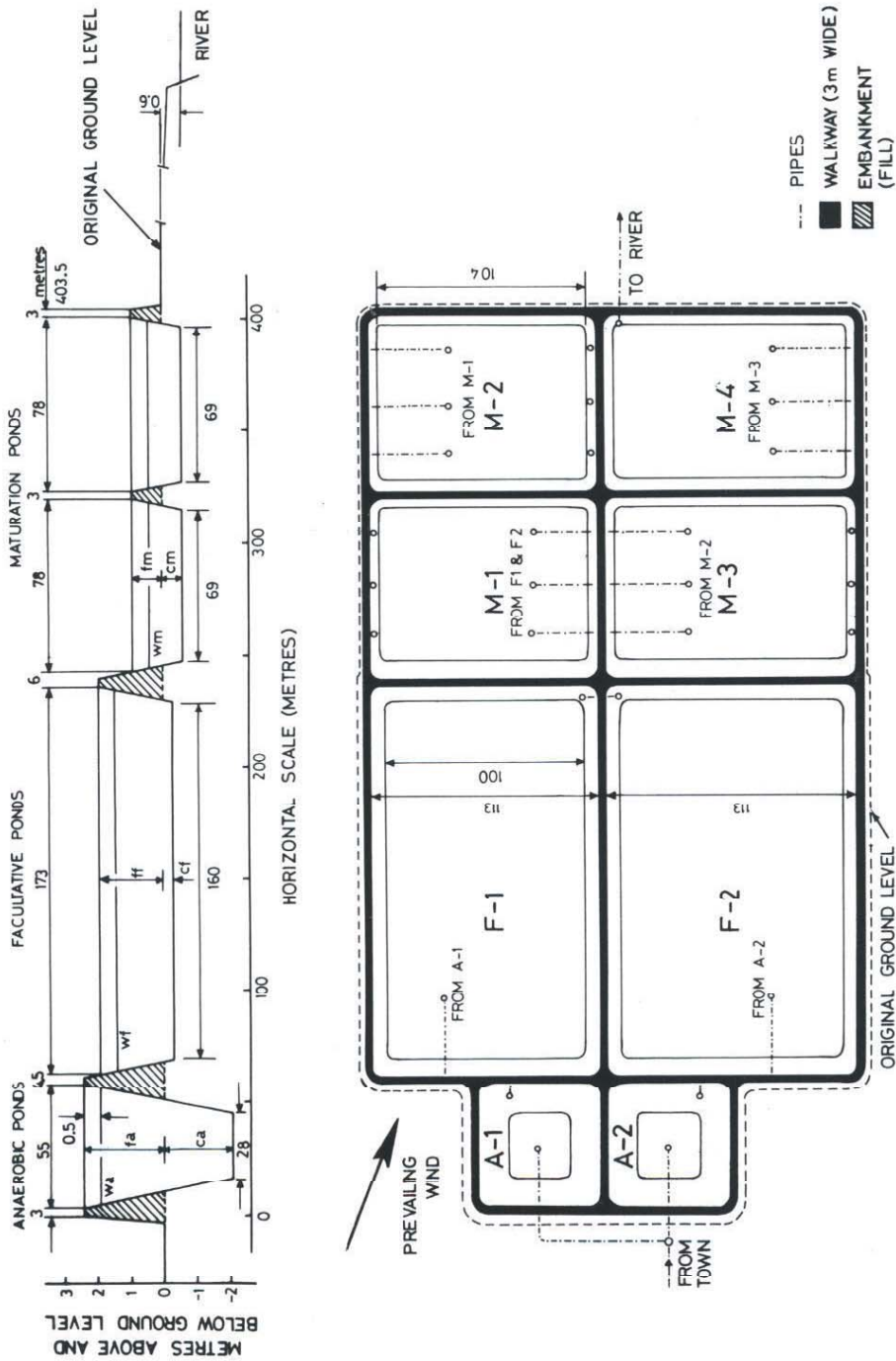


FIG.A-3. Detailed plan and elevation of the system of anaerobic, facultative and maturation ponds designed on the basis of data specified in the Appendix. The vertical scale in the elevation is expanded to permit various levels to be clearly shown.

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The corners are rounded, a standard 10 m radius being chosen for embankment level (see Fig.A-3), and a standard rate of decrease of radius for all ponds, this being a reduction from 10 m to 4 m radius over the height of 4.5 m (top of embankment to bottom of anaerobic ponds).

The detailed calculation is presented in Annex I. The estimate to be used for costing and assessment purposes would use for the cut depths:

$$ca = 2.10 \text{ m}; \quad cf = 0.30 \text{ m}; \quad cm = 0.60 \text{ m} \quad (A-25)$$

The heights of the embankments above original ground level would then be:

$$fa = 2.40 \text{ m}; \quad ff = 1.90 \text{ m}; \quad fm = 0.90 \text{ m} \quad (A-26)$$

while the heights of the water levels in the respective ponds above ground level would be:

$$wa = 1.90 \text{ m}; \quad wf = 1.40 \text{ m}; \quad wm = 0.40 \text{ m} \quad (A-27)$$

The total volume of earth excavated would be $32\,700 \text{ m}^3$, being 5000, 9700 and $18\,000 \text{ m}^3$ for the anaerobic, facultative and maturation ponds, respectively. With compaction to 90% of the in-place volume, the compacted volume available from the cut would be $29\,400 \text{ m}^3$. Since the compacted volume needed for the embankments is $27\,500 \text{ m}^3$, there would be an excess of some 1900 m^3 . (It should be noted that such an excess can easily be compensated at the final design stage; for example, by making the cut for the anaerobic ponds alone 0.1 m less deep, thereby raising the respective embankments by the same amount, some 1100 m^3 of the excess would be eliminated).

The water level in the maturation ponds would be 0.40 m above the original ground level, that is 1.0 m above the level of the river. Since the river is known not to flood, this would be acceptable for discharge under most normal conditions. Whether pumping is to be provided for the final effluent at certain times of the year depends on a "worst conditions" history of the river levels. If records have not been kept, one or more river gauges should be installed as soon as possible, with daily recording, to ensure that a reasonable body of data is obtained. If pumping can be avoided, it significantly reduces costs, and maintenance and energy requirements.

The purpose of this calculation was to provide an example of a methodology that would provide a good estimate of wastewater treatment pond sizes so that, in turn, a meaningful estimate of land requirements and construction work could be made. This estimate would enable senior decision-makers in government and in

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district, municipal and community administrations who are concerned with choosing a practical wastewater treatment system to make comparisons with other, more complex treatment methods. In such assessments, the possibility of motivating community involvement and self-help as well as the value to the community of the effluent re-use potential, be it for agriculture or fish-rearing, would need to be borne in mind. The potential for community involvement in the construction and operation of wastewater stabilization ponds is greater than with most other wastewater treatment methods.

It should, however, be noted that there is no intention to suggest that the configuration of wastewater stabilization ponds calculated above be considered as anything but one possible solution; a number of different pond configurations could equally reasonably have been chosen. The calculational methodology would be similar.

Further information may be sought from the more detailed design manuals to which reference has already been made, e.g. Refs [1, 6, 7, 10]. In this context, attention should be drawn to the US Environmental Protection Agency's document "Design Manual – Municipal Wastewater Stabilization Ponds" issued in October 1983 [47] and the WHO Regional Office for Europe's document "Waste Stabilization Ponds: Design Manual for Mediterranean Europe" to be issued in the course of 1987 [48].

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Annex I

CALCULATION OF CUT AND FILL VOLUMES

The following example indicates a methodical approach to the calculation of cut depths and fill heights. Totals are given to two places of decimals, ignoring the question of accuracy required. With even simple calculators, it is safer and easier to work to a fixed number of decimal places and to round the data near the end of the calculation; it is also easier to check the working subsequently. Furthermore, for the case considered here, the reader will be able to follow the calculation in detail before undertaking his own to suit local needs and conditions. The question of accuracy is discussed at the end of this Annex.

The plan and elevation of the ponds is shown in Fig.A-3 (see the Appendix). The embankments can be considered as comprised of a number of right-prisms of either triangular or rectangular cross-section of height f with slopes of $1/3$ on the water side and $1/1.5$ on the land side. In addition, in the 45° corners, there are elements that are either right-triangular prisms or pyramids on a triangular or rectangular base. The breakdown of the embankment section is shown in Fig.A-4. The main

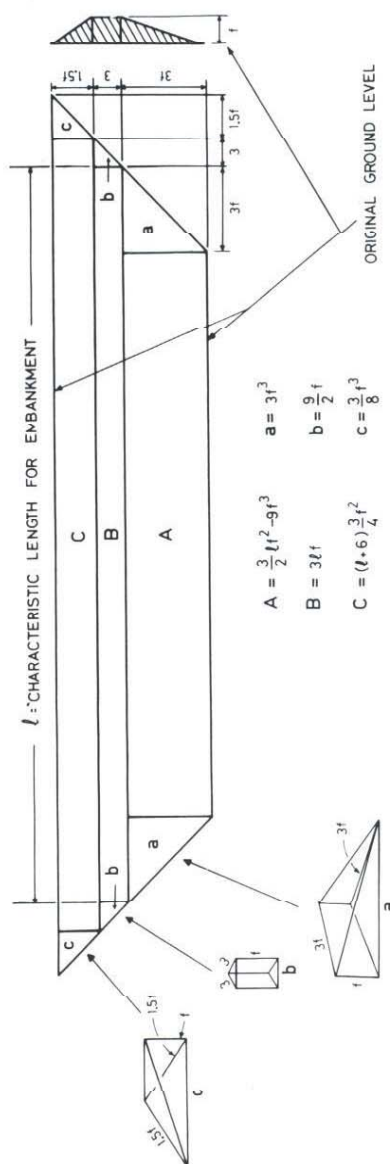
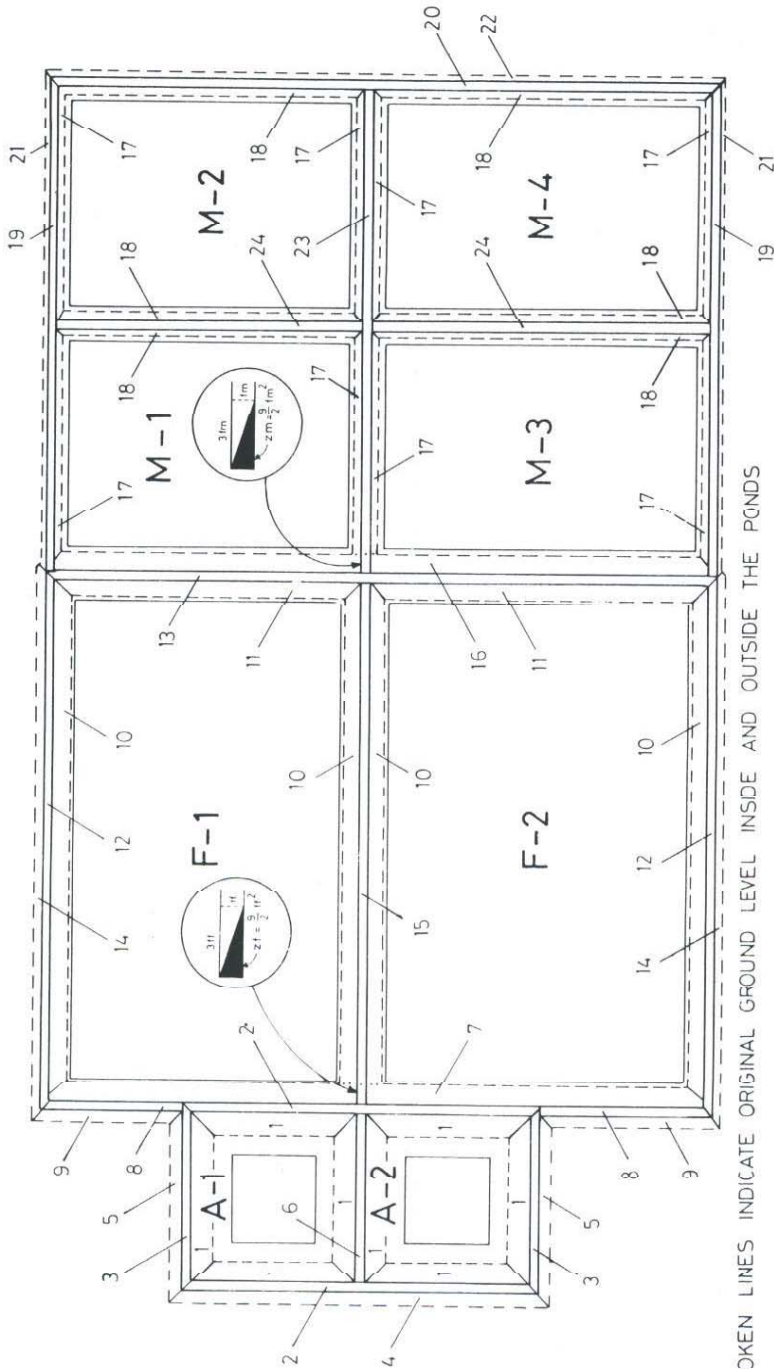


FIG.A-4. Breakdown of embankment into constituent prisms and pyramids. The volumes of the six individual elements are given in terms of the fill height, f .

prisms are labelled A to C, and the corner elements are labelled a to c. The volumes corresponding to the main prisms and the elements are indicated. The characteristic length **for embankments** is the length of the inner (pond-side) edge at the **top** of the embankment, as calculated for each pond (see Fig.A-3).



BROKEN LINES INDICATE ORIGINAL GROUND LEVEL INSIDE AND OUTSIDE THE PONDS

FIG.A-5. A schematic plan of the pond system of Fig.A-3, showing the embankment's broken down into 24 entities corresponding to the elements shown in Fig.A-4. Some entities occur several times each.

Fig. A-5 is a plan of the ponds showing the embankments divided into 24 separate, numbered entities, most of which are repeated several times. Tables A-3 to A-5 show the summation of the entities for each set of ponds. The configuration referred to is derived from Fig. A-4. The second letter after f for fill height, namely a, f or m refers to anaerobic, facultative or maturation ponds, respectively.

The embankment between the anaerobic and facultative ponds is considered as belonging to the anaerobic ponds, since it has height 'a'; that between the facultative and maturation ponds as belonging to the facultative ponds, since it has height 'f'. A small allowance can be made for elements labelled 'z' and 'm', respectively. The allowance for rounding of the pond corners is discussed later.

TABLE A-3. CALCULATION FOR ANAEROBIC POND EMBANKMENTS

Item	No.	Configuration	Charac. length	Calculational element	Calculation	Tabulation of sub-total coefficients f_a^1 f_a^2 f_a^3
1	8	A + 2a	55	$(55 \times 3/2) f_a^2 - 9 f_a^3 + 6 f_a^3$	$8 \times (82.5 f_a^2 - 3 f_a^3)$	+ 660.0 - 24.0
2	2	B + 2b	113	$(113 \times 3) f_a + 9 f_a$	$2 \times (348 f_a)$	+ 696.0
3	2	B + 2b	55	$(55 \times 3) f_a + 9 f_a$	$2 \times (174 f_a)$	+ 348.0
4	1	C + 2c	113	$[(113 + 6) \times 3/4] f_a^2 + (3/4) f_a^3$	$1 \times (89.25 f_a^2 + 0.75 f_a^3)$	+ 89.25 + 0.75
5	2	C + (c-c)	55*	$[(55 \times 3) \times 3/4] f_a^2$	$2 \times (43.5 f_a^2)$	+ 87.0
6	1	B	55	$(55 \times 3) f_a$	$1 \times (165 f_a)$	+ 165.0
7	1	A + 2a	229	$(229 \times 3/2) f_a^2 - 9 f_a^3 + 6 f_a^3$	$1 \times (343.5 f_a^2 - 3 f_a^3)$	+ 343.5 - 3.0
8	2	B + b	55	$(55 \times 3) f_a + (9/2) f_a$	$2 \times (165.5 f_a)$	+ 339.0
9	2	C + (c-c)	55*	$[(55 \times 3) \times 3/4] f_a^2$	$2 \times (43.5 f_a^2)$	+ 87.0
Total for 2 ponds						+ 1548.00 f_a + 1266.75 f_a^2 - 26.25 f_a^3

* Because of the "inside corner" at the facultative pond/anaerobic pond junction, add only 3 to characteristic length.

TABLE A-4. CALCULATION FOR FACULTATIVE POND EMBANKMENT

Item	No.	Configu- ration	Charac. length	Calculational element	Calculation	Tabulation of sub-total coefficients ff^1	ff^2	ff^3
10	4	A + 2a	173	$(173 \times 3/2)ff^2 - 9ff^3 + 6ff^3$	$4 \times (259.5ff^2 - 3ff^3)$	+ 1038.0	-	12.0
11	2	A + 2a	113	$(113 \times 3/2)ff^2 - 9ff^3 + 6ff^3$	$2 \times (169.5ff^2 - 3ff^3)$	+ 339.0	-	6.0
12	2	B + 2b	173	$(173 \times 3)ff + 9ff$	$2 \times (528ff)$	+ 1056.0		
13	1	B + 2b	229	$(229 \times 3)ff + 9ff$	$1 \times (696ff)$	+ 696.0		
14	2	C + 2c	173	$[(173+6) \times 3/4]ff^2 + (3/4)ff^3$	$2 \times (134.25ff^2 + 0.75ff^3)$	+ 268.50	+ 1.5	
15	1	B - zf	173	$(173 \times 3)ff - (9/2)ff^2$	$1 \times (519ff - 4.5ff^2)$	+ 519.0	- 4.5	
16	1	A + 2a	229	$(229 \times 3/2)ff^2 - 9ff^3 + 6ff^3$	$1 \times (343.5ff^2 - 3ff^3)$	+ 343.5	- 3.0	
Total for 2 ponds						+ 2271.00ff	+ 1984.50ff ²	- 19.50ff ³

TABLE A-5. CALCULATION FOR MATURATION POND EMBANKMENTS

Item	No.	Configu- ration	Charac. length	Calculational element	Calculation	Tabulation of sub-total coefficients fm^1	fm^2	fm^3
17	8	A + 2a	78	$(78 \times 3/2)fm^2 - 9fm^3 + 6fm^3$	$8 \times (117fm^2 - 3fm^3)$	+ 936.0	-	24.0
18	6	A + 2a	113	$(113 \times 3/2)fm^2 - 9fm^3 + 6fm^2$	$6 \times (169.5fm^2 - 3fm^3)$	+ 1017.0	-	18.0
19	2	B + b	159	$(159 \times 3)fm + (9/2)fm$	$2 \times (481.5fm)$	+ 963.0		
20	1	B + 2b	229	$(229 \times 3)fm + 9fm$	$1 \times (695fm)$	+ 696.0		
21	2	C + c	159*	$[(159 \times 3) \times 3/4]fm^2 + (3/8)fm^3$	$2 \times (121.5fm^2 + 0.375fm^3)$	+ 243.0	+ 0.75	
22	1	C + 2c	229	$[(229+6) \times 3/4]fm^2 + (3/4)fm^3$	$1 \times (175.25fm^2 + 0.75fm^3)$	+ 176.25	+ 0.75	
23	1	E - zm	159	$(159 \times 3)fm - (9/2)fm^2$	$1 \times (477fm - 4.5fm^2)$	+ 477.0	- 4.5	
24	2	E	113	$(113 \times 3)fm$	$2 \times (339fm)$	+ 678.0		
Total for 4 ponds						+ 2814.00fm	+ 2367.75fm ²	- 40.50fm ³

* The one end is already included in item 14, hence add 3 to the characteristic length, not 6.

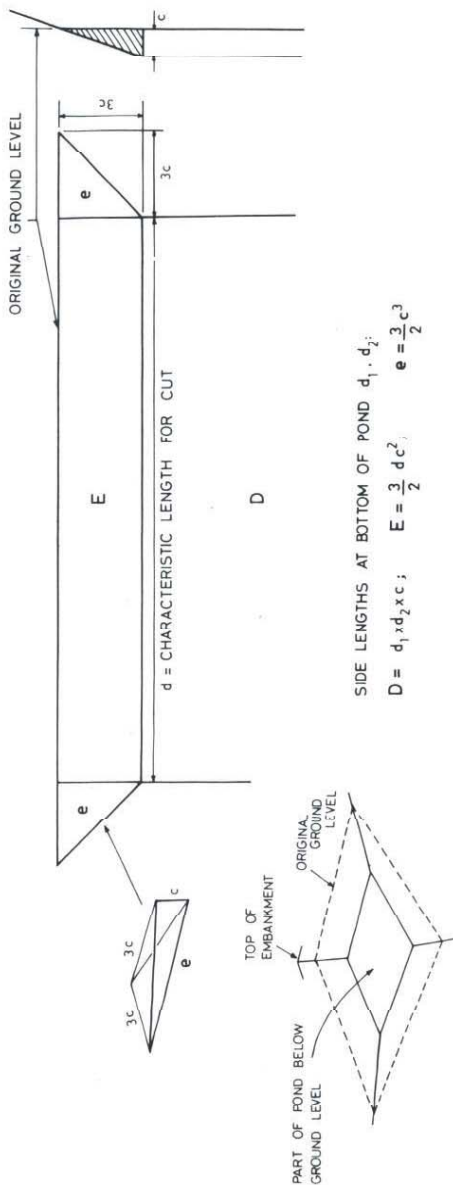


FIG.A-6. Breakdown of excavated volume of a pond into its constituent elements. They comprise: a box shape, D , its base being the rectangular (or square) bottom of the pond and its height the cut depth, c ; a prism, E ; and the pyramid, e . The individual volumes are given in terms of cut depth.

Figure A-6 shows the box-shape, the prism and the end elements used to calculate the cut volume, while Fig.A-7 is a plan of the ponds indicating the entities numbered 25 to 32 that are needed to describe the volumes in terms of cut depth. The characteristic length in this case is the length of the side at the bottom of the pond, as calculated for each pond (see Fig.A-3). Tables A-5 to A-8 show the summation of the entities.

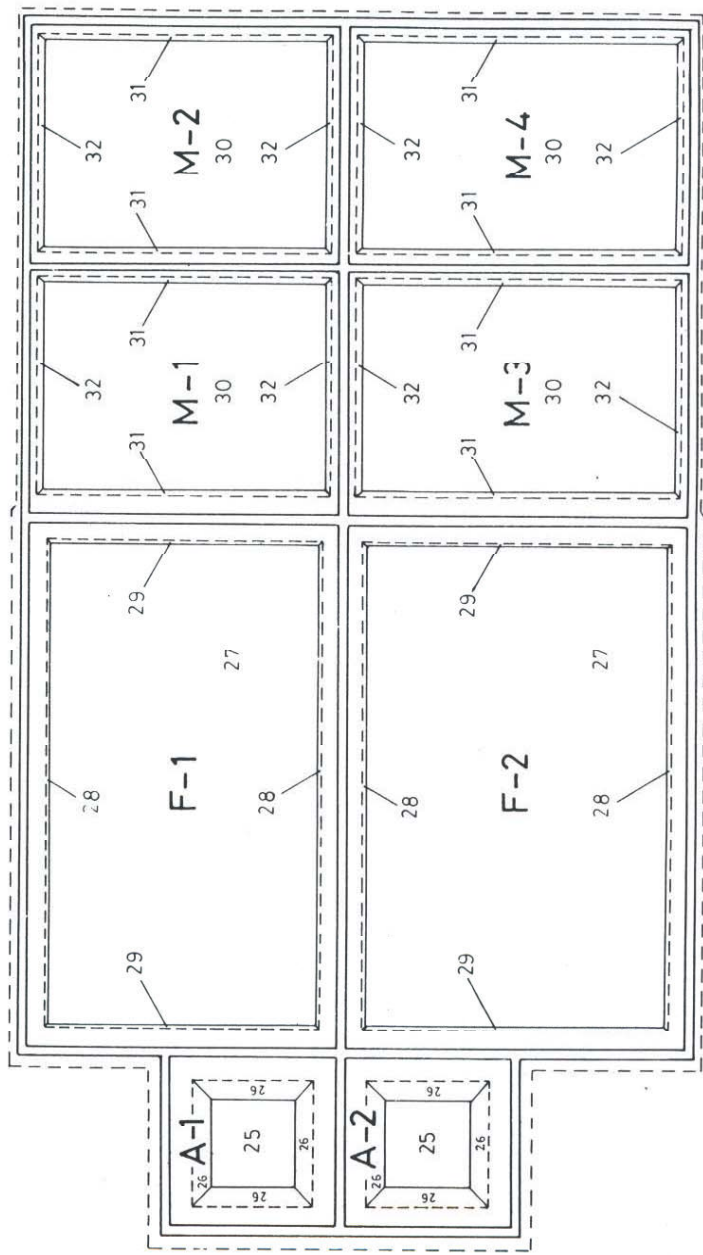


FIG.A-7. A schematic plan of the pond system of Fig.A-3 showing the excavation volumes broken down into 8 entities (Nos 25 – 32) corresponding to the elements shown in Fig.A-6. As before, some entities occur several times.

ANNEX I. CALCULATION OF CUT AND FILL VOLUMES

TABLE A-6. CALCULATION FOR ANAEROBIC POND CUTS

Item	No.	Configu- ration	Charac. length	Calculational element	Calculation	Tabulation of sub-total coefficients $\frac{1}{ca}$ $\frac{2}{ca^2}$ $\frac{3}{ca^3}$
25	2	D (d1=d2)	28	$(28)^2 \times ca$	$2 \times 784ca$	+ 1568.0
26	8	E + 2e	28	$(28 \times 3/2)ca^2 + 3ca^3$	$8 \times (42ca^2 + 3ca^3)$	+ 336.0 + 24.0
Total for 2 ponds						+ 1568.00ca + 336.00ca ² + 24.00ca ³

TABLE A-7. CALCULATION FOR FACULTATIVE POND CUTS

Item	No.	Configu- ration	Charac. length	Calculational element	Calculation	Tabulation of sub-total coefficients $\frac{1}{cf}$ $\frac{2}{cf^2}$ $\frac{3}{cf^3}$
27	2	D < (d1 (d2	160) > 100)	$(160 \times 100)cf$	$2 \times 16000cf$	+32000.0
28	4	E + 2e	160	$(160 \times 3/2)cf^2 + 3cf^3$	$4 \times (240cf^2 + 3cf^3)$	+ 960.0 + 12.0
29	4	E + 2e	100	$(100 \times 3/2)cf^2 + 3cf^3$	$4 \times (150cf^2 + 3cf^3)$	+ 600.0 + 12.0
Total for 2 ponds						+32000.00cf + 1560.00cf ² + 24.00cf ³

TABLE A-8. CALCULATION FOR MATURATION POND CUTS

Item	No.	Configu- ration	Charac. length	Calculational element	Calculation	Tabulation of sub-total coefficients $\frac{1}{cm}$ $\frac{2}{cm^2}$ $\frac{3}{cm^3}$
30	4	D < (d1 (d2	104) > 69)	$(104 \times 69)cm$	$4 \times 7176cm$	+28704.0
31	8	E + 2e	104	$(104 \times 3/2)cm^2 + 3cm^3$	$8 \times (15cm^2 + 3cm^3)$	+ 1248.0 + 24.0
32	8	E + 2e	69	$(69 \times 3/2)cm^2 + 3cm^3$	$8 \times (101.5cm^2 + 3cm^3)$	+ 828.0 + 24.0
Total for 4 ponds						+28704.00cm + 2076.00cm ² + 48.00cm ³

TABLE A-9. CONVERSION OF ALL CUT VOLUMES TO COEFFICIENTS OF ca

Term	Coefficient	Corresponding expression in ca	Tabulation of sub-total coefficients ca^0 ca^1 ca^2 ca^3
$ca \cdot s$			
cf	+ 3200.00	- 1.8 + ca	+ 1568.00 + 336.00 + 24.00
cf^2	+ 1560.00	+ 3.24 - 3.5 ca + ca^2	- 57600.00 + 32000.00
cf^3	+ 24.00	- 5.832 + 9.72 ca - 5.4 ca^2 + ca^3	+ 5054.40 - 5616.00 + 1560.00
cm	+ 28704.00	- 1.5 + ca	- 139.97 + 233.28 - 129.60 + 24.00
cm^2	+ 2076.00	+ 2.25 - 3.0 ca + ca^2	- 43056.00 + 28704.00
cm^3	+ 48.00	- 3.375 + 6.75 ca - 4.5 ca^2 + ca^3	+ 4671.00 - 6228.00 + 2076.00
Total cut volume in terms of ca for all ponds (CV)			- 162.00 + 324.00 - 216.00 + 48.00
Volume allowing for compaction (i.e. 0.9CV)			- 91232.57 + 50985.28 ca + 3626.40 ca^2 + 96.00 ca^3
Volume allowing for compaction (i.e. 0.9CV)			- 82109.31 + 45886.75 ca + 3263.76 ca^2 + 86.40 ca^3

Section E of Appendix I indicated that the difference in water levels between anaerobic and facultative ponds is taken to be 0.5 m, and that between facultative and maturation ponds to be 1.0 m. Since the embankment heights vary similarly, while the freeboard (0.5 m) and the different depths of water are known, the following relationships can be set down. Here, f represents the fill height, c the cut depth, and w the water level, each relative to the original ground level.

$$\left. \begin{aligned}
 fa &= 4.5 - ca; & ff &= 2.2 - cf; & fm &= 1.5 - cm; \\
 wa &= fa - 0.5; & wf &= ff - 0.5; & wm &= fm - 0.5 \\
 ff &= fa - 0.5; & & & &
 \end{aligned} \right\} \text{(A-28)}$$

Hence, all entities can be written in terms of ca to enable the calculation to be reduced to a polynomial of one variable, ca . For example, $cf = ca - 1.8$, $ff = 4.0 - ca$, etc. These are shown in Tables A-9 and A-10, in which total fill and cut volumes taken from Tables A-3 to A-8 are re-formed as functions of ca .

TABLE A-10. CONVERSION OF ALL EMBANKMENT (FILL) VOLUMES TO COEFFICIENTS OF ca

Term	Coefficient	Corresponding expression in ca	Tabulation of sub-total coefficients		
			ca^0	ca^1	ca^2
fa	+ 1548.00	+ 4.5 - ca	+ 6966.00	- 1548.00	
fa^2	+ 1266.75	+ 20.25 - 5.0 ca + ca^2	+ 25651.69	- 11400.75	+ 1256.75
fa^3	- 26.25	+ 91.125 - 60.75 ca + 13.5 ca^2 - ca^3	- 2392.03	+ 1594.69	- 354.38
ff	+ 2271.00	+ 4.0 - ca	+ 9084.00	- 2271.00	
ff^2	+ 1984.50	+ 16.0 - 8.0 ca + ca^2	+ 31752.00	- 15876.00	+ 1934.50
ff^3	- 19.50	+ 64.0 - 48.0 ca + 12.0 ca^2 - ca^3	- 1248.00	+ 936.00	- 234.00
fm	+ 2814.00	+ 3.0 - ca	+ 8442.00	- 2814.00	
fm^2	+ 2367.75	+ 9.0 - 6.0 ca + ca^2	+ 21309.15	- 14206.50	+ 2357.75
fm^3	- 40.50	+ 27.0 - 21.0 ca + 9.0 ca^2 - ca^3	- 1093.50	+ 1093.50	- 354.50
Embankment volume in terms of ca for all ponds			+ 98471.91	- 44492.06 ca	+ 4656.13 ca^2 + 86.25 ca^3
Add allowance for corners (see text later)			+ 1100.00		
Total embankment volume including allowance for corners (EV)			+ 99571.91	- 44492.06 ca	+ 4656.13 ca^2 + 86.25 ca^3

For minimum excavation, the fill volume and the cut volume, allowing for compaction, must be equal:

$$99571.91 - 44492.06 ca + 4666.13 ca^2 + 86.25 ca^3$$

$$= - 82109.31 + 45886.75 ca + 3263.76 ca^2 + 86.40 ca^3$$

This gives

$$181681.22 - 90378.81 ca + 1402.37 ca^2 - 0.15 ca^3$$

or, reducing the coefficient of ca^2 to unity:

$$129.55 - 64.45 ca + ca^2 - 0.0001 ca^3$$

(A-29)

(A-29')

(A-29'')

TABLE A-11. CUT AND FILL VOLUMES^a
FOR VARIOUS VALUES OF *ca*

<i>ca</i> (m)	Cut volume CV (m ³)	Compacted volume 0.9CV (m ³)	Embankment volume EV (m ³)	Difference (0.9CV-EV) (m ³)
2.00	26 000	23 400	29 900	- 6 500
2.077	31 200	28 100	28 100	0
2.10	32 700	29 400	27 500	+ 1 900
2.20	39 500	35 600	25 200	+10 400
2.30	46 400	41 800	23 000	+18 800
2.70	74 800	67 300	15 200	+52 100

^a Fill and cut volumes from Tables A-9 and A-10 respectively.

It can be seen that the *ca*³ term can be ignored and Eq. (A-28'') can be solved as a quadratic equation in *ca*. The solution of any quadratic equation $ax^2 + bx + c = 0$ is:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

(A-30)

In the case considered, $a = 1$, $b = -63.57$ and $c = 127.83$. Hence, ignoring the mathematically correct but technically meaningless solution of $ca = 61.49$ m:

$$ca = 2.077 = 2.08 \text{ m (rounded)}$$

(A-31)

Taking the various equivalences for *fa* to *fm*, and *cf* and *cm* given in Tables A-9 and A-10 and the fact that all water levels are 0.5 m below the embankment tops:

$$ca = 2.08;$$

$$cm = 0.58$$

$$fa = 2.42;$$

$$fm = 0.92$$

$$wa = 1.92;$$

$$wr = 0.42$$

(A-32)

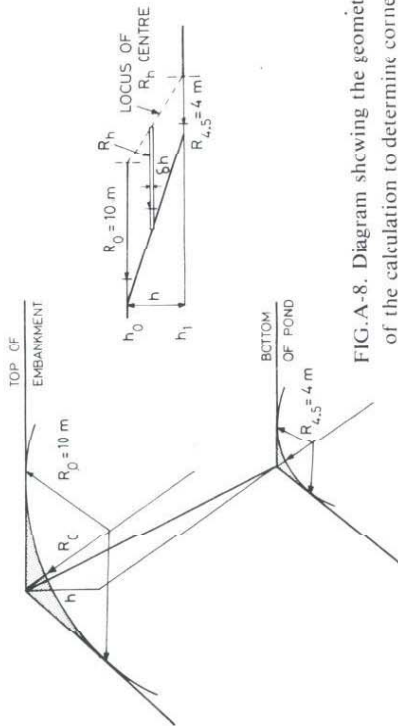


FIG.A-8. Diagram showing the geometrical basis of the calculation to determine corner volume.

This suggests an accuracy far beyond what can be estimated in this type of calculation (see below), and the figures are rounded to ca = 2.10 m, etc. (see Eqs (A-25 to A-27) in Appendix I). The effect of the value of ca on cut and fill volumes is shown in Table A-11, which also serves as a check on the calculation result.

Allowance for the rounding of the corners

For the sake of completeness, the calculation which makes it possible to allow for the rounding of the corners is given below. The corner curvature at the top of the embankments is uniformly taken to be 10 m (= radius in the horizontal plane), while the linear rate of reduction of radius is similar for all ponds, giving a radius of 4 m at the bottom of the anaerobic pond for a vertical drop, h , of 4.5 m.

As indicated in Fig.A-8, the volume due to corner rounding is calculated by considering an element of thickness h , subtracting the area of the quadrant of radius R_h from the square of side R_h and integrating from $h = 0$ to the depth of the bottom of the pond, h being measured downwards from the embankment top. R_h is a linear function of h , as given below:

$$R_h = \left(10 - \frac{4}{3} h\right) = \frac{2}{3} (15 - 2h) \quad (\text{A-33})$$

i.e. when $h = 0$, $R = 10$, and when $h = 4.5$, $R = 4$. In the limit, the volume of the corner element to be integrated from h_0 to

h_1 is given by:

$$V = \int_{h_0}^{h_1} [(R_h)^2 - \frac{\pi}{4} (R_h)^2] dh = \left(\frac{4 - \pi}{4} \right) (R_h)^2 dh \quad (A-34)$$

Substituting for R_h from Eq.(A-33) and integrating:

$$\frac{4 - \pi}{27} [675h - 90h^2 - 4h^3]_{h_0}^{h_1} \quad (A-35)$$

It is clear that, with corner rounding, there is less taken from the cut and more is needed for the embankments. Strictly, the amount less in the cut should be deducted from the volume excavated, and the amount extra needed for the embankments should be added to the embankment volume. However, ignoring the 10% decrease in volume of the cut material in this case as being a second-order-of-magnitude effect, it is clear by inspection of Eq.(A-28) that the total corner volume can be added to the fill side of the equation, and this is done in Table A-10.

Substituting in Eq.(A-35) to obtain the corner volume for each type of pond and multiplying by the number of corners per type of pond, the respective corner allowances for each type of pond are:

Anaerobic ponds:	$50.3 \text{ m}^3 \times 8$	$= 402 \text{ m}^3$
Facultative ponds:	$34.2 \text{ m}^3 \times 8$	$= 278 \text{ m}^3$
Naturation ponds:	$26.2 \text{ m}^3 \times 16$	$= 420 \text{ m}^3$
Total:		$= 1100 \text{ m}^3$

(A-36)

Bearing in mind that the total cut volume without allowance for corners is about $28\,250 \text{ m}^3$, the total allowance for the corners represents a 4.3% addition ($100 \times 1100/0.9 \times 28\,250$) to the amount to be excavated.

Accuracy

It is clear that most of the data given in Table A-1 for population size, volume of influent, number of coliforms in the influent etc., while based on experience, are really only estimates. The margin of error in the "guessimations" is quite large. Here, as in the calculations, an attempt is made to ensure that the results are "on the safe side".

The philosophy in the above calculation is to get a "best" result, attempting to allow for any variables that exert an effect of around 5% or more, while following a routine that minimizes calculational errors. As stated above, the number of decimal places chosen for the working simplifies the calculational procedure **and is not an indication of assumed accuracy**. Since, in the pattern of the calculation, the differences between large numbers plays a vital role, it is better to make approximations only at the final step. For the purpose of estimating, the final result chosen is likely to have an accuracy of around $\pm 10\%$, which is sufficient in the light of the estimates made.

It should be noted that while the ca^3 terms can be neglected when solving Eq. (A-29), they cannot necessarily be ignored when individual cut and fill volumes for the various ponds are calculated subsequently.

If the ponds are considered individually without allowance for shared embankments etc., a very different result may be obtained. It is salutary to note that, for the case considered here, the cut depth for one of the anaerobic ponds considered alone turns out to be 2.70 m, i.e. 60 cm deeper than calculated above! This has a marked effect when considering other pond water levels and gives the impression that pumping of final effluent would definitely be needed.

Extension to irregular pond shapes

The routine shown above can be extended to irregular shapes, where ponds need to be fitted into natural features of the landscape. The ponds should be sketched on "millimetre" paper, and contours representing different cut depths and embankment heights drawn. Numbering these and summing the volumes contained between the individual contour lines (mean area \times length of the contour at mid-section) will enable a process similar to that given above to be followed. As with Simpson's Rule for estimating the area under a curve, on which the method is based, the accuracy is determined by the choice of separation of the successive contours — a choice left to the designer.

LIST OF ABBREVIATIONS, SYMBOLS AND CONVERSION FACTORS

BOD	biochemical oxygen demand
BOD ₅	5-day biochemical oxygen demand
CEPIS	Pan-American Center for Sanitary Engineering and Environmental Sciences
CETESB	Environmental Protection Agency of São Paulo, Brazil
COD	chemical oxygen demand
IDWSSD	International Drinking Water Supply and Sanitation Decade
IPHER	Institute of Public Health Engineering and Research, Lahore, Pakistan
IRCD	International Development Research Centre, Canada
MPN	most probable number (of)
TDS	total dissolved solids
TOC	total organic carbon
USAID	United States Agency for International Development
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
World Bank	International Bank for Reconstruction and Development

Variables and symbols in equations used for calculating pond sizes and temperatures:

A_p	pond surface area (m ²)
f	proportionality factor in Eq. (1); algal inhibition factor elsewhere
f'	chemical oxygen demand
$K [K_T]$	biodegradation rate constant [at temperature T°C] (d ⁻¹)
$K' [K'_T]$	(bacterial) die-off constant [at temperature T°C] (d ⁻¹)
L_p	pond (and effluent) BOD ₅ (mg/L)
$L_{s,0}$	maximum surface loading rate (kg BOD ₅ /ha·d)
L_u	ultimate BOD (mg/L)
L_0	influent BOD ₅ (mg/L)
(lat)	latitude (°N)
n	number of maturation ponds
N_R	bacterial population after R days (bacteria/100 mL)
N_0	bacterial population in influent (bacteria/100 mL)
$R [R_T]$	retention time [at temperature T°C] (d)
Q	wastewater flow rate (L/d) or (m ³ /d)
T	pond water temperature, lowest mean monthly (°C)
T_a	ambient air temperature, lowest mean monthly (°C)
T_p	pond water temperature in Eq. (1)
T_0	influent temperature (°C)
V	pond volume (m ³)
θ	temperature reaction coefficient
θ'	temperature coefficient for die-off constant

Variables and other symbols in equations and diagrams used for calculating cut and fill (embankment) volumes of ponds:

a	anaerobic pond, when used as second letter to variables c, f or w (e.g. ca)
f	facultative pond, when used as second letter to variables c, f or w (e.g. cf)
m	maturation pond, when used as second letter to variables c, f or w (e.g. cm)
c	cut (excavation) depth (m)
f	fill (embankment) height (m)

w	depth of water (m)
A, a; B, b; C, c	geometrical elements used for calculating fill (embankment) volumes
D, d, d ₁ , d ₂ ; E, e	geometrical elements used for calculating cut (excavation) volumes
R _h	corner radius at height h, measured downwards from the embankment top to bottom of pond (m)
V	volume of corner element (m ³)

CONVERSION FACTORS TO SI UNITS

Mass

tonne (metric ton)	1 t	=	1.0 x 10 ³ kg
pound	1 lb	=	4.536 x 10 ⁻¹ kg
ounce	1 oz	=	2.835 x 10 ¹ g

Length

statute mile	1 mile	=	1.609 km
yard	1 yd	=	9.144 x 10 ⁻¹ m
foot	1 ft	=	3.048 x 10 ⁻¹ m
inch	1 in	=	2.54 cm

Area

hectare	1 ha	=	1.0 x 10 ⁴ m ²
acre	1 acre	=	4.047 x 10 ³ m ²
square yard	1 yd ²	=	8.361 x 10 ⁻¹ m ²
square foot	1 ft ²	=	9.290 x 10 ⁻² m ²

Volume

litre	1 L	=	1.0 x 10 ⁻³ m ³
cubic yard	1 yd ³	=	7.646 x 10 ⁻¹ m ³
cubic foot	1 ft ³	=	2.832 x 10 ⁻² m ³
gallon (imperial)	1 gal (UK)	=	4.546 x 10 ⁻³ m ³
gallon (US liquid)	1 gal (US)	=	3.785 x 10 ⁻³ m ³

Temperature

degree Fahrenheit	$\frac{9}{5} [t (^{\circ}\text{F}) - 32]$	=	t (°C)
degrees of temperature difference	$\frac{9}{5} \Delta t (^{\circ}\text{F})$	=	$\Delta t (^{\circ}\text{C})$

Miscellaneous

surface loading rate	1 lb BOD ₅ /acre·d	=	1.121 kg BOD ₅ /ha·d
volumetric loading rate	1 oz BOD ₅ /yd ³ ·d	=	37.07 g BOD ₅ /m ³ ·d

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