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WASTE STABILIZATION PONDS

WASTE STABILIZATION PONDS

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PREFACE

With increasing urbanization and industrialization, the volume of domestic sewage, industrial effluents, agricultural wastes, and urban run-offs is steadily growing. All these waste-waters must be assimilated into the environment without impairing the health and well-being of man. It is therefore often necessary to assist the natural processes of purification through the use of biological waste treatment plants. The type of facility required will depend upon the assimilative capacity of the environment and upon the use that will be made of the receiving water or, in some cases, of the treated waste-water itself.

Waste stabilization ponds provide a useful method of waste-water treatment and disposal for growing communities where both funds and trained personnel are in short supply. In these ponds, beneficial organisms stabilize the waste-water into a liquid that can be released to the environment without endangering man directly or affecting the environment adversely, and that does not place an undue cost burden on a downstream user.

Up to now the technical literature on the management and design of low-cost waste-water treatment systems has not been readily available in usable form. The purpose of this monograph is to summarize the available information on waste stabilization ponds: it defines acceptable design criteria based on public health considerations, suggests alternative approaches to design, provides data on pond design, and deals with the operational problems that ultimately determine the success or failure of any waste-water treatment facility. Some of the background information was obtained through a survey conducted by WHO of the use of waste stabilization ponds in a number of countries. In addition, the monograph provides useful information on the theory of biological waste treatment.

The monograph is directed specifically to the design engineer who has limited funds at his disposal, who has to rely on modest construction facilities, and who has to provide operating instructions that can be followed by unskilled personnel. It will assist him in selecting the most suitable design in the light of economic considerations, availability of raw materials, climatic conditions, and social factors.

A preliminary draft of the monograph was circulated to experts in different parts of the world, and the present publication incorporates many of their suggestions. A list of these reviewers will be found on pages 7-9. To them, and particularly to the author, Dr E. F. Gloyne, the World Health Organization expresses its sincere gratitude.

General Considerations

The activities of man give rise to a wide range of waste products, many of which become waterborne and must be carefully treated before being released to the environment. Such waste-waters may contain excreta, household wastes, industrial discharges, agricultural run-offs, and urban storm drainage. All these wastes, individually or collectively, can pollute and contaminate¹ the environment.

There is an increasing need for low-cost methods of treating waste-waters, particularly municipal sewage and industrial effluents. The operation of such methods, and the maintenance of the necessary plant and equipment, must be within the capability of developing urban centres and industrial complexes.

As migration from rural to urban areas continues, the control of waste-water² will become increasingly difficult. This problem has two aspects: water must be supplied for the carriage of household and industrial wastes, and the waterborne wastes from a community that has an adequate water supply must be safely disposed of.

The protection of water resources against pollution is basic to the development of a sound economy. For both the maintenance of public health and the conservation of water resources, it is essential that pollution be controlled.

As urbanization continues household privies, septic tanks, sand-filter drains, and other methods of disposing of excreta may create economic and health problems. Such practices as the disposal of night-soil by burial or the disposal of waste-waters in cesspools (underground pits) can also contribute significantly to the pollution of soil and water if attempted on the scale required for a large urban centre.

Newly developing areas must determine the waste-water treatment measures that are required, and government agencies should proceed as

¹ A *polluted* water contains organic materials or other wastes to the extent that it is not suitable for domestic use, whereas a *contaminated* water contains disease-causing agents. A water polluted with excreta will undoubtedly be contaminated.

² The term "waste-water" is used in preference to "sewage". The excreta and other substances in domestic waste-waters may be suspended, dissolved, or in the colloidal state.

rapidly as possible with planned waste-control programmes. Problems usually arise in allocating funds for water supply and waste-water disposal and expenditures must be equitably distributed between the collection and the treatment of community wastes. An elaborate treatment scheme, whether biological or chemical, is impractical without a satisfactory collection system.

It is generally recognized that some form of biological treatment provides the most economical solution for handling domestic and most industrial waste-waters. Waste stabilization ponds—the form of biological treatment with which this monograph is concerned—are most suitable for locations where land is inexpensive, organic loadings fluctuate, currency restrictions are in force, and there is a shortage of trained operating personnel.

The design of a waste stabilization pond depends on the treatment objectives. A pond system is usually designed to receive untreated domestic or industrial wastes, but may also be designed to treat primary or secondary treatment plant effluents, excess activated sludge, or diluted night-soil. The ponds may be used to pretreat wastes, to remove most of the biochemical oxygen demand (BOD),¹ and to reduce the concentration of disease-causing agents.

In waste stabilization ponds, the decomposable organic wastes are stabilized by micro-organisms and the numbers of disease-causing agents are reduced significantly, primarily due to the long detention period required for stabilization. In some types of pond, aerobic conditions can be maintained by the natural photosynthetic processes of algae. These green plants provide most of the oxygen required for aerobic stabilization. The remainder of the oxygen is transferred from the air to the water by natural surface mixing processes.

An inspection of costs will show that it is considerably cheaper to treat waste-water in stabilization ponds than by other methods, provided land costs are not prohibitive. The cost of reducing the putrescible content of waste-water in waste stabilization ponds is usually less than half that of other methods of treatment (South Africa, National Institute for Water Research, 1965). Furthermore, the costs per caput of the population for small pond systems do not increase rapidly with decreasing size, as they do with other methods of treatment.

Types of Pond

Many different terms have been applied to the different types of waste stabilization pond, including sewage lagoons, oxidation ponds, redox ponds, maturation ponds, facultative lagoons, anaerobic lagoons, aerobic stabilization ponds, and mechanically-assisted oxidation ponds.

¹ The concept of biochemical oxygen demand is explained on p. 51.

For the purposes of this monograph, ponds are defined as follows. The term *waste stabilization pond* is used to describe any pond or pond system designed for biological waste treatment. A pretreatment *anaerobic waste stabilization pond* is essentially a digester that requires no dissolved oxygen, since anaerobic bacteria break down the complex organic wastes. An *aerobic waste stabilization pond* is one in which aerobic bacteria break down the wastes and algae, through photosynthetic processes, provide sufficient oxygen to maintain an aerobic environment. A *facultative waste stabilization pond* is one in which there is an upper aerobic zone (maintained by algae) and a lower anaerobic zone. Aerobic, facultative, and anaerobic organisms might be found in a facultative waste stabilization pond. A *mechanically aerated waste stabilization pond* is one in which mechanical aerators either supplement or replace algae as a means of providing the required dissolved oxygen. This type of pond may function as an aerobic or facultative system. In some mechanically aerated ponds the turbulence may not be sufficient to keep all solids in suspension; therefore, sludge may settle and undergo anaerobic decomposition while most of the pond remains aerobic.

Ponds receiving untreated waste-waters are referred to as raw or *primary waste stabilization ponds*. Ponds receiving effluents from primary settling tanks or secondary biological treatment units are called *secondary waste stabilization ponds*. Similarly, a second or third pond in a series of ponds functions as a secondary facultative or aerobic treatment unit. A pond whose primary function is to reduce the number of disease-causing microorganisms through extended detention time is called a *maturation pond*. A maturation pond may also be used to rear fish such as carp and it may then be termed a fish pond. The physical layout and mode of operation can also be used to categorize a pond system. Ponds may be designed to operate singly, in series, or in parallel.

Most waste stabilization ponds, as at present used, are facultative treatment units. In this respect, they resemble rivers and lakes. Aerobic conditions are maintained near the surface and sometimes throughout most of the depth of the pond. However, an anaerobic environment persists near the bottom, where there will always be some settled organic debris.

History of Pond Development

Ponds have been used for centuries to store and treat animal and household wastes. However, only within the last two decades have specific design criteria been developed in terms of volumetric requirements, organic loading rates, and detention periods.

In 1901 the city of San Antonio, Tex., constructed an impoundment of 275 ha with an average depth of about 1.4 m. This pond, now known as Mitchell Lake, is still in use. Following this successful experiment, other cities in Texas, California, North Dakota, and elsewhere in the USA used

ponds as a means of treating sewage (Caldwell, 1946). However, the use of ponds prior to the last two or three decades seemed to be more by accident than design (Giesecke & Zeller, 1936; Pearse et al., 1948). As an example, in 1924 the city of Santa Rosa, Calif., attempted to avoid the cost of a waste-water treatment plant by uncovering gravel beds which, it was believed, could be used as natural filters prior to discharging waste-water into the then highly polluted Santa Rosa Creek (Gillespie, 1944). As might be expected the gravel bed became partially sealed, resulting in an impoundment of sewage to a depth of about 90 cm. The effluent from this pond was reported to resemble that from a trickling filter. The first pond in North Dakota was put into operation in 1928 because there was no nearby stream to dilute or even carry away the waste-water collected by the newly constructed sewer system. It was decided to empty the waste-water into a natural depression some distance from town, in the hope that this would prevent odour problems. This pond remained in operation for over 30 years (Svore, 1961). During the second world war, significant operating experience was gained at military installations in the USA (Mohlman et al., 1946).

Little engineering or research went into the construction of early ponds, some of which failed. The geometry and loading of the pond varied with the "lie of the land". Receiving-stream requirements were frequently not considered. Finally, however, the acceptance of ponds in the southwestern USA brought a semblance of design into being and the operation of these ponds has been steadily improving. A similar series of events occurred in Europe (Imhoff, 1926).

It seems that the first use of a pond system specifically designed to treat raw waste-water occurred in North Dakota (Van Heuvelen & Svore, 1954). This pond received the unconditional approval of the State Health Department in 1948. By 1960 there were over 100 such installations in North Dakota and about 300 pond systems, mostly of the secondary treatment type, in Texas.

Following a period of field studies in 1940-50, the development of rational design criteria for pond systems was undertaken. After 1950 significant research and field data began to appear in the literature (Gotaas et al., 1954; Hermann & Gloyna, 1958; Wennstrom, 1955; Towne et al., 1957; Parker et al., 1959), and many reviews of such literature are available (e.g., Fitzgerald & Rohlich, 1958; US Public Health Service, 1961a, 1961b; India, Central Public Health Engineering Research Institute, 1964). By 1962, there were 1647 stabilization ponds in use in the USA for the treatment of municipal wastes (Porges & Mackenthun, 1963) and possibly an equal number for the treatment of industrial or agricultural wastes (Porges, 1963). Successful experiences have been reported in Australia (Parker, 1962); New Zealand (Collom, 1965); Israel (Wachs et al., 1961; Watson, 1962); Brazil (Azevedo-Netto, 1967); South Africa (Shaw, 1962; Stander & Meiring, 1962;

South Africa, National Institute for Water Research, 1965); India (India, Central Public Health Engineering Research Institute, 1964); and Canada (Fisher et al., 1968). Plants have been operated successfully in arctic regions such as Alaska and northern Canada with the assistance of aerators (Reid, 1965; Pattison, 1966).

Within the last few years a number of design recommendations have been made by various health departments in the USA. These have been in the form of suggested loading or detention¹ standards. For example, design criteria have been adopted by the 10 Missouri Basin states (Van Heuvelen et al., 1960) and the Oregon State Board of Health (1965). Some states in the southwestern USA recommend an upper BOD₅ loading² of 56 kg/ha per day until better design experience becomes available for a given waste and location.

Basic research on waste stabilization ponds has also grown rapidly in recent years. Pond designs based on laboratory and field experiences have shown increasing approximation (Oswald, 1963; Marais, 1966; Hermann & Gloyna, 1958). Significant studies on bacteria reduction in ponds (Coetzee & Fourie, 1965; Yousef, 1962), operational practices (Ullrich, 1967), and the toxicity of industrial wastes (Gloyna & Espino, 1967; Huang & Gloyna, 1968) have produced basic data for better designs and operation.

It is the opinion of a growing number of engineers that waste stabilization ponds have undergone sufficient study and development to be classified as one of the major types of waste-water treatment system.

Modes of Operation

It is difficult to classify ponds by wastes received, size, shape, mode of operation and treatment objectives; however, some typical modes of operation are discussed below.

Where BOD reduction is a major consideration, the practice is to use either a combination of anaerobic and facultative waste stabilization ponds or facultative ponds independently. However, when it is important to reduce the numbers of pathogenic organisms, series-connected ponds produce the best results. A series-connected system might include anaerobic, facultative, and maturation ponds or the latter two types only.

The layout and mode of operation will depend upon the objectives and the degree of flexibility required. Series design is usually used where the organic load is great and where it is desirable to reduce the coliform count. Parallel systems are used where it is desirable to provide considerable flexibility of operation. Recirculation, although rarely used, provides a

¹ Throughout this monograph, the term "detention" is applied to liquid, and the term "retention" is applied to solids such as grit and sludge.

² BOD₅ (biochemical oxygen demand₅) is the biochemical oxygen demand as determined by standard laboratory procedures for 5 days at 20°C ± 1°C.

means of bringing some of the oxygen-rich waters from near the effluent area to the part of the system where oxygen must be supplied at the greatest rate.

Wastes containing large amounts of solids and those containing toxic or coloured substances require special treatment. In contrast to domestic waste-water, each industrial waste must receive special attention.

The biological processes are controlled essentially by the detention time and the temperature. For ideal operation, it is usually desirable that the effluent and influent flow rates be equal. Although an imbalance in flows will not destroy the system, excessive percolation and evaporation may exert a powerful influence on a waste stabilization pond system. Since inorganic solids may accumulate in ponds from which extensive evaporation occurs, special attention must be given to the design of systems in arid regions. Similarly, excessive percolation may adversely affect nearby groundwaters and reduce the treatment efficiency of a pond.

The maturation pond is becoming an integral part of waste-water treatment systems in South Africa (Van Eck, 1961). In terms of *E. coli* count the effluents from these ponds are comparable with those obtainable by the chlorination of sand-filtered effluents (Stander & Meiring, 1962).

Waste stabilization ponds are increasingly being built in the USA to receive the effluents from overloaded biological waste-water treatment units. These ponds are designed to improve the effluents of activated sludge plants, biological filters, anaerobic and facultative ponds, etc. Usually, the objective is to prepare the water for reuse by reducing the BOD.

In several countries increasing attention is being given to the recharging of groundwater with treated waste-water. In Israel, where waste-water treatment in stabilization ponds has considerable engineering and economic advantages over treatment in conventional plants, plans have been developed for the possible use of this method for a city having a population of more than 1 000 000. The design recommendations include the use of both anaerobic and facultative ponds (Amramy, 1965). The effluent would be pumped to spreading basins and the reclaimed water would be withdrawn through wells.

At Santee, Calif., effluent from an activated-sludge treatment plant is detained in a waste stabilization pond for 30 days; the waste-water is then chlorinated at a level of about 15 mg/litre and is permitted to travel about 2.5 km through a natural sand and gravel formation 3–4 m thick. The water is collected in the first of two recreational lakes (Askew et al., 1965). During the test period from March to November 1963, all samples of the raw sewage, primary effluent, and activated sludge effluent were found to contain 1 or more of 13 different viruses. During the same period, only 25 % of the samples of the effluent of the stabilization ponds were found to contain viruses. Samples collected from the recreational lakes have been consistently negative for virus. These results confirm other California

studies that have indicated that travel of enteropathogens with percolating water is not always a critical factor in determining the method of waste treatment and the feasibility of recharge.

In a number of areas night-soil or wastes intermediate between night-soil and raw waste-water (i.e., wastes containing more water than night-soil but less water than that obtained from a water carriage system) must be treated, and such treatment can be carried out in waste stabilization ponds. Tentative results indicate that ponds receiving night-soil and conserving tank effluents will remain aerobic if the loading does not exceed the contribution from 3 000–5 000 persons per hectare per day and if the minimum depth is about 1 m (Shaw, 1962). Evaporation and seepage losses must be compensated for if ponds of this type are to continue operating.

Instructions for the design of farm ponds, particularly for the treatment of hog wastes, are now available for some US farming communities (Bay, 1962). It is reported that there are over 200 ponds for the treatment of hog wastes in the State of Missouri alone. Unfortunately, few data are available on the performance of these farm systems.

Extent of Waste Stabilization Pond Usage

This chapter briefly discusses the results of a survey of pond usage, present practices in some countries that have reported operational experience, and costs.

Worldwide Survey

From 1964 to 1967, WHO carried out a survey of the extent to which ponds were being used for waste-water treatment and of the problems associated with their operation. Through the assistance of the WHO Regional Offices, ministries of health, and local health establishments, it was possible to assemble a vast amount of design and operational data.

The information obtained from this survey and other sources showed that waste stabilization ponds are in use in at least 39 countries:

Argentina ¹	Netherlands
Australia	New Zealand
Bolivia	Nicaragua
Brazil	Nigeria
Canada	Pakistan ¹
Colombia	Peru
Costa Rica	Romania
Cuba	Saudi Arabia
Ecuador	South Africa
Federal Republic of Germany	Southern Rhodesia
Finland	Sweden
German Democratic Republic	Thailand
Ghana	Trinidad and Tobago
Guatemala	Uganda
India	Union of Soviet Socialist Republics
Israel	United Arab Republic ¹
Japan	United States of America
Kenya	Venezuela
Mauritius	Zambia
Mexico	

¹ Experimental ponds.

Such ponds are in use from the polar areas to the equator. Small hamlets that have recently received the benefits of a water supply, as well as some large metropolitan areas, find waste stabilization ponds both economical and practical. Some typical results are summarized below. However, this summary does not cover North American ponds, which are too numerous and in any case are discussed in some detail on pp. 31-39.

As might be expected, the organic and volumetric loadings were found to vary considerably. Some of the pretreatment anaerobic ponds, especially those receiving industrial wastes, receive several hundreds or even thousands of kilograms of BOD₅ per hectare per day.

The removal efficiencies for comparable areas and loadings seem to be fairly uniform throughout the world. It is not uncommon to obtain better than 90 % BOD removal in waste stabilization ponds.

Excluding North America, reports were received from the operators of 49 plants. Of these, 28 % reported no problems, 16 % indicated occasional or frequent odours, 5 % noted problems with chironomid midges, 4 % were concerned with flies, and 4 % reported mosquito problems. Of those reporting, 36 % indicated that the most prevalent odours occurred during the summer. This is indicative of the geographical location of most of these ponds (i.e., they are probably located in regions where there is no ice cover in the winter and consequently odours associated with a spring readjustment period do not occur). Some operators have controlled all these nuisances by well-planned maintenance programmes.

Of the 49 plants that reported effective operational control of various problems, 50 % maintained some control of mosquitos, 40 % were active in removing accumulated scum, and 31 % practised erosion control of the embankments. About 65 % of the ponds were fenced.

The populations served by the ponds varied from less than 1 000 to several hundred thousand in number. The manpower requirements were most significant: the man-hours per month needed for plants serving populations in the range 1 000-10 000 varied from 2 to 180. It would appear that manpower requirements are wholly dependent on the social and economic status of the area.

The design criteria varied considerably. Some countries were concerned with the removal of BOD, coliform and other micro-organisms, and suspended solids. Other countries based designs on BOD removal only, and these designs usually specified depth, surface area, and organic loading. Colour, dissolved oxygen, and certain components of industrial wastes were also specified as important design criteria by some countries.

Almost all the plants on which reports were received had the ability to carry out some laboratory analyses or could call upon a central authority for such service. Excluding North America, 38 plants in 10 countries kept records. Of these plants, 94 % measured pH, 79 % analysed for BOD, and 68 % measured dissolved oxygen. The MPN index (most probable number

of coliform organisms per 100 ml of sample) was determined by only 19 plants in 7 countries.

The physical arrangements and auxiliary equipment varied greatly. The majority of the ponds were constructed by cut-and-fill methods. The preferred shape seemed to be rectangular, and the most common depth was 1–2 m. On the basis of surface area, the ponds fell into 3 approximately equal groups: those of less than 4 000 m², those of 4 000–20 000 m², and those larger than 20 000 m². The detention time was generally greater than 10 days. About 50 % of the plants had no type of flow-measuring device. Most of the inlets were constructed at the edge of the pond, although some were located at the centre.

Since it is impossible to describe in detail all the plants and the special designs used in all the countries, a few countries representing a geographical distribution, certain designs, and unique modes of operation have been selected.

India

India, with more than 35 waste-water treatment ponds, has been working for the past decade through the Central Public Health Engineering Research Institute, Nagpur, on different aspects of waste-water treatment by ponds. The climate in India—considerable sunshine and generally warm weather—is ideal for such treatment. The solar radiation is apparently of the order of 250–500 langleys per day, according to season. Loadings of 22–440 kg BOD₅/ha per day may be used, depending upon the climatic conditions. A pond area of 1 ha is sometimes used for each 5 000–10 000 people. The recommended pond depth is 1–2 m.

Table 1 shows that the BOD removal efficiency is usually well above 85 %. However, it must be assumed that many of the ponds are anaerobic. The cost of a pond is about 7–10 % of the cost of conventional alternatives. Fig. 1 shows the relationship between cost per caput, population served, and latitude. The cost data would apply to many developing countries. The annual maintenance costs of ponds in India are 3–5 % of the construction costs. It may be noted that mechanical parts are more costly in developing countries, and maintenance of the parts is both costly and difficult owing to the scarcity of skilled workers.

Israel

Since 1960 detailed studies have been made of several waste stabilization ponds in Israel (Wachs et al., 1961; Watson, 1962). During the decade preceding 1960, more than 60 waste stabilization ponds were built, the construction costs being only 5–20 % of those of conventional biological waste treatment plants, excluding land costs.

TABLE 1
MONTHLY AVERAGE DATA SHOWING BOD REMOVAL EFFICIENCY
OF PONDS AT BHANDEWADI, NAGPUR, INDIA *

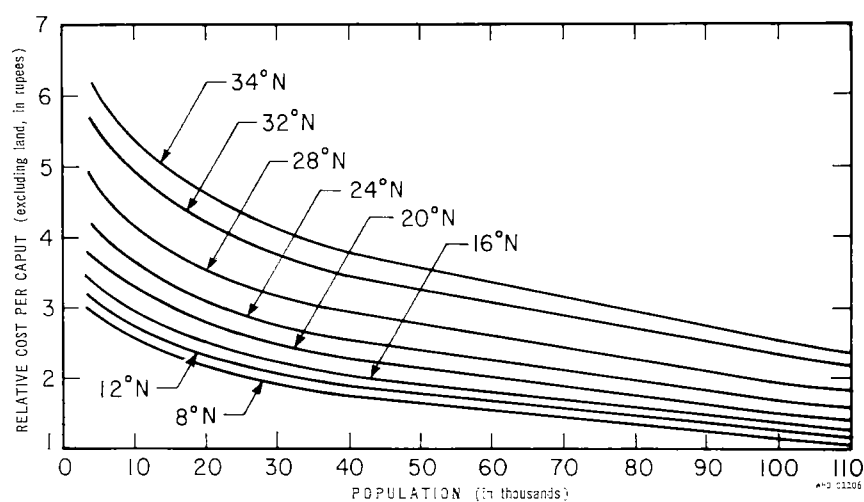
Month	Detention period (days)	BOD of raw sewage (mg/litre)	BOD of effluent (mg/litre)	Load (lb BOD ₅ /ac per day) ^a		BOD reduction (%)
				Applied	Removed	
1965 :						
March	4.6	113	9.6	590.0	540.0	91.0
April	4.6	115	6.0	596.0	565.0	94.8
May	5.6	70	12.0	298.0	247.0	32.9
June	4.9	80	15.0	387.0	315.0	81.3
July	5.0	210	28.0	1 000.0	865.0	86.5
August ^b	3.9	235	60.0	961.0	716.0	74.5
September ^b	4.7	235	58.0	785.0	591.0	75.3
October ^b	5.0	264	63.0	832.0	633.0	76.1
November ^b	4.7	272	57.0	923.0	730.0	79.0
December	4.5	149	37.3	778.0	583.0	75.0
1966 :						
January	5.7	252	37.0	1 028.0	877.0	85.3
February	4.5	245	28.0	1 281.0	1 135.0	88.5
March	3.9	418	34.0	2 800.0	2 389.0	85.3
April	5.6	417	33.0	1 766.0	1 626.0	92.1
May	5.5	351	36.8	1 509.0	1 350.0	89.4
July	6.7	282	22.0	1 007.0	928.0	92.2

* Reproduced, by permission, from Mehta (1966).

^a 1 lb BOD₅/ac per day = 1.1 kg BOD₅/ha per day.

^b One pond was out of commission for repairs.

FIG. 1. COST OF STABILIZATION PONDS IN INDIA IN RELATION TO SIZE OF POPULATION SERVED AND TO LATITUDE*



* Data from Arceivala & Desai (personal communication, 1968).

These experiences have been summarized by Watson (1962, pp. 35–36):

Experience shows that after primary treatment the BOD of domestic sewage usually varies from 0.08 lb to 0.12 lb per capita. A BOD of 250 p.p.m. can be reduced after 5 days in a pond to 50 p.p.m., and to about 30 p.p.m. after a further 5 days' detention.

Primary treatment more than $\frac{1}{4}$ mile from nearest house

Open earth basins built in duplicate or triplicate have the following properties:

Detention:	20 hours after 6 months' operation
Reduction of BOD:	40 %–55 %
De-sludging:	Annually
Depth of basin:	8 ft excluding freeboard
	Average depth of sludge after 1 year: 3 ft
	Average depth of scum after 1 year: 16 in.
	Average depth of liquid after 1 year: 3 ft 8 in.

Oxidation pond, first stage

Loading:	Maximum 4 000 persons per acre, which equals about 250 lb BOD/acre/day.
Detention:	5 days at constant depth.
Depth:	3 ft 6 in. + 3 ft freeboard (possibly 4 ft 6 in. in summer).
Cleaning:	No cleaning so far. Provision must be made to drain a section of the pond without upsetting the operation of the plant.
Storage reservoir:	Necessary, as pumping direct from first stage oxidation pond is undesirable.
Overflow:	Necessary from oxidation pond and from reservoir.

Oxidation pond, second stage

At a somewhat reduced loading and with detention for a further 15 days in aerobic oxidation ponds, an effluent can be produced which will be little, if at all, inferior to full treatment in the conventional activated sludge or high-rate bio-filtration plant. A good effluent requires that the depth of the pond does not fluctuate.

A compromise was found by using the storage reservoir for second-stage oxidation. The depth will naturally fluctuate, depending on the extent of use. The design of the reservoir is based on at least 5 days' additional detention, if the reservoir is to be thought of as an oxidation pond where the algae will continue their purification process. More often the reservoir provides 1 day's storage and is in use only during the summer months.¹

In 1958 the Ministry of Health established tentative guide-lines for the design of waste stabilization ponds whose effluent is to be used for agricultural irrigation. The minimum detention periods required were 18–24 hours in first-stage ponds and 5 days in aerobic² second-stage ponds, with a BOD of 20–25 kg/1 000 m² per day. Most early ponds in Israel were built to these requirements, although some were even more heavily loaded (H. I. Shuval—personal communication, 1967). Recent studies have shown that it is desirable to reduce the BOD loading of ponds to a maximum of 13–15 kg/1 000 m² per day in order to overcome anaerobic conditions during

¹ Quoted by kind permission of the Council, Institution of Civil Engineers, London, England.

² According to the definitions used in this monograph (see p. 15), these ponds would be regarded as facultative.

the winter months. Recent practice in Israel has tended towards increasing detention periods and reducing loads to this level in order to provide a greater safety factor in pond design (Samsonov, 1965).

The key to successful operation and maintenance has been simplicity in design and careful attention to the details of maintenance. For example, primary pretreatment ponds must be desludged periodically, repairs must be made to dikes and other structures, and weeds must be cut.

Recent reports indicate that thought is being given to deeper ponds and to the problem of maintaining an effluent that is chemically suitable for irrigation. The greater depth assists in the maintenance of a suitable anaerobic-facultative environment; it also reduces evaporation losses, resulting in a lower salinity of the effluent, which is consequently of better quality for irrigation.

Experience with the extra-deep pond at Ashkelon indicates that when loadings acceptable for Israel's climate are used during the warm months, a pronounced thermal gradient causes the upper part of the pond to behave as a conventional facultative pond "floating" on an anaerobic one (Wachs & Berend, 1968). Such stratification is enhanced by the fact that both the inlet and the outlet are located at the surface.

During the warmer months effluent with a lower concentration of algae can be obtained through an outlet at a depth of 1 m, although such an effluent is deficient in dissolved oxygen at all times.

For anaerobic-facultative pond systems, which are popular in Israel, the construction costs (excluding land costs) are roughly US\$ 9 000–45 000 per 1 000 m³ per day (A. Amramy—personal communication, 1966).

Central and South America

It has been reported that ponds in Brazil, Colombia, Costa Rica, and Peru have performed well with no nuisances at loadings of 3 000 population equivalents¹ per ha (230 kg of BOD₅/ha per day) (E. Ribeiro—personal communication, 1966). It appears that anaerobic ponds can be loaded at rates of 6 000–15 000 population equivalents per ha. In Brazil the facultative ponds have been designed on the basis of 100 kg of BOD₅/ha per day, which represents 1 750 population equivalents per ha. For systems consisting of an anaerobic pond followed by a facultative pond, the designs of the two ponds are based on 720 and 100 kg of BOD₅/ha per day, respectively.² The average waste-water flow is about 185 litres *per caput* per day (Azevedo-Netto, 1967). Some plants in Costa Rica have been designed on the basis

¹ "Population equivalents" are sometimes used to express loads of putrescible organic matter and suspended solids, particularly when non-domestic sewage is involved. Frequently a load of 54 g of BOD and 90 g of suspended solids *per caput* daily is used to represent one population equivalent.

² Strictly speaking, it is incorrect to refer to anaerobic pond design on the basis of area (i.e., in terms of BOD/ha per day), but the system is used in this monograph in order to compare the capabilities of facultative and anaerobic waste stabilization pond systems.

of 55–83 kg of BOD_5 /ha per day. In terms of population this represents a load of the wastes from 1 000–1 600 persons/ha. The average sewage flow is about 0.4 m^3 *per caput* per day. The operating depth of the ponds is about 1 m (F. Saenz, unpublished data, 1965).

South Africa

Extensive work has been carried out by the South African Council for Scientific and Industrial Research (Stander & Meiring, 1965). Developments in the design of maturation ponds, primary waste stabilization ponds, facultative waste stabilization ponds, and ponds for the treatment of night-soil and conserving tank effluent are well advanced.

The maturation pond is used to reduce the enteric bacterial count in the effluent from facultative ponds and conventional biological treatment plants. Effluents from humus-tanks,¹ sand-filters, or other treatment systems are allowed to flow at a continuous predetermined rate into maturation ponds, which improve their biochemical and bacteriological quality. The factors that affect the performance of maturation ponds are the extent of mixing, the amount of oxygen that is introduced, the intensity of solar radiation, the temperature, short-circuiting, and the loading. The extent of mixing is dependent on the wind, density stratification, and pond turnover resulting from changes in surface temperature and influent arrangements. Oxygenation is primarily dependent, as in other ponds of this type, on the amount of algae present. In addition to supplying heat and energy for photosynthesis, solar radiation may contribute to the reduction of bacteria. Temperature appears to be one of the most important factors affecting the performance of maturation ponds. It is also noteworthy that the total quantity of dissolved solids is reduced in maturation pond systems. Ponds can be designed according to a formula that ensures that the pond will remain aerobic and that BOD and, more important still, the enteric bacteria content are reduced to a satisfactorily low level.

Shaw et al. (1962) suggest the following criteria as guides for the design of primary waste stabilization ponds in South Africa:

General principles

Topography : For the sake of economy, advantage should be taken of topographical features to reduce the cost of constructing stabilization ponds. Investigations should, therefore, start with the selection of the most suitable site.

Pond arrangement : A single pond will generally not provide a satisfactory effluent and is, therefore, not recommended. Three or four cells in series are normally recommended, depending on the quality of waste being treated and the effluent quality desired.

¹ *Humus* is the solid material left after biological treatment of waste-water (sewage), when decomposition has advanced to the point where the original form of the material can no longer be distinguished.

Flexibility : In view of the scant knowledge of all the factors affecting pond performances, a flexible system should be planned, i.e., units initially designed for operation in series should, if possible, have provision for conversion to units in parallel, and provision should be made for extension of both primary and secondary ponds. This will enable operating experience gained *in loco* to be used to the best advantage in future extensions.

Character of influent

Domestic effluents : Ponds will effectively stabilize raw sewage, settled sewage, septic tank effluent, as well as partly treated sewage effluent.

Industrial effluents : Where industrial effluents are accepted into sewers and mixed with domestic sewage, due regard must be given to the possible toxic or other detrimental effects on the biological processes in the ponds.

Primary pond loading

As a general guide a loading of approximately 145 lbs BOD per acre per day can be adopted for domestic raw sewage in a four-foot deep pond. This is approximately equivalent to 1 200 persons per acre,¹ or 40 000 gallons per acre per day, with normal domestic sewage. For exceptionally strong sewages, or for effluents from aqua privies, septic tanks or settlement tanks the loadings can be estimated...

Arrangement of secondary ponds

The retention time in the secondary ponds should be approximately twenty days total. The secondary pond area should be divided into 3 cells in series, having detention times of ten days, five days and five days respectively. Where topography is favourable to a different subdivision of area, this may be used but the minimum retention in any pond should be at least five days.

Physical features

Depth : Ponds should have a mean depth of three to six feet; the depth need not be uniform but limits of three feet minimum to eight feet maximum are suggested.

Inlet : Discharge into primary should be on bottom of pond to prevent thermal short-circuiting. Influent velocity should not be directed towards outlet. If this is unavoidable, a baffle should be provided to dissipate incoming velocity.

Outlet : The outlet draw-off should be provided with a scumboard to prevent surface short-circuiting and to prevent wind-blown scum going out with effluent.

Embankments : Slopes of embankments should be dictated by normal engineering practice for small dams. Details at fringes should be designed for preventing ingress of vegetation. Capital investment on weed-prevention, by stone pitching or using soil-cement at verges may well be repaid by savings on maintenance.

Pond bottoms : Bottoms may be level or graded, but hollow pockets should be avoided.

Pond shape : The shape of the ponds will normally vary with topography. The main consideration is the siting of inlets and outlets so as to avoid short-circuiting or dead spots.

¹ For metric conversion factors, see Annex 3.

Measuring devices

Some form of flow measuring and/or recording device should be installed ahead of the primary pond. Besides providing a check on the pond loading, this will furnish valuable data for use when the pond system is extended. A weir or similar device should also be installed, where possible, between ponds and at the final outlet, to afford a check on seepage losses.

Coarse screens and detritus channels

It is recommended that coarse screens¹ and detritus channels be installed ahead of stabilization ponds.

Evaporation and seepage

Evaporation is normally unimportant as it will generally not exceed $\frac{3}{16}$ " per day.²

Initial seepage will normally be reduced by bacterial and organic clogging. An average value for seepage after a year would be about $\frac{1}{8}$ " per day.

Groundwater contamination from seepage: A careful investigation should be made to assess possibility of dangerous groundwater pollution by seepage from ponds.

Sludge accumulation

At the loadings recommended for raw sewage, sludge accumulation is unlikely to exceed 18" in 5 years.

Mosquito breeding

To prevent mosquito breeding all verges must be kept free of vegetation.

The anaerobic-facultative pond system, whereby the conventional facultative pond is preceded by an anaerobic pond, is also receiving considerable attention. Effluents from the facultative pond are recirculated and mixed with the sewage entering the anaerobic pond. This recirculation appears to control odours. Unfortunately, during the winter months when the temperature varies between 15°C and 20°C, BOD removal decreases and an unsightly thick scum that promotes fly-breeding forms on the anaerobic ponds. However, this problem can be overcome by increased maintenance.

The use of ponds for treating concentrated wastes such as night-soil has been studied in considerable detail (Shaw, 1962). For climatic conditions similar to those of Pretoria, a pond loading of wastes from 2 740 persons/ha per day appears suitable. In South Africa the organic concentration is higher and the volume of water lower than in geographical areas where water is abundant and water carriage systems are predominantly used. The pond must be filled with water, and liquid must be added periodically to offset evaporation and seepage losses. The recommended

¹ Because of maintenance problems, many authorities do not recommend any form of screen.

² Excessive evaporation and seepage can present a problem in certain arid areas.

depth is 60–150 cm. Of considerable importance is the fact that the sludge accumulation is only about 4 cm per year. There has been no evidence of the breeding of flies or mosquitos in these special ponds if they are well maintained, but the degree of maintenance required is high.

Concrete approach ramps must be provided to ensure that all dumped material is washed into the pond. A pump should be available to assist with washing down the ramps and breaking up floating solids.

Europe

In Europe, as in China, some form of waste stabilization pond was in use long before modern times. It appears that fish ponds were built by the early Greeks at Agrigantum, Sicily. During the nineteenth century fish ponds were used throughout central Europe with considerable success (Hickling, 1962).

Aerobic and facultative waste stabilization ponds have been used extensively in various European countries for treating wastes from small communities. This type of waste-water treatment with recirculation has proved most successful in Sweden (Wennstrom, 1955). For the most part, operating data of European facilities have not been used in empirical design equations.

Various kinds of anaerobic pond have been used to treat beet-sugar mill wastes, paper-mill effluents, and domestic sewage (F. Pöpel—personal communication, 1968).

Australia

Some of the first detailed studies on the treatment of raw waste-water were undertaken near Melbourne (Parker et al., 1950). These studies led to the construction of “lagoons” (waste stabilization ponds) for two-stage treatment. Since 1947, 28 000–90 000 m³ of raw sewage has been treated in this way. Much of the first pond, which receives the solids, is essentially anaerobic, and this results in removal of about 70–85 % of the BOD, compared with the removal of 30–40 % that might be expected from solids removal alone. The destruction of organic matter, as measured by changes in volatile solids, is shown in Table 2. In the absence of digestion and assuming that 7.5 % (by weight) of the sludge consists of solids, an accumulation of 1 cm represents 7 200 kg/ha and a rate of accumulation of 1 cm per year represents a suspended solids loading of 19.3 kg/ha per day.

Where high-rate anaerobic ponds receive raw waste-water and the solids loading is of the order of 500 kg/ha per day in the first pond, the rate of build-up of solids is substantial. The solids deposition in two Australian ponds is given in Tables 3 and 4. This build-up raises the question of whether, when, and how the accumulated solids should be removed.

Experience at Werribee indicates that at installations using several ponds in series, effective operation can be continued until the sludge layer occupies at least three-quarters of the pond depth. The sludge layer can be dried only during the hot summer months. The semi-dry sludge may be pushed out by a bulldozer. In smaller installations, sludge has been pumped out wet.

TABLE 2
COMPOSITION OF SLUDGE SOLIDS IN
AN ANAEROBIC POND, MELBOURNE, AUSTRALIA *

Characteristic	Raw sludge	Lagoon sludge
Total solids (by weight)	5.3 %	14.9 %
Moisture (by weight)	94.7 %	85.1 %
Volatile solids (by weight)	74.0 %	38.3 %
pH	5.8	7.5

* After Parker (1966).

TABLE 3
SOLIDS DEPOSITION IN EXPERIMENTAL ANAEROBIC PONDS,
BACCHUS MARSH, AUSTRALIA *

Characteristic	Pond 1	Pond 2	Pond 4
Average inflow (UKgal/d) ^a	3 500	1 000	4 000
Solids content of inflow (mg/l)	323	323	323
Period of inflow	18 months	18 months	18 months
Solids added (lb/d) ^a	5 660	1 615	6 460
Depth of sludge (in) ^a	7	7	29
Solids content (by weight)	2.49 %	2.79 %	4.81 %
Total sludge (lb dry weight)	182	204	125
Sludge solids accumulated (by weight)	3.2 %	12.1 %	1.9 %

* After Parker (1966).

^a For conversion factors, see Annex 3.

TABLE 4
SOLIDS DEPOSITION IN A SERIES OF 7 ANAEROBIC PONDS, EACH
APPROXIMATELY 10 ACRES (4 HA) IN AREA, WERRIBEE, AUSTRALIA *

Characteristic	Results ^a
Average inflow	4 500 m ³ /day
Solids content of inflow	400 mg/l
Period of inflow	5 years
Solids added	4 500 lb/day; 1 640 000 lb/year; 8 200 000 lb over 5 years
Depth of sludge, 1st pond	24 in
Total sludge accumulation in all ponds	3 170 000 lb
Sludge solids accumulated in all ponds	37 % by weight

* After Parker (1966).

^a For conversion factors, see Annex 3.

Anaerobic ponds are not recommended for highly saline and mineralized waste-waters, since massive sulfide generation occurs in the first lagoon and normal methane fermentation is completely inhibited. It is true that organic matter is destroyed even in the absence of methane fermentation, since it is used for sulfate reduction, and BOD is thereby removed from the supernatant water; but the resulting high concentrations of sulfide impose an additional load on the subsequent anaerobic units.

New Zealand

A number of small ponds are being used in New Zealand, but a system that merits special attention is the Manukau Sewerage Scheme, constructed by the Auckland Metropolitan Drainage Board (Collom, 1964).

The size of the pond complex is 530 ha. Provision has been made for primary settling, facultative pond treatment, partial anaerobic digestion, and sludge "lagoons" (stabilization ponds). The 26-ha sludge lagoons are operated in a manner similar to facultative waste stabilization ponds. After the sludge has been digested to a level where about 93 % of the available methane has been collected, the remaining sludge is pumped to one of three ponds about 3 m deep. This is done in the morning to take advantage of photosynthetic oxygenation. The solids settle, and the liquid above the sludge is dark in colour and contains algae and oxygen. In 1963 the minimum loading was 224 kg BOD₆/ha per day, while the weight of dry solids put into the ponds was about 3 900 000 kg. The rate of build-up of sludge has proved significantly lower than expected. The residual solids appear to be uniformly deposited over the pond bottom, and are then either brought into solution or re-suspended and passed on to the facultative ponds.

The waste stabilization ponds receive primary settled waste-water. BOD reduction has been most satisfactory, but *Chironomus zealandicus*, a non-biting midge indigenous to New Zealand that reproduces in shallow, slightly polluted ponds, has created a problem. It has been controlled by (a) increasing the organic load, which appreciably reduces the concentration of midge larvae (bloodworms), (b) applying certain chemicals around the perimeters of the pond, and (c) deepening the shallow areas of the pond.

United States of America

In 1962, 1 647 waste stabilization ponds were being used in the USA to treat municipal waste-waters (Porges & Mackenthun, 1963), and some 1 600 ponds were being used for industrial wastes (Porges, 1963). It is only within the last 10 or 20 years, however, that there has been a concerted effort to come to a better understanding of the critical design factors.

Industrial ponds

Porges (1963) prepared an inventory of waste stabilization pond practices in industry on behalf of the US Public Health Service. Detailed information was obtained regarding the type of facility, method of operation, pretreatment, efficiency, waste characteristics, and operational reports. The findings were summarized as follows (Porges, 1963, p. 467):

No discharges were reported for 151 ponds. Land application of pond effluent was practiced at 18 installations. Supplemental treatment, such as aeration, screening, trickling filters, and the use of chemicals was indicated for 45 installations. Thirty-nine installations reported that the industrial waste was combined with sewage before treatment.

The data indicates widespread use of 827 ponds by 31 industrial groups in the United States. The industry showing the greatest number of ponds is the canning group with 29 percent of the reported installations. Second is meat and poultry with 20 percent. Chemical industry is next with 7 percent.

As an example of industrial usage, the waste stabilization pond is the form of secondary treatment most widely used by the pulp and paper industry. At least 25 large mills and many smaller mills use this technique (Gehm, 1963; Gellman & Berger, 1968), operating at pond loadings from 11.4 to 345 kg BOD₅/ha per day. Loadings of 57 kg BOD₅/ha per day result in removal of at least 85 % of the BOD₅, and no odours develop. The use of ponds as pretreatment units (primarily for the physical separation of solids) followed by odour-free facultative ponds has met with equal success.

The National Council for Stream Improvement and its member pulp and paper mills have readily accepted the mechanically aerated waste stabilization pond. In 1966 there were existing and planned facilities for treating 2 440 000 m³ waste per day from 26 mills by this technique. Both fixed and floating mechanical aerators of a wide range of sizes are in use. The efficiency of BOD removal can be varied from 50 % to 95 % by control of nutrients, air, detention time, and secondary clarification.

Many other industries are beginning to use mechanically aerated ponds. These ponds are frequently designed to provide preliminary treatment and are followed by facultative waste stabilization ponds. In general, surface aerators are used to provide the dissolved oxygen.

Domestic ponds

Since waste stabilization ponds are widely used to treat municipal wastewaters, only a few typical examples are given in this section.

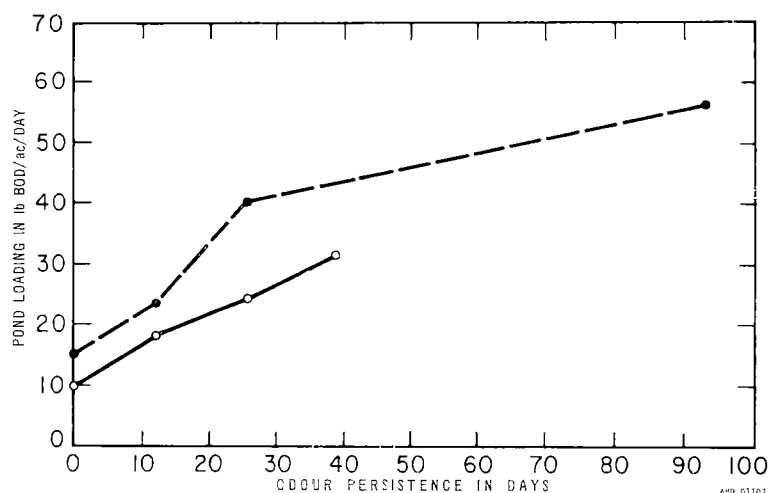
In the southern and southwestern states of the USA the organic loading usually recommended is 56 kg BOD₅/ha per day. There is no problem of ice formation on ponds in this area, but long hot summers tend to promote excessive concentrations of blue-green algae, particularly when the water temperature exceeds 30°C. The floating "mats" caused by algal growths

or by gasification of benthic sediments can be controlled by building deeper ponds and by wetting down the mats once or twice a week along the pond edges. The mats must be broken up before they have an opportunity to decay.

In Texas in 1966, there were 317 waste treatment plants employing ponds and several more with experimental ponds, primarily anaerobic waste stabilization ponds. The average organic loading to the facultative waste stabilization pond is 56 kg BOD₅/ha per day, based on primary settled waste-water. The detention time is roughly one month. Anaerobic pre-treatment is not encouraged, for it is believed that the insect vectors of encephalitis may multiply in ponds that are septic. During the last 20 years or more there has been a great deal of experimentation, and the trend is towards greater pond depths ranging from 1.5 to 2.7 m.

An organic loading of 22.4 kg BOD₅/ha per day has been set as the design standard in the Missouri Basin, Upper Mississippi Basin, and the Great Lakes states. The principal reason for this low value is the need to control odours during the spring ice break-up. Odour control is the most important single item the design engineer in this area has to consider. As shown in Fig. 2, a loading of 11.2 kg BOD₅/ha per day with a depth of almost 1 m usually eliminates odours during the spring ice break-up (Porges,

FIG. 2. STABILIZATION POND LOADING IN lb BOD/ac/DAY* IN RELATION TO ODOUR PERSISTENCE AFTER BREAK-UP OF ICE



Reproduced, in modified form, from Svore (1958), p. 428, by permission of the publishers.
 * 1 lb BOD/ac = 1.12 kg/ha.

1964). However, loadings of less than 22.4 kg BOD₅/ha per day may result in an insufficient supply of water during the hot, dry summer months. In all cases, evaporation losses must be considered.

The state of Michigan built its first waste stabilization pond in 1961, and seven years later 72 installations were in operation or planned. The ponds operate with a minimum of nuisance and provide effective pollution control (Pierce & Richmond, 1966). Treatment of waste-water by waste stabilization ponds has proved at least as effective as conventional secondary treatment with regard to removal or reduction of BOD, total suspended solids, and coliform organisms. Michigan has some highly porous soils, and clay admixtures have been used successfully for sealing the bottom and sides of ponds.

The state of Colorado (Horn, 1965) has divided defects of design, construction, and operation into three main categories: (1) liquid depth not maintained; (2) water surface area inadequate; and (3) settleable solids not evenly distributed.

The current practice of some midwestern and southwestern states is to use two ponds in series. The first pond is designed for loadings of 22.4–56 kg BOD₅/ha per day, while the second pond is considerably smaller in size. This system provides a degree of flexibility and is similar to the maturation pond system used in South Africa.

In western areas of the USA, many ponds are built as percolation and evaporation ponds. The advantages of this practice must be weighed against the disadvantages of a possible loss of a surface water resource.

Many states require disinfection of all domestic wastes. For example, Oregon requires disinfection of such wastes between May 1 and November 1 or as directed by the State Sanitary Authority. Consequently, some ponds are built with sufficient capacity to hold all wastes discharged during this period.

The State of Iowa, which has over 100 operational ponds, has found that ponds of over 2.5 ha each are more efficient in the winter because the larger size permits the wind to remove snow. A pond design based on 250 population equivalents per hectare is recommended for winter operations (Stouse, 1964).

In Alaska, experiments by the Arctic Health Research Center, US Public Health Service, have demonstrated that some of the disadvantages of pond operations in very cold climates can be overcome by the use of submerged aeration systems. Aeration permits higher loadings and shorter detention times (Reid, 1965). At detention times of 15–20 days and loading rates of 85–112 kg BOD₅/ha per day, the BOD removal rate stayed between 75 % and 80 %. Ice formation during the winter helps to conserve heat. The equipment and ponds have functioned at temperatures of –46°C. Fig. 3 shows the ice cover over an aerated sewage lagoon at Eielson, Alaska. The stalagmites are formed by the freezing of moist air from the pond.

FIG. 3. AERATION UNDER ICE COVER, EIELSON, ALASKA*



* Reproduced from Reid (1965) by courtesy of the Hinde Engineering Company, Highland Park, Ill., USA.

Canada

Ponds were first used for waste treatment in Canada in the prairie provinces. Now they are found in every part of the country, serving communities with populations ranging from only a few hundred to more than 200 000. The largest pond systems are located near Regina and Winnipeg. It is estimated that in 1966 there were about 500 waste stabilization facilities in Canada (Fisher et al., 1968).

The geographical location and size of Canada give rise to climatic extremes of temperature, humidity and solar radiation. Because these factors greatly affect the design and operation of ponds, no single design criterion can be applied (Stanley, 1959). The most commonly used criterion is the organic loading, usually expressed in terms of kg BOD/ha per day. To a lesser extent, designs are based on volumetric loadings, in which case a theoretical minimum detention time is used, together with an estimated or observed volumetric *per caput* flow rate. In some provinces both volumetric and organic loading factors are used to determine dimensions. The following description of ponds in the various provinces illustrates some of the special features used in the design of Canadian ponds.

Maritime provinces

The suggested design of waste stabilization ponds in the eastern provinces is based on organic loadings of 17–39 kg BOD₅/ha per day. Since most ponds are designed to serve small communities under moderately severe winter conditions, design procedures have been kept simple, and ponds are generally of the facultative type. The Atlantic Ocean keeps the climate of these provinces from becoming really severe, and only in a few cases is storage throughout the winter required. Data for spring and summer operations indicate removal rates of 85 % for BOD and 70 % for suspended solids. At most installations the reduction in coliform organisms appears to be in excess of 99 %. Offensive odours, if they occur at all, are observed during the spring thaws.

Most ponds in the maritime provinces have centre-discharging inlets located about 30 cm above the bottom. Variable overflow weirs are often used to maintain desired liquid levels.

Ontario and the prairie provinces

The criteria for pond design in Ontario are somewhat similar to those in the maritime provinces. Regulations of the Ontario Water Resources Commission require that the organic loading rate should not exceed 22 kg BOD₅/ha per day, or 250 population equivalents per ha per day.

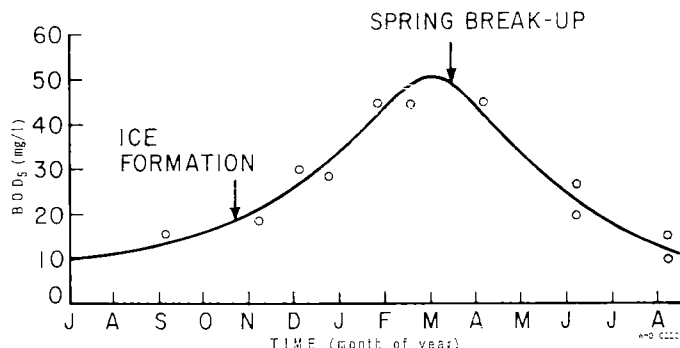
In Manitoba, the recommended organic loading rate is 45–55 kg BOD₅/ha per day (500–620 population equivalents per ha per day). Higher organic loadings are permitted for installations that are operated only during the summer. The recommended depths vary between 0.6 and 1.5 m. Multiple ponds, either in series or in parallel, are recommended when the total pond area is greater than 4 ha, and provision must be made for a winter detention period of 120 days where there is a small dilution factor in the receiving stream. In Ontario many facilities are operated in parallel during the winter and in series during the summer. Multiple ponds may be used to avoid discharges during the summer months when the green effluent would adversely affect recreational areas.

The seasonal variation in effluent BOD is highly dependent on temperature. Fig. 4 shows BOD₅ values for summer and spring of 10 and 50 mg/litre respectively. An annual average BOD reduction of 90 % is reported, although annual figures for individual ponds range from 65 % to 96 %. Reduction of coliform organisms exceeds 99.5 % in some ponds, including those receiving raw (untreated) domestic waste-water.

At some plants that receive waters from both sanitary sources and storm sources, grit accumulations in the inlet works have created problems. In addition, silt banks have been built up in many ponds. At low depths of liquid, short-circuiting and odours have developed, and difficulties with weeds have been encountered at nearly half the ponds on which data are

available. Erosion is a constant problem at some installations, and is generally associated with large surface areas or with dike walls having inside slopes greater than the recommended 25 %.

FIG. 4. SEASONAL VARIATIONS IN BOD OF EFFLUENT FROM WASTE STABILIZATION PONDS



Reproduced, in modified form, from Fisher et al. (1968), p. 443, by permission of the publishers.

It is recommended that the inlet pipe be located near the centre of the pond. For gravity flow, the inlet may be allowed to discharge horizontally. When the flow is under pressure, a vertical discharge is required, but the velocity must not exceed 60 cm per second. Adjustable overflow weirs are used to control depth.

On the prairies the summers are hot and dry, while the winters are extremely cold and long with a mean January temperature of about -10°C . In Saskatchewan, ponds consist of two units, operated in series with a total detention time of 180 days. The detention time is based on the full volume of the second-stage unit plus an amount equivalent to a depth of 60 cm in the first-stage unit. The first pond is designed for a maximum organic loading rate of 45 kg BOD₅/ha per day. However, most ponds have storage capacity for 4–6 months, so they can be partially emptied during the autumn prior to the winter freeze-up and again in the spring when dilution water is available. BOD removal rates are reported to exceed 90 % in summer and to average 54 % in winter. Throughout the prairie, reduction of coliform organisms in ponds is in excess of 99 %, an important factor because many of the ponds discharge across farmland and receive little or no dilution.

A diffused aeration system was constructed throughout the existing lagoons at Regina, Saskatchewan when the facility became grossly overloaded. The system consists of aeration tubing, weighted feeder tubing, and blowers. Results so far indicate a high degree of treatment, and the BOD of the treated effluent is well below the level of 40 mg/litre stipulated

by the Department of Public Health. Temperatures as low as -40°C do not appear to halt the aeration process.

In the province of Alberta, facultative waste stabilization ponds are used extensively. The ponds are large enough to contain the waste inflow over a period of 6–18 months. Some facilities in this province use anaerobic pretreatment ponds with detention periods of 2–4 days, followed by second-stage ponds with detention periods of 3–6 months. The observed organic loadings of facultative ponds vary from 21 to 25 kg BOD_5/ha per day for single-unit systems and from 56 to 280 kg BOD_5/ha per day for multiple-unit systems. The loading rates for anaerobic installations range from 0.04 to 0.28 kg BOD_5 per m^3 per day. The BOD removal rates are between 45 % and 90 %, the lowest levels occurring during the colder periods. The anaerobic ponds are some 2.5–3.5 m deep, the secondary ponds 1.0–1.6 m deep.

The removal of suspended solids by anaerobic ponds during the winter has ranged from 64 % to 91 %. Where ponds are operated in series, more than 55 % of the suspended solids are removed in the first pond. In both Alberta and Saskatchewan the sludge accumulation was less than 0.34 litres *per caput* per day. As a rule, accumulation in summer is about one-third of the winter value.

The thawing of the ice cover in the spring is often accompanied by objectionable odours. These odours are most prominent around facultative ponds. Anaerobic pretreatment ponds tend to exhibit less intensive spring odours because of their thinner ice cover and shorter periods of coverage. However, these pretreatment ponds produce low-intensity odours throughout the year, often accompanied by floating sludge, scum, and grease.

Dikes that enclose large ponds may be eroded by wave action and by storm water run-off. Studies involving dikes with inside slopes varying from 16% to 11 % showed that flattening the slopes does not necessarily prevent erosion.

Mosquitos have been controlled effectively through the use of insecticides and other measures. The severity of mosquito breeding should be determined by field surveys.

British Columbia

Most ponds in this province are of the facultative type. Recently, however, an installation consisting of four anaerobic pretreatment ponds and three facultative ponds has been constructed, designed to permit operation in series or in parallel. The anaerobic ponds are loaded at a rate of 220 kg BOD_5/ha per day, the facultative ponds at a rate of 6 kg BOD_5/ha per day. The BOD_5 removal rates vary from 75 % to 90 %, the higher levels being obtained with the system using anaerobic pretreatment. The only odours reported have come from the anaerobic ponds during the spring thaw.

Since the severity of the winters is moderated by the Pacific Ocean, cold weather storage is not necessary; consequently, there is little difference in this region between winter and summer pond operating practices.

North-west Territories

A pond located at latitude $68^{\circ}12' \text{ N}$ is used to treat the wastes from 1 500 people. The average monthly temperatures range from 14.6°C to -28.6°C , while daily temperatures in summer range from about 21°C in the afternoon to 7°C at night. Ice may occur from September to the middle of June, and odours have been noticed during the spring thaw. The surface area of this pond is 17 ha, and its depth varies between 30 cm and 2 m; the volumetric loading rate is 820 m^3 per day and the organic loading rate about $10 \text{ kg BOD}_5/\text{ha}$ per day. The BOD_5 level is about 210 mg/litre in the influent wastes and about 40 mg/litre in the effluent, giving a removal rate of about 80 %. The dissolved oxygen level has been reported to be high during the long-daylight summer months.

Cost

Waste stabilization ponds offer considerable economic advantages over other forms of municipal and industrial waste-water treatment. Although ponds naturally require more space than most other methods, the construction, operating and maintenance costs are lower and may even be less than half. Furthermore, the cost *per caput* of small installations does not increase so rapidly with diminishing size. When reduction of BOD and bacteria is the only criterion, therefore, the waste stabilization pond has little competition. Obviously, however, there are other criteria that must be considered in the appraisal of alternative treatment systems. For example, the effluent from a waste stabilization pond may not be of adequate chemical quality to meet the requirements, or there might be some aesthetic reason for not using ponds. Such decisions involving projected water uses and comparisons of alternatives must remain the responsibility of the engineer. He must design treatment facilities within the framework of local, regional, and national regulations and needs, taking both health considerations and water resources into account.

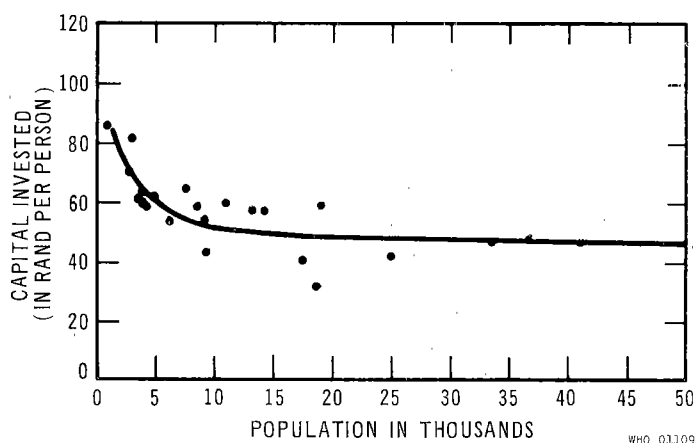
Waterborne sanitation

Unless the initial cost of a treatment facility and the costs of operation and maintenance are reasonable, waste treatment will be out of the financial reach of a large number of small communities. Usually, the cost *per caput* of waste-water purification increases sharply as the volume of water to be treated decreases (Stander & Meiring, 1965). A survey carried out in

South Africa indicates that the average annual cost per site of a sewerage system in a low-income area and the cost of a pail-latrine (night-soil) removal system are roughly the same. The adjusted total annual cost per site for waterborne sanitation, including the cost of water and one water closet per site, ranged from \$11.53 to \$21.22. The annual cost of sanitary pail removal and waste-water disposal into sewer inlets 5 km away ranged from \$13.39 to \$22.32 per site. The cost of treatment was not included. As a further yardstick for comparison, the total annual cost of a pit latrine system combined with septic tanks and a subsurface waste-water disposal system was \$5.32 (Kieser, 1964).

Finally, the provision of a central collection system may involve costly outfall lines, pumps, etc. In a typical sewerage scheme, the sewer network accounts for about 75 % of the total cost, and the cost of the network *per caput* increases sharply as the size of the community decreases (Fig. 5). Through the use of waste stabilization ponds, it is often possible to provide a treatment facility in each drainage basin and thus avoid the costly transfer of waste-water from one basin to another.

FIG. 5. CAPITAL INVESTED IN SEWERS IN A NUMBER OF SOUTH AFRICAN TOWNS, IN RAND*



Data from Stander & Meiring (1955), p. 1026.

* 1 Rand = US \$ 1.40.

General treatment costs

The cost of sewage treatment can be illustrated by comparing various treatment and construction costs.

Table 5 illustrates the earlier statement that there is a sharp increase in the cost of treatment per unit of volume as the size of the community decreases, except in the case of waste stabilization ponds where the estimated costs remain the same.

TABLE 5
ESTIMATED COST OF WASTE-WATER TREATMENT PER PERSON *

Population	Capital cost (US \$)		Annual running costs (US \$)	
	Conventional purification works ^a	Stabilization ponds without sealing of bottom	Conventional purification works	Stabilization ponds
240	86.80	5.60	—	0.84
900	44.80	5.60	—	0.56
1 000	50.40	5.60	—	0.42
3 000	36.40	5.60	4.20	0.42
5 000	33.60	5.60	—	0.42
10 000	21.00	5.60	—	0.42
30 000	22.40	5.60	2.80	0.42
50 000	16.80	5.60	—	0.42
200 000	22.40	5.60	—	0.42
1 000 000	9.80	5.60	0.84	0.42

* Data from Stander & Meiring (1965), p. 1026.

^a The values in this column are specimen costs taken from the literature. Consequently the decrease in cost for increasing population size is not regular.

According to the US Public Health Service, construction costs represent about 80 % of the total estimated cost of sewage treatment facilities. Other cost items include: (a) facilities such as interceptors and outfall sewers; (b) pumping stations not contiguous to the treatment plant; (c) land; and (d) administrative, engineering, and legal services.

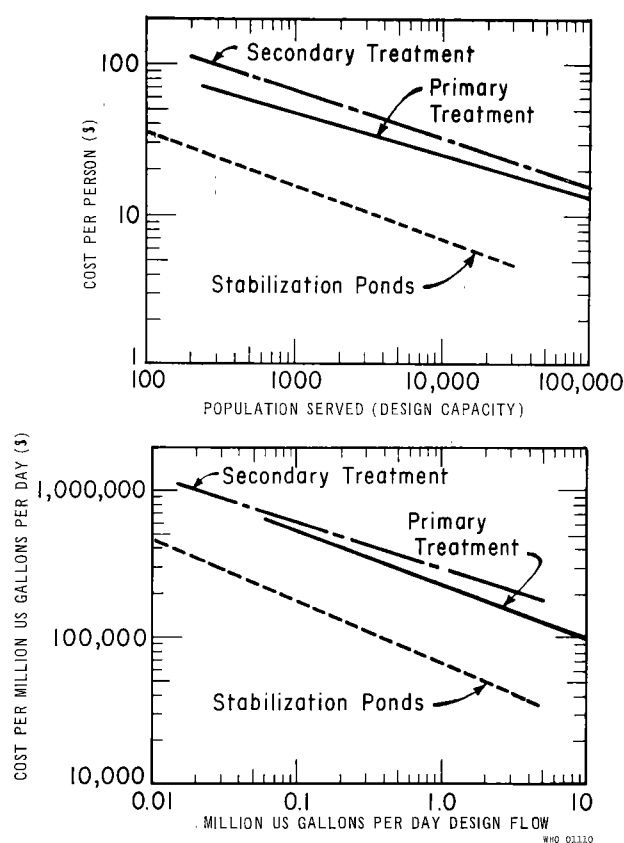
Comparative costs of secondary treatment plants in the USA are shown in Fig. 6. Here again, the cost *per caput* for treatment plants other than ponds is appreciably higher for the smaller plants.

Separate cost comparisons for five types of treatment in the USA are shown in Tables 6–10. These costs are based on the design capacity. Since these cost data are derived statistically, lower and upper confidence limits are given. The construction cost of a treatment system can be expected to be within these limits about two-thirds of the time.

Waste stabilization pond costs

A study of the economics of waste stabilization ponds in the midwestern states of the USA provides a basis for comparisons (Tables 11 and 12). The designs were based on loadings ranging from 150 to 48 000 population equivalents. In these calculations, one population equivalent (PE) is equal to 75 g BOD₅ per day. The data were derived from 262 treatment plants, comprising 13 primary sedimentation and digestion plants, 81 secondary biological plants, and 168 waste stabilization plants. Of the latter, 160 received raw waste-water and 8 received effluent from conventional treatment plants. No differentiation is made between waste stabilization ponds according to loading and size, layout (whether single-unit or multiple unit),

FIG. 6. COMPARISON OF CONSTRUCTION COSTS FOR DIFFERENT TYPES OF WASTE TREATMENT, IN US DOLLARS



Data from US Public Health Service (1965), pp. 18 and 33.
Note: 1 million US gallons = 3785 m³.

TABLE 6
CONSTRUCTION COST PER CAPUT,
IMHOFF TANK PLANTS *

Design population	Construction costs (US \$)		
	Lower limit	Expected value	Upper limit
100	80.23	146.80	268.59
1 000	24.89	45.54	83.33
10 000	7.72	14.13	25.85
100 000	2.40	4.38	8.02

* Reproduced, in modified form, from Clare & Weiner (1965), p. 80, by permission of the publishers.

TABLE 7
CONSTRUCTION COST *PER CAPUT*, PRIMARY
TREATMENT PLANTS WITH SEPARATE SLUDGE
DIGESTION *

Design population	Construction costs (US \$)		
	Lower limit	Expected value	Upper limit
100	77.12	114.96	171.36
1 000	37.52	55.93	83.37
10 000	18.25	27.21	40.56
100 000	8.88	13.24	19.73

* Reproduced, in modified form, from Clare & Weiner (1965), p. 80, by permission of the publishers.

TABLE 8
CONSTRUCTION COST *PER CAPUT*, WASTE
STABILIZATION PONDS *

Design population	Construction costs (US \$)		
	Lower limit	Expected value	Upper limit
100	19.96	36.31	66.10
1 000	8.85	16.10	29.31
10 000	3.92	7.14	13.00
100 000	1.74	3.17	5.77

* Reproduced, in modified form, from Clare & Weiner (1965), p. 81, by permission of the publishers.

TABLE 9
CONSTRUCTION COST *PER CAPUT*, TRICKLING
FILTER PLANTS WITH SEPARATE SLUDGE DIGESTION *

Design population	Construction costs (US \$)		
	Lower limit	Expected value	Upper limit
100	109.83	161.91	238.70
1 000	50.58	74.57	109.93
10 000	23.29	34.34	50.63
100 000	10.73	15.81	23.32

* Reproduced, in modified form, from Clare & Weiner (1965), p. 81, by permission of the publishers.

TABLE 10
CONSTRUCTION COST *PER CAPUT*,
ACTIVATED SLUDGE TREATMENT *

Design population	Construction costs (US \$)		
	Lower limit	Expected value	Upper limit
100	84.39	124.98	185.07
1 000	44.47	65.85	97.52
10 000	23.43	34.70	51.39
100 000	12.35	18.29	27.08

* Reproduced, in modified form, from Clare & Weiner (1965), p. 82, by permission of the publishers.

or earthwork and land costs. Table 11 presents a comparison of the actual contract costs, including construction, land and outfall sewer costs. Table 12 shows the land costs for treatment works.

It is estimated that the operation and maintenance costs for waste stabilization ponds range from \$0.20 to \$1.00 per population equivalent per year. These costs have been estimated for ponds with different design loadings, and very little difference has been found (Frankel et al., 1965).

TABLE 11
COMPARISON OF CONSTRUCTION COSTS OF 262 WASTE TREATMENT
PLANTS IN THE MIDWESTERN STATES OF THE USA, 1957-1959 *

Population equivalents ^a	Cost per design population equivalent (US \$)			
	Primary settling and digestion plants	Secondary biological treatment plants	Secondary waste stabilization ponds	Raw sewage ponds
100	77.91	127.30	103.20	29.36
1 000	40.05	64.83	53.34	18.52
10 000	20.58	33.02	27.04	11.69
100 000	10.58	16.82	13.71	7.37

* Data from Clare & Weiner (1961), p. 164.

^a One population equivalent = 75 g BOD₅ per day.

TABLE 12
LAND COSTS FOR WASTE TREATMENT
PLANTS IN THE MIDWESTERN STATES OF THE USA,
1957-1959 *

Type of plant	Cost in US \$ per population equivalent ^a
Primary treatment	1.25
Secondary treatment	1.20
Raw sewage waste stabilization ponds	3.10
Secondary waste stabilization ponds	2.30

* Data from Clare & Weiner (1961), p. 64.

^a The figures are based on loadings of approximately 22 kg BOD₅/ha per day.

Summary of Practices

The benefits that can be derived from the use of waste stabilization ponds in rural areas, small communities, and even in large cities are measurable and significant. The effective use of low-cost facilities in waste-water treatment is an investment in the improvement of environmental health.

While stabilization ponds cannot rival an efficiently operated activated sludge treatment plant in producing a turbidity-free effluent, the thousands of ponds in operation attest to their usefulness. Only when a cleaner effluent is required does it become necessary to adopt a more expensive method of treatment.

Waste-water Characteristics and Biological Stabilization

Waste stabilization ponds can be made to function most effectively if the designer and operator have a basic understanding of waste-water characteristics and of the principles of biological stabilization.

The nature of pollution, the characteristics of wastes, biological reactions, oxygen demand, and the stoichiometry of algae and bacterial systems are briefly discussed in this chapter. A more detailed description of pond organisms and other factors affecting waste stabilization ponds is provided in Annex 2. For further details the reader is referred to the technical literature on biological waste-water treatment.

Nature of Pollution

Pollutants may be classified as biodegradable or non-biodegradable. Pollutants such as inorganics are not biodegraded, and once they enter the receiving water they may be diluted but are not necessarily reduced in quantity.

Other pollutants are changed in character by biological, chemical, and physical forces, and because of these changes the unstable organic waste in domestic waste-water can be converted to inoffensive substances. Likewise, some industrial wastes can be converted into stable effluents.

The substances and organisms contained in wastes may include: (a) infectious agents, (b) oxygen-demanding wastes, (c) plant nutrients, (d) organic chemicals (including many pigments), (e) inorganic chemical and mineral substances, (f) sediments, and (g) radioactive materials.

Waste Characteristics

The amount and composition of the wastes, whether waterborne or not, are of prime importance to the designer and operator of a treatment facility. Although there is considerable similarity in basic content, the volume and

character of wastes obviously vary from one country to another. Climatic conditions and social customs are but two of the many factors that cause the type and volume of wastes to differ.

Table 13 shows the quantities of domestic sewage normally produced in different areas of the world. However, caution should be exercised in using these figures as a basis for any specific design.

TABLE 13
QUANTITY OF DOMESTIC
SEWAGE PRODUCED PER HOUSE-
HOLD, IN SELECTED COUNTRIES *

Country	Water carriage in litres <i>per caput</i> per day
Brazil	150-300
Costa Rica	262-379
Cuba	190-225
Ecuador	100
Ghana	90-145
India	100-250
Israel	80-415
Japan	250
Mauritius	63-144
New Zealand	226-230
Nigeria	80
Peru	140
Saudi Arabia	158
Southern Rhodesia	7-77

* Author's survey.

In general, the amount of water accompanying the organic material increases as the community water supply and industrial complex become more highly developed. The solids content of waste-water will be greater in villages having limited water supplies than in cases where a highly developed water carriage system is used to carry away the sewage.

The organic matter in domestic waste-water can be divided into three main classes: proteins, carbohydrates, and fats. The proteins, which comprise 40-50 % of the organic matter, are complexes of amino acids and constitute the major source of bacterial nutrients. Roughly 50-60 % of the protein may be found in the dissolved fraction of domestic waste-water and 20-30 % in the settleable fraction. The carbohydrates consist of readily degraded starches and sugars and of cellulose, which is less readily degraded. The percentages of carbohydrates found in the dissolved and settleable fractions are similar to those for protein. The fats, including fatty acids, are usually not very soluble and are degraded more slowly.

Gotaas (1956, p. 35) gave the following figures for the quantity and composition of human body wastes:

Human faeces without urine

Approximate quantity

135-270 g *per caput* per day moist weight

35-70 g *per caput* per day dry weight

Approximate composition

Moisture content	66-80 %
Organic matter content (dry basis)	88-97 %
Nitrogen	5.0-7.0 %
Phosphorus (as P_2O_5)	3.0-5.4 %
Potassium (as K_2O)	1.0-2.5 %

Carbon	(dry basis)	. . . . .	40-55 %
Calcium (as CaO)	" "	. . . . .	4-5 %
C/N ratio	" "	. . . . .	5-10

Human urine*Approximate quantity*Volume: 1.0-1.3 litres *per caput* per dayDry solids: 50-70 g *per caput* per day*Approximate composition*

Moisture content	. . . . .	93-96 %
Organic matter content (dry basis)	. . . . .	65-85 %
Nitrogen	" "	15-19 %
Phosphorus (as P ₂ O ₅)	" "	2.5-5 %
Potassium (as K ₂ O)	" "	3.0-4.5 %
Carbon	" "	11-17 %
Calcium (as CaO)	" "	4.5-6 %

The composition of wastes from animals is shown in Table 14. The values are based on a 2.25-kg chicken (usual laying hen), a 454-kg bovine (small dairy cow or marketable beef animal), and a 45-kg pig (half-grown to market size) (Hart & Turner, 1965). In terms of population equivalents, the BOD₅ of animal wastes is as follows (Butler et al., 1964, p. 12):

<i>Source</i>	<i>Population equivalents</i>
Man	1.0
Cow	16.4
Horse	11.3
Chicken	0.014
Sheep	2.45
Pig	3.0

TABLE 14
CHARACTERISTICS OF LIVESTOCK MANURE *

Factor	Poultry	Cattle	Swine
Total solids in faeces and urine (g per day)	30	4730	360
Solids content of freshly collected total sample (%)	23	18	19
Volatile solids, as percentage of total solids	77.5	80.3	78.5
Volatile solids (g per day)	23	3800	282
BOD ₅ (mg BOD ₅ /mg volatile solids)	0.288	0.183	0.320
BOD ₅ (g O ₂ per day)	6.8	700	91
COD ^a (mg COD/mg volatile solids)	1.11	1.0	1.2
COD ^a (g O ₂ per day)	25.8	3800	340
Nitrogen, as N, in fresh manure (percentage of total solids)	5.4	3.7	4.0
NH ₄ nitrogen (percentage of total N)	74	—	75
Phosphorus, as P ₂ O ₅ (percentage of total solids)	4.6	1.1	3.1
Potassium, as K (percentage of total solids)	2.1	3.0	1.4
Volatile acids, as acetic acid (percentage of total solids)	5.8	3.2	4.8

* Data from Hart & Turner (1965), p. 1580.

^a Chemical oxygen demand.

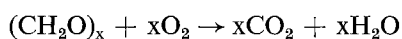
Table 15 shows the approximate quantity and composition of sewage and sewage sludge from various sources. The wastes from each community, particularly where industries are present, require careful analysis, for flow patterns and waste characteristics are likely to vary considerably. For example, toilet paper usage may vary from nil to 20 g per person per day, and the concentration of such paper in domestic waste-waters may be as much as 20–80 mg/litre. Home clothes-washing devices may contribute 55–110 mg/litre solids and 15–30 mg/litre BOD₅ (Durfur & Becker, 1962). In dishwater the solids content and BOD both vary considerably.

Mode of decomposition

The decomposition of organic material may take place under aerobic or anaerobic conditions (Gloyne & Eckenfelder, 1968). The aerobic process requires a continuous supply of free dissolved oxygen and is the most efficient method for reducing the organic content of dilute liquid wastes. However, where solids must be liquefied and where the wastes are highly concentrated, as in the case of settled organic solids from domestic waste-waters, night-soil, and wastes from abattoirs, the anaerobic process is extremely effective.

Aerobic process

In the aerobic metabolism of organic matter, much of the carbon serves as a source of energy for the organisms and is respired as carbon dioxide (CO₂). The organisms involved are mostly bacteria, but also include fungi and protozoa. They use the remainder of the carbon, together with phosphorus and nitrogen, to form new cells. In typical domestic waste-waters, the weight of cells produced is roughly equal to 40 % and 60 %, respectively, of the weight of chemical oxygen demand (COD) and BOD₅ removed. The major reactions likely to occur in an aerobic waste stabilization pond system are as follows:



Protein (organic N) → ammonia → nitrite → nitrate

Organic sulfur → sulfate

Organic phosphate → H₃PO₄ → CaPO₄

The quantity of oxygen required to stabilize the organic material in the waste depends on the BOD satisfied during treatment. This BOD is the oxygen that must be supplied to waste stabilization ponds by photosynthetic means, transferred across the air-water interface, or obtained from oxygen-containing compounds such as nitrates, phosphates, and sulfates. Similarly, the rate at which oxygen is used is an important factor in the design of a treatment plant.

TABLE 15
APPROXIMATE QUANTITY AND COMPOSITION OF VARIOUS TYPES OF SEWAGE AND SEWAGE SLUDGE *

Item	Quantity of solids, dry basis (g per head per day)	Composition on dry basis (%)				
		Organic matter	Minerals	Nitrogen (N)	Phosphate (P ₂ O ₅)	Potash (K ₂ O)
Fresh domestic sewage	81.5-100	60-85	15-40	5.0-10.0	2.5-4.5	3.0-4.5
Inhoff tank, well digested	22.6-36.2	30-45	55-70	2.0-3.0	1.2-3.5	0.1-0.5
Primary, fresh	45.4-63.4	60-80	20-35	1.5-4.0	0.8-4.0	0.1-0.5
Primary, digested	27.0-40.5	35-60	40-65	1.0-3.5	1.2-4.0	0.1-0.5
Primary and trickling-filter humus, fresh	58.4-76.3	50-75	25-50	2.0-4.5	0.8-3.6	0.1-0.5
Primary and trickling-filter humus, digested	36.0-49.5	35-60	40-65	1.0-3.5	1.0-3.8	0.1-0.5
Primary and activated sludge, fresh	72.0-90.0	50-80	20-50	2.3-5.2	1.2-4.0	0.2-0.6
Primary and activated sludge, digested	45.4-46.3	35-55	45-65	2.0-4.8	1.3-4.0	0.2-0.6
Primary sludge, digested, and fresh activated sludge	54.0-72.0	40-60	40-60	2.2-5.0	1.3-4.0	0.3-0.8

* After Gotaas (1956), p. 40.

Aerobic micro-organisms have the ability to synthesize new cell material from wastes containing complex organic compounds. Thus some of the organic material is used to make protoplasm and some of the waste is degraded into low-energy compounds. Oxygen must be supplied continuously during the aerobic process, for it acts as the final hydrogen acceptor during the oxidation of organic matter and the reaction ceases if it is not available. Liberation of energy occurs during this hydrogen transfer.

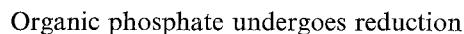
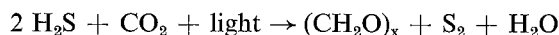
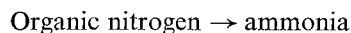
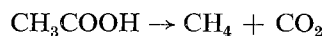
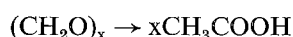
Anaerobic process

Putrefactive breakdown of organic material takes place during anaerobic fermentation. This is a two-step process. First, a special group of acid-producing bacteria known as facultative heterotrophs degrade organic matter into fatty acids, aldehydes, alcohols, etc. Then a group of methane bacteria convert the intermediate products to methane (CH_4), ammonia (NH_3), carbon dioxide (CO_2), and hydrogen (H_2). Like the aerobic process, the anaerobic process converts carbon, nitrogen, phosphorus, and other nutrients to cell protoplasm. However, the mechanisms of anaerobic decomposition are exceedingly complex and are not thoroughly understood.

Oxygen is also required for the anaerobic process, but its source is chemical compounds, not free dissolved oxygen. In anaerobic decomposition the end products are quite complicated; the reactions are slower and the products may be odoriferous.

There is always some anaerobic activity in the bottom muds and sediments, even in ponds designed to operate aerobically. In deep ponds, too, there is likely to be a layer of liquid near the bottom that will support anaerobic organisms.

The biochemical reactions that occur in the anaerobic decomposition of wastes might be expressed as follows:



Biological Reactions

As has been made clear in the previous section, the biological organisms in a waste-water treatment plant may produce many biochemical changes. The major biological reactions occurring in waste stabilization ponds include: (a) oxidation of organic material by aerobic bacteria, (b) nitrification of protein and other nitrogenous material by aerobic bacteria, (c) reduction of organic material by anaerobic bacteria living in bottom deposits and liquids, and (d) oxygenation of surface liquids by algae.

Certain basic facts regarding the oxidation of organic wastes are now accepted: (a) the dissolved oxygen is reduced during stabilization of organic material; (b) the rate of oxidation is independent of the amount of dissolved oxygen available; (c) the type and number of organisms present is important; and (d) changes in oxygen content can serve as a measure of the quantity and character of oxidizable organic matter.

Oxygen Demand

The oxygen demand of waste-water may be expressed in terms of the biochemical oxygen demand (BOD) and the chemical oxygen demand (COD). These values do not necessarily measure the same things, but both are useful indicators of the total oxygen demand that may be imposed on a treatment plant or waterway by a waste. The total oxygen demand is exerted by three groups of matter: carbonaceous material, oxidizable nitrogen, and certain reducing compounds. The oxygen demand of the carbonaceous and nitrogenous material is usually measured in terms of a BOD test, while the total demand is generally expressed by the COD.

BOD test

The BOD test measures the amount of dissolved oxygen required by living organisms for the aerobic destruction or use of organic matter. Thus the BOD represents the amount of dissolved oxygen that will be required to develop and sustain the biological activity needed to degrade a given quantity of waste; if the aerobic treatment is prolonged, the BOD may also include the amount of oxygen required to degrade part of the biological cell material that was produced from the initial waste.

As shown in Fig. 7, the BOD of freshly polluted waste-water develops in two stages. During the first stage, the carbonaceous material is largely oxidized, while in the second stage a significant amount of nitrification takes place. During the first stage, the rate of organic breakdown at any time is assumed to be directly proportional to the amount of biologically degradable material present. The biological stabilization of a waste may take a long time, and for practical purposes a 5-day incubation period, BOD_5 , has been accepted as a standard reference.

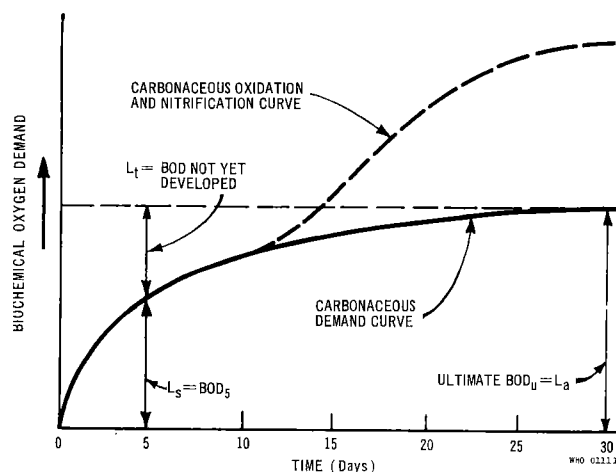
The tests involved in the evaluation of BOD have been thoroughly discussed by the American Public Health Association et al. (1965) and Åkerlindh (1953).

Particular care must be taken when neutralizing the wastes and when seeding the dilution water with sewage, polluted stream water, or special biological cultures that have become adapted to specific industrial wastes. In order to obtain the maximum BOD value, it is also important to use the proper dilution to ensure that any toxic effect is removed and that not all the dissolved oxygen is used. When increasing dilutions show increasing

BOD values, the dilutions should be increased until the BOD levels off at its maximum.

The ultimate BOD, BOD_u , is the sum of the carbonaceous BOD already satisfied and the carbonaceous BOD remaining (Equation 1). In the case of domestic waste-waters, the ultimate demand may be attained after about 20 days of incubation at 20°C. After 5 days of incubation at this temperature, about 60–90 % of the ultimate (first-stage) demand of typical domestic waste-waters is satisfied.

FIG. 7. DEVELOPMENT OF BIOCHEMICAL OXYGEN DEMAND



$$L_a = L_s + L_t \quad (1)$$

where

L_a = ultimate BOD, BOD_u (mg/litre)¹

L_s = BOD satisfied after t days (mg/litre)

L_t = BOD not yet developed after t days (mg/litre)

Equations 2–4 describe the rate at which the carbonaceous BOD will be satisfied. The rate constant, k , is dependent upon the waste characteristics and temperature. In Equations 3 and 4, typical values of k may vary from 0.10 to 0.30 for domestic waste-waters, from 0.15 to 0.25 for untreated domestic waste-waters and high-rate treatment effluent, from 0.04 to 0.07 for high-level biological treatment plant effluent, and from 0.04 to 0.06 for streams with minor pollution.

¹ In most cases, the symbols used in this monograph are explained only where they first appear. A full list of the symbols and their meanings is provided in Annex 2 (p. 160).

$$-\frac{dL_t}{dt} = k_1 L_t \quad (2)$$

$$\frac{L_t}{L_a} = e^{-k_1 t} = 10^{-kt} \quad (3)$$

$$L_s = L_a - L_t = L_a(1 - 10^{-kt}) \quad (4)$$

where

- t = time (days)
- L_a = BOD_u or initial BOD (mg/litre)
- k_1 = reaction constant, log_e (breakdown/day)
- k = reaction constant, log₁₀ (breakdown/day)

The use of Equation 4 is complicated by the fact that L_a and k are generally not known. The values must be estimated from laboratory data by one of several methods that are commonly used for determining L_a and k from a series of observations of L_s and t .

COD test

As at present carried out, the chemical oxygen demand determination provides a measure of the oxygen equivalence of that portion of the organic matter in a sample which is susceptible to oxidation by a strong chemical oxidizer. If wastes contain toxic substances, this test may be the only practical method for determining the organic load. Because of interpretation problems, the COD test becomes really meaningful only after many values of both BOD and COD have been collected and correlated with each other.

Nitrification

In some waste-water treatment requirements, emphasis is placed on the removal of nitrogen from the treated effluents in order to minimize the release of plant nutrients to the receiving water, for a build-up of such nutrients in the waterway or impoundment accelerates the aging process known as eutrophication. As yet, waste stabilization ponds have not been used successfully for denitrification, but this might be possible. Denitrification is carried out by facultative, heterotrophic, anaerobic bacteria that reduce nitrates to N₂, N₂O, and NO. Before this can be done the nitrogenous material must first be converted aerobically to nitrates. The level of dissolved oxygen should be near zero when reduction takes place. As the pH value of a pond rises during high light intensity, significant quantities of ammonia may be liberated from the pond surface; where significant anaerobic lysis is operating, breakdown protein residues are directly

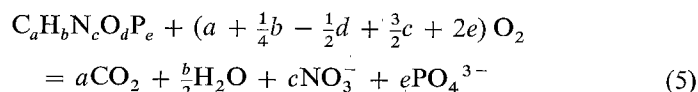
converted to ammonia, nitrogen gas may be released, and the conversion of ammonia into protein in newly synthesized algal cells may provide a useful path for further denitrification.

Anaerobic reduction

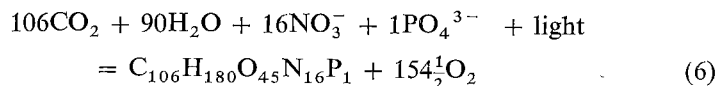
The residual products remaining after anaerobic decomposition will diffuse into the upper liquid of a waste stabilization pond, so increasing the oxygen demand. This factor is sometimes overlooked in the design and operation of waste stabilization ponds. The settleable solids will eventually undergo anaerobic decomposition and thus create a BOD in the upper, aerobic sections of the pond. The total oxygen requirement for the aerobic zone will be the amount needed to stabilize the dissolved and suspended organic material together with that fraction of the settleable organic material that is resuspended.

Stoichiometry of Algal and Bacterial Systems

A quantitative chemical relationship exists between the organic wastes treated and the micro-organisms produced. The decomposition of organic material by heterotrophic bacteria (decomposers) and the ingestion of organisms by animals (consumers) result in the return of soluble inorganic components to the water. This decomposition may be expressed by Equation 5:

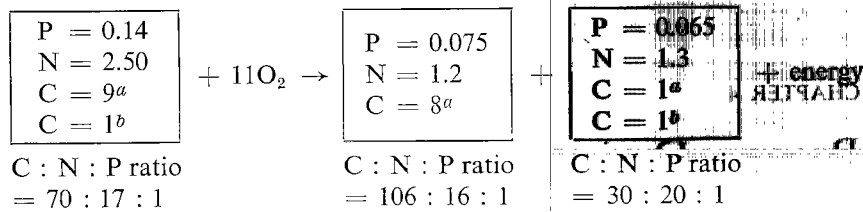


Conversely, the algae, acting as autotrophic organisms, produce organic material from inorganic substances. The reconstitution of simple materials to cellular substance might be represented by Equation 6:

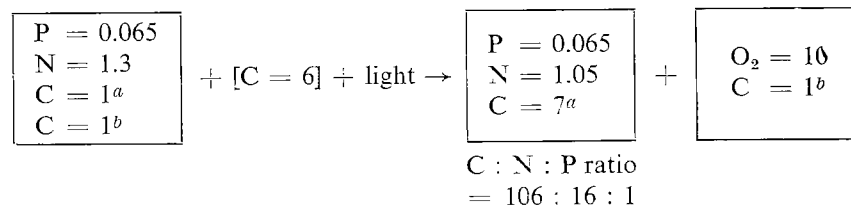


As shown in Equations 7 and 8, the effluent from a conventional wastewater treatment plant contains about 50 % of the phosphorus and nitrogen initially present in the raw waste-water, as well as significant amounts of carbon dioxide. The exact amount will depend on the design and operation of the biological treatment plant. These ingredients, together with the trace elements normally present in domestic effluents, constitute a suitable nutrient for the development of algal growths. Equation 7 depicts the available nutrients in a maturation pond following a conventional biological treatment plant. The data in Equations 7 and 8 are expressed in mmol per litre and are fairly typical of domestic waste-waters in the USA (Stumm & Morgan, 1963).

Untreated waste-water + oxygen \rightarrow bacterial sludge + treated effluent (7)

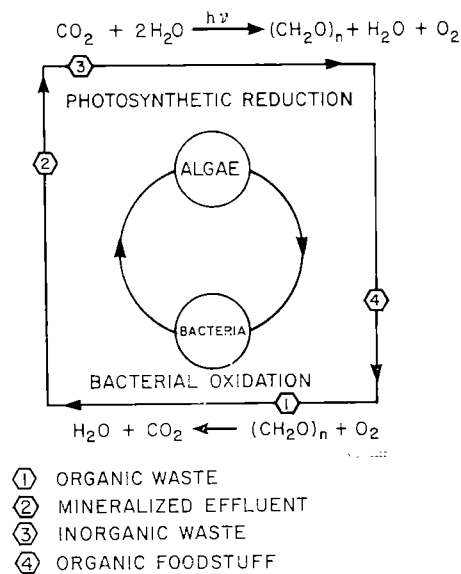


Treated effluent + carbon dioxide $\xrightarrow{\text{light}}$ algal mass + oxygen (8)



The algae-bacteria relationship found in a pond is shown in simplified form in Fig. 8. These two groups of micro-organisms may live with one another effectively; they are not parasitic to each other.

FIG. 8. SIMPLIFIED DIAGRAM OF ALGAE-BACTERIA COMMENSALISM-CARBON CYCLE



^a Assimilable carbon.

^b Non-assimilable carbon.

Process Design Procedures

Previous chapters of this monograph have provided essential background information on the needs of waste-water management, the history of waste stabilization pond development, and biological treatment. This and the following chapters are concerned with the design and operation of ponds in relation to BOD removal, disease transmission control, physical facilities, and operation and maintenance needs. The examples provided in these chapters are intended as guides: as in the design of any waste-water treatment plant, the engineer's judgement must play a leading part in the overall planning process.

This chapter deals with the establishment of the physical size of various types of individual waste stabilization ponds on the basis of recognized concepts of biological degradation. Although the main emphasis in this monograph is on facultative ponds, attention is also directed to the design of anaerobic and maturation ponds. Some mention is made of the pretreatment of wastes by aqua privies because of their possible use in low-income housing developments. Finally, a brief account is given of the use of mechanically aerated waste stabilization ponds as a pretreatment measure, followed by facultative ponds; where waste discharges are large, the combination of these two types of pond may be a realistic method of waste-water treatment.

The design engineer may wish to use the examples presented in this chapter for establishing base-line comparisons or to use a particular example to develop a complete design. Where climatic conditions and local customs are known to be similar to those applying to a particular example given below, that example should be used. Where basic data are not available, however, the designer should compare the various alternatives and select the design with the largest pond volume or the longest detention time. Equations, graphs and specimen calculations are provided for the engineer's use.

Predesign Considerations

Before a design for a specific installation is attempted, it is necessary to obtain as much background information concerning the problem as

possible. Where low-cost waste treatment plants are contemplated, most of the basic data will not normally be available and sound engineering judgement will be needed. Where there are no records, for example, the engineer may have to estimate the anticipated BOD load, the solids content, and the amount of waste-water, and even seasonal temperatures and solar radiation. The following list of data requirements may be useful; the items in parentheses are of particular significance.

Waste classification

Domestic (type, age, mode of delivery)
Industrial (type, age, mode of delivery)
Agricultural (type, age, mode of delivery)
Combination (type, age, mode of delivery, relative percentages)

Waste characteristics

Volume (minimum, average, maximum daily)
Concentration of organic materials (BOD_5 , BOD_u , COD)
Solids (special industrial wastes; total, settleable, suspended, dissolved, total volatile, and fixed solids)
Nutrient concentrations (nitrogen, phosphorus)
Colour materials (suspended, dissolved)
Toxicity (BOD reduction rates, bioassays, and specific aquatic micro-organisms)
pH (minimum, average, maximum)
Quality of tap water (mineral analyses)

Hydrology and meteorology

Evaporation (average, seasonal variations)
Rainfall (average, seasonal variations)
Air and water temperatures (average, seasonal average, average hottest month, average coldest month)
Groundwater (average depth, permeability of formation)
Percolation rates (preferably measured with waste to be treated)
Wind (strength and direction for time of day, seasonal average)
Cloud cover (percentage of daytime, season, and year)

Light

Solar radiation (minimum monthly, average annual, seasonal variations)

Topography

Soil characteristics (ease of excavation, embankment use, percolation, compaction)
Flood stages (high-water marks)
Availability of contour map
Location of houses, industries, agriculture
Streams (drainage of all types)

Regulations, public health data

Potential odour problems
Potential insect problems
Community data (local zoning restrictions, effluent and stream standards, ownership of lands, location of waterworks)
Health regulations (effluent and stream standards, coliform bacteria standards, special quality regulations for drinking-water and food processing, bathing water criteria, regulations on sea-food, freshwater fish)

Regulations of water resource authorities (stream and estuarine standards; effluent criteria; wildlife, recreation, fisheries regulations; and prior appropriated rights to waste-waters)

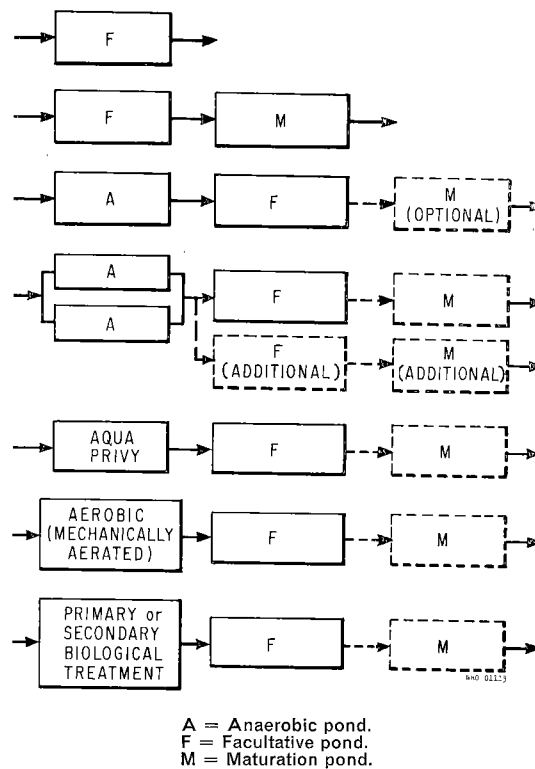
Use of effluent

Groundwater supplementation
Surface water supplementation
Immediate irrigation
Industrial re-use
Development of wildlife
Recreational use

Typical Pond Layouts

The waste stabilization pond system may comprise one pond only (facultative) or several types of pond in series (anaerobic, facultative, and maturation) (Fig. 9). In addition, it may be desirable to construct a number of series of the same type so as to permit parallel operation. For example, facultative or anaerobic ponds may be designed to operate

FIG. 9. A NUMBER OF TYPICAL WASTE STABILIZATION POND SYSTEMS



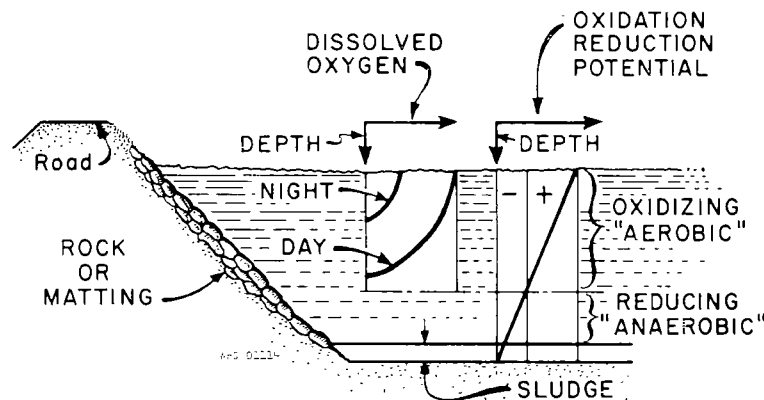
singly or in parallel. If a higher degree of treatment is desired, a maturation pond might be added beyond the facultative pond. Similarly, wastes from aqua privies may be further treated in facultative ponds. In some cases, mechanically aerated waste stabilization ponds may be used for preliminary aerobic treatment of biological wastes.

Facultative Ponds

Facultative waste stabilization ponds are those in which the upper layer is aerobic, the central area supports facultative bacteria, and the bottom sludge zone is truly anaerobic. At present most primary waste stabilization ponds treating raw waste-waters are of the facultative type. The settleable solids cause a layer of sludge or benthos to form on the bottom of the pond. In a facultative pond receiving raw waste-waters, the build-up of settleable solids is a function of temperature, but in all cases the degradable solids exert a major influence on the behaviour of the pond. Where a facultative pond follows an anaerobic pond the sludge layer is negligible. Similarly, the detritus in a maturation pond following a facultative pond consists principally of cell debris.

The facultative pond is oxygenated principally by the photosynthetic activity of algae under the influence of solar radiation, although in the larger ponds surface aeration by wind action contributes significantly to the total oxygen budget. The dissolved oxygen and the oxidation-reduction potential patterns of a typical facultative waste stabilization pond are indicated in Fig. 10. The dissolved oxygen concentration is greater during daylight periods than at night. The measurement of oxidation-reduction potential shows the tendency towards true aerobic or anaerobic conditions. The reducing environment will be found near the bottom, indicating true anaerobic conditions.

FIG. 10. A FACULTATIVE WASTE STABILIZATION POND



Because of sunlight absorption by the algal cells, effective light penetration may be less than 1 m; consequently, oxygen generation is frequently confined to the upper layer. If there is no mixing, gradients of dissolved oxygen develop, descending from a maximum at the surface of the pond to zero or near zero in the deeper sections. There is concomitant development of temperature gradients, which may effectively inhibit mixing of the pond contents by wind action.

Wind is usually the principal source of energy for mixing the water in facultative ponds, but a secondary cause of mixing that may be of significance in tropical areas when the wind velocity is low is differential heating. Mixing is an important physical parameter affecting the growth of algae, for many algae are non-motile and mixing is necessary to bring them into the zone of effective light penetration. Reduction of the duration of mixing during the usual diurnal cycle may lead to a reduction in the quantity of algae and a shift from one dominant species of algae to another. Moreover, mixing during daylight contributes to the distribution of dissolved oxygen.

Temperature is of great importance because it affects the rate of biochemical degradation. The average temperature, daily fluctuations, and yearly variations all influence the biological, physical, and chemical processes in the pond.

An empirical equation based on the kinetics of degradation of waste within a facultative pond was first presented by Hermann & Gloyna (1958); the idea was further developed by Marais & Shaw (1961), Marais (1966), Huang & Gloyna (1968), and Gloyna & Espino (1969).

Kinetic model of pond breakdown action

If it is assumed that all the influent BOD is stabilized by facultative organisms, that complete mixing occurs, and that breakdown takes place according to a first-order reaction, the effluent and influent BOD concentrations may be described by Equation 9. Although it provides a useful basis, this is an idealized equation that does not take into account the difference between the biological breakdown rates of the soluble material and those of the settleable solids.

$$L_p = \frac{L_o}{K_T R_T + 1} \quad (9)$$

where

L_p = pond and effluent BOD_5 (mg/litre)

L_o = influent BOD_5 (mg/litre)

K_T = breakdown rate at temperature T

R_T = detention time at temperature T

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

$$\frac{K_{35}}{K_T} = \theta^{(35-T)} \quad (10)$$

where

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

θ = temperature reaction coefficient = 1.085

and K_{35} = breakdown rate at 35°C

For a fixed percentage reduction of BOD, the symmetry of K_T and R_T in Equation 9 permits Equation 10 to be expanded as follows:

$$\frac{K_{35}}{K_T} = \theta^{(35-T)} = \frac{R_T}{R_{35}} \quad (11)$$

where

R_{35} = detention time at 35°C

Data obtained by Suwannakarn & Gloyna (1964) from a series of laboratory-scale ponds treating a synthetic non-settling waste at a number of different temperatures were analysed by Marais (1966), who obtained values for K_{35} and θ of 1.2 and 1.085 respectively. Extensive laboratory and field studies (Hermann & Gloyna, 1958) have shown that certain beneficial green algae cease to function effectively at water temperatures in excess of 35°C . Using Equation 9 and a measured value for K_{35} , therefore, the detention time for any percentage reduction at 35°C can be determined. At any other temperature (T), the detention time (R_T) for the same percentage reduction can be determined by using Equation 11.

The correlation between Suwannakarn & Gloyna's experimental BOD_5 data and theoretical values is shown in Fig. 11. These data verify the mathematical model under idealized conditions of waste composition, temperature, and mixing.

The projected efficiency of a facultative pond might be established by tabulating various values of K_T , R_T and T . Table 16 provides values of K_T for different temperatures, assuming the reaction rates remain constant.

TABLE 16
VALUES OF K_T *

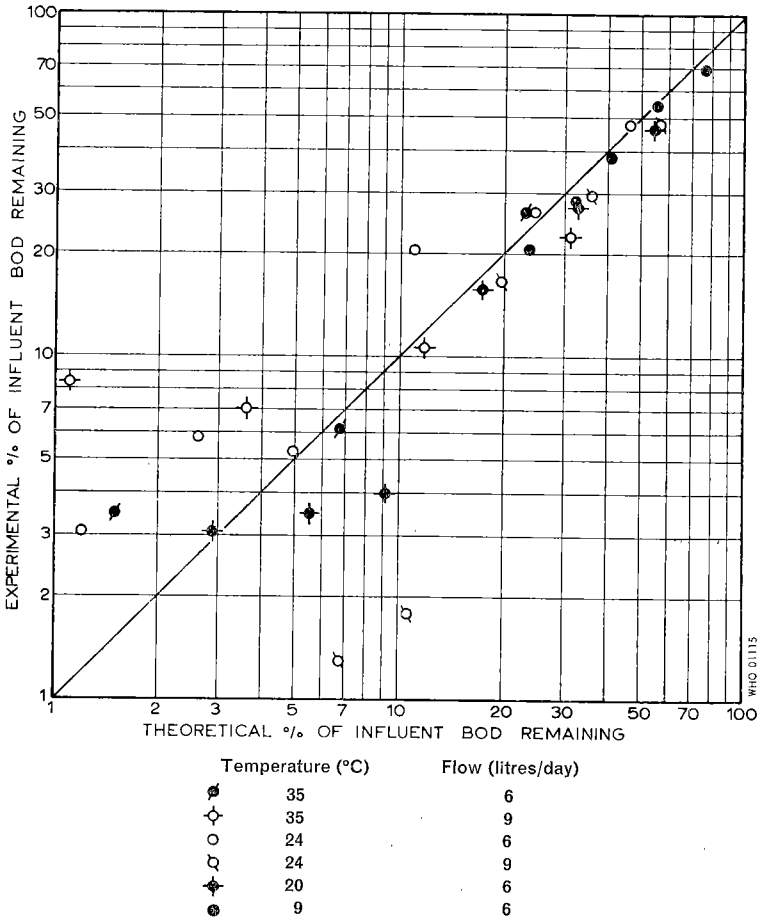
Temperature ($^{\circ}\text{C}$)	5	10	15	20	25	30	35
K_T per day	0.103	0.12	0.24	0.35	0.53	0.80	1.2

* After I. Duarte (personal communication, 1968).

On the basis of Equation 9, the BOD removal efficiencies can be calculated for various values of R_T and K_T :

Removal (%) = $\left(\frac{L_o - L_p}{L_o}\right) 100 =$
 $\left(1 - \frac{1}{K_T R_T + 1}\right) 100 = \left(\frac{R_T}{\frac{1}{K_T} + R_T}\right) 100$ (12)

FIG. 11. BOD REMOVAL IN LABORATORY-SCALE SERIES OF OXIDATION PONDS: CORRELATION OF EXPERIMENTAL AND THEORETICAL RESULTS



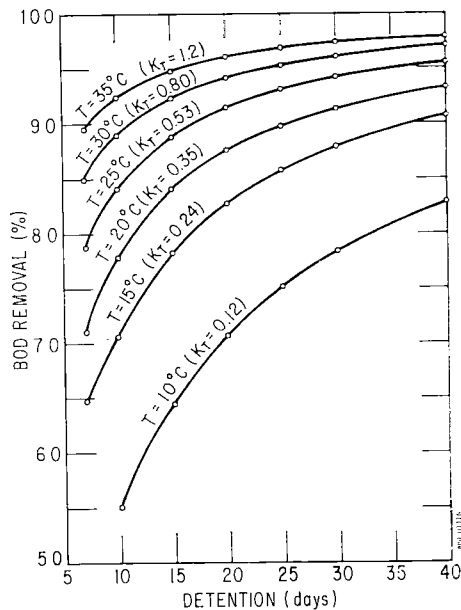
From Marais (1966), based on experimental data obtained by Suwannakarn & Gloyna (1964).

In Fig. 12, idealized removal efficiencies are plotted against various detention periods. While this graph does not provide all the information required to design a pond, it does demonstrate the important relationship between temperature and detention time.

It is evident, however, that the equations suggested above may fail to describe the effects produced by settleable solids. For example, they do

not take into account the influence of soluble BOD released from the sludge layers and the toxicity effects exhibited by certain industrial wastes (Gloyna & Espino, 1969; Huang & Gloyna, 1968).

FIG. 12. IDEALIZED BOD₅ REMOVAL RATES IN FACULTATIVE PONDS



Data from I. Duarte (personal communication, 1968).

Design methods

The actual design of a facultative pond depends on a great variety of local conditions, but a number of useful and rational design procedures are available. Four such procedures are described in this section. They are based on (1) load per unit area; (2) the empirical procedure; (3) South African practice; and (4) suggestions made by the Indian Central Public Health Engi-

neering Research Institute (CPHERI). Where little is known about the climatic conditions, the empirical procedure is recommended.

1. Load per unit area procedure

Experience has shown that certain generalizations can be made concerning the acceptable organic load of a facultative waste stabilization pond. Table 17 shows BOD loading values that have been used successfully in various geographical areas, but obviously great care must be exercised in using these values for design purposes.

Unpleasant odours may occur as a result of extremes in seasonal temperatures, inadequate surface area, uneven distribution of settleable solids, or inadequate liquid depth (Fisher et al., 1968; Horn, 1965; Svore, 1968). The distribution of settleable solids can be improved through the use of multiple inlets and deeper ponds (1.5–2 m). Maintenance of liquid depth depends principally on the control of seepage and evaporation. Understandably the operation of the entire pond system is dependent on the volumetric loading, BOD loading per unit area, and the concentration of

organic matter in the waste-water. Where the water content is low it may be difficult to maintain sufficient liquid over the settled solids. In this case, water must be added or the pond should be designed to function without any overflow.

TABLE 17
GENERALIZED BOD LOADING PER UNIT AREA PER DAY UNDER
VARIOUS CLIMATIC CONDITIONS

Surface loading (kg BOD ₅ /ha per day) ^a	Population per ha ^b	Detention time (days) ^c	Environmental conditions
Less than 10	Less than 200	More than 200	Frigid zones, with seasonal ice cover, uniformly low water temperatures and variable cloud cover
10- 50	200-1000	200-100	Cold seasonal climate, with seasonal ice cover and temperate summer temperatures for short season
50-150	1000-3000	100- 33	Temperate to semi-tropical, occasional ice cover, no prolonged cloud cover
150-350	3000-7000	33- 17	Tropical, uniformly distributed sunshine and temperature, and no seasonal cloud cover

^a These estimates are based on the assumption that the effluent volume is equal to the influent volume, i.e., the sum of the evaporative and seepage losses is not greater than rainfall.

^b Assuming a contribution of 50 g BOD₅ per person per day in developing areas.

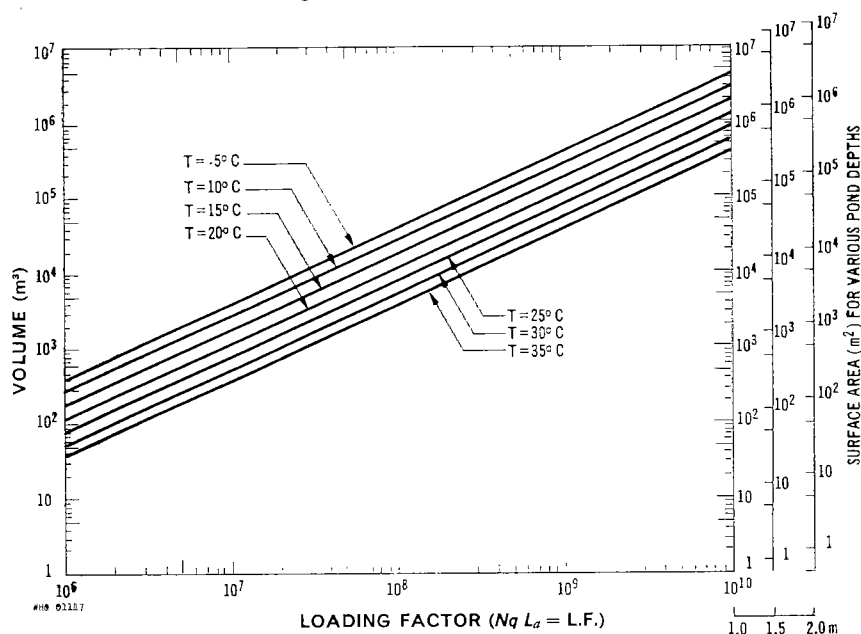
^c Based on an influent volume of 100 litres of waste per person per day.

2. Empirical procedure

After observing the results of many small laboratory ponds, larger pilot plants, and over 200 operating ponds, the author of this monograph and his collaborators have developed formulations that can be used to relate pond volume to temperature, BOD, influent volume and toxicity. The first of these equations, in which the estimated BOD removal efficiency is 85–95 %, was published by Hermann & Gloyna (1958).

The required volume of a facultative pond can be estimated with the aid of Fig. 13. A loading factor (L.F.) is computed by multiplying the number of persons contributing waste (N) by the product of the *per caput* contribution in litres per day (q) and the BOD (L_a). (BOD₅ should be used for weak or presettled waste-waters, BOD_u for strong or untreated waste-waters.) Field observations have shown that if the average water temperature of the coldest month of the year is known and cloud cover does not last for more than a few days at a time, a reasonably accurate design can be developed from this graph. A vertical line is drawn from the calculated loading factor to the selected temperature; the required volume in m³ can then be read off on the left ordinate, and the required surface area on the right ordinate. Recommended depths are considered later (Table 19).

FIG. 13. GRAPH FOR CALCULATING THE REQUIRED VOLUME AND SURFACE AREA OF A FACULTATIVE POND *



* Pond depth ≥ 1 m. Influent volume must be sufficient to maintain liquid depth.
 T = average water temperature of coldest month ($^{\circ}\text{C}$)

Light intensity, wind, total dissolved solids, and a host of other factors may influence the required pond volume, but where the waste-water is domestic sewage temperature is usually the most important single consideration (Suwannakarn & Gloyna, 1964). The basis of Fig. 13 is:

$$V = (3.5 \times 10^{-5}) NqL_a \theta^{(35 - T_m)} \quad (13)$$

where

- V = pond volume (m^3)
- N = number of people contributing waste
- q = *per caput* waste contribution (litres/day)
- θ = temperature reaction coefficient = 1.085
- T_m = average water temperature of coldest month ($^{\circ}\text{C}$)

The volume and surface area must be increased for wastes containing more than 500 mg/litre of sulfate ion (Gloyna & Espino, 1969). Similarly, a larger volume is required for some industrial wastes because they are not readily biodegradable, because they are toxic to the algae, or because they reduce the chlorophyll content (Huang & Gloyna, 1968; Thirumurthi & Gloyna, 1965).

If specific *per caput* contributions of BOD and waste volume are assumed, Fig. 13 may be used for other purposes. For example, a new graph can be drawn to show the permissible population contributions to a given pond under different temperature conditions. If the following assumptions are made:

$$\begin{aligned}\text{Area} &= 1 \text{ ha} \\ \text{Depth} &= 1.5 \text{ m} \\ \text{BOD}_u(L_a) &= 300 \text{ mg/litre} \\ \text{Waste volume } (q) &= 100 \text{ litres per caput per day}\end{aligned}$$

the loading factor can be obtained from Fig. 13 and the population per ha can be calculated by solving for N (Table 18).

TABLE 18
SPECIMEN DATA FOR CALCULATING
PERMISSIBLE WASTE DISCHARGES INTO
FACULTATIVE PONDS, BASED ON FIG. 13

Loading factor (L.F.) = NqL_a	T_m (°C)	$N = \frac{L.F.}{qL_a}$
4×10^7	5	1.3×10^3
6×10^7	10	2×10^3
9×10^7	15	3×10^3
1.5×10^8	20	5×10^3
2×10^8	25	6.7×10^3
3×10^8	30	1×10^4
4.2×10^8	35	1.4×10^4

It is difficult to write a generalized equation that describes the influence of light intensities, but this factor must be considered. Surface area must be increased where prolonged cloudy weather is known to occur. The use of an anaerobic pretreatment unit might be advisable where complete cloud cover may persist for periods of two or more weeks.

Values for insolation are not included in the empirical design equation, but a correction factor for this may be applied, since insolation and even temperature are usually related to the degree of latitude. For probable values of insolation at various latitudes, the reader is referred to Table 27 (Annex 2).

One reason why no precise figures can be given for light and depth relationships is that wind and temperature gradients help to mix the contents of ponds. As a result of this mixing the algal mass, above the thermocline at least, is exposed to usable light.

The appropriate pond depth is determined by environmental conditions, by the type of waste to be treated, and by the general safety factors desired.

When the required volume has been estimated in accordance with Equation 13, the depth is selected with the aid of Table 19. If the pond is too shallow (less than 1 m), emergent vegetation may destroy it and unpleasant odours may develop during the hot season. Depths in excess of 1.5 m are for sludge storage or excess capacity during cold weather.

TABLE 19
RECOMMENDED DEPTHS OF FACULTATIVE PONDS IN RELATION TO ENVIRONMENTAL CONDITIONS AND TYPE OF WASTE

Recommended depth (m)	Environmental conditions and type of waste
1.0	Uniform warm temperature; presettled waste-water
1.0 - 1.5	Uniform warm temperature; untreated waste-water
1.5 - 2.0	Moderate seasonal temperature fluctuations; raw waste-water containing settleable solids
2.0 - 3.0	Wide seasonal temperature variations; large amounts of settleable grit or settleable solids

Specimen calculations of pond design using the Gloyna procedure are shown below. Alternative solutions are provided to show the influence of temperature.

Given

A locality where the waste-water consists mainly of domestic wastes

Influent BOD_5 , 20°C	250 mg/litre
Influent BOD_u (L_a)	300 mg/litre (3×10^{-4} kg/litre)
Population contributing waste (N)	20 000
Contribution <i>per caput</i> (q)	150 litres/day
Flow (Nq)	3 000 m ³ /day (3×10^6 litres/day)
Average water temperature of coldest month (T_m)	10°C
Temperature coefficient (θ)	1.085
Percolation rate	negligible
Evaporation	= rainfall
SO_4^{--}	less than 500 mg/litre
Industrial toxicity	negligible

Required

Calculations showing (a) organic load; (b) volume; (c) depth; (d) surface area; (e) detention time; and (f) surface loading.

Solution

$$\begin{aligned}
 \text{(a) Organic load} &= BOD_u \times Nq \\
 &= 3 \times 10^{-4} \times 3 \times 10^6 \\
 &= 900 \text{ kg } BOD_u/\text{day}
 \end{aligned}$$

$$\begin{aligned}
 (b) \text{ Volume (Equation 13)} &= (3.5 \times 10^{-5}) NqLa\theta^{(35-T_m)} \\
 &= 3.5 \times 10^{-5} \times 3 \times 10^6 \times 300 \times 1.085^{(35-10)} \\
 &= 2.4 \times 10^5 \text{ m}^3 \text{ (} 0.7 \times 10^5 \text{ m}^3 \text{)}^a \\
 (c) \text{ Depth} &= 1.75 \text{ m}^b \\
 (d) \text{ Surface area} &= \frac{\text{volume}}{\text{depth}} \\
 &= \frac{2.4 \times 10^5}{1.75} \\
 &= 1.4 \times 10^5 \text{ m}^2 = 14 \text{ ha (} 4.1 \times 10^4 \text{ m}^2 = 4.1 \text{ ha)}^a \\
 (e) \text{ Detention time} &= \frac{\text{volume}}{\text{flow per day}} \\
 &= \frac{2.4 \times 10^5}{3000} \\
 &= 80 \text{ days (24 days)}^a \\
 (f) \text{ Surface loading} &= \frac{\text{organic load}}{\text{surface area}} = \frac{900}{14} \\
 &= 65 \text{ kg BOD}_u/\text{ha per day (222 kg BOD}_u/\text{ha per day)}^a
 \end{aligned}$$

3. South African procedure

While developing criteria for the design of facultative ponds in southern and central Africa, Marais & Shaw (1961) noted that (a) with low wastewater flow and a large surface area *per caput*, the pond did not attain the required liquid depth on account of losses through seepage and evaporation; (b) the effluent BOD remained substantially constant irrespective of the seasonal variations in temperature; (c) BOD loadings per unit area could be increased above those frequently reported in the literature; and (d) anaerobic conditions developed in the summer, while during the winter the ponds appeared to operate satisfactorily.

In South Africa the maximum BOD load for a facultative pond was initially related to the depth:

$$L_p = \frac{1\,000}{(0.18\,d + 8)} \quad (14)$$

where

$$d = \text{depth (m)}$$

Marais & Shaw later reduced the dividend in this equation from 1000 to 750. On the basis of a study of the long-term behaviour of the ponds, Shaw, Meiring & van Eck (1962) reduced this value still further to 600, so that Equation 14 is now written as follows:

^a The solutions in parentheses are for the case where $T = 25^\circ\text{C}$. It should be noted that uniformly warm climates assist in reducing the size of the facultative pond. If the solids content is relatively high, anaerobic pretreatment is required. Provided that climatic conditions are uniform, that sunlight is uniform and intense, that evaporation and seepage are equal to rainfall, and that the solids-to-liquid ratio is low, the depth of the pond could be reduced to 1 m.

^b Assuming specific climatic conditions and type of waste (see Table 19).

$$L_p = \frac{600}{(0.18 d + 8)} \quad (15)$$

Field data indicated that the effluent BOD could be formulated in terms of Equation 16. By setting the value of K_T in Equation 9 at 0.17, it is possible to estimate the BOD in the effluent (L_p) if the initial BOD (L_o) and the detention time (R_T) are known. Similarly, it is possible to determine R_T if both L_p and L_o are known.

$$L_p = \frac{L_o}{0.17 R_T + 1} \quad (16)$$

The effluent BOD₅ from a pond with a depth of 2 m and designed in accordance with Equations 15 and 16 will be approximately 60 mg/litre. If this level is not acceptable, additional treatment in secondary and tertiary ponds may be required. These extra ponds should be designed so as to provide a detention time of 7 days or more per pond. Field experience has shown that the effluent BOD₅ from the series-connected ponds should not exceed 20 mg/litre. On no account should the total area of series-connected ponds be averaged to obtain the acceptable BOD load for the first pond.

A specimen calculation of facultative pond design using the South African procedure is given below. This example may be particularly applicable for subtropical areas and domestic wastes containing a high solids-to-water ratio.

Given

A domestic waste-water:
 BOD₅(L_o) = 250 mg/litre (2.5×10^{-4} kg/litre)
 BOD_u(L_a) = 300 mg/litre (3×10^{-4} kg/litre)
 Flow = 3 000 m³/day (3×10^6 litres/day)

Required

Calculations showing (a) expected effluent BOD₅ concentration, (b) detention time, (c) surface area, and (d) surface loading.

Solution

(a) On the basis of Equation 15 and assuming a depth of 1.75 m, the effluent BOD₅ (L_p) is:

$$\begin{aligned} & \frac{600}{0.18 d + 8} \\ &= \frac{600}{(0.18)(1.75) + 8} = 72 \text{ mg/litre} \end{aligned}$$

(b) On the basis of Equation 9, the detention time (R_T) = $\left(\frac{L_o}{L_p} - 1 \right) \frac{1}{K_T}$

$$= \left(\frac{250}{72} - 1 \right) \frac{1}{0.17} = 14.5 \text{ days}$$

$$\begin{aligned}
 \text{(c) Surface area} &= \frac{\text{volume}}{\text{depth}} \\
 &= \frac{\text{flow} \times \text{detention time}}{\text{depth}} \\
 &= \frac{3\,000 \times 14.5}{1.75} = 25\,000 \text{ m}^2 \\
 &= 2.5 \text{ ha} \\
 \text{(d) Surface loading} &= \frac{\text{organic load}}{\text{area}} \\
 &= \frac{\text{BOD} \times \text{flow}}{\text{area}} \\
 &= \frac{2.5 \times 10^{-4} \times 3 \times 10^6}{2.5} \\
 &= 300 \text{ kg BOD}_5/\text{ha per day}
 \end{aligned}$$

If these results are compared with those obtained by the empirical procedure, it can be seen that there is considerable uniformity. In both cases, the settleable solids must never be exposed to the air and sunshine. There must be adequate liquid present to fill the ponds and ensure satisfactory operation, otherwise alternative pretreatment is required.

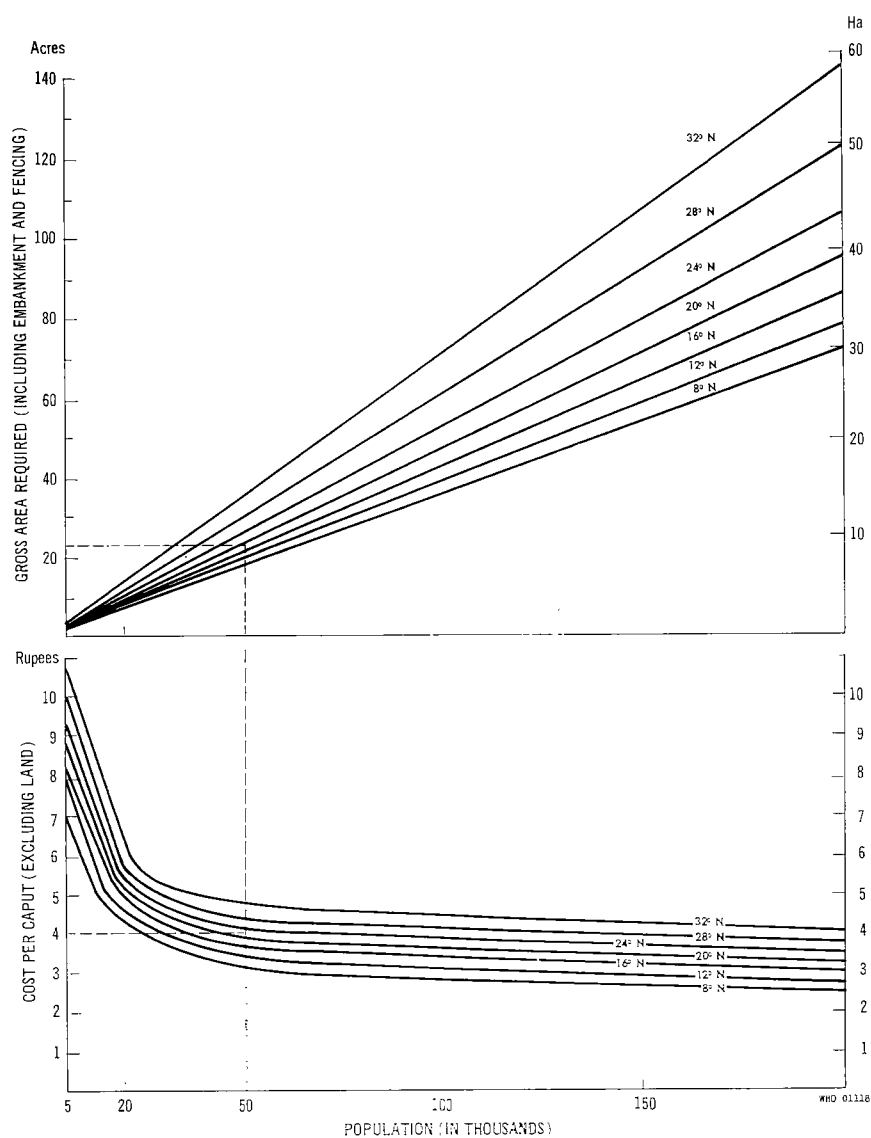
4. *Procedure based on suggestions by the Central Public Health Engineering Research Institute (CPHERI), India*

In tropical India, the design of facultative waste stabilization ponds for domestic waste-waters has been based on a loading of 336 kg BOD₅/ha per day and an operating depth of 1.22 m (Dave & Jain, 1967). A study of 8 ponds has shown a BOD reduction for this loading of 70–85 %. It is noteworthy that this organic loading is considered unattainable in many geographical areas, even though summer temperature conditions approach those found in India. In some cases, moreover, BOD removals in excess of 70–85 % are required. To increase the BOD removal to 90 % usually requires a significant increase in detention time. The average sludge build-up appears to be as little as 2–4 cm per year; this low value may be associated with the uniform and relatively high temperatures. Nevertheless, Indian practice suggests that it is desirable to have 2 ponds wherever possible to facilitate servicing, cleaning, etc.

CPHERI prefers the multi-cell pond system (parallel units) when the flow exceeds 2 250 000 litres/day. This use of small ponds contrasts with experiences in the USA and South America, where wind action on larger ponds has helped to maintain desirable conditions.

Another design has been suggested by Arceivala & Desai (personal communication, 1968). In Fig. 14, population is plotted against gross pond area and against cost for various latitudes. This graph takes into account such

FIG. 14. REQUIRED AREA AND COST OF PONDS FOR DIFFERENT POPULATIONS
AT VARIOUS LATITUDES, INDIA, 1969*



* Reproduced, in modified form, from Arceivala et al. (1969) by permission of the publishers.

* Exchange rate (1969): US \$ 1.— = Rs 7.50.

Example: For a population of 50 000 located at 20° N, the chart shows the cost of pond construction to be Rs 4.— per caput, and the gross land requirement to be 23.10 acres. If the cost of land is Rs 8 000 per acre, the total pond cost will be:
 $\text{Rs } 4.— \times 50\,000 + 8\,000 \times 23.1 = \text{Rs } 384\,800.$

factors as oxygen production, conversion of solar energy, and temperature. It is understood that these two approaches to pond design provide reasonably similar results.

Calculations for the design of a facultative pond, using the procedure suggested by CIPHERI, are shown below:

Given

Population	= 10 000 persons
Water supply	= 227 litres <i>per caput</i> per day
Waste-water flow	= 1.82×10^6 litres/day (80 % of water supply)
Influent BOD ₅	= 300 mg/litre
Suspended solids	= 300 mg/litre
Width-to-length ratio	= 1 : 2
Operational depth	= 1.22 m
Organic loading per hectare	= 336 kg BOD ₅ /ha per day

Required

Calculations showing (a) total organic load and (b) surface area.

Solution

(a) Total organic load	= flow \times influent BOD ₅
	= $1.82 \times 10^6 \times 300$ mg/day
	= 546 kg/day
(b) Surface area	= $\frac{\text{total organic load}}{\text{organic load per ha}}$
	= $\frac{546}{336}$ = 1.63 ha

Shape and depth of facultative ponds

The length-to-width ratio of the ponds may vary from 1 : 1 to 2 : 1. Fluctuations in seasonal temperatures will make deeper ponds necessary. The findings of Svore (1968) and Oswald (1968) and observations of ponds in Texas, USA, show that ponds only 75 cm deep do not provide the best stabilization. Because of their shallowness, the ponds may attain high temperatures during the day and this may adversely affect algal growth. Moreover, the sludge layer in shallow ponds may rise or turn septic and cause bad odours. Oswald (1968) reported that odours occurred when the liquid depth was 60 cm, but not when the depth was increased to 2 m.

Sludge layer

The rate of gas evolution from the sludge layer is a sensitive measure of the biological activity in the bottom layers of a facultative pond. In Fig. 15 the gas evolution from digesting sludge is plotted against temperature. There is approximately a fourfold increase in gas evolution for every 5°C

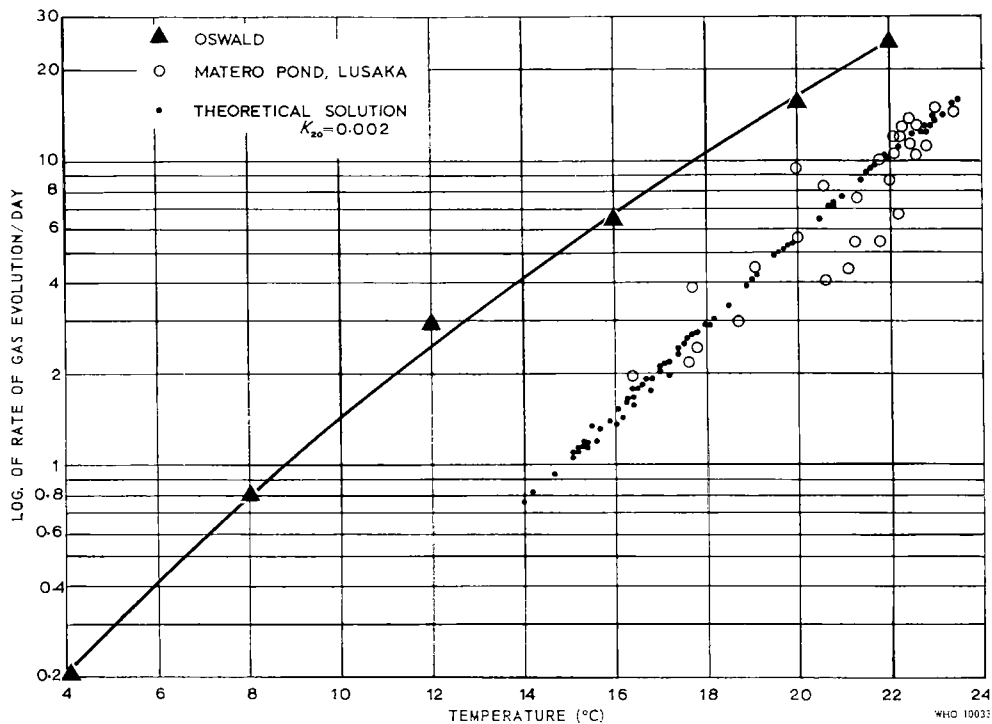
rise in temperature between 4° and 22°C. The digestion rate can be estimated with the aid of Equation 17 (G. v. R. Marais—personal communication, 1968):

$$K_{s(T)} = 0.002 (1.35)^{-(20-T)} \quad (17)$$

where

$K_{s(T)}$ = digestion rate (rate of evolution from the sludge layer)

FIG. 15. EXPERIMENTAL AND THEORETICAL RELATIONSHIPS BETWEEN TEMPERATURE AND GAS EVOLUTION PER DAY FROM SLUDGE LAYER IN A PRIMARY OXIDATION POND *



Reproduced from Marais (1966).

* It will be noted that the points representing the theoretical solution do not lie on a smooth curve. This is because two points at the same temperature may relate to different parts of the yearly temperature cycle; owing to the change in the volume of sludge in the time interval, the amounts of gas evolved are not identical.

The influence of the sludge layer on the pond can be described as follows. During the early life of a primary facultative pond receiving settleable solids, a portion of the observed reduction of BOD in the pond is due to the settlement of organic material as sludge. Anaerobic fermentation develops in the sludge, reducing its organic load but releasing fermentation products to the pond liquid. Under uniform conditions of deposition and

temperature the volume of sludge will increase, releasing correspondingly greater quantities of fermentation products, until a state of equilibrium is reached in which the BOD added to the sludge by new deposits is equal to the BOD released as fermentation products.

During the cold season, little breakdown takes place in the sludge and the pond bottom becomes primarily a sludge storage area. During the hot season, the fermentation products from the sludge add to the BOD in the pond liquid. Eventually a condition is attained where there is an annual cyclic variation in sludge volume, high in the winter and low in the summer. During the summer the increased feedback of fermentation products from the sludge to the pond liquid may exceed the reoxygenation capacity of the pond and turn it anaerobic. This is particularly serious if the warmer temperatures coincide with cloud cover that reduces solar radiation.

In the tropics and subtropics, high BOD surface loading rates can be utilized. If water consumption *per caput* is low, however, the sludge will occupy a greater proportion of the pond volume and its influence may become a dominant factor in design.

Mixing

Several factors are usually responsible for the mixing patterns that develop in facultative ponds. Wind and heat are probably the most important. Mixing by wind energy depends on the surface area of the pond. The maximum effect of the wind can be obtained when there is an unobstructed wind path of 100–200 m. Thus, smaller ponds are more likely to remain stratified than larger ones.

The effect of mixing on pond behaviour is profound. Mixing during daylight hours distributes the temperature and oxygen uniformly throughout the body of the pond, thereby inducing aerobic conditions throughout the pond depth. Mixing also transports non-motile algae into the region where usable light energy is available. During long periods of stratification, the non-motile species gradually settle on the sludge layer, resulting in a marked decrease in the algal concentration in the liquid. Only motile forms survive in any number, and this may be why the motile *Euglena* is sometimes dominant. It has been observed in several countries that ponds may be green in the morning because the *Euglena* algae are near the surface, but turn grey as the day progresses because the algae move out of the intensely sunlit and heated top layers. Typically, the motile algae may form a dense layer a few centimetres thick above the thermocline. The thermocline is the layer of water separating an upper warmer zone from a lower colder zone.

Data on thermal mixing have been obtained in several localities (Fisher & Gloyna, 1963; Marais, 1966).

Typically, during the morning, if there is any wind, there is a period of complete mixing in which the temperature is uniform throughout the pond but, owing to the absorption of radiation, [the temperature] gradually increases. At some time, usually

during a short lull in the wind, stratification develops abruptly and a thermocline forms. The temperature above the thermocline increases to a maximum and then decreases, while below the thermocline the temperature rapidly falls to a value approximately that of the earth and thereafter remains practically constant. . . .

In the afternoon and evening, a second period of mixing may be initiated as follows:

(a) Above the thermocline, under quiescent wind conditions, the top layers lose their heat more rapidly than the bottom layers. The cooler top layers sink, inducing mixing, with the result that the temperature down to the thermocline remains approximately uniform but gradually decreases. The thermocline gradually sinks and, . . . with further cooling, mixing [may be] initiated and sustained throughout the pond.

(b) Under windy conditions, usually during the period of decreasing temperatures, the energy imparted by the wind to the water above the thermocline at some stage overcomes the stratification forces, [causing the temperature to be uniform throughout].

It is possible that during summer, when the wind speeds are low, cooling by radiation is not sufficient to equalize the temperatures throughout the pond and the thermocline persists.¹

In some semi-tropical areas, therefore, the thermocline may oscillate daily, but on the average it is less pronounced during the summer than during the winter.

Anaerobic Ponds

Anaerobic pretreatment of untreated domestic waste-waters significantly affects the behaviour of the primary facultative waste stabilization pond. It reduces the BOD load on the facultative pond and changes the nature of the settleable solids in the sludge layer. The sludge in a facultative pond that is preceded by an anaerobic pond has a reduced fermentation potential, so that little sludge rises during the hot season. Furthermore, the sludge is of a granular consistency and tends to break up on rising to the surface. In contrast, extensive drifting sludge of a sticky consistency may form in facultative ponds receiving untreated domestic wastes.

The main disadvantage of anaerobic treatment is the possibility of uncontrolled odour development. Consequently, the proximity of anaerobic ponds to dwellings is a factor in design that must always be considered.

Anaerobic breakdown in septic tanks, aqua privies, and anaerobic ponds appears to be identical. The reduction of BOD is a function of the retention time of the solids (i.e., as compared to the detention time of the soluble fraction).

The establishment of stable fermentation conditions in an anaerobic unit may take a considerable time, depending on the temperature. In a subtropical area, with an average annual temperature of about 20°C, BOD measurements in 150 aqua privy tanks have shown that approximately 4 months must elapse before the tanks deliver a stable effluent (Marais, 1966). If the average temperature is lower, this may take considerably longer. An indication of the relationship between temperature and digestion is provided by Fig. 15.

¹ Marais (1966).

Design

Southern African practice

The results of experiments with septic and aqua privy tanks in the USA (Weibel et al., 1949) and in Zambia (Vincent et al., 1963) indicate that in tropical and subtropical regions the reduction in BOD can be approximated by Equation 18 (Vincent et al., 1963). An influent and pond temperature of 20°C is assumed.

$$L_p = \frac{L_o}{K_n \left(\frac{L_p}{L_o} \right)^n R + 1} \quad (18)$$

where

R = detention time for completely mixed system (days)

n = exponent, to be determined by experimentation (for Zambia, $n = 4.8$)

K_n = design coefficient

Often no data on the influent BOD are available and estimates of the influent BOD contribution and waste flow *per caput* must be based on past experience. Table 20 provides a rough estimation of the quantity of body wastes produced daily. For design purposes, total excreta may be taken to be about 1 kg per person per day (Wagner & Lanoix, 1958). Vincent et al. (1963) reported a daily BOD₅ contribution *per caput* of 0.036 kg in low-cost, high-density housing areas of Zambia; Van Eck (1965) reported 0.03 kg from similar areas in Durban, South Africa. In the USA a figure of 0.073 kg is used, and in other countries the level is probably about 0.05 kg.

TABLE 20
ESTIMATES OF THE QUANTITY OF HUMAN WASTES PRODUCED DAILY
IN VARIOUS PARTS OF THE WORLD

Geographical area	Wastes (in g per person per day)			Reference
	Human faeces (wet weight)	Urine	Urine and cleansing water	
World-wide summary	135-270	1000-1300		Gotaas, 1956
India	400		2300	
Tropics	280-530	600-1130		Macdonald, 1952
Philippines	665 ^a			Wagner & Lanoix, 1958
Asia	200-400			Wagner & Lanoix, 1958
European and American countries	100-150			Wagner & Lanoix, 1958

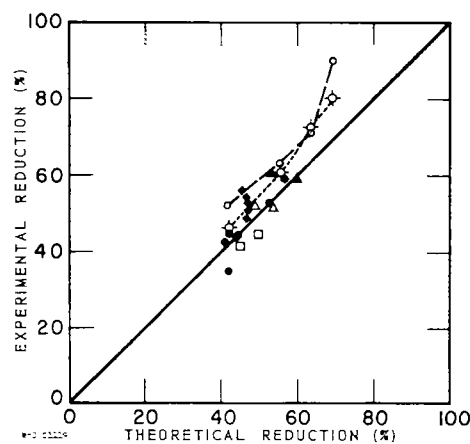
^a Including some urine.

It seems probable that domestic waste-waters in the developing areas have low *per caput* BOD values because very little garbage is disposed of through the sewer. An estimate of 0.05 kg BOD₅ *per caput* per day is probably on the high side but will serve as a safe estimate for developing countries. Effluent flow in these areas varies widely within a range of 20–150 litres per person per day. In developed industrial areas, the range may be many times greater than these levels. Usually an estimate can be based on the consumption of other communities in the area.

Correlation plots between observed BOD reduction and theoretical reduction calculated according to Equation 18 are shown in Fig. 16. Table 21 illustrates the relationship between theoretical BOD reduction and detention time under conditions typical of Zambia. Under such conditions there is little advantage in extending the detention time beyond one day. Normally 30–40 % BOD removal can be expected from sedimentation alone, although this settled organic matter would still have to undergo some form of biological breakdown.

The rate of breakdown decreases sharply with reduction in temperature, and fermentation is negligible at temperatures below about 15°C, when the anaerobic pond serves principally as a sedimentation tank (Oswald, 1968) and becomes in effect a sanitary landfill. Van Eck (1965) found no reduction of BOD in anaerobic ponds during the winter months when the temperature was below 10°C, reductions of 40–60 % at 20°C, and reductions exceeding 80 % at temperatures of 25°C and above. Parker et al. (1950) also observed that ponds in Melbourne, Australia, with liquid detention times during the summer of about 1.2 days gave BOD reductions of 65–80 % but that during the winter months, although the detention time was increased to 5–7 days, the BOD reduction dropped to 45–60 %.

FIG. 16. EXPERIMENTAL AND THEORETICAL REDUCTION OF BOD CONCENTRATION IN SEPTIC TANKS, AQUA PRIVIES AND ANAEROBIC PONDS



Reproduced, by permission, from Vincent et al. (1963), p. 160.

- ◆ ● Septic tank with single compartment
- △ Septic tank with 4 compartments: effluent from 4th
- ▲ Septic tank with 2 compartments: effluent from 2nd
- ◇ ○ Anaerobic ponds (4 in series)
- Aqua privy with single compartment

TABLE 21
THEORETICAL BOD REMOVAL
IN ANAEROBIC PONDS *

Detention time (days)	BOD remaining (%)	BOD reduction (%)
0.12	80	20
0.40	70	30
0.71	65	35
1.3	60	40
2.4	55	45
4.7	50	50
9.4	45	55

* Data based on Equation 18, taking $n = 4.8$ and $K_n = 6$ at 22°C.

Specimen calculations for the design of an anaerobic pond in a subtropical area are shown below:

Given

Population = 8 000
Influent BOD₅ (L_o) = 400 mg/litre
Effluent BOD₅ (L_p) = 240 mg/litre
 K_n = 6.0
 n = 4.8
Waste production = 70 litres *per caput per day*

Required

Recommendations showing (a) detention time, (b) pond volume, (c) pond area, (d) number and arrangement of anaerobic ponds, and (e) additional treatment.

Solution

(a) Detention time, R , based on Equation 18

$$L_p = \frac{L_o}{K_n \left(\frac{L_p}{L_o} \right)^n R + 1}$$

$$\text{or } R = \left(\frac{L_o}{L_p} - 1 \right) \left[\frac{1}{K_n \left(\frac{L_p}{L_o} \right)^n} \right]$$

$$= \left(\frac{400}{240} - 1 \right) \frac{1}{6 \left(\frac{240}{400} \right)^{4.8}} = 1.3 \text{ days}$$

- (b) Volume = days \times population \times waste *per caput*
 $= 5 \times 8\,000 \times 70 \text{ litres}$
 $= 2\,800 \text{ m}^3$
- (c) Area (assuming depth of 2 m) = $\frac{\text{volume}}{\text{depth}} = \frac{2\,800}{2} = 1\,400 \text{ m}^2$
 $= 0.14 \text{ ha}$
- (d) Number and arrangement of ponds = 2 in parallel
- (e) Additional treatment Can be provided by a facultative waste stabilization pond or a facultative pond connected in series with a maturation pond

The following specimen calculations relate to the design of an anaerobic pond to treat the effluent from a low-cost, high-density housing area:

Given

Population	= 8 000
Waste	= 70 litres <i>per caput</i> per day
Soil	= impermeable
Lowest monthly average temperature	= 10°C

Required

Calculations showing (a) pond volume, (b) pond area, and (c) effluent quality.

Solution

On account of the low temperature, a detention time of 5 days is used.

$$\begin{aligned}
 \text{(a) Volume} &= \text{days} \times \text{population} \times \text{waste per caput} \\
 &= 5 \times 8\,000 \times 70 \text{ litres} \\
 &= 2\,800 \text{ m}^3
 \end{aligned}$$

$$\begin{aligned}
 \text{(b) Area (assuming depth of 2.5 m)} &= \frac{\text{volume}}{\text{depth}} = \frac{2\,800}{2.5} = 1\,120 \text{ m}^2 \\
 &= 0.11 \text{ ha}
 \end{aligned}$$

(c) Effluent quality

Assuming that influent BOD *per caput* per day = 0.05 kg,

$$\begin{aligned}
 \text{influent BOD per litre} &= \frac{\text{BOD per caput per day}}{\text{wastes per caput per day}} \\
 &= \frac{0.05 \text{ kg}}{70 \text{ litres}} \\
 &= 714 \text{ mg per litre}
 \end{aligned}$$

Assuming 60 % BOD removal in winter due to sedimentation and some bio-degradation,

$$\text{BOD in effluent} = \frac{714 \times 60}{100} = 428 \text{ mg per litre}$$

Design guide-lines used in Israel

Designers in Israel systematically use anaerobic ponds for the pretreatment of domestic waste-waters (Amramy et al., 1962; Watson, 1962). More recently, studies have been completed on some deep ponds (Wachs & Berend, 1968).

The general guide-lines used by the Israel Ministry of Health are as follows (H. I. Shuval—personal communication, 1966):

Primary anaerobic pond: 125 kg BOD per 1 000 m³ per day;
 Secondary aerobic pond: 15–20 kg BOD per 1 000 m³ per day.

Pond depths are usually 1.2–1.5 m.

Design used by the Melbourne Water Science Institute, Australia

The ratio between the area of facultative and anaerobic ponds appears to be a significant design factor in Australia (Parker, 1962), where facultative: anaerobic ratios between 10 : 1 and 5 : 1 are found useful. Ponds with a

low ratio of 3 : 1 are sensitive to short-term changes in the BOD. The city of Melbourne uses a summer detention period of 1.25 days (1 120–2 240 kg BOD/ha per day) in the anaerobic ponds and 7.5 days in the facultative ponds. In winter the detention periods are increased almost fourfold. The BOD reduction is reported to be 65–80 % in summer and 45–65 % in winter. Detention in anaerobic ponds is not extended beyond 5 days because the ponds then act as facultative ponds. Sludge removal from the anaerobic ponds is necessary.

Type and location of anaerobic ponds

The type of anaerobic facility chosen depends upon the magnitude of the waste flow and the proximity of the ponds to dwellings. Open anaerobic ponds are indicated where the volume of waste-water is too great to be treated by septic tanks and where the pond system can be located at least 0.5–1 km from human habitation. In the tropics a liquid detention time of 1–5 days is recommended. Longer detention may cause the upper layers of the pond to become aerobic and reduce the obligate anaerobic conditions necessary for maximum efficiency. In temperate regions where the average monthly temperature during the winter is less than 10°C, the liquid detention time during the winter should be about 5 days, and the sludge retention time should be based on a digestion reaction rate at 15°C.

Grit banks

Where combined sewers for domestic wastes and storm run-off are used and where the wastes contain large amounts of sand and grit, it is necessary to remove these deposits periodically. To provide continuous treatment, therefore, anaerobic pond units should be built in duplicate. Where the installation consists of a number of parallel units, one additional pond must be provided so as to permit those in operation to be taken out of commission, one at a time, for desludging.

Inlets and outlets

Inlet and outlet designs for anaerobic ponds present problems. Combined sewer systems carrying both storm run-off and domestic wastes may carry a large amount of grit, so that an inlet at the bottom of the pond is not practical. Nevertheless, it is desirable to keep the inlet submerged because this will relieve the floatable solids problem: many solids that would otherwise float will stay submerged if introduced near the bottom of the pond or at least at mid-depth. For small anaerobic ponds less than 0.5 ha in area a single inlet is sufficient. Larger ponds require several inlets so as to spread the grit and sludge load.

Outlets may be of the surface type, but a scum board must be provided to prevent the discharge of drifting sludge.

Sludge mats

During the winter months when the fermentation rates are low, "mats" of sludge are likely to form on the surface of the pond; as a result, hydrogen sulfide odours may become a nuisance and fly-breeding in the drifting sludge is likely. During warm weather intense fermentation will break up the drifting sludge, the bottom sludge layers will decrease in thickness, and there will probably be no odours. Hydrogen sulfide production has been effectively stopped by recycling up to 40 % of the effluent from the secondary or tertiary ponds to the influent line (Van Eck, 1965). This solution has also been advocated by Abbott (1962) and Oswald (1968). Where the temperatures in the anaerobic ponds are above 20°C, the ponds normally remain free of floating sludge throughout the year. It has been noted that the BOD reduction increases as the sludge layer increases (Parker et al., 1950; Weibel et al., 1949).

Because open anaerobic ponds have a large exposed surface, heat loss is considerable and they are subject to large temperature fluctuations. In contrast, covered septic tanks tend to retain the temperature of the influent waste-water. Heat loss from the surface of open ponds can be reduced by increasing the depth and thereby increasing the detention time for the same surface area (Oswald, 1968; Wachs & Berend, 1968).

Enclosed anaerobic facilities

In some cases it is desirable to pretreat the wastes in enclosed anaerobic units such as septic tanks. These units are discussed below because of their close association with various waste stabilization pond systems. Details of design for enclosed systems have been provided by the African Housing Board, Lusaka (Vincent et al., 1963).

For communities of 1 000–10 000 people, where the anaerobic waste stabilization pond system is located near houses, anaerobic pretreatment may be accomplished more effectively in enclosed tanks. A pretreatment tank facility for a population of about 8 000 has been put into operation in the suburb of Chelston, Lusaka. There two tanks are operated in parallel so that one may be taken out of commission if the tanks need to be desludged manually. Desludging can also be carried out by vacuum tanker or, if sufficient fall is available, by the installation of a siphon. If a siphon is used, it is advisable to withdraw the sludge at frequent intervals to prevent the sludge and grit mixture from becoming densely compacted. Sludge accumulation at the draw-off point can be encouraged by constructing the tank with a conical or sloping bottom. In areas with high water tables the tank must be designed to resist the resulting upward pressures. The liquid detention time in these large tanks is approximately 18–24 hours. Sludge accumulation can be determined on the basis of approximately 0.03–0.05 m³ *per caput* per year.

For smaller communities (up to 1 000 people) rectangular pretreatment tanks are frequently provided, as these are usually easier to construct than circular ones. Sludge and grit are periodically removed by vacuum tanker or manual labour. In very small communities where vacuum tankers are available, single-chamber tanks may be installed. It is also desirable in such communities to increase the unit volume *per caput* of the tank so as to lengthen the interval between desludging. The tank is then designed on the basis of sludge accumulation, as shown in the following example:

Given

Sludge accumulation	0.03 m ³ per person per year
Population	200
Frequency of desludging	every 5 years

Required

Volume of tank

Solution

Desludging is normally necessary when the tank is half-filled with sludge, therefore the tank volume should be $200 \times 0.03 \times 5 \times 2 = 60 \text{ m}^3$.

Anaerobic pretreatment of domestic wastes in aqua privies serving individual houses before discharge to sewers and waste stabilization ponds has been widely applied in Zambia (Vincent et al., 1963), where sewer systems have been built in areas with very flat topography. To ensure velocities adequate for self-cleaning in sewers carrying raw waste and grit, the gradients must give a velocity at maximum flow of about 1 m per second. With level terrain, provision would normally have to be made for deep cuts or lift pumps. However, where anaerobic pretreatment is applied at each home or group of homes, the sand and grit are retained in the tank and the organic solids are digested. Consequently, sewers conveying this effluent can be laid at gradients giving a velocity of about 0.3 m per second at maximum flow. This means that the sewers can remain fairly close to the surface and cuts down the work of trench construction.

The sewer network for Bwacha suburb in Kabse, Zambia, has a maximum average slope over the housing area of 1 : 400 and a minimum gradient of 1 : 780. This gradient, which is over a small distance, provides a velocity of only 0.25 m per second. While this velocity is not recommended for normal design, the system has worked satisfactorily for 3 years.

When the main sewer carries anaerobically pretreated waste, no raw waste-water should be discharged into it even if the rate of flow in the sewer is sufficient for normal self-cleansing, because the mixing of oxygen in the raw waste with the anaerobic waste may cause corrosion. As a precautionary measure, sewers carrying pretreated effluents are sealed by heavy-duty manhole covers that prevent the public from gaining access to them.

Aerobic Ponds

Aerobic waste stabilization ponds have a place in the planning of low-cost waste-water treatment systems. The design of aerobic ponds may be based on three concepts: (a) minimum depth and maximum algae production; (b) equalization of BOD removal and pathogen control (maturation ponds); and (c) induced mechanical mixing or aeration, which may support aerobic bacterial activity without necessarily involving photosynthetic processes.

Minimum depth and maximum algal production

The high-rate aerobic waste stabilization ponds are still in the experimental phase of development. The purpose of these ponds is to convert as much carbon dioxide into algal cell material as possible. In this manner maximum protein and oxygen production can be maintained. Designs of such ponds are based on large area-to-volume ratios, and under these conditions large amounts of algae may be grown. The organic loading in a continuously mixed pond may be in excess of 56 g BOD₅/m² per day. However, a more likely range of values is 10–35 g BOD_u/m² per day, with a removal efficiency of about 70 %.

If aerobic ponds are designed to produce oxygen in quantities exceeding the influent BOD, the contents must be mixed for about 3 hours per day to keep the settled sludge in an aerobic condition (Oswald et al., 1957). Mixing at velocities of about 50 cm per second brings an additional supply of nutrients to the surface, where they can be utilized most efficiently with the available light. It is essential with these ponds to skim and separate the algae from the effluent, for otherwise the organic load supplied to a stream by the algal cells may present a problem.

In the design of aerobic ponds, it is important to make an accurate estimate of the density of the algal cells and to relate oxygen production to the light conversion efficiency and light intensity (Oswald, 1963). Equation 19 states that oxygen production is directly related to light intensity.

$$O = 0.22 FI_L \quad (19)$$

where

O = oxygen production (kg/ha per day)

F = light conversion efficiency (%); values may range from 0.5 to 6.0

I_L = light intensity (cal/cm² per day)¹

The energy balance in an aerobic pond can be reduced to a fairly simple relationship. Experimentally, it has been found that the production of

¹ For values, see Table 27 (p. 154).

algal cells is related to the product of the light conversion efficiency and the solar radiation:

$$Y_a = 0.125 FI_L \quad (20)$$

where

Y_a = yield of algal cells (kg algae/ha per day)

The ratio between oxygen production and algal cell production is about 1.6 : 1. The highest percentage BOD removal occurs when the oxygenation factor, which is the ratio of the oxygen produced to the oxygen required, is about 1.6. The energy balance thus becomes:

$$\frac{HO'}{1.6} = FI_L R \frac{10}{d} \quad (21)$$

where

H = heat of combustion of cells = 6 cal/mg

O' = oxygen production (mg/cm³)

At present, a pond of this type would be uneconomical, for it would require an unusual amount of attention. In the future, when there may be a market for plant protein, this type of pond may have some merit.

Maturation ponds

The main purpose of maturation ponds is to provide a high-quality effluent. Maturation ponds are not intended to relieve facultative waste stabilization ponds or conventional biological treatment plants that have proved too small or to reduce expenditure on operating costs and supervision.

The principal factor in the design of a maturation pond is detention time, but for efficient reduction of the faecal bacteria it is essential that the pond be arranged in series with the preceding pond (Van Eck, 1961). The detention time in a maturation pond, as well as the number of ponds, is determined primarily by the degree of bacterial purification required. Usually the maturation pond should provide 7–10 days' detention, and a liquid depth of 1 m. The rate of disappearance of faecal bacteria in aerobic ponds follows the relationship given in Chapter 5.

Induced mechanical mixing and aeration

Low-cost mechanical aeration is a useful engineering alternative when waste loads increase, when space is limited, and when high-quality effluents are required. Aeration and mixing may be accomplished by (a) recirculation of oxygen-rich waters from the effluent of a facultative or maturation pond system to the influent area; (b) mechanically induced surface aeration; (c) diffused aeration using compressed air; or (d) combinations of the above techniques.

Recirculation of oxygen-rich pond waters helps to maintain an oxygen balance and eliminate odours in one or more series-connected ponds. Such recirculation of algae-rich waters and a form of stepped loading are employed extensively in South Africa and Sweden (Abbott, 1962).

A very successful and relatively economical aeration system is the mechanically aerated waste stabilization pond. Aerobic and facultative micro-organisms are supplied with oxygen by mechanical aerators (usually surface-type units), whereas in normal facultative ponds algae provide the oxygen. Inexpensive earthen ponds may be used.

Two types of pond using surface aerators are generally used (Fig. 17). Pond A is kept completely aerobic. All the solids are maintained in suspension, and the solids in the effluent are equal to the solids in the pond. Pond B is mostly aerobic, but the velocities and mixing characteristics permit much of the non-oxidized biological solids to settle to the bottom. These deposits must undergo anaerobic decomposition. In both cases, the effluent can be further treated in a facultative waste stabilization pond.

Surface aerators may be fixed in one position or used as floating units. Generally, 10–20 % of the total oxygen required results from oxygen transfer across the surface interface, and the rest is provided through mixing and entrainment of air. Mechanical aeration units of the surface type can be expected to supply about 1–1.8 kg oxygen/hph (horsepower-hour). The larger the pond, the lower the value.

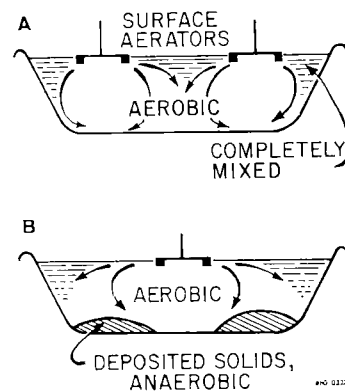
The oxygen supplied by mechanical aeration is usually determined as follows:

$$O_s = O_m \frac{C_{sw} - C}{C_s} \times \alpha \times \theta^{(T-20)} F_A \quad (22)$$

where

- O_s = oxygen supplied by mechanical aeration (kg oxygen/hph)
- O_m = manufacturer's rating of aerator, usually 1.8–2.1 kg oxygen/hph
- C_{sw} = O_2 saturation level in the pond at temperature T (mg/litre)
- C = level of dissolved oxygen in pond (mg/litre)
- C_s = O_2 saturation level of distilled water at 20°C (mg/litre)

FIG. 17. TWO TYPES OF AERATED WASTE STABILIZATION POND



- α = $\frac{\text{overall transfer coefficient of the waste-water}}{\text{overall transfer coefficient of the tap water}}$
 (typical values range between 0.6 and 1.1)
 θ = temperature reaction coefficient = 1.02
 F_A = correction factor for altitudes above about 1 200 m (use standard air density relationships)

Equation 23 can be used for calculating the oxygen requirements in an aerobic system with complete mixing. Such ponds need oxygen for the BOD exerted by the micro-organisms that are degrading the influent wastes and to degrade at least some of the accumulated biological volatile solids.

$$O_n = a' (L_o - L_p) + b' X_t \quad (23)$$

where

- O_n = oxygen required (mg/litre)
 a' = BOD removed and used to provide energy for growth, as fraction of BOD_u or COD (varies from $\frac{1}{2}$ to $\frac{1}{1}$)
 b' = endogenous respiration rate per day, as fraction of BOD_u or COD ($\frac{1}{100}$ to $\frac{10}{100}$)
 X_t = volatile suspended solids in mixed liquor (mg/litre)

In most ponds where only pretreatment or supplemental aeration is required, the quantity of biological solids can be maintained at a low level. Consequently, Equation 23 can be simplified as follows:

$$O_d = a'' L_r \quad (24)$$

where

- O_d = oxygen required (kg/day)
 a'' = coefficient (values range from 0.7 to 1.4)
 L_r = BOD removed (kg/day)

The following calculations illustrate the use of Equations 22 and 24 in the design of an aerobic pretreatment unit.

Given

- Flow = 7 570 m³/day
 BOD_s = 250 mg/litre
 BOD_u = 305 mg/litre
 C = 1.5
 C_s = 9.2
 C_{su} = 10.2
 T = 15°C
 a'' = 0.7
 O_m = 1.6 kg O₂/gross hph at 20°C and when DO is zero
 α = 0.90
 K_T = 0.35 per day

Required

The size and number of mechanical aerators necessary to reduce the influent BOD by 50 %.¹

Solution

$$\begin{aligned}
 (a) \text{ Organic load} &= \text{BOD}_5 \times \text{flow} \\
 &= 250 \times 7\,570 \times 1\,000 \text{ mg BOD/day} \\
 &= 1\,829.5 \text{ kg BOD/day, say } 1\,900 \text{ kg/day} \\
 \text{BOD to be removed} &= 950 \text{ kg/day} \\
 (b) \text{ Detention time (Equation 9)} = R_T &= \frac{L_0 - L_p}{K_T L_p} \\
 &= \frac{250 - 125}{0.35 \times 125} = 2.86 \text{ days} \\
 (c) \text{ Volume} &= \text{detention time (in days)} \times \text{flow (per day)} \\
 &= 2.86 \times 7\,570 = 21\,600 \text{ m}^3 \\
 (d) \text{ Surface area (assuming depth of 3 m)} &= \frac{\text{volume}}{\text{depth}} = \frac{21\,600}{3} = 7\,200 \text{ m}^2 \\
 &= 0.72 \text{ ha} \\
 (e) \text{ Oxygen requirement (Equation 24)} &= O_d = a'' L_r = 0.7 \times 950 \\
 &= 665 \text{ kg O}_2/\text{day} = 27.7 \text{ kg O}_2/\text{hour} \\
 (f) \text{ Mechanical aeration requirement} &= O_s = O_m \frac{C_{sw} - C}{C_s} \times \alpha \times \theta^{(T-20)} \\
 \text{(Equation 22)} &= 1.6 \times \frac{10.2 - 1.5}{9.2} \times 0.90 \times 1.02^{(15-20)} \\
 &= 1.23 \text{ kg O}_2/\text{hph} \\
 (g) \text{ Power requirements} &= \frac{\text{oxygen requirement}}{\text{amount of oxygen per hph}} \\
 &= \frac{27.7}{1.23} \\
 &= 22.5 \text{ hp}
 \end{aligned}$$

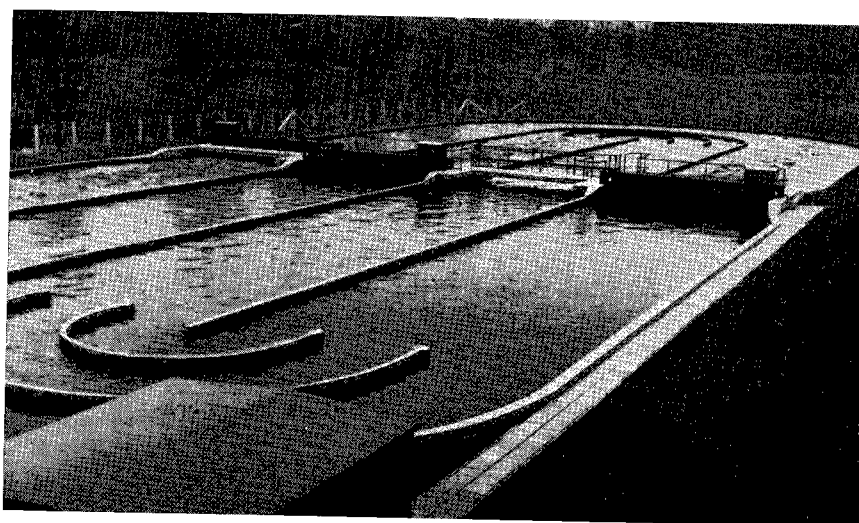
One 25-hp aeration unit is therefore required (1 hp = 0.7457 kW).

Air diffusion systems consisting of blowers and aeration tubing have been used in some places to provide the oxygen required. Weighted tubing placed on the bottom of a pond helps to keep the pond mixed. In cold climates, the submerged tubing is not as likely to be damaged with ice as are some types of surface aerator; moreover, heat may be conserved through the use of submerged tubing.

¹ If the effluent from the aerated pond requires further treatment, this may be provided by a facultative waste stabilization pond. It should be remembered that the remaining BOD will be the residual soluble BOD plus that BOD exerted by the biological cell material produced in the aerated lagoon. It is therefore necessary to use the total BOD (BOD_T) for the design of the facultative pond.

Another system employing prolonged aeration is the oxidation ditch, in which rotating brushes are used to agitate the surface of the liquid as it circulates. Although this system of aeration is usually used in activated sludge units, it can also be used for pretreatment in units followed by waste stabilization ponds. The oxidation ditch (Baars, 1962) provides full treatment of waste-water for small communities at the same cost *per caput* as treatment by the conventional activated sludge system for large communities. The mixed liquor in the ditch circulates at about 25–30 cm per second. Kessener brushes or rotors rotate at 75–125 rev/min and provide about 3 kg of oxygen per kilowatt. This system provides flexibility in that it permits intermittent fill-and-draw operations. Other uses for the oxidation ditch have been described by Pasveer (1962). A ditch used for a community of 7 000 in the Netherlands is shown in Fig. 18.

FIG. 18. OXIDATION DITCH FOR 7 000 INHABITANTS, SCHERPENZEEL, NETHERLANDS



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Summary and Design Recommendations

The designer of a waste stabilization pond system may find that many of the data he needs are not available. Consequently, engineering decisions must sometimes be made on the basis of experiences gained in other regions having comparable climatic conditions or on the basis of data obtained locally from experimental ponds. The type of waste-water, special environmental factors, local customs, and the specific treatment objectives should all be considered carefully by the engineer.

Experience gained through the operation of a local waste stabilization pond is of the utmost value. If properly operated for at least a year a single pond, even an experimental pond, can provide very useful design information.

The waste stabilization pond arrangements suitable for different types of waste may be summarized as follows:

<i>Waste characteristics</i>	<i>Suitable treatment processes ^a</i>
High solids content (i.e., night soil with minimum water added)	(a) A + F (b) A + F + M
Water-carried waste-water (domestic only)	(a) A + F + M (b) F (c) F + M
Water-carried waste-water (domestic and industrial)	(a) A + F + M (b) F (c) F + M (d) MA + F + M

Some procedures that have been found useful in the design of waste stabilization ponds under varying conditions are outlined below:

Case A. Water carriage waste system

1. Determine the influent flow by estimating the contributing population (N) and the *per caput* waste-water contribution (q). Flow = Nq litres/day. If data on quantities of domestic wastes are not available, Table 13 (p. 46) will provide a basis for initial estimates.

2. Estimate the concentration of BOD in the waste-water, and calculate the loading factor. In developing areas, a conservative estimate is 50 g BOD₅ per person per day, i.e., 1 kg BOD₅ = 20 population equivalents. BOD₅ may be assumed to be about 70 % of BOD_u. From these data it is possible to calculate the loading factor (L.F. = Nq BOD_u) and to locate a point on the abscissa of Fig. 13.

3. Evaluate temperature conditions; establish or estimate the mean temperature for the coldest month (needed for the design of facultative ponds); and establish or estimate the mean annual temperature (needed for estimating the breakdown rate and solids storage capacity of anaerobic ponds or the sludge storage volume of facultative ponds).

^a A = anaerobic waste stabilization pond
F = facultative waste stabilization pond
M = maturation pond
MA = mechanically aerated waste stabilization pond

4. Review the meteorological and hydrological characteristics of the local environment, i.e., estimate periods of protracted cloud cover, wind, rainfall, evaporation.

(a) The surface area of a facultative pond must include a safety factor if there are periods of extended cloud cover. Cloud cover for periods of a month or more may require a safety factor of as much as 25 %.

(b) Wind is important to the operation of a facultative pond. If there is no likelihood of wind, add 10–20 % to the surface area. Continuous strong wind will increase pond mixing and compensate for the decrease in photosynthetic oxygenation resulting from moderate cloud cover.

(c) Rainfall and evaporation may influence the choice of the number of ponds, depth, type of embankment, drainage, etc. Excessive evaporation in anaerobic and facultative ponds may expose deposited sludge and give rise to odours.

5. Survey the local terrain for soil characteristics and the location of ground-water and receiving streams or waterways.

6. Evaluate alternative combinations of ponds: (a) facultative only, (b) anaerobic plus facultative, and (c) anaerobic plus facultative plus maturation. The decision as to which arrangement to use will depend on the amount of water, the size of the plant, bacteriological requirements, and other factors. For communities with low water consumption (less than 50 litres *per caput* per day) and where evaporation rates are high, serious consideration should be given to using an anaerobic pond as a pretreatment unit, followed by a facultative pond, or to giving the facultative pond extra depth if it is to be used independently. The use of a maturation pond will depend upon the desired degree of biodegradation and coliform removal and on permissible evaporation.

Facultative ponds

(a) Estimate surface area, volume, and detention time (1) for the case where the total BOD_u enters the facultative pond and (2) for the case where 50 % of BOD_u is removed by preliminary treatment in an anaerobic pond and only the remaining 50 % enters the facultative pond.

(b) Calculate surface area and volume, using Fig. 13 or Equation 13.

(c) Use a design depth of 1 m in tropical climates. In temperate climates add 50 cm for sludge and grit storage; in cold climates add 1 m for variable liquid storage and for long-term sludge storage during cold periods when anaerobic decomposition virtually ceases.

Anaerobic ponds

Such ponds should be considered only if the sludge temperature is expected to be above 16°C.

(a) Estimate the digestion rate on the basis of Equation 17 and BOD_5 removal on the basis of data in Table 21. Adjust the estimated de-

tention time according to the ratio between $K_{s(T)}$ and $K_{s(22)}$; as calculated by Equation 17, T is the mean annual temperature of the sludge layer.

(b) Determine volume and area. The depth should be 1.5–2 m (exclusive of grit storage).

(c) For large facilities or where the waste contains a large amount of grit, construct 2 ponds in parallel so that one may be cleaned periodically.

Maturation ponds

Design a maturation pond on the basis of 7 days' detention time and a depth of 1 m.

(7) Compare estimates of waste stabilization pond sizes, volumes, and depths with other suggested procedures. Suggest appropriate dimensions for the first pond system in a given locality.

(8) Prepare an operation and inspection schedule such as to provide data that can be used for improving the design of future waste-water treatment plants.

Case B. No local data available

Design a pilot facultative pond on the basis of Table 17, and observe operation for at least one year, or preferably longer. The pond should have a minimum depth of 1 m; it should be provided with inlet and outlet facilities as described in chapter 6, including measuring devices for influent and effluent flow. The data collection programme should include:

(1) BOD₅ measurements of influent and effluent (at least once a fortnight for a period of one year). Caution must be observed in measuring the BOD of water containing algae: the dark-bottle technique should be used to eliminate oxygenation due to photosynthesis by algae in the effluent. At least 5 of these BOD measurements should be made on composited 24-hour samples, i.e., samples taken every 4 hours over a period of 24 hours and weighted according to flow.

(2) Total residue of influent and effluent.

(3) Total volatile residue of influent and effluent.

(4) Settleable solids of influent and effluent.

(5) Influent and effluent flow measurements taken over a 24-hour period (each fortnight). A removable V-notch weir or a plastic (or fibreglass) Parshall flume is recommended.

(6) Fortnightly measurements of diurnal pH and dissolved oxygen. These measurements should be made over both a vertical profile (every 20 cm) and a horizontal profile (at 3 points).

(7) Depth measurements around the inlet, in order to assess the degree of solids build-up (once a year).

(8) Periodic observations and notes describing (a) odours; (b) colour of pond; (c) types of insect around the pond, particularly any increase in numbers of insects (e.g., flies, midges) that were not present prior to the construction of the pond; (d) water temperatures; (e) sludge temperatures; (f) suspended solids; (g) dissolved oxygen (of effluent); (h) changes in the apparent algal population and types of algae present; (i) presence and frequency of floating debris in the pond; (j) need for maintenance of embankments, etc.

Case C. Special case (night-soil)

Shaw (1962) suggests a loading of wastes from 2 740 persons per ha per day, with a depth of 60–150 cm if the climatic conditions are similar to those in Pretoria, South Africa. Concrete ramps or chutes should be provided to ensure that all residual night-soil can be washed or drained into the pond. Sludge banks should be dispersed. Anaerobic ponds should be filled with water before night-soil is added. Additional water may be required if evaporation and seepage rates exceed rainfall.
