Introduction to Wastewater Treatment Processes

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Preface

This book is an introductory presentation meant for both students and practicing engineers interested in the field of wastewater treatment. Most of the earlier books discuss the subject industry by industry, providing solutions to specific treatment problems. More recently, a scientific approach to the basic principles of unit operations and processes has been utilized. I have used this approach to evaluate all types of wastewater problems and to properly select the mode of treatment and the design of the equipment required.

In most cases, the design of specific wastewater treatment processes, e.g., the activated sludge process, is discussed following (1) a summary of the theory involved in the specific process, e.g., chemical kinetics, pertinent material and energy balances, discussion of physical and chemical principles; (2) definition of the important design parameters involved in the process and the determination of such parameters using laboratory-scale or pilot-plant equipment; and (3) development of a systematic design procedure for the treatment plant. Numerical applications are presented which illustrate the treatment of laboratory data, and subsequent design calculations are given for the wastewater processing plant. The approach followed, particularly in the mathematical modeling of biological treatment processes, is based largely on the work of Eckenfelder and associates.

Clarity of presentation has been of fundamental concern. The text should be easily understood by undergraduate students and practicing engineers. The book stems from a revision of lecture notes which I used for an introductory course on wastewater treatment. Not only engineering students of diverse backgrounds but also practicing engineers from various fields have utilized these notes at the different times this course was offered at Laval University and COPPE/UFRJ (Rio de Janeiro, Brazil). Favorable acceptance of the notes and the encouragement of many of their users led me to edit them for inclusion in this work.

I wish to express my appreciation to the secretarial staff of the Chemical Engineering Department of Laval University, Mrs. Michel, Mrs. Gagné, and Mrs. McLean, and to Miss Enidete Souza (COPPE/UFRJ) for typing the manuscript. I owe sincere thanks to Mr. Alex Légaré for the artwork, to Dr. and Mrs. Adrien Favre for proofreading the manuscript, and to Mr. Roger Thériault for his assistance in the correction of the galleys. The valuable suggestions made by Dr. M. Pelletier (Laval University) and Dr. C. Russo (COPPE/UFRJ) are gratefully acknowledged.

R. S. Ramalho

1

Introduction

1. Introduction

It was only during the decade of the 1960's that terms such as "water and air pollution," "protection of the environment," and "ecology" became household words. Prior to that time, these terms would either pass unrecognized by the average citizen, or at most, would convey hazy ideas to his mind. Since then mankind has been bombarded by the media (newspapers, radio, television), with the dreadful idea that humanity is effectively working for its self-destruction through the systematic process of pollution of the environment, for the sake of achieving material progress. In some cases, people have been aroused nearly to a state of mass hysteria. Although pollution is a serious problem, and it is, of course, desirable that the citizenry be concerned about it, it is questionable that "mass hysteria" is in any way justifiable. The instinct of preservation of the species is a very basic driving force of humanity, and man is equipped to correct the deterioration of his environment before it is too late. In fact, pollution control is not an exceedingly difficult technical problem as compared to more complex ones which have been successfully solved in this decade, such as the manned exploration of the moon. Essentially, the basic technical knowledge required to cope with pollution is already available to man, and as long as he is willing to pay a relatively reasonable price tag, the nightmare of self-destruction via pollution will never become a reality. Indeed, much higher price tags are being paid by humanity for development and maintenance of the war-making machinery.

This book is primarily concerned with the engineering design of process plants for treatment of wastewaters of either domestic or industrial origin. It is only in the last few years that the design approach for these plants has changed from empiricism to a sound engineering basis. Also, fundamental research in new wastewater treatment processes, such as reverse osmosis and electrodialysis, has only recently been greatly emphasized.

2. The Role of the Engineer in Water Pollution Abatement

2.1. THE NECESSITY OF A MULTIDISCIPLINARY APPROACH TO THE WATER POLLUTION ABATEMENT PROBLEM

Although it has been stated previously that water pollution control is not an exceedingly difficult technical problem, the field is a broad one, and of sufficient complexity to justify several different disciplines being brought together for achieving optimal results at a minimum cost. A systems approach to water pollution abatement involves the participation of many disciplines: (1) engineering and exact sciences [sanitary engineering (civil engineering), chemical engineering, other fields of engineering such as mechanical and electrical, chemistry, physics]; (2) life sciences [biology (aquatic biology), microbiology, bacteriology]; (3) earth sciences (geology, hydrology, oceanography); and (4) social and economic sciences (sociology, law, political sciences, public relations, economics, administration).

2.2. A SURVEY OF THE CONTRIBUTION OF ENGINEERS TO WATER POLLUTION ABATEMENT

The sanitary engineer, with mainly a civil engineering background, has historically carried the brunt of responsibility for engineering activities in water pollution control. This situation goes back to the days when the bulk of wastewaters were of domestic origin. Composition of domestic wastewaters does not vary greatly. Therefore, prescribed methods of treatment are relatively standard, with a limited number of unit processes and operations involved in the treatment sequence. Traditional methods of treatment involved large concrete basins, where either sedimentation or aeration were performed, operation of trickling filters, chlorination, screening, and occasionally a few other operations. The fundamental concern of the engineer was centered around problems of structure and hydraulics, and quite naturally, the civil engineering background was an indispensable prerequisite for the sanitary engineer.

This situation has changed, at first gradually, and more recently at an accelerated rate with the advent of industrialization. As a result of a new large variety of industrial processes, highly diversified wastewaters requiring more complex treatment processes have appeared on the scene. Wastewater treatment today involves so many different pieces of equipment, so many unit processes and unit operations, that it became evident that the chemical engineer had to be called to play a major role in water pollution abatement. The concept of unit operations, developed largely by chemical engineers in the past fifty years, constitutes the key to the scientific approach to design problems encountered in the field of wastewater treatment.

In fact, even the municipal wastewaters of today are no longer the "domestic wastewaters" of yesterday. Practically all municipalities in industrialized areas must handle a combination of domestic and industrial wastewaters. Economic and technical problems involved in such treatment make it very often desirable to perform separate treatment (*segregation*) of industrial wastewaters, prior to their discharge into municipal sewers.

Even the nature of truly domestic wastewaters has changed with the advent of a whole series of new products now available to the average household, such as synthetic detergents and others. Thus, to treat domestic wastewaters in an optimum way requires modifications of the traditional approach.

In summary, for treatment of both domestic and industrial wastewaters, new technology, new processes, and new approaches, as well as modifications of old approaches, are the order of the day. The image today is no longer that of the "large concrete basins," but one of a series of closely integrated unit operations. These operations, both physical and chemical in nature, must be tailored for each individual wastewater. The chemical engineer's skill in integrating these unit operations into effective processes makes him admirably qualified to design wastewater treatment facilities.

2.3. A CASE HISTORY OF INDUSTRIAL WASTEWATER TREATMENT

An interesting case history, emphasizing the role of the chemical engineer in the design of a wastewater treatment plant for a sulfite pulp and paper mill, is discussed by Byrd [2]. This pulp and paper plant was to discharge its wastewaters into a river of prime recreational value, with a well-balanced fish population. For this reason, considerable care was taken in the planning and detailed design of the wastewater treatment facilities. A study of assimilative capacity of the river was undertaken and mathematical models were developed.

Design of the treatment plant involved a study to determine which wastewater effluents should be segregated for treatment, and which ones should be combined. For the treatment processes a selection of alternatives is discussed [2]. Some of the unit operations and processes involved in the treatment plant, or considered at first but after further study replaced by other alternatives, were the following: sedimentation, dissolved air flotation, equalization, neutralization, filtration (rotary filters), centrifugation, reverse osmosis, flash drying, fluidized bed oxidation, multiple hearth incineration, wet oxidation, adsorption in activated carbon, activated sludge process, aerated lagoons, flocculation with polyelectrolytes, chlorination, landfill, and spray irrigation.

Integration of all these unit operations and processes into an optimally designed treatment facility constituted a very challenging problem. The treatment plant involved a capital cost of over $10 million and an operating cost in excess of $1 million per year.

2.4. THE CHEMICAL ENGINEERING CURRICULUM AS A PREPARATION FOR THE FIELD OF WASTEWATER TREATMENT [5]

Chemical engineers have considerable background that is applicable to water pollution problems. Their knowledge of mass transfer, chemical kinetics, and systems analysis is specially valuable in wastewater treatment and control. Thus, training in chemical engineering represents good preparation for entering this type of activity. In the past, the majority of engineers working in this field have been sanitary engineers with a civil engineering background.

The multidisciplinary nature of the field should be recognized. Chemical engineering graduates envisioning major activity in the field of wastewater treatment are advised to complement their background by studying microbiology, owing to the great importance of biological wastewater treatment processes, and also hydraulics [since topics such as open channel and stratified flow, mathematical modeling of bodies of water (rivers, estuaries, lakes, inlets, etc.) are not emphasized in fluid mechanics courses normally offered to chemical engineering students].

2.5. "INPLANT" AND "END-OF-PIPE" WASTEWATER TREATMENT [6]

2.5.1. Introduction

Frequently one may be tempted to think of industrial wastewater treatment in terms of an "end-of-pipe" approach. This would involve designing a plant without much regard to water pollution abatement, and then considering separately the design of wastewater treatment facilities. Such an approach should not be pursued since it is, in general, highly uneconomical.

The right approach for an industrial wastewater pollution abatement program is one which uncovers all opportunities for inplant wastewater treatment. This may seem a more complicated approach than handling wastewaters at the final outfall. However, such an approach can be very profitable.

2.5.2. What Is Involved in Inplant Wastewater Control

Essentially, inplant wastewater control involves the three following steps:

Step 1. Perform a detailed survey of all effluents in the plant. All pollution sources must be accounted for and cataloged. This involves, for each polluting stream, the determination of (a) flow rate and (b) strength of the polluting streams.

(a) *Flow rate.* For continuous streams, determine flow rates (e.g., gal/min). For intermittent discharges, estimate total daily (or hourly) outflow.

(b) *Strength of the polluting streams.* The "strength" of the polluting streams (concentration of polluting substances present in the streams) is expressed in a variety of ways, which are discussed in later chapters. For organic compounds which are subject to biochemical oxidation, the biochemical oxygen demand, BOD (which is defined in Chapter 2, Section 2.3) is commonly employed. In the case history summarized in Section 2.5.3 of this chapter, BOD is used to measure concentration of organics.

Step 2. Review data obtained in Step 1 to find all possible inplant abatement targets. Some of these are (1) increased recycling in cooling water systems; (2) elimination of contact cooling for off vapors, e.g., replacement of barometric condensers by shell-and-tube exchangers or air-cooling systems; (3) recovery of polluting chemicals: Profit may often be realized by recovering such chemicals, which are otherwise discharged into the plant sewers. A by-products plant may be designed to recover these chemicals; (4) reuse of water from overhead accumulator drums, vacuum condensers, and pump glands. Devise more consecutive or multiple water uses; (5) design a heat recovery unit to eliminate quenching streams; and (6) eliminate leaks and improve housekeeping practices. Automatic monitoring and additional personnel training might be profitable.

Step 3. Evaluate potential savings in terms of capital and operating costs for a proposed "end-of-pipe" treatment, if each of the streams considered in Steps 1 and 2 are either eliminated or reduced (reduction in flow rates or in terms of strength of polluting streams). Then design the "end-of-pipe" treatment facilities to handle this reduced load. Compare capital and operating costs of such treatment facilities with that of an "end-of-pipe" facility designed to handle the original full load, i.e., the pollutant streams from a plant where inplant wastewater control is not practiced. The two case histories described in Ref. [6] are quite revealing in this respect.

For practicing inplant wastewater control, a deep knowledge of the process and ability to modify it, if necessary, are required. The chemical engineer is admirably well suited to handle this job.

2.5.3. Case Histories of Inplant Wastewater Control

Two interesting case histories are discussed by McGovern [6]. One of these, pertaining to a petrochemical plant, is summarized next.

A petrochemical plant already in operation conducted an effluent and inplant survey while evaluating a treatment plant to be designed and built, which would handle 20 million gal/day of wastewater with a BOD load of 52,000 lb/day. The plan called for an activated sludge unit to remove over 90% of the BOD load. This included vacuum filtration and incineration of the sludge, and chlorination of the total effluent.

Capital cost of the treatment facility was estimated at $10 million. Operating and maintenance costs were also estimated. All cost data were converted to an annual basis, using a 20-year project life and 15% interest rate.

Then a study of the possibility of reducing both the flow and the strength of the wastewaters was undertaken. This study followed the steps outlined under Section 2.5.2, with a number of changes being proposed for the process flowsheet. The reduction accomplished in flow rate and strength resulted in substantial savings in the total cost of the proposed treatment plant. Figure 1.1 shows a graph, prepared for this case history, illustrating the effect of reduction in BOD or flow rate upon the capital cost of the treatment facilities. This graph is valid to approximately 60% reduction in flow or BOD. Any further reduction probably requires a significantly different treatment system.

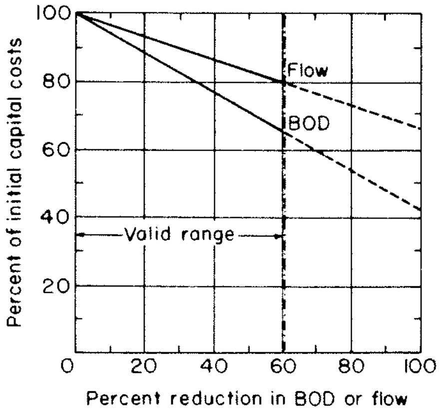

***Fig. 1.1. Effect of waste load reductions on capital cost of treatment plant* [6].** (*Excerpted by special permission from Chemical Engineering, May 14, 1973. Copyright by McGraw-Hill, Inc., New York, 10020.*)

TABLE 1.1
Savings from Inplant Wastewater Reductions[a]

Inplant savings	$/year
Flow reduction (1424 gal/min)	$410,000
BOD reduction (2000 lb/day)	302,000
Water use reduction	
Treated water (0.24 MGD)	34,000
River water (1.37 MGD)	14,000
Product recovery	14,000
Total inplant saving	$774,000
Cost of inplant control	$/year
Engineering	$ 15,000
Capital investment	150,000
Operating and maintenance	33,000
Total cost of inplant control	$198,000
Net savings: $774,000 − $198,000 = $576,000/year	

[a] Excerpted by special permission from *Chemical Engineering*, May 14, 1973; Copyright by McGraw-Hill, Inc., New York, 10020.

Savings from inplant wastewater control are tabulated in Table 1.1. Wastewater flow was cut to 85% of its value prior to inplant control and BOD load was cut to 50%. Moreover, the cost of these inplant controls was more than offset by economies in the treatment plant. As shown in Table 1.1 the program realized a net saving of $576,000/year.

2.6. A NEW CONCEPT IN PROCESS DESIGN: THE FLOWSHEET OF THE FUTURE

The considerations in Section 2.5 are leading engineers to a new concept in process design. The flowsheet of the future will no longer show a line with an arrowhead stating "to waste." Essentially everything will be recycled, byproducts will be recovered, and water will be reused. Fundamentally the only streams in and out of the plant will be raw materials and products. The only permissible wastages will be clean ones: nitrogen, oxygen, carbon dioxide, water, and some (but not too much!) heat. In this connection, it is appropriate to recall the guidelines of the United States Federal Water Pollution Control Act of 1972: (1) best *practical* control technology, by July 1, 1977; (2) best *available* technology, by July 1, 1983; and (3) zero discharge by July 1, 1985.

3. Degrees of Wastewater Treatment and Water Quality Standards

The degree of treatment required for a wastewater depends mainly on discharge requirements for the effluent. Table 1.2 presents a conventional classification for wastewater treatment processes. Primary treatment is employed for removal of suspended solids and floating materials, and also conditioning the wastewater for either discharge to a receiving body of water or to a secondary treatment facility through neutralization and/or equalization. Secondary treatment comprises conventional biological treatment processes. Tertiary treatment is intended primarily for elimination of pollutants not removed by conventional biological treatment.

TABLE 1.2
Types of Wastewater Treatment

- Primary treatment
  - Screening
  - Sedimentation
  - Flotation
  - Oil separation
  - Equalization
  - Neutralization
- Secondary treatment
  - Activated sludge process
  - Extended aeration (or total oxidation) process
  - Contact stabilization
  - Other modifications of the conventional activated sludge process: tapered aeration, step aeration, and complete mix activated sludge processes
  - Aerated lagoons
  - Wastewater stabilization ponds
  - Trickling filters
  - Anaerobic treatment
- Tertiary treatment (or "advanced treatment")
  - Microscreening
  - Precipitation and coagulation
  - Adsorption (activated carbon)
  - Ion exchange
  - Reverse osmosis
  - Electrodialysis
  - Nutrient removal processes
  - Chlorination and ozonation
  - Sonozone process

These treatment processes are studied in following chapters. The approach utilized is based on the concepts of unit processes and operations. The final objective is development of design principles of general applicability to *any* wastewater treatment problem, leading to a proper selection of process and the design of required equipment. Consequently, description of wastewater treatment sequences for specific industries, e.g., petroleum refineries, steel mills, metal-plating plants, pulp and paper industries, breweries, and tanneries, is not included in this book. For information on specific wastewater treatment processes, the reader should consult Eckenfelder [3] and Nemerow [7].

Water quality standards are usually based on one of two criteria: stream standards or effluent standards. *Stream standards* refer to quality of receiving water downstream from the origin of sewage discharge, whereas *effluent standards* pertain to quality of the discharged wastewater streams themselves.

A disadvantage of effluent standards is that it provides no control over total amount of contaminants discharged in the receiving water. A large industry, for example, although providing the same degree of wastewater treatment as a small one, might cause considerably greater pollution of the receiving water. Effluent standards are easier to monitor than stream standards, which require detailed stream analysis. Advocates of effluent standards argue that a large industry, due to its economic value to the community, should be allowed a larger share of the assimilative capacity of the receiving water.

Quality standards selected depend on intended use of the water. Some of these standards include: concentration of dissolved oxygen (DO, mg/liter), pH, color, turbidity, hardness (mg/liter), total dissolved solids (TDS, mg/liter), suspended solids (SS, mg/liter), concentration of toxic (or otherwise objectionable) materials (mg/liter), odor, and temperature. Extensive tabulation of water quality standards for various uses and for several states in the United States is presented by Nemerow [7].

4. Sources of Wastewaters

Four main sources of wastewaters are (1) domestic sewage, (2) industrial wastewaters, (3) agricultural runoff, and (4) storm water and urban runoff. Although the primary consideration in this book is the study of treatment of domestic and industrial wastewaters, contamination due to agricultural and urban runoffs is becoming increasingly important. Agricultural runoffs carrying fertilizers (e.g., phosphates) and pesticides constitute a major cause of eutrophication of lakes, a phenomena which is discussed in Section 7 of this chapter. Storm runoffs in highly urbanized areas may cause significant pollution effects. Usually wastewaters, treated or untreated, are discharged into a natural body of water (ocean, river, lake, etc.) which is referred to as the receiving water.

5. Economics of Wastewater Treatment and Economic Balance for Water Reuse

In the United States average cost per thousand gallons of water is approximately \$0.20, which corresponds to \$0.05/ton. It is a relatively cheap commodity, and as a result the economics of wastewater treatment is very critical. In principle, by utilizing sophisticated treatment processes, one can obtain potable water from sewage. Economic considerations, however, prevent the practical application of many available treatment methods. In countries where water is at a premium (e.g., Israel, Saudi Arabia) some sophisticated water treatment facilities, which are not economically justified in North America, are now in operation. In evaluating a specific wastewater treatment process, it is important to estimate a *cost–benefit ratio* between the benefit derived from the treatment to obtain water of a specified quality, and the cost for accomplishing this upgrading of quality.

Reuse of water by recycling has been mentioned in connection with inplant wastewater control (Section 2.5). Selection of an optimum recycle ratio for a specific application involves an economic balance in which three factors must be considered [3]: (1) cost of raw water utilized in the plant; (2) cost of wastewater treatment to suitable process quality requirements (in Example 1.1, this is the cost of wastewater treatment preceding recycling to the plant for reuse); and (3) cost of wastewater treatment prior to discharge into a receiving water, e.g., in a river.

This economic balance is illustrated by Example 1.1.

Example 1.1 [3]

A plant uses 10,000 gal/hr of process water with a maximum contaminant concentration of 1 lb per 1000 gal. The raw water supply has a contaminant concentration of 0.5 lb/1000 gal. Optimize a water reuse system for this plant based on raw water cost of \$0.20/1000 gal. Utilize data in Fig. 1.2 to estimate costs for the two water treatment processes involved in the plant. The contaminant is nonvolatile.

The following conditions apply: (1) evaporation and product loss (stream E in Fig. 1.3): 1000 gal/hr of water; (2) contaminant addition (stream Y in Fig. 1.3): 100 lb/hr of contaminant; and (3) maximum discharge allowed to receiving water: 20 lb/hr of contaminant.

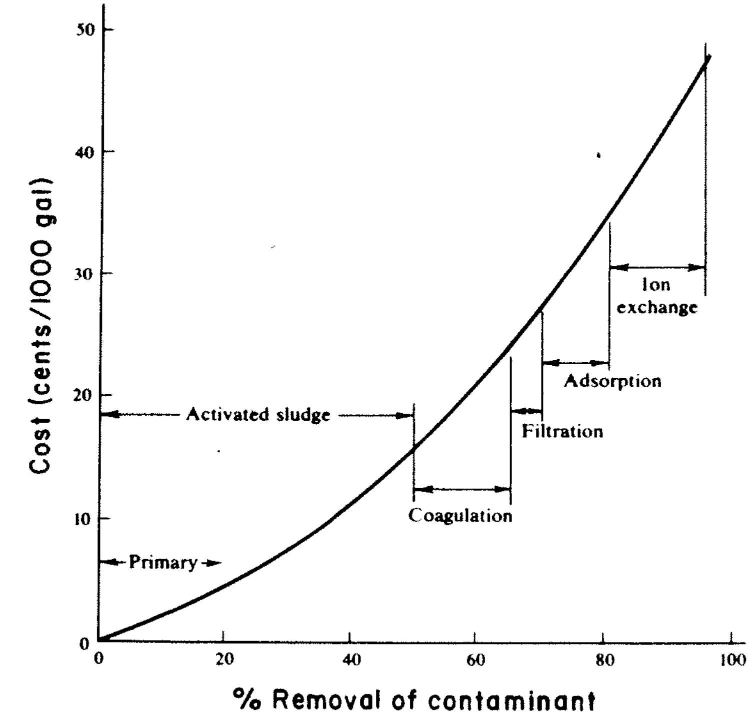

Fig. 1.2. Relationship between total cost and type of treatment [3].

SOLUTION A block flow diagram for the process is presented in Fig. 1.3. Values either assumed or calculated are underlined in Fig. 1.3. Values not underlined are basic data for the problem. Volumetric flow rates of streams 9, 10, and 11 are negligible.

The procedure for solution consists of assuming several values for the water recycle R (gal/hr). For each assumed value, the material balance is completed and the economic evaluation is made.

Step 1. Start assuming a 70% recycle, i.e., $R/A = 0.7$ (recycle ratio), where R is the recycle, i.e., stream 2 (gal/hr), and A is the combined feed, i.e., stream 3 (10,000 gal/hr). Then, calculate the recycle:

$$R = (0.7)(A) = (0.7)(10{,}000) = 7000 \text{ gal/hr} \quad [\text{stream } 2]$$

Thus, stream 5 in Fig. 1.3 also corresponds to a flow rate of 7000 gal/hr since the volumetric flow rate of contaminant removed [stream 11] is negligible.

Step 2. For this assumed recycle, the raw water feed [stream 1] is

$$F = A - R = 10{,}000 - 7000 = 3000 \text{ gal/hr}$$

Step 3. Effluent from the plant [stream 4] is

$$A - E = 10{,}000 - 1000 = 9000 \text{ gal/hr}$$

Step 4. From the material balance it follows that since stream 4 is split into streams 5 and 6,

Stream 6: 9000 − 7000 = 2000 gal/hr
Stream 7: 2000 gal/hr

Thus for 70% recycle, volumetric flow rates for all streams in Fig. 1.3 are now determined.

Step 5. Mass flow rate of contaminant in raw water [stream 1] is

$$F \times (0.5/1000) = 3000(0.5/1000) = 1.5 \text{ lb/hr}$$

Step 6. Mass flow rate of contaminant in stream 3 is

$$(1/1000) \times 10{,}000 = 10 \text{ lb/hr}$$

Step 7. Mass flow rate of contaminant in the recycle [stream 2] is

$$10 - 1.5 = 8.5 \text{ lb/hr}$$

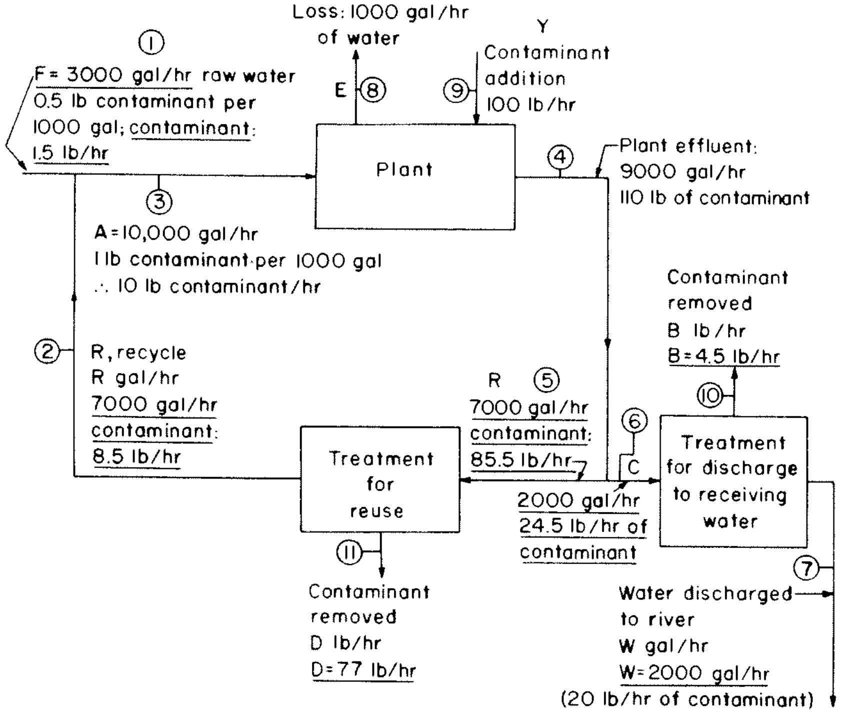

Fig. 1.3. Flow diagram for Example 1.1. Encircled numbers are streams. (*Adapted from Eckenfelder* [3].)

Step 8. Mass flow rate of contaminant in the plant effluent [stream 4] is

$$10 \text{ [from stream 3]} + 100 \text{ [from stream 9]} = 110 \text{ lb/hr}$$

Step 9. Mass flow rate of contaminant in streams 5 and 6 is

Stream 5: (7000/9000) × 110 = 85.5 lb/hr
Stream 6: 110 − 85.5 = 24.5 lb/hr

Step 10. Since the mass flow rate of contaminant in stream 7 is 20 lb/hr, that for contaminant in stream 10 is

$$24.5 - 20.0 = 4.5 \text{ lb/hr}$$

Step 11. Mass flow rate of contaminant removed in the treatment for reuse [stream 11] is

$$85.5 - 8.5 = 77.0 \text{ lb/hr}$$

Step 12. The % removal of contaminant in the two treatments is

Treatment for reuse: (77/85.5) × 100 = 90%
Treatment for discharge to receiving water: (4.5/24.5) × 100 = 18.4%

Step 13. The type of treatment required is essentially established from these % removals of contaminant (Fig. 1.2). In the treatment for reuse (90% removal), ion exchange is indicated. For discharge to receiving water (18.4% removal), Fig. 1.2 indicates that primary treatment is sufficient. Costs for these treatments are read from Fig. 1.2.

Treatment for reuse (90% removal): \$0.42/1000 gal
Treatment for discharge to receiving water (18.4% removal): \$0.05/1000 gal

Step 14. Daily cost for 70% recycle:

Raw water: $3000\,\frac{\text{gal}}{\text{hr}} \times \frac{\$0.20}{1000 \text{ gal}} \times 24\,\frac{\text{hr}}{\text{day}} = \$14.40/\text{day}$

Cost

Effluent treatment for discharge to river:

$$2000\,\frac{\text{gal}}{\text{hr}} \times \frac{\$0.05}{1000 \text{ gal}} \times 24\,\frac{\text{hr}}{\text{day}} = \$\ 2.40/\text{day}$$

Treatment for reuse: $7000\,\frac{\text{gal}}{\text{hr}} \times \frac{\$0.42}{1000 \text{ gal}} \times 24\,\frac{\text{hr}}{\text{day}} = \$70.56/\text{day}$

Total: \$87.36/day

Step 15. This cost is plotted in Fig. 1.4 vs. 70% reflux. A similar series of calculations is made for freshwater inputs varying from 10,000 to 2000 gal/hr,

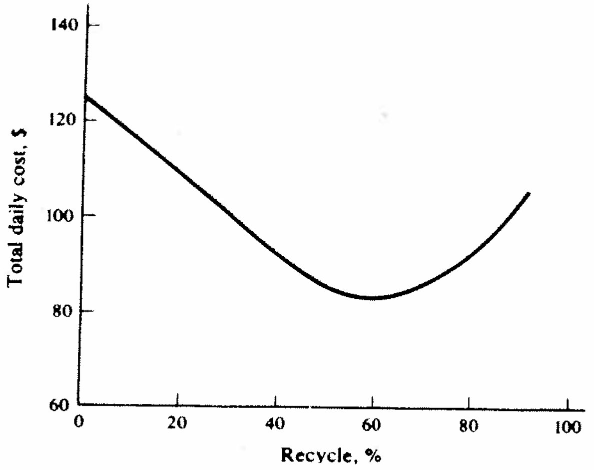

Fig. 1.4. Relationship between total daily water cost and treated waste recycle for reuse [3].

with recycles varying, respectively, from 0–80%. Figure 1.4 is obtained, which indicates that the optimum recycle is approximately 60% for a cost of about $83.00/day.

6. Effect of Water Pollution on Environment and Biota

Bartsch and Ingram [1] made an interesting study of the effect of water pollution on environment and biota. These effects are illustrated by Figs. 1.5–1.10, and a summary of their work is presented next. The source of pollution considered was raw domestic sewage for a community of 40,000 people, flowing to a stream with a volume flow of 100 ft^3/sec. Lowering of the concentration of dissolved oxygen (DO) and formation of sludge deposits are the most common environmental disturbances which may damage aquatic biota.

6.1. OXYGEN SAG CURVE

The curve in Fig. 1.5, referred to as dissolved oxygen curve, is a plot of dissolved oxygen concentration (mg/liter) for a stream. It is referred to hence as oxygen sag curve. Sewage is discharged at the point identified as zero (0) on the abscissa axis. The values to the right of point zero represent miles downstream of the point of sewage discharge. Complete mixing is assumed, and the water temperature is 25°C. An alternative scale for the abscissa, in terms of days of flow, is shown in Fig. 1.5.

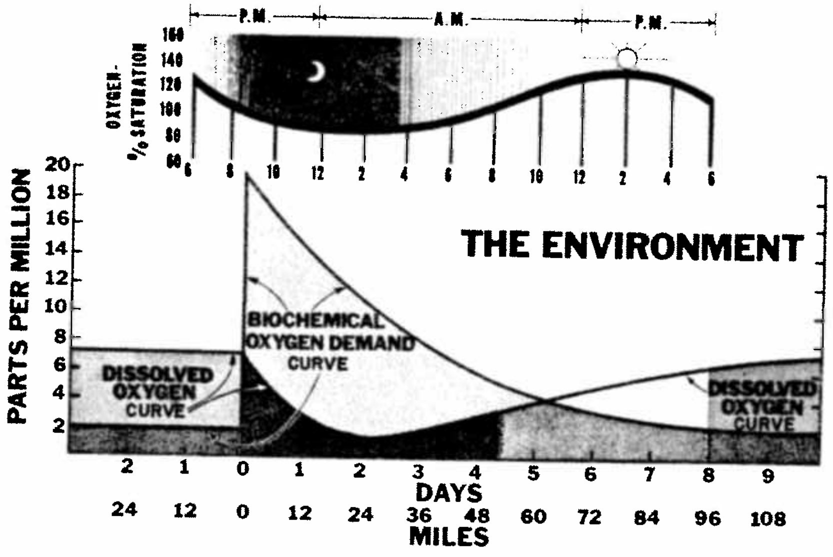

Fig. 1.5. DO and BOD curves for a stream [1].

Ordinate of the DO sag curve is in terms of mg/liter of dissolved oxygen. The shape of the DO sag curve, downstream of the point of sewage discharge, is understood from examination of Fig. 1.6. The DO sag curve is the net resultant of two curves: one corresponding to depletion of dissolved oxygen due to its utilization for oxidation of organic materials from the sewage discharge, and the other corresponding to oxygen gain by natural reaeration. Figure 1.5 shows that the DO sag curve reaches a low point about 27 miles downstream of the point of sewage discharge, corresponding to 2¼ days of flow and a DO of about 1.5 mg/liter.

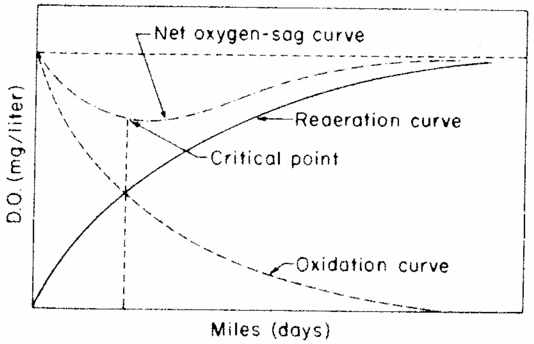

Fig. 1.6. Oxygen sag curve.

This process of deoxygenation would reduce the DO to zero in about 1½ days flow, if there were no factors in operation that could restore oxygen to water. The river reach where DO would be completely gone would occur about 18 miles downstream from the discharge of sewage. After reaching its minimum, DO level rises again toward a restoration, eventually reaching a value nearly equal to that for the upstream unpolluted water, i.e., a DO of approximately 7 mg/liter.

If population of the city remains fairly constant throughout the year, and flow rate is relatively constant, the low point of the DO sag curve moves up or down the stream with fluctuations in temperature. During the winter the rate of oxidation is lower and gain of oxygen by reaeration is greater, as solubility of oxygen in water increases at lower temperatures. These two factors combined cause the low point of the oxygen sag curve to move farther downstream. During the summer, on the other hand, the rate of oxidation is higher and gain of oxygen by reaeration is less pronounced. These two factors combined cause the low point of the oxygen sag curve to move upstream.

The reach of any stream where the DO sag curve attains its low point represents the stream environment poorest in DO resources. Living specimens that need a high DO, such as cold water fish, suffocate and move to other stream areas where the DO resources are greater.

The other curve shown in Fig. 1.5 corresponds to the *biochemical oxygen demand* (BOD). This important parameter is discussed in Chapter 2, Section 2.3. The biochemical oxygen demand is used as a measure of the quantity of oxygen required for oxidation by aerobic biochemical action of the degradable organic matter present in a sample of water. The BOD is low in the upstream unpolluted water (about 2 mg/liter), since there is not much organic matter present to consume oxygen. Then BOD increases abruptly at point zero (sewage discharge), and gradually decreases downstream from this point, as organic matter discharged is progressively oxidized, until reaching eventually a value of approximately 2 mg/liter, indicative of unpolluted water. At this point the raw sewage is stabilized. As indicated in Fig. 1.5, stabilization is achieved at approximately 100 miles downstream from the sewage discharge. BOD and DO are so interrelated that dissolved oxygen concentration is low where BOD is high, and the converse also is true.

Four distinct zones are shown in Fig. 1.5 underneath the DO curve: (1) clean water zone; (2) zone of degradation; (3) zone of active decomposition; and (4) zone of recovery.

6.2. EFFECT OF LIGHT

In Fig. 1.6 the effects of oxygen depletion by oxidation of organic materials and oxygen gain by reaeration are the only ones considered in explaining the shape of the oxygen sag curve. For a more complete analysis of the problem one needs, in addition, to consider the effect of light.

At any selected point in the stream, there is a variation in concentration of dissolved oxygen depending on the time of day. During daylight hours, algae and other plants give off oxygen into the water through the process of photosynthesis. This amount of oxygen may be so considerable that the water usually becomes supersaturated at some time during daylight hours. In addition to giving off oxygen, the process of photosynthesis results in the manufacture of sugar to serve as the basis of support for all stream life. This corresponds to the chemical reaction shown in Eq. (1.1).

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \qquad (1.1)$$

While photosynthesis occurs, so does respiration, which continues for 24 hr a day, irrespective of illumination. During respiration O_2 is taken in and CO_2 is given off. During daylight, algae may yield oxygen in excess of that needed for respiration, as well as in excess of that required for respiration by other aquatic life, and for satisfaction of any biochemical oxygen demand. This could be true in the recovery zone particularly. Under these conditions, supersaturation of oxygen may occur, and surplus oxygen may be lost to the atmosphere.

During the night, photosynthesis does not occur and the surplus DO is gradually used up by respiration of all forms of aquatic life, as well as for the satisfaction of biochemical oxygen demand. Therefore, concentration of dissolved oxygen is at its minimum during early morning hours. To take into account such DO variations, sampling of streams for sanitary surveys is conducted over a 24-hr period.

6.3. DECOMPOSITION OF CARBONACEOUS AND NITROGENOUS ORGANIC MATTER

Accelerated bacterial growth is a response to rich food supplies in the domestic sewage. During rapid utilization of food, bacterial reproduction is at an optimum, and utilization of DO becomes fairly proportional to the rate of food utilization. Figure 1.7 illustrates the progressive downstream changes of organic nitrogen to ammonia, nitrite, and finally nitrate. A high initial consumption of oxygen by bacterial feeding on proteinaceous compounds

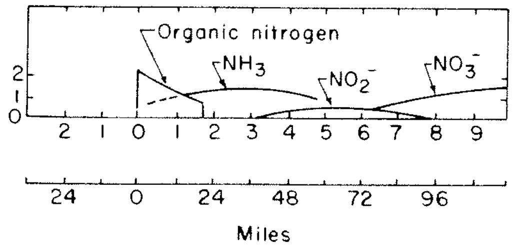

Fig. 1.7. Aerobic decomposition of nitrogenous organic matter [1].

available in upstream waters takes place due to the freshly discharged domestic sewage. With fewer and fewer of these compounds left in downstream waters, the DO concentration is progressively recovered, reaching eventually its initial value of approximately 7 mg/liter.

A similar process takes place with fat and carbohydrate foodstuffs. The final products of aerobic and anaerobic decomposition of nitrogenous and carbonaceous matter are

1. Decomposition of nitrogenous organic matter
   Aerobic (final products): NO_3^-, CO_2, H_2O, SO_4^{2-}
   Anaerobic (final products): mercaptans, indole, skatole, H_2S, plus miscellaneous products
2. Decomposition of carbonaceous matter
   Aerobic: CO_2, H_2O
   Anaerobic: acids, alcohols, CO_2, H_2, CH_4, plus miscellaneous products

Nitrogen and phosphorus in sewage proteins cause special problems in some receiving waters. High concentrations of these elements in water create conditions especially favorable for growing green plants. If the water is free flowing (rivers, brooks), green velvety coatings grow on the stones and possibly lengthy streamers, popularly known as mermaid's tresses, wave in the current. These growths are not unattractive and also constitute a miniature jungle in which animal life of many kinds prey on each other, with the survivors growing to become eventual fish food. If, however, the water is quiet (e.g., lakes), growth of very undesirable types of algae is stimulated. These algae make the water pea green, smelly, and unattractive. This phenomenon is discussed in Section 7 of this chapter. Sometimes, these blue-green algae develop poisons capable of killing livestock, wildlife, and fish.

6.4. SLUDGE DEPOSITS AND AQUATIC PLANTS

A profile showing sludge depth vs. distance from the outfall of the sewage is shown in the bottom part of Fig. 1.8. Maximum depth occurs near the outfall, and then the sludge is gradually reduced by decomposition through the action of bacteria and other organisms, until it becomes insignificant about 30 miles below the municipality.

Also at the outfall there is great turbidity due to the presence of fine suspended solids. As these solids settle, the water becomes clear and approaches the transparency of upstream water, above the point of sewage discharge.

Distribution of aquatic plants is indicated in the upper part of Fig. 1.8. Shortly after the discharge, molds attain maximum growth. These molds and filamentous bacteria (*Sphaerotilus*) are associated with the sludge deposition shown in the lower curve. From mile 0 to mile 36, high turbidity is not conducive to production of algae, since they need sunlight in order to grow and light cannot penetrate the water effectively. The only type of algae that may grow are blue-green algae, characteristic of polluted waters. They may cover marginal rocks in slippery layers and give off foul odors upon seasonal decomposition.

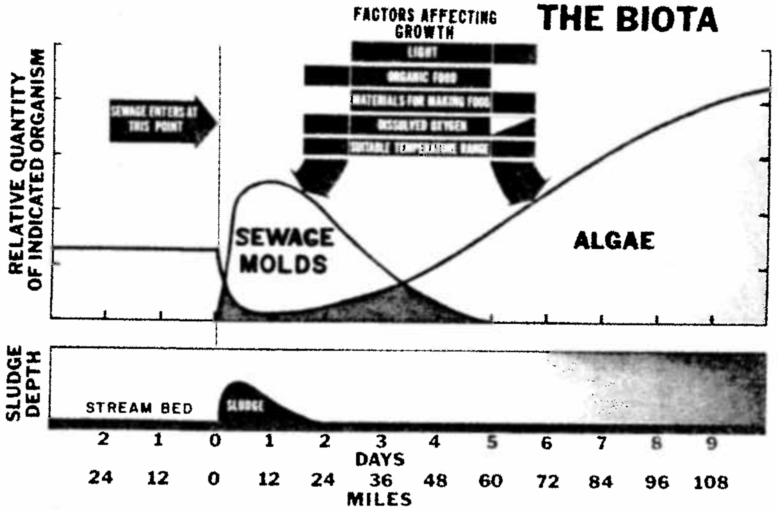

Fig. 1.8. Sludge deposits and aquatic plants [1].

Algae begin to increase in number at about mile 36. Plankton or free-floating forms become steadily more abundant. They constitute an excellent food supply for aquatic animals and also provide shelter for them. Thus, as plants respond downstream in developing a diversified population in the recovery and clean water zones, animals follow a parallel development, producing a great variety of species.

6.5. BACTERIA AND CILIATES

Figure 1.9 illustrates the interrelation between bacteria and other forms of animal plankton such as ciliated protozoans, rotifers, and crustaceans. Two die-off curves are shown, one for total sewage bacteria and the other for coliform bacteria only. The two bell-shaped curves pertain to ciliated protozoans and rotifers and crustaceans.

After entering the stream with the sewage, bacteria reproduce and become abundant, feeding on the organic matter of sewage. Ciliated protozoans, initially few in number, prey on the bacteria. Bacteria population decreases gradually, both by a natural process of "die-off," and from the predatory

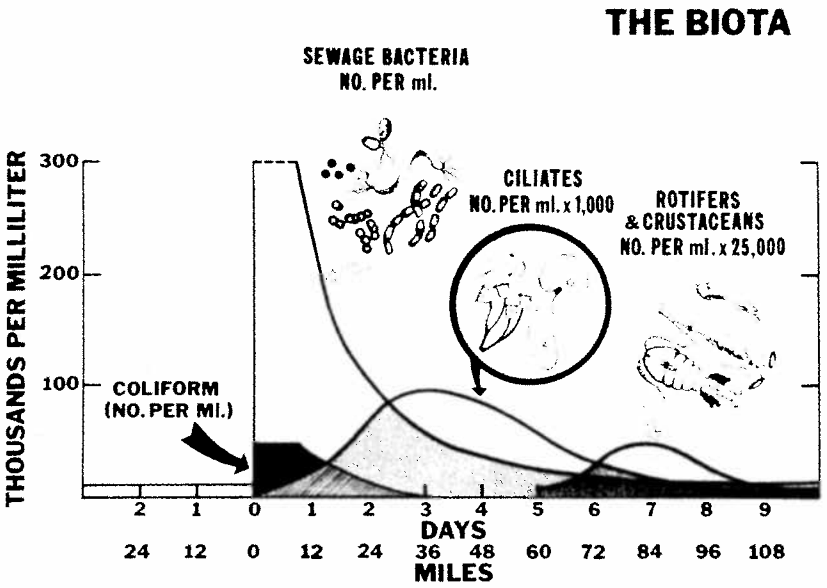

Fig. 1.9. Bacteria thrive and finally become prey of the ciliates, which, in turn, are food for the rotifers and crustaceans [1].

feeding by protozoans. After about 2 days flow, approximately 24 miles downstream of point zero, the environment becomes more suitable for ciliates, which form the dominant group of animal plankton. After about 7 days, 84 miles downstream of point zero, ciliates fall victim to rotifers and crustaceans, which become the dominant species. Thus, this sewage-consuming biological process depends on a closely interrelated succession of species of animal plankton, one kind of organism capturing and eating another.

This relationship between bacteria eaters and their prey is found in the operation of a modern sewage treatment plant. In fact, the stream can be thought of as a natural sewage treatment plant.

Stabilization of sewage in a plant is more rapid when ferocious bacteria-eating ciliates are present to keep the bacteria population at a low but rapidly growing state. In some sewage treatment plants, microscopic examination is made routinely to observe the battle lines between bacteria eaters and their prey.

6.6. HIGHER FORMS OF ANIMAL SPECIES

Figure 1.10 illustrates these types of organisms and their population along the course of the stream. Curve (a) represents the variety, i.e., the numbers of species of organisms found under varying degrees of pollution. Curve (b) represents the population in thousands of individuals of each species per square foot.

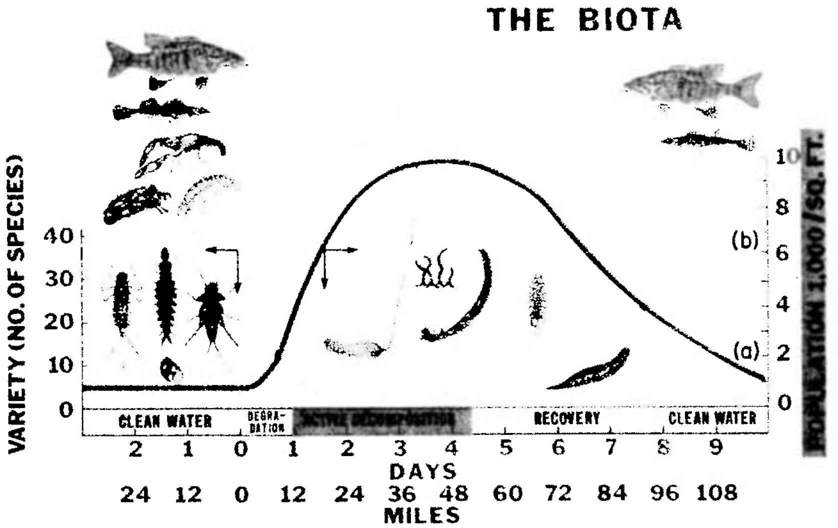

Fig. 1.10. Curve (a) shows the fluctuations in numbers of species; (b) the variations in numbers of each species [1].

In the clean water, upstream of point zero, a great variety of organisms is found with very few of each kind present. At the point of sewage discharge, the number of different species is greatly reduced and there is a drastic change in the species makeup of the biota. This changed biota is represented by a few species, but there is a tremendous increase in the numbers of individuals of each kind as compared with the density of population upstream.

In clean water upstream there is an association of sports fish, various minnows, caddis worms, mayflies, stoneflies, hellgrammites and gill-breathing snails, each kind represented by a few individuals. In badly polluted zones this biota is replaced by an association of rattailed maggots, sludge worms, bloodworms, and a few other species, represented by a great number of individuals. When downstream conditions again resemble those of the upstream clean water zone, the clean water animal association tends to reappear and the pollution-tolerant group of animals become suppressed.

Pollution-tolerant animals are especially well adapted to life in thick sludge deposits and to conditions of low dissolved oxygen. The rattailed maggot, for example, possesses a "snorklelike" telescopic air tube which is pushed through the surface film to breathe atmospheric oxygen. Thus, even in total absence of dissolved oxygen it survives. These types of animals are found commonly around sewage treatment plants near the supernatant sludge beds.

The relationship between the number of species and the total population is expressed in terms of a *species diversity index* (SDI), which is defined in Eq. (1.2).

$$\mathrm{SDI} = (S-1)/\log I \qquad (1.2)$$

where S, number of species; I, total number of individual organisms counted.

From the preceding discussion it is clear that the SDI is an indication of the overall condition of the aquatic environment. The higher its value the more productive is the aquatic system. Its value decreases as pollution increases.

7. Eutrophication [4]

Eutrophication is the natural process of lake aging. It progresses irrespective of man's activities. Pollution, however, hastens the natural rate of aging and shortens considerably the life expectancy of a body of water.

The general sequence of lake eutrophication is summarized in Fig. 1.11. It consists of the gradual progression ("ecological succession") of one life stage to another, based on changes in the degree of nourishment or productivity. The youngest stage of the life cycle is characterized by low concentration of plant nutrients and little biological productivity. Such lakes are called oligotropic lakes (from the Greek *oligo* meaning "few" and *trophein* meaning "to nourish," thus oligotropic means few nutrients). At a later stage in the succession, the lake becomes mesotrophic (*meso* = intermediate); and as the life cycle continues the lake becomes eutrophic (*eu* = well) or highly productive. The final life stage before extinction is a pond, marsh, or swamp.

Enrichment and sedimentation are the principal contributors to the aging process. Shore vegetation and higher aquatic plants utilize part of the inflowing nutrients, grow abundantly, and, in turn, trap the sediments. The lake gradually fills in, becoming shallower by accumulation of plants and sediments on the bottom, and smaller by the invasion of shore vegetation, and eventually becoming dry land. The extinction of a lake is, therefore, a result of enrichment, productivity, decay, and sedimentation. The effect of nitrogen- and phosphorus-rich wastewater discharges on accelerating eutrophication has been discussed in Section 6 of this chapter.

8. Types of Water Supply and Classification of Water Contaminants

According to their origin, water supplies are classified into three categories: (1) surface waters, (2) ground waters, and (3) meteorological waters. Surface waters comprise stream waters (e.g., rivers), oceans, lakes, and impoundment

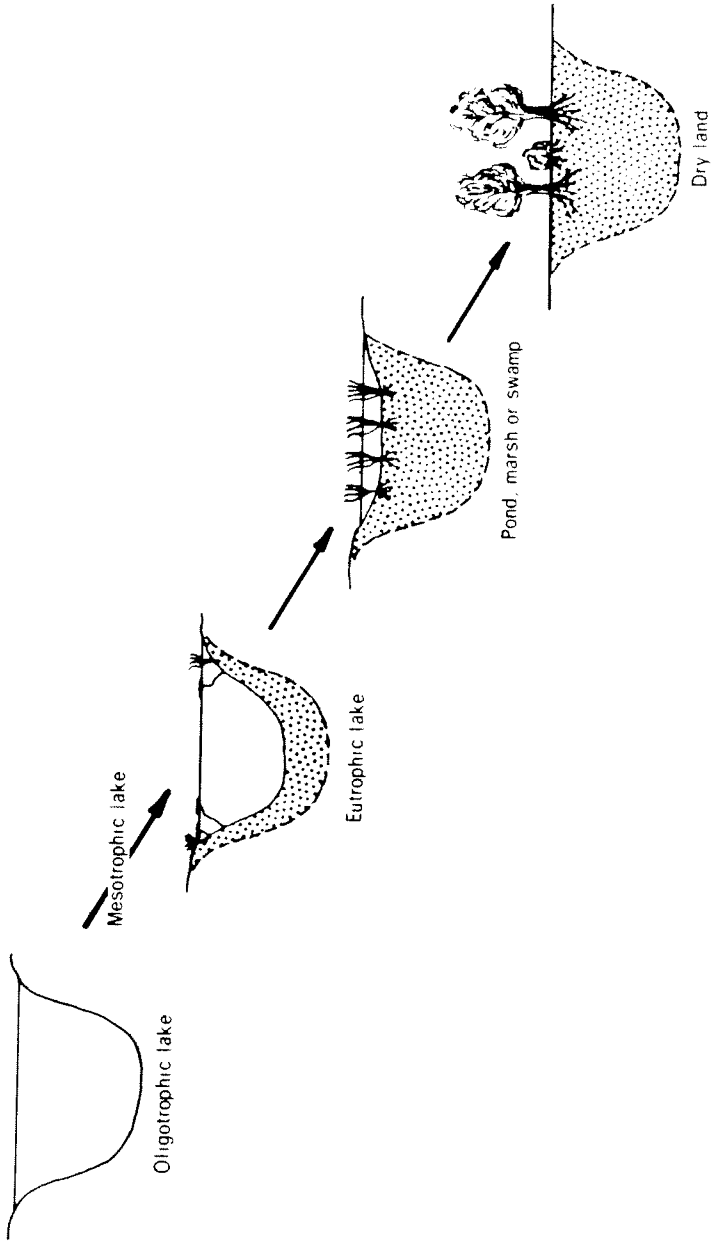

Fig. 1.11. Eutrophication—the process of aging by ecological succession [4]. *(Reprinted with permission. Copyright by American Water Resources Association.)*

waters. Stream waters subject to contamination exhibit a variable quality along the course of the stream, as discussed in Section 6. Waters in lakes and impoundments, on the other hand, are of a relatively uniform quality. Ground waters show, in general, less turbidity than surface waters. Meteorological waters (rain) are of greater chemical and physical purity than either surface or ground waters.

Water contaminants are classified into three categories: (1) chemical, (2) physical, and (3) biological contaminants. Chemical contaminants comprise both organic and inorganic chemicals. The main concern resulting from pollution by organic compounds is oxygen depletion resulting from utilization of DO in the process of biological degradation of these compounds. As discussed in Section 6, this depletion of DO leads to undesirable disturbances of the environment and the biota. In the case of pollution resulting from the presence of inorganic compounds the main concern is their possible toxic effect, rather than oxygen depletion. There are, however, cases in which inorganic compounds exert an oxygen demand, so contributing to oxygen depletion. Sulfites and nitrites, for example, take up oxygen, being oxidized to sulfates and nitrates, respectively [Eqs. (1.3) and (1.4)].

$$SO_3^{2-} + \tfrac{1}{2}O_2 \rightarrow SO_4^{2-} \tag{1.3}$$

$$NO_2^{-} + \tfrac{1}{2}O_2 \rightarrow NO_3^{-} \tag{1.4}$$

Heavy metal ions which are toxic to humans are important contaminants. They occur in industrial wastewaters from plating plants and paint and pigment industries. These include Hg^{2+}, As^{3+}, Cu^{2+}, Zn^{2+}, Ni^{2+}, Cr^{3+}, Pb^{2+}, and Cd^{2+}. Even their presence in trace quantities (i.e., minimum detectable concentrations) causes serious problems.

Considerable press coverage has been given to contamination of water by mercury. Microorganisms convert the mercury ion to methylmercury (CH_3Hg) or dimethylmercury [$(CH_3)_2Hg$]. The dimethyl compound, being volatile, is eventually lost to the atmosphere. Methylmercury, however, is absorbed by fish tissue and might render it unsuitable for human consumption. Mercury content in fish tissue is tolerable up to a maximum of 15–20 ppm. Methylmercury present in fish is absorbed by human tissues and eventually concentrates in certain vital organs such as the brain and the liver. In the case of pregnant women it concentrates in the fetus. Recently in Japan, there were several reported cases of deaths from mercury poisoning, due to human consumption of mercury-contaminated fish. Analysis of fish tissue revealed mercury concentrations of approximately 110–130 ppm. These high mercury concentrations, coupled with the large fish intake in the typical Japanese diet, caused this tragedy.

Contamination by nitrates is also dangerous. Fluorides, on the other hand, seem actually beneficial, their presence in potable waters being responsible for appreciable reduction in the extent of tooth decay. There is, however, considerable controversy concerning fluoridization of potable water.

Some physical contaminants include (1) temperature change (thermal pollution). This is the case of relatively warm water discharged by industrial plants after use in heat exchangers (coolers); (2) color (e.g., cooking liquors discharged by chemical pulping plants); (3) turbidity (caused by discharges containing suspended solids); (4) foams [detergents such as alkylbenzene sulfonate (ABS) constitute important cause of foaming]; and (5) radioactivity.

Biological contaminants are responsible for transmission of diseases by water supplies. Some of the diseases transmitted by biological contamination of water are cholera, typhoid, paratyphoid, and shistosomiasis.

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