APPLIED STREAM SANITATION

Second Edition

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PREFACE

Applied Stream Sanitation as developed in this text is intended as a complementary contribution to that well-known classic, *Stream Sanitation*, by the late Earle B. Phelps.* Much that we know today about the fundamentals of stream sanitation and the capacity of streams to assimilate natural and man-made wastes stems from the early work of Phelps. His persistent interest in the stream as a living thing extended beyond scientific observation and description to a canny insight and capacity to synthesize its complex behavior into quantitative formulations. These formulations are the foundations of modern stream sanitation or, more broadly, the field of *potomology*.

As defined by Phelps in *Stream Sanitation*, potomology applies knowledge from many areas of the physical and biological sciences and mathematics; the potomologist need not qualify as a specialist in each of these areas, but he must be able to integrate knowledge from all of them as he pursues his own speciality, the *science of rivers*. The definition of potomology in the present volume is extended to also include knowledge in areas of the social sciences and engineering, essential elements in effective pollution control and wise use of water resources. Furthermore, in application potomology becomes as much an *art* as a *science*, tempered by experience and professional judgment.

In terms of practical usefulness the waste assimilation capacity of streams as a water resource has its basis in the complex phenomenon termed stream self-purification. This is a dynamic phenomenon reflecting hydrologic and biologic variations, and the interrelations are not yet fully understood in precise terms. However, this does not preclude applying what is known. Sufficient knowledge is available to permit quantitative definition of resultant stream conditions under expected ranges of variation to serve as practical guides in decisions dealing with water resource use, development, and management.

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* Phelps, E. B., *Stream Sanitation*, Wiley, New York, 1944.

The orientation of this text is therefore toward practical application, in terms useful not only to the professional potomologist, whether scientist or engineer, but also to the conservationist, economist, lawyer, and administrator. In addition to presenting useful tools for evaluating solutions to water pollution, it is hoped it will assist in developing an informed, intelligent appreciation of the complex problem of waste disposal and pollution control in a technological society.

Over the years I have been fortunate in my associations with government and industry in studies of many rivers. From this work I have drawn liberally, including the practical illustrations. I acknowledge gratefully the cooperation and extensive data supplied by associates in government and industry, and the contributions by colleagues and my many students through academic years. I wish particularly to acknowledge the research support and the survey and river sampling data provided by National Council for Stream Improvement, Inc., which have made possible the detailed studies of many of these rivers. Since the publication of the first edition of this book in 1970, my continuing work as a consultant to government agencies, especially the U.S. Geological Survey, and to private industry has brought forth a wealth of new information, which I have incorporated into the second edition.

Here I pay special tribute to the memory of my first wife, Harriet O'Brien Velz, who participated in all of my river studies and without whose painstaking researches and constant assistance many of the studies could not have been undertaken and accomplished. In the preparation of this second edition, I am deeply indebted to my wife, Patricia, for her critical editorial work and Spanish translations.

Finally, I pay tribute to the memory of Earle B. Phelps. It has been my great privilege to have known Professor Phelps intimately as his student, associate, and friend during his fruitful years. The potomologist will long be in his debt, and to me it is especially gratifying to extend the usefulness of his work in applying to practical problems the fundamentals of stream sanitation he so brilliantly conceived and formulated.

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Longboat Key, Florida
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CHAPTER 1

INTRODUCTION

THE WASTE PRODUCTS OF MAN'S ACTIVITIES

In the natural cycle there is no waste in the sense of loss; each living thing borrows its substance briefly only to return to the inanimate storehouse and itself be reused by countless generations. Man makes very inefficient use of the natural resources that he borrows and in the process creates a colossal amount and variety of waste products, *solid, gaseous*, and *liquid*. Raw material is seldom suitable for direct use. In the process of refining, fashioning, and converting a large fraction is discarded. Some is reused for other purposes, but inevitably there are unwanted, unprofitable waste products. Some are dumped in spoil banks; some are burned, with end products exhausted to the atmosphere; some are buried; some are promiscuously scattered in cities and over the countryside; and an increasing amount is discharged into the intricate water-carriage systems we call sewers and ultimately reaches streams, rivers, lakes, and estuaries.

In a simple agrarian society the waste products are few and are either plowed into the soil or are so widely distributed as to be unnoticeable as they return to the land. Not so in the modern urban-industrial concentrations. Technology has reached a stage at which it is relatively simple to extract and fashion the useful fraction of raw materials—the real challenge is how to dispose of the ever-increasing quantities of unwanted solid, gaseous, and liquid waste products without befouling the environment in which we live and work.

The *solid wastes*, garbage and trash, collected by organized American community refuse systems in 1960 averaged over 4 lb/capita/day, or 0.73 ton/year; and it was estimated then that by 1980 refuse production will approach

1 ton/capita/year. As reported by Glysson [5], studies conducted in Ann Arbor, Michigan in 1975 and 1981 that segregated the community solid waste production into three classifications disclosed a typical refuse generation rate of 43% residential, 50% commercial, 5% industrial, and 2% uncertain. This comprised a total as 6.0 lb/capita/day, or about 1 ton (2190 lb)/capita/year. These rates of community refuse generation were confirmed as also representative of other communities, providing a city is not heavily industrialized; if the industrial portion tends to exceed 5%, the industry would more likely dispose of its own solid wastes.

Glysson and other authorities believe earlier estimates of continued increase in rates of refuse production were much too high, and that rates have rapidly rounded off to saturation levels at about 1 ton/capita/year.

There are few quantitative measures of the amount of *gaseous waste* products, but the pall over cities testifies to increasing magnitude. It is estimated that the burning of coal, oil, and natural gas adds six billion tons of carbon dioxide to the earth's atmosphere yearly. At this rate, by the year 2000 there will be approximately 25% more carbon dioxide in the atmosphere than at present [1]. In addition, industrial processing releases a variety of other gaseous end products that usually contain large quantities of particulate matter settling thinly over wide areas, but massive in the aggregate.

The *liquid waste,* our primary concern in this book, comprises the *spent water supply* of industries, communities, and individual households, to which has been added in the process of use almost an infinite variety of unwanted waste products. In addition, agricultural drainage, urban storm drainage, and natural landwash carry large quantities of waste products to the streams. We shall deal with these in more detail later.

Interlinkage of Solid, Gaseous, and Liquid Waste Products

Although our focus in this text is on waste products that ultimately reach a watercourse, rationally the waste disposal problem must be considered as a unit in toto, the solids, the gases, and the liquids. The three states in which man produces his waste products are interlinked. Simply to transform a waste product from one state to another does not necessarily constitute satisfactory disposal; in fact it can aggravate the problem of ultimate disposal. Incineration of solid wastes may add to already serious air pollution. The products of evaporation and burning may present more difficulty in ultimate disposal in the atmosphere than treatment in liquid form with the residual effluent assimilated in the stream. On the other hand, condensates from evaporation, burning, scrubbing, and industrial recovery processing may produce liquid wastes greatly adding to stream pollution. Drainage from solid waste landfill disposal systems may degrade nearby streams. The contributions of ground garbage and other solids to the sewers may increase the residual effluent load to the watercourse already burdened beyond its waste assimilation capacity. The ease of water-carriage transport leads to an ever increasing wastewater burden, residuals of which ultimately reach the stream.

Overall waste disposal is a complex problem for which no simple solution can be applied wholesale. Regardless of how we treat the wastes, an inevitable *residual* remains for ultimate disposal on land, in the atmosphere, and in the steam. Each must be assigned a share of the burden, depending on relative assimilation capacities and technical and economic feasibility.

In a sense civilization is measured by how it deals with its waste products and the kind of environment in which it is content to live and work. Primitive man has no system; waste disposal is wholly promiscuous. When the environment becomes too befouled, he moves. Modern man, who cannot escape by moving, has to a degree applied science and engineering principles to waste disposal, but as yet he can claim only limited success. The magnitude is overwhelming, unpopular, and costly. There is, however, increasing evidence that modern man in his affluence is not satisfied with a deteriorated environment in which he merely can survive and that he is willing to work and pay for quality environment in which he can thrive.

In setting levels of quality environment it is well to keep in mind that it is the public who pays—that the cost is passed on either directly in taxes or indirectly in increased prices of products of industry or increased rates of utility services. Prudence dictates that careful evaluation be given to alternative methods.

Definition of Pollution

"Pollution" is a very general term and is defined in many ways. In its broadest sense as conceived by the layman it is the befouling of the environment by man's activities, particularly by the disposal of solid, gaseous, and liquid waste products. It also carries a relative connotation as to degree of befouling (impurity) in relation to interference with intended uses of land, air, and water. This leads to many conflicting interpretations of what constitutes pollution and the necessity for more precise definitions suitable fc administrative management and legal control. These phases are considered further in Chapter 15.

By virtue of the physiological necessity of drinking water for man and other animals, water pollution falls into two rather sharply defined classifications—namely (a) pathogenic organisms or toxic substances harmful and hazardous and (b) substances that are deleterious, offensive to sight, taste, and smell, or detrimental to the usefulness of natural waters. "Pollution" is the inclusive term; "contamination" is the distinguishing term that is applied to harmful and hazardous waste constituents.

With the increasing variety and quantity of waste products and the interlinkage among solid, gaseous, and liquid states, the hazard of stream pollution is great. Gross pollution that seriously interferes with the beneficial uses of water resources is unnecessary, controllable, and manageable by scientific and engineering methods. However, complete elimination is *impossible;* some degree of pollution is *inevitable*. Man should not delude himself about this; he must accept and learn to accommodate himself to it. It is a matter of degree, not a matter of elimination. The degree of pollution that is acceptable depends on what we are willing to work for and pay for.

Waste disposal and pollution control are an integral part of the broader problem of the development, use, and management of the total water resource. The socioeconomic importance of water resources therefore forms a basis for more detailed consideration.

Socioeconomic Importance of Water Resources

The socioeconomic structure of entire regions is shaped to a large degree by the water resource available and how it is used, developed, and managed. Paradoxically, in areas blessed with abundant water resources the relation to growth and prosperity is not always adequately appreciated. Too frequently water is taken for granted, often with waste and abuse. In arid regions, when wells fail and rivers dry up, bitter experience teaches the meaning of water resources. Then comes fuller appreciation of the need for control, development of the little available, and careful use and management.

A glance at a map quickly reveals that all large cities straddle a river or border a large lake or an estuary; the same applies to the distribution of industry. In the arid regions population is sparse and cities are few, with but a scattering of industry. Water is the lifeblood of community and industrial activity. The regions that plan ahead and exercise intelligent management of their water resources will thrive; those that drift and do not foresee needs and problems, even if endowed with good water resources, will decline.

The United States population-socioeconomic structure has made a rapid shift from a rural-agricultural way of life to that of an urban-industrial character, and is likely to remain so. This shift from dispersed-rural to complex centralization of an urban-industrial way of life results in a double-edged pressure upon water resources: first, in the concentrated withdrawal of *quantity* for water supply needs; and second, in the concentrated impact upon *quality* of the watercourse receiving the discharge of the spent water supply, the urban-industrial wastewater.

It is not surprising that these new patterns of growth and increasing demands on limited water resources give rise to water use conflicts and rivalries in which the complex problem of waste disposal and pollution control intensifies. An overview of the multiple-use character of water resources and the impact on the waste-assimilation capacity of streams provides an orientation to the role of the science and art of *applied stream sanitation*. A brief critical review of past piecemeal attack on water-resource problems also provides a background for understanding both why we are where we are and the need for a more rational approach to meeting future needs.

Rational Water Resource Development and Use

A rational approach to water-resource development and use implies that, first, we be realistic about our concept of conservation. Interest in water resources is not for the sake of water but for the sake of people who must use it. Irrationally, some hold that conservation implies forbidding use. *Nonuse is total waste* and is as much a loss as destructive overuse. (This does not imply that some areas should not be preserved in their natural state, as contemplated in the Wild Rivers program.) Irrationally others hold that "first come first served," and would appropriate water resources for their exclusive use to the detriment of other users. This is *abuse*. The rational concept is balanced multiple use with the objective of fullest use over the years without waste or abuse.

Two unique characteristics of water resources should be appreciated if a rational balance among uses is to be attained: first, that water is a dynamic resource; second, that it is inherently a multiple use resource.

In addition to a very unequal geographical distribution, water in the natural setting is a highly *dynamic* resource. Unlike a fixed mineral deposit, water varies in the amount that is available at any location from day to day and season to season. Seen from aloft a river appears as a fixed entity whose size is measured by the number of square miles of tributary drainage area, but seen from a location on its bank a river becomes dynamic, its size varying with the amount of water flowing by in a unit of time. What appears to be a large river during the spring flood may become a small creek during the summer drought. It is this highly dynamic character of streams that adds to the difficulties of dependable use and control of quality.

Nevertheless, "dynamic" does not mean "chaotic"; observed over a period of years stream runoff, although variable, is orderly, following the laws of chance occurrence—unless the natural setting has been tampered with. Statistical analyses of the runoff records determine the *range* of streamflow available and the drought severities that can be expected. Man must either design his activities within this range of variation and decide on a level of risk of water shortage during droughts or *develop* the water resource by such practice as drought control to regulate variations between the extremes of flood and drought. In turn, the natural waste assimilation capacity of the stream and the associated water quality are not fixed quantities but rather ranges in potential paralleling the natural variations in streamflow.

When man enters the scene, nature's orderly system is altered. Depending on how they are planned and operated, man-made river developments and water uses can have an effect that is either beneficial or detrimental to the waste assimilation capacity and associated water quality. Thus a second complicating factor is the multiple use character of water resources.

Inherently, water is a *multiple-use* resource. Moreover, seldom is a city alone on a river; others are either above or below, and what they or some private or governmental agency may do with water has an *impact* on other users. As the urban-industrial complex grows, competition for the limited water resources intensifies among potential uses:

1. Community and industrial water supply.
2. Electric power generation—hydro, fossil fueled, and atomic fueled.
3. Recreation—bathing, boating, and water sports.
4. Irrigation.
5. Navigation.
6. Fish, shellfish, and wildlife.
7. The inevitable necessity of ultimately disposing of the residual of wastes from communities, industries, agriculture, and natural sources.

Each of these individual water uses is important; often, to the specific user, his or her use is the most important. Herein lies the basis for difficulties and conflicts of interest. Incompatibility among uses is possible, but uses need not be mutually exclusive. The matter of priority and degree of use among users may change in place and time. The shift from an agricultural to an urban-industrial society places higher priorities on community and industrial water supply, tremendous needs of water for steam-electric generation, and water-based recreation.

Although not generally recognized as such, a key water-resource use in a technological society is satisfactory ultimate disposal of the residual of the waste products of man's activities. The waste assimilation capacity of the stream becomes a *prime* water resource asset to be wisely used and developed. Thus it is crucially important to carefully evaluate the impact, beneficial or detrimental, of other water resource developments and uses on the waste-assimilation capacity of the stream.

As the pressures of urban-industrial growth continue, multiple water uses become more and more inextricably interrelated. No longer can each use be viewed in isolation; a *rational, integrated* approach is essential.

RATIONAL STREAM SANITATION

Historical Perspective

A brief review of past practice may provide a background illuminating the need for a more rational approach.

Piecemeal Development

In the past, water-resource development and use, with notable exceptions, has taken place largely on a piecemeal basis, with each water use considered much as a problem independent of all others. In this practice, pollution control did not keep pace with national growth.

In some instances a disaster, such as a flood, has dictated a one-sided view; development centered on flood control, with inadequate consideration of the overall water needs, including satisfactory waste disposal. In other instances some special public or private interest dominated, and a single-minded development, such as large-scale navigation works, proceeded on a narrow basis, often to the detriment of the waste assimilation capacity of the stream and the associated water quality. Another example is hydroelectric power, which often has been oriented to serving the peak of the electrical power demand without concern for the desirability of continuity in streamflow; if a power plant reduces streamflow to a trickle on weekends and at nonpeak hours, the effect on the waste-assimilation capacity of the stream can be disastrous.

Public agencies assigned powers and responsibilities to deal with community and industrial water supply and waste disposal have, possibly unwittingly, fostered further fractionalization, piecemeal development, and inadequate stream pollution control. The two interrelated phases of the water contact cycle were split as though they were independent; incoming water supply was dealt with largely as a problem separate from that of the outgoing wastewater return. Incoming supply received the major attention, whereas the satisfactory disposal of the spent water supply, the wastewater return to the stream, received scant or, at best, belated attention.

In turn, each of these two phases was further fractionalized. In many instances community water supply was planned and developed on a narrow basis, leaving industries and rapidly expanding fringes outside the central political unit to fend for themselves. Hodgepodge water-supply systems resulted, to the detriment of community and industrial growth.

Similarly, the disposal of wastewater was fractionalized. In many instances industrial waste was considered as a problem separate from that of community sewage disposal and deliberately excluded from the municipal sewers and treatment works. Pollution control was disease-oriented, centered on sewage, with divided and belated attention to industrial waste-disposal problems.

Furthermore, regulatory agencies, with but few exceptions, depended almost exclusively on treatment as the cure-all for pollution prevention and abatement. Treatment is an essential line of defense but, since it is a percentage removal, there always remains a residual to be handled by self-purification of the stream. When design emphasized details of treatment works rather than quantitative determination of the waste-assimilation capacity of the receiving stream, there was a tendency to add costly features that did not contribute to the removal of the wasteload. The expenditure could more profitably have been devoted to other means of enhancing the waste-assimilation capacity and water quality.

Much is to be learned from our past practices, but clearly, if we are to meet society's current and future needs, much more rigorous scientific and engineering analysis must form the basis for integrated water-resource development and use, including a more comprehensive approach to stream sanitation.

The Early Scientific Base

The rational method of stream analysis as applied to assessment of river quality is by no means new; it has a long history of growth, development, and application, dating back to 1886 and the establishment of the Lawrence Experiment Station of the State Board of Health of Massachusetts [6]. This marks the beginning, because the concept of satisfaction of organic waste was changed from a purely chemical one, equivalent to combustion, to the concept of biochemical change brought about by biological life. This was the dramatic change in approach that emerged from the Lawrence station, referred to by Phelps [7]:

> *During the first years of that station's existence the essential bio-chemical nature of the processes of oxidation in sewage treatment was so adequately demonstrated and the details of the process so thoroughly studied as to establish this major concept as one of the foundation stones of all future work.*

On this foundation rests the fundamentals of organic self-purification in streams, as conceived and developed by Phelps and the early research staff of the U.S. Public Health Service.

The original concept of biochemical oxidation rate of organic matter was first outlined by Phelps in the relative stability tests in 1907–1909 [8], referred to in Chapter 4 as *Phelps' BOD law:*

> *The rate of biochemical oxidation of organic matter is proportional to the remaining concentration of unoxidized substance, measured in terms of oxidizability.*

Stated in another way, the BOD is satisfied at a constant rate. This law has stood the test of time and is the basis of almost all deoxygenation formulations. It is of interest to note that the principle of constant rate also applies to a large degree to bacterial death, radioactive decay, and heat dissipation.

About the same time (1911) Phelps [10], in studies of pollution of New York Harbor, developed the first basis for determining reoxygenation by reaeration from the atmosphere based on the laws of solution and diffusion.

Later, Streeter and Phelps (1924), based on the Ohio River studies, combined deoxygenation and reaeration concepts into a simplified formulation, commonly referred to as the *oxygen sag equation*. The major difficulty in application to other rivers is derivation of the appropriate reaeration coefficient for the varying reaches of a river. Too frequently, generalized deoxygenation and reaeration rates are employed without knowledge of the channel characteristics of the specific river. As a consequence, such computed DO profiles frequently are in poor agreement with observed river conditions except on the particular river on which they were developed.

A number of investigators have developed methods for deriving more specific reaeration rates based on river parameters (such as turbulence), in themselves difficult to measure, and hence there is considerable deviation in results among methods, as discussed in Chapter 4.

The reason Phelps' original basic reaeration formulation was not applied for many years was the complex and lengthy mathematical solutions involved. Velz (1939) [11] provided a rapid graphical solution which made possible practical application to stream conditions, taking into account changes in channel characteristics easily measurable from reach to reach. This method led to many detailed stream analysis assessment applications which have been verified against observed river dissolved oxygen profiles. (See Chapter 4.)

Stages in Application

Awareness of the early scientific work ought to be supplemented by awareness of the stages in *practical application* in regulatory control of water pollution. In the early years, outside of academic and research circles, little thought was given to pollution control. Most municipal and industrial wastes were discharged raw into the nearest water course.

This negligence was followed by a period of awakening, but of cautious exercise of state control in what might be termed the *half-loaf* philosophy—get the municipalities to treat their wastes and then pursue the other half, the industrial wastes.

There ensued the Great Depression of the 1930s and the unemployment public works relief programs. They permitted a great expansion in sewerage and sewage treatment construction, resulting in more municipal treatment than was achieved in the entire effort of prior years.

Following the interlude of World War II, the states experienced public support for more vigorous pollution abatement, both municipal and industrial. This was the beginning of the era of which Phelps [12] so prophetically spoke.

> *It is within the framework of such overall river standards that the local treatment plant should be designed. It must carry its proper burden of pretreatment and, what is equally as important and equitable, not wastefully overdo under the given circumstances. We are happily passing out of that primitive period during which it was popular to enact laws calling for a given standard of treatment—generally a very high one—throughout the state regardless of the character or use of the stream. Our present purpose is, and must increasingly become, an attempt to fit the design of the works to the design of the stream with all that this implies. Only in this way shall we achieve a true conservation of a natural resource.*

It was during this period that state regulatory agencies began intensive stream analysis and river-quality assessment studies as an aid to deciding on alternative solutions to problems and establishing priorities in action programs. A notable example was the work of the Michigan Water Resources Commission in preparation of comprehensive hydrologic and stream analysis assessment reports of drainage basins in Michigan. Efforts were also made in that direction by other states.

It was also in the decade following the war that industry recognized its responsibility and began seriously to consider its role in waste treatment and conservation of water resources. A good example is the formation of the National Council for Stream Improvement of the Pulp, Paper and Paper Board Industries, Inc. The council sponsored research, including river-quality assessment studies, to guide remedial effort and to aid in site selection for new mills. Many of these river basin studies, such as the Willamette in 1950 [13], were made by independent academic organizations, with results accepted by both the state regulatory agencies and the industries as the basis for action programs.

This was an era of enlightenment, when substantial progress was being made in water quality management and resource development through state and local initiative.

State and Local Initiative

Contrary to current misconception, the traditional state programs over the years have achieved a great deal—much more than they have been given credit for—and at much less cost than is often assumed. Considering the tremendous growth and industrial expansion in the last half-century, the water pollution control programs of the states, by and large, have done a remarkable job; the nation's rivers have not been defiled. Furthermore, the states have pioneered the development of sound rational programs based on constantly improving analysis and assessment as a basis for action.

As one of many examples, Gleeson's [14] history, *The Return of a River: The Willamette River, Oregon* is a description of state and local initiative and intelligent action that should be required reading for everyone interested in pollution control.

Local initiative dominated. Industry and state and local government considered the Willamette River Basin as a whole, as a long-range program. Water and land resources were viewed in relation to people's needs and desires and to the economy of the area. The program had a strong scientific base throughout; rational stream analysis and assessment guided decisions. Cooperative effort was the theme; the state law was persuasive enough to obtain voluntary compliance. There were no punitive court cases—industries were not put out of business. State financial aid and tax incentives were provided (less than 13% of the total cost was from federal sources). Actions were not arbitrary; flexibility involved multiple lines of defensive and offen-