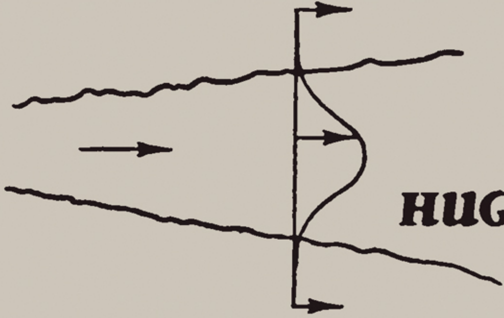
MIXING in Inland and Coastal Waters



HUGO B. FISCHER
E. JOHN LIST
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NORMAN H. BROOKS

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HUGO B. FISCHER

Department of Civil Engineering
University of California
Berkeley, California

E. JOHN LIST

ROBERT C. Y. KOH

W. M. Keck Laboratory of Hydraulics
and Water Resources
Division of Engineering and Applied Science
California Institute of Technology
Pasadena, California

JÖRG IMBERGER

Department of Civil Engineering
University of California
Berkeley, California

NORMAN H. BROOKS

W. M. Keck Laboratory of Hydraulics
and Water Resources
Division of Engineering and Applied Science
California Institute of Technology
Pasadena, California

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Preface

This book is an outgrowth of research contributions and teaching experiences by all of the authors in applying modern fluid mechanics to problems of pollutant transport and mixing in the water environment. It should be suitable for use in first year graduate level courses for engineering and science students, although more material is contained than can reasonably be taught in a one-year course, and most instructors will probably wish to cover only selected portions. The book should also be useful as a reference for practicing hydraulic and environmental engineers, as well as anyone involved in engineering studies for disposal of wastes into the environment. The practicing consulting or design engineer will find a thorough explanation of the fundamental processes, as well as many references to the current technical literature which may be followed for greater detail. Besides being led to the current literature, the student should gain a deep enough understanding of basics to be able to read with understanding the future technical literature in this evolving field.

Chapter 1 discusses the relevance of this book to overall environmental management and explains certain basic concepts which apply throughout, such as dimensional reasoning. Chapter 2 presents the classical theory of diffusion in the context of molecular diffusion, primarily as an introduction to the equations and concepts used in later chapters (e.g., Chapter 3 on turbulent mixing). Chapter 4 describes shear flow dispersion—that phenomenon that describes the stretching and mixing of pollutant clouds caused by the combined action of shear and lateral mixing—and completes the presentation of background material necessary to the study of mixing in the environment. Chapters 5–7 apply the material in the earlier chapters to the cases of mixing in rivers, in reservoirs, and in estuaries, and Chapter 8 completes the discussion of rivers and estuaries by describing the use of physical and numerical models.

Whereas the previous chapters deal with natural flow conditions, Chapter 9 treats buoyant jets and plumes, strong man-induced flow patterns used to achieve rapid initial dilutions for water quality control. Chapter 10 gives a design-oriented discussion of outfall diffusers and includes sections on the internal hydraulics of outfalls and the techniques of hydraulic modeling of outfall flows with density differences.

The level of treatment presumes that the reader has an understanding of calculus up to some introductory work on partial differential equations, and an undergraduate level background in hydraulics or fluid mechanics; some knowledge of the science of hydrology and the basic characteristics of rivers, lakes, estuaries, and the coastal ocean, and a general orientation in environmental engineering, including water supply and waste treatment will also be helpful. The senior author has taught most of the material (Chapters 6 and 9 excepted) to a class of beginning and advanced graduate students in hydraulic and sanitary engineering at Berkeley for the past 10 years. Those students who brought only the usual undergraduate background in Civil Engineering have been able to understand the course, but it is certainly the case that the practitioner of mixing studies in the environment will benefit from advanced courses in fluid mechanics and mathematics, and the better the background the student brings to this book the more easily he or she will understand the material.

A note is in order on the writing of the various chapters. Although this is a jointly authored book, each chapter had a primary author or authors. Chapter 1 is by NHB; Chapters 2 and 3 are jointly by EJL, JI, and HBF. Chapters 4, 5, 7, and 8 are primarily by HBF, Chapter 6 by JI, Chapter 9 by EJL, and Chapter 10 by RCYK.

Acknowledgments

This book was begun in 1970 during the first author's sabbatical leave at the University of Cambridge, and much of it was completed during the same author's second sabbatical at the Woods Hole Oceanographic Institution in 1977. Most sincere thanks are due for the gracious hospitality and assistance at both institutions and particularly to hosts Professor George Batchelor and Dr. Gabriel Csanady. The authors would particularly like to express their appreciation for the stimulus and valuable research contributions made by their students and colleagues, and for comments received on portions of the manuscript from Jack Kennedy, William Sayre, Ian Wood, Frederick Sherman, and Lloyd Townley. J. C. Patterson, Ian Loh, and R. H. B. Hebbert assisted in the writing and computations of Section 6.8.2 and collaborated in the collection of much of the data from the Wellington Reservoir. Karen Ray at Berkeley and Theresa Fall and David Byrum at Caltech assisted in typing and drafting. Finally, we are particularly appreciative of the efforts of Mabel Iwamoto, secretary of the Hydraulics Group at Berkeley, and Joan Mathews, secretary of the Keck Hydraulics Laboratory.

We also gratefully acknowledge the sponsorship over many years of the research that led to this book by the National Science Foundation, the U.S. Public Health Service, the Environmental Protection Agency, the Ford Energy Program at Caltech, the Southern California Edison Company, the Pacific Gas and Electric Company, the U.S. Geological Survey, the Australian Water Resources Council, the Australian Research Grants Committee, the Public Works Department and the Metropolitan Water Board of Western Australia, and last but most certainly not least, the Water Resources Center of the University of California. We particularly note the support of the California Institute of Technology and the University of California, Berkeley, in the final preparation of the manuscript; without the support of these institutions and ultimately of the people of the state of California there would be no book.

Finally, for the support and patience of our five families we are truly thankful.

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Chapter 1

Concepts and Definitions

In recent years hydraulic engineers have frequently been asked to analyze and predict mixing in natural bodies of water. It is no longer sufficient to deal only with water *quantities* because of the growing concern over water *quality*. Many pollutants enter the hydrologic cycle both intentionally and unintentionally; downstream water quality depends on both the hydrodynamics of transport and mixing, and the chemistry and biology of natural water systems. The purpose of this book is to deal with the hydrodynamic aspects of water quality management in natural bodies of water.

1.1 THE ROLE OF HYDROLOGY AND HYDRAULIC ENGINEERING IN ENVIRONMENTAL MANAGEMENT

The hydrosphere, like the atmosphere, is of extraordinary importance to mankind because water and air are fluids. By their motions they transport and disperse many essential elements for life and productivity. They are also absolutely essential for management of the quality of the natural environment, including the disposal of residuals. Examples range all the way from ordinary breathing (you exhale extra carbon dioxide to be dispersed) to massive discharges of wastewater into rivers and oceans. Regardless of the size of the problem, if these vital fluids were utterly motionless we would suffocate or be inundated in our liquid wastes!

1.1.1 Overall Framework for Environmental Management

Hydrologic mixing processes are but a small part of the overall process of environmental management. How the overall environmental system works is shown by the diagram in Fig. 1.1, applying to all environmental media—air, water, land. It applies to the management of hundreds of different pollutant substances, which do not act independently because there are many synergisms. For example, an increase in the temperature of a river, due to heated water discharge, may decrease its assimilative capacities for oxygen-demanding wastes such as sewage effluents. Note that the diagram is not limited to emission-response relations for pollutants, but also implicitly covers the environmental effects of all kinds of activities—e.g., building dams or dredging harbors, two typical hydraulic activities.

For problems dealing with the water environment, the hydraulic engineer works mainly on the box called "Transport, Transformation, Accumulation." This box is shared with chemists and biologists, who are also concerned with the processes that take place between the point where a pollutant is discharged into the water environment and some other sites where the ambient water quality is observed. The hydraulic engineer has a special challenge, however, because the design of hydraulic structures, such as outfalls, may have a profound effect on the water quality observed. Therefore, he must at times be the designer who takes the ambient water quality requirements and works backwards to develop the concepts and dimensions for an engineering system to achieve those results.

A good environmental control system is one which skillfully optimizes, depending upon the pollutants being handled, the combination of: (a) control of pollutants at the source (often called "pretreatment" for sewer systems), (b) wastewater treatment, and (c) dispersal in the environment. In summary, hydraulic engineers are often called upon to make the interfaces between man's activities, involving water and wastewater, and the natural environment. For a long time (all the way back to the Roman Empire!), they have had the responsibility for drawing our water supply from natural water bodies; now we must pay equal attention to how it is returned—in diminished amounts and of poorer quality.

1.1.2 Using the Water Environment for Waste Assimilation

From the geologic point of view, the fresh waters of the earth have always carried away the residuals from the land, usually delivering them to the ocean. This includes weathered mineral matter either in solution or as sedimentary particles. Much organic debris is also swept along by the rivers. The ocean has always been the sink for all the material washed off the land. Therefore, it is a

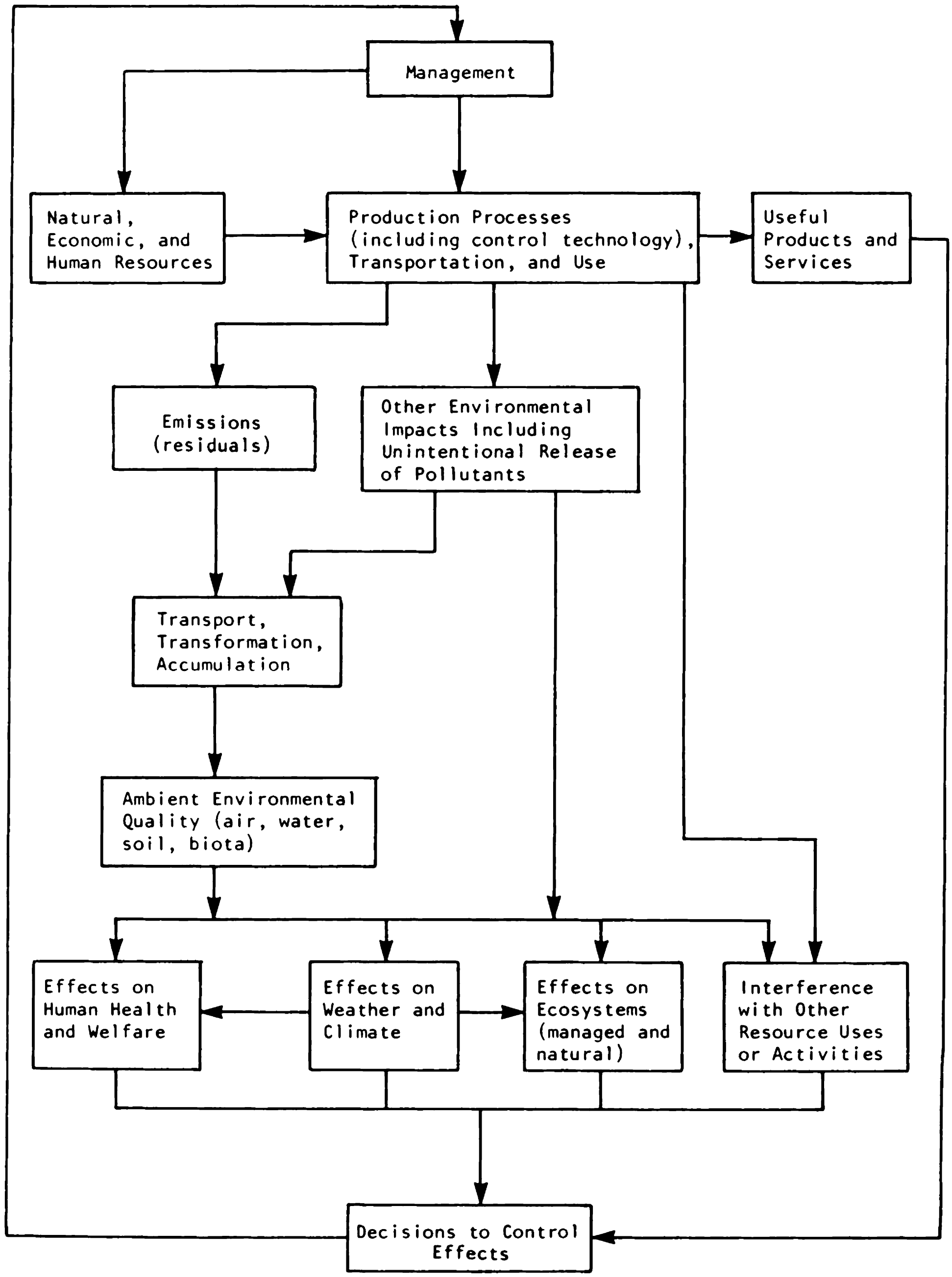

Figure 1.1 Framework for environmental protection. [From National Academy of Sciences (1977).]

perfectly natural thing for man also to use, in a limited way, the hydrologic cycle to transport his residuals. In fact, some of the dissolved salts, which must be flushed out to maintain mass balance of salts, initially enter the water supply systems by diversions from natural streams or groundwater.

If we think of using the water environment for receiving wastewater or residuals, it is important to consider the wide range of typical waste materials. We can arrange a list starting with the least dangerous types of pollutant and proceeding to the most hazardous.

(1) *Natural Inorganic Salts and Sediments.* These materials are not toxic and only become possible pollutants in excessive doses, such as increases in turbidity due to dredge-spoil dumping.

(2) *Waste Heat.* Once-through cooling systems for electric generating plants use water for carrying away large quantities of low-grade waste heat. When the body of water is large enough, it serves as the cold reservoir of the plant's thermodynamic cycle.

(3) *Organic Wastes.* Domestic sewage containing ecosystem materials (like carbon, nitrogen, and phosphorous) can cause bad stenches and nuisances, but if adequately treated and dispersed, these ecosystem materials can be safely assimilated into large water bodies. The biochemical oxygen demand may be sufficiently reduced by dilution so that it can be satisfied by the natural dissolved oxygen in the water body.

(4) *Trace Metals.* Examples are lead, mercury, and cadmium which are naturally present in the environment in very small amounts, but man's wastewaters often have very much higher concentrations which can be toxic.

(5) *Synthetic Organic Chemicals.* These substances are slow to degrade in the environment and are often bioaccumulated in the food chain. Even though wastewaters may be subjected to high initial dilution, the food chain is capable in some instances of multiplying the concentrations by a factor of 10^5 in successive food chain steps. It is remarkable how biological processes can do just the opposite of the physical process of turbulent mixing which reduces concentration.

(6) *Radioactive Materials.* The necessity of long-term storage of radioactive wastes without leakage or contamination of natural waters is causing grave concern because of the high toxicity of these materials (e.g., plutonium).

(7) *Chemical and Biological Warfare Agents.* Clearly these can not be dispersed in the environment without great danger to human beings as they are designed to be exceedingly toxic in very small doses.

With an extreme range of types of water pollutants from something as ubiquitous as waste heat to deathly chemicals, environmental strategies must obviously relate to the substance to be disposed of! For example, the strategy of *wide dispersal* ("dilution is the solution to pollution") is suitable only for heat and natural organic materials which are to be reassimilated in the global ecosystem. Trace metals in small amounts and nontoxic compounds can be dispersed in large bodies of water if the resulting increases in the background concentrations are minimal. But the strategy of *containment* or prevention of the release of the pollutant is by far preferable for persistent organic chemicals as well as for trace metals. Nonproduction and nonuse is certainly the safest strategy for really lethal chemicals; as for radioactive wastes, many argue that they are so dangerous as to warrant banning of nuclear power plants.

If all kinds of waste materials are allowed to be mixed together, then we have a very difficult problem of devising a suitable strategy. Treatment systems are not efficient in separating toxic materials from nontoxics; for example, trace metals tend to be preferentially attached to sewage particles. The metals are then preferentially removed by treatment along with particles that become part of the sludges. We then have the problem of what to do with sewage sludge which is "enriched" with trace contaminants, even though the liquid effluent is improved.

If we try to contain *all* of our wastes, including organic carbon, we simply have an impossible storage problem. Therefore, effective management necessitates keeping materials which can be reasonably dispersed in the environment separate from those which, because of their characteristics, should not be released.

The purpose of this book is to present the fundamental hydrodynamics for predictions of the dispersal of wastewater, both for intentional releases and for accidental spills.

1.1.3 Mass Balance Concepts in Residuals Management, Involving the Hydrologic Cycle

A fundamental and inescapable law of environmental management is conservation of mass. Usually we deal with the flux of a substance starting from its source of release into the environment; the fluxes for subsequent transport and diffusion must balance the source flux with adjustments for chemical and biological conversions and sinks, such as deposition on the seafloor. The fluxes of some substances may follow multiple pathways in air, land, or water. An example is lead in gasoline which is mostly emitted as aerosols from the exhaust pipes of automobiles. Subsequently, these particles may fall into the street and be washed by the storm runoff to the nearest natural body of water; or they may be carried by the wind and deposited in nearby or faraway land masses or oceans. For such substances, clearly there is no point in trying to devise a management strategy without considering the complete mass balance.

Sometimes it is useful to take an even larger view. By drawing a circle around a city, for example, we can say that the total influx of substance X must equal total efflux if we expect to have a steady state. Similarly, an irrigation tract cannot have a long-term salt balance unless the total dissolved solids removed by drainage balance the incoming salts in the water supply.

The regulatory system generally distinguishes between point and nonpoint sources of pollutants. A point source is the discharge from a structure which is specifically designed for the outflow of wastewater from some industrial process or municipal sewerage system. Point sources have been the target of most of the laws and regulations for water pollution control. The accidental spill of oil from a ship and the release of radioactive wastes from a power plant can also be considered as point sources.

Nonpoint sources, on the other hand, are defined as widely distributed points where pollutants are introduced into the hydrologic cycle. In such cases, water treatment is usually not feasible. Examples are the runoff of salts used for deicing highways in winter, soil erosion, acid rainfall, and street drainage. These examples illustrate that there is a wide variety of man's activities impacting the water environment for which careful analysis is needed in order to devise effective control strategies.

1.1.4 Impacts of Some Traditional Activities of Hydraulic Engineers

The analyses given in this book are intended not only to help the hydraulic engineering profession to design works specifically required for water quality control, such as outfalls, but also to be useful in the study and control of the adverse effects of traditional hydraulic works. Some examples are enumerated below.

Man-made reservoirs may cause deterioration in water quality because of summertime thermal stratification associated with oxygen depletion in the lower layers. Diversion of water for various consumptive uses or to other watersheds reduces river flow and its ability to provide natural flushing and repel salinity intrusion in estuaries. Various conveyances, like canals, can transport huge amounts of dissolved salts, sediment, nutrients and parasites to places that otherwise would not receive such doses of these materials. Agricultural drainage systems may greatly accelerate the leaching of nutrients and salts from the land into natural hydrologic systems. Breakwaters for harbors interfere with natural nearshore circulation which could otherwise carry away pollutants. Estuarine modifications or barriers can radically change the circulation patterns with dire consequences for flushing of pollutants.

The message is clear. Water quality has become a key issue of practically every hydraulic engineering endeavor, whether constructed specifically for water quality control or for other purposes.

1.2 ENVIRONMENTAL HYDRAULICS

Doing environmental analyses of various hydraulic works requires more than the traditional hydraulic subjects, as suggested in the following paragraphs.

1.2.1 Hydrologic Transport Processes

This subject refers to the physical processes of flow of natural water bodies which cause pollutants or natural substances to be transported and mixed, or exchanged, with other media. It is similar to what the chemical engineers call "transport processes," but here we apply it to a natural water environment rather than to man-made unit processes. Included among hydrologic transport processes are the following:

Advection. Transport by an imposed current system, as in a river or coastal waters.

Convection. Vertical transport induced by hydrostatic instability, such as the flow over a heated plate, or below a chilled water surface in a lake.

Diffusion (Molecular). The scattering of particles by random molecular motions, which may be described by Fick's law and the classical diffusion equation.

Diffusion (Turbulent). The random scattering of particles by turbulent motion, considered roughly analogous to molecular diffusion, but with "eddy" diffusion coefficients (which are much larger than molecular diffusion coefficients).

Shear. The advection of fluid at different velocities at different positions; this may be simply the normal velocity profile for a turbulent flow where the water flows faster with increasing elevation above the bed of the stream; or shear may be the changes in both magnitude and direction of the velocity vector with depth in complex flows such as in estuaries or coastal waters.

Dispersion. The scattering of particles or a cloud of contaminants by the combined effects of shear and transverse diffusion.

Mixing. Diffusion or dispersion as described above; turbulent diffusion in buoyant jets and plumes (see following section); any process which causes one parcel of water to be mingled with or diluted by another.

Evaporation. The transport of water vapor from a water or soil surface to the atmosphere.

Radiation. The flux of radiant energy, such as at a water surface.

Particle Settling. The sinking (or rising) of particles having densities different from the ambient fluid, such as sand grains or dead plankton. (In lakes and oceans the latter may be the dominant mechanism for downward transport of nutrients, often all the way to the bottom.)

Particle Entrainment. The picking up of particles, such as sand or organic detritus, from the bed of a water body by turbulent flow past the bed.

In varying ways these processes apply to various types of water bodies—lakes, rivers, estuaries, coastal oceans, and groundwater. This book concentrates on mixing in open bodies of water (i.e., excluding ground water), and does not treat the last two items on the above list.

When we calculate the flow of water in a channel, we need only know the *mean* velocity. However, for the analysis of pollutant transport and dispersal, the velocity variations in both time and space, and the irregularities of channel geometry, are all very important in determining what happens. It is important to remember the general principle that the *fluctuations and irregularities in hydrologic systems are just as important as the mean flows for pollutant analysis.*

1.2.2 Buoyant Jets and Plumes

To increase the dilution of an effluent discharge with the surrounding waters, engineers use structures which produce submerged jets, or if the discharge fluid is lighter or heavier the flows are called submerged buoyant jets. If the initial momentum is of no consequence then the flow pattern is called a plume. The analysis of buoyant jets or plumes depends not only on the jet parameters but also on the ambient conditions represented by the ambient density stratification and the current profile. Since the jet flows of hydrologic interest are practically all turbulent, their behavior has to be described in a suitable statistical sense.

For large discharges a multiple jet arrangement is used, which can often produce immediate initial dilutions of several hundred to one (volume of mixture divided by initial effluent volume). This subject is treated in detail in Chapter 9, and applications are described in Chapter 10.

1.2.3 Density-Stratified Flows in a Natural Environment and Geophysical Fluid Mechanics

Many problems in mixing in the natural environment are often complicated by density stratifications due to temperature variation in lakes and reservoirs, or salinity profiles in estuaries. This internal structure has a very great effect on both mean flow fields and the turbulent mixing and dispersion. But since often stratification results from transport processes, we have a strong feedback system, i.e., mixing depends on the flow field and the density stratification, while on the other hand, the flow and stratification depend on the mixing.

In a broader sense, the entire flow patterns in the ocean are related to density stratification and rotation of the earth, as well as surface exchanges with the atmosphere, tidal and wave effects, and fresh water inflows at the continental margins. However, these subjects are beyond the scope of the current book.

Analysis and effects of density-stratified flows in lakes and estuaries are presented in Chapters 6 and 7, respectively.