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Introduction

1.1 Role of Hydraulics and Pneumatics in Environmental Engineering Design

The environmental engineer has historically been the leading professional in water supply and wastewater collection and disposal. In that capacity, he or she was earlier known as a *sanitary engineer*, a reflection of the public health significance of those endeavors. As this spectrum of activities broadened to deal with the environmental problems facing an increasingly complex society and as the broader environmental objectives of the sanitary engineer's endeavors became apparent, the term *environmental engineer* became more popular within the profession. The aforementioned objectives include protection of drinking water supplies, protection and propagation of aquatic life, aesthetic and recreational aspects, and agricultural (livestock water supply and irrigation) and industrial water supply. In 1972, the Sanitary Engineering Division of the American Society of Civil Engineers formally changed its name to the Environmental Engineering Division. The environmental engineer's areas of activity were at that time considered to include the following: air pollution, environmental quality, water supply, municipal wastes, industrial wastes, agricultural wastes, urban (and rural) land runoff, thermal pollution, nuclear energy, and solid wastes. It was noted that all civil engineers (and other engineers as well) deal with the environment. However, the sole focus of the environmental engineer is on *environmental protection* as opposed to *production* or *environmental modification*. Whereas other branches of engineering deal with activities of potential impact on the environment, that is not their primary interest. Environmental engineering has a singular concern and responsibility for environmental protection.

Hydraulics is the engineering art and science dealing with the macroscopic, physical behavior of liquids. Relating this definition to the above areas of activity, *environmental engineering hydraulics* deals with the hydraulic aspects of: the environmental quality of water in the hydrologic cycle: municipal and industrial water supply; municipal, industrial, and agricultural wastewaters and stormwater runoff plus thermal and nuclear pollution and solids wastes. Environmental quality is impacted by the above wastewater and stormwater runoff plus thermal and nuclear pollution and solid waste.

Pneumatics is the art and science of dealing with the movement of air, generally in human-made systems. (Its inclusion makes this book's title a slight misnomer.) In environmental engineering applications, pneumatic systems assumed initial importance in the aeration of activated sludge. Now air and other gases (mentioned in Chapter 9) play an important role in a wider range of the abovementioned areas of activity. The emphasis in this book is on pneumatic (air) systems, but many of the principles are more generally applicable.

In providing the services mentioned above, the environmental engineer integrates various natural sciences and engineering disciplines. This integration is the result of his or her own interdisciplinary training and experience, and the support of other professionals. The water-oriented environmental engineering curriculum usually provides a smattering of chemistry, microbiology, aquatic ecology, and process theory. The latter entails a mixture of fundamental science and empiricism relating to influent and effluent characteristics of unit processes. Practicing engineers apply this knowledge with the consulting support of specialists within their own field (most particularly process specialists and aquatic chemists). The supporting role of the aquatic ecologist is relatively recent and increasing. The support of the chemist and aquatic ecologist is most significant during the preliminary design phase when treatment processes are being selected and environmental impact assessed.

During the design phase of a project, the support of other design professionals is commonly provided. These include architects, structural engineers, electrical and instrumentation engineers, and mechanical engineers. The latter generally design, as a minimum, the HVAC (heating, ventilating, and air conditioning) and plumbing systems. In some large consulting

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firms, mechanical engineers may design process piping, pump systems, and the like, although the environmental engineer is called upon to do this in many offices. Through his training (both formal and on-the-job) and the professional assistance of equipment manufacturers, the environmental engineer is usually capable of handling many aspects of the "mechanical" design.

Although of major significance, the hydraulic engineering aspects present a particular challenge and somewhat of an anomaly in this scheme of things. The environmental engineer is not often trained beyond the undergraduate level in fluid mechanics; many graduate environmental engineering curricula do not include a hydraulic engineering course. Equipment manufacturers are only a limited source of professional support since hydraulic structures (including process tanks) are generally made of concrete with mechanical equipment constituting a small fraction of the cost. Environmental engineering textbooks and design manuals provide some practical hydraulics, but they are often oversimplified and erroneous. Hydraulic engineers are often appalled at the "hydraulics" presented in the environmental engineering literature. Ironically, most hydraulic and environmental engineers have civil engineering backgrounds, and yet the methods of these two branches of civil engineering have not been well integrated. Engineering firms, particularly larger ones, may have one or more engineers with graduate-level training in hydraulics whose advice and review are solicited. This serves both to improve the design and the hydraulic knowledge of the environmental engineers who are exposed to this input. However, hydraulic engineering expertise is often not available; environmental engineering systems do not commonly incorporate the major hydraulic structures that justify a hydraulic engineering staff such as might be found in a hydroelectric design firm.

Furthermore, even when available, the hydraulic engineer may have had little experience with the unique environmental systems.

The availability of hydraulic engineers with experience in environmental engineering systems would reasonably resolve the problems referred to above. However, there is an additional dimension to consider. All water-oriented environmental engineering processes, both in constructed facilities and in the environment, are largely hydraulic processes, and many are predominantly so. However, there is a large gap between hydraulic engineering and environmental engineering technology. The environmental engineer's understanding of the processes with which he is concerned would greatly benefit from an understanding of hydraulic fundamentals. This benefit would extend to research efforts as well as practical applications.

The author has become of the opinion that hydraulics should be as much a part of the environmental engineer's fundamental background as chemistry and microbiology. It is hoped that the chapters which follow speak for themselves in this regard and that the reader will eventually share this opinion.

1.2 Scope, Organization, and Approach

1.2.1 Scope and Organization

Following this introductory chapter are four chapters (Chapters 2 through 5), which deal with basic hydraulic concepts and provide the theoretical foundation for the subsequent chapters. They do, however, incorporate some practical information, which stands by itself. Chapter 2 rigorously employs system and control volume concepts in the presentation and application of mass, momentum, and energy relations. This has been a sound trend in engineering education, and the author believes it to be unifying and of practical importance in the broader range of applications that includes, e.g., open-channel flows. The importance of the Navier–Stokes equations and dissipation function (Chapter 3) lies partially in their relation to "G-value," a seriously misapplied notion that has gained undue prominence. This book attempts to correct the notion of G-value and provide (in later chapters) suitable alternatives. The Navier–Stokes equations are also used (Chapter 4) as a point of departure for the unified discussion of various types of flow. Dimensional analysis (Chapter 5) is dealt with as an important concept that deserves greater attention, both for the perspective it provides and as an analytic tool.

From Chapter 6 on, the book deals with specific applications of the basic concepts presented earlier. Chapters 6 through 14 deal essentially with man-made environmental engineering systems. Although Chapters 6 through 13 fall within the conventional provinces of hydraulics and pneumatics, they are considered here from the standpoint of the environmental engineer's applications. This seems very useful and is done here for the first time known to the author. Chapter 14 deals with process applications from what the author believes is a sound and useful hydraulic perspective. In the design and research aspects of treatment processes, the significance of hydraulics needs greater appreciation. There is a significant disparity between existing knowledge in the field of hydraulics and its applications to treatment processes. The author believes strongly that experimental and theoretical hydraulics, in fact, provide the best framework for properly understanding certain treatment processes and help to elucidate all treatment processes. Hydraulics plays a major, if not dominant, role in essentially all unit processes of water and wastewater treatment. The breadth and utility of the author's interpretation of *environmental engineering hydraulics and pneumatics* should be made clearer by the inclusion of Chapter 13.

Chapter 15 deals with what has loosely been termed "natural systems," and provides an introduction to the hydraulics of such systems. That large subject area is only dealt with in an introductory way for several reasons: (1) natural systems have benefited from more complete treatment by hydraulic engineers; (2) the literature on natural systems (as cited in Chapter 15) is technically sound and reasonably consolidated; (3) the study of natural systems is generally more complex and specialized; and (4) the need for involving specialists in this area is generally recognized by environmental engineers.

This book is intended to prepare the environmental engineer to handle many but not all of the hydraulic aspects that will be encountered. The author has endeavored to point out those areas where the complexity of a problem warrants the hydraulic specialist's involvement. A serious effort has also been made to point out those areas in which hydraulic design errors are often made and to point out where application of methods presented in this book can avoid those pitfalls. Areas that could benefit from research efforts are pointed out; the encouragement of such research is among the purposes of this book.

There are some areas of hydraulics that the environmental engineer may deal with that are not covered in this book. Dam design is a specialty drawing from the disciplines of structural, soil, and hydraulic engineering and is dealt with in books devoted largely to that subject (Davis and Sorensen 1969, USBR 1965). It is not addressed here. Municipal storm drainage systems, largely because of their similarity to sanitary sewer systems, have traditionally been within the province of the environmental engineer. They have become even more proper with the recognition of the pollution associated with urban stormwater runoff. The hydraulic principles of municipal storm sewer design are covered here. Land drainage [as distinguished from municipal storm drainage (Linsley and Franzini 1964, pp. 52–54)] is not covered in any purposeful detail. The principles presented in this text should, however, permit ready transition via self-study or additional course work.

1.2.2 Approach

The author believes strongly in the practical value of a fundamental understanding as opposed to "cookbook" ("add water and stir") approaches. Armed with a fundamental understanding, errors can be better avoided, and problems associated with new applications can be more successfully formulated and solved. There has been a tendency, particularly in large design firms, toward standardization of design. Unfortunately, the reasons behind many such standards have been left with the engineers of earlier days. They are sometimes applied more as a matter of faith without necessary regard to their current applicability. The dissemination of computer programs to those not conversant with the techniques embodied in the programs has been a related concern. The author's observations in this regard are supported by Beck (1979) and Orenstein (1984). Partly to deal with these concerns, the emphasis here is placed on the "why" as well as the "how." Sewer design is a case in point. Too often sewer designers are unfamiliar with the meaning and nature of uniform flow, subcritical vs. supercritical, etc., and run the risk of erring. Most books treating sewer design are of little help in this regard. Unfortunately, hydraulic errors may go undiscovered because the design capacity of sewers (and treatment plants) is years into the future. And conduits receiving storm flows are rarely observed during storm conditions. This book attempts to provide concepts necessary to rectify such design inadequacies. The emphasis is on understanding and design of components for integration into systems described in the popular texts on water supply and wastewater systems.

A rigorous yet practical text incorporating principles for applications to new systems has been the goal. The author has strived to provide a clear exposition of all results. Choices of analytical tools have been made, which are likely to be of practical use. Theoretically oriented hydraulicians have studied phenomena such as turbulence and pipe resistance on a fine scale. The approach here will be a more large-scale and empirical one. A better merger between theory and practice is an intended result.

Examples given throughout this book are from projects successfully designed by the author. References include recent publications, but also older ones of lasting value.

1.3 Fluid Flow Phenomena

Hydraulic engineering is very much an art as well as a science. Many of the systems with which the hydraulic engineer deals are not amenable to complete theoretical analysis. The understanding of a hydraulic system or proportioning of a hydraulic structure must often be arrived at by a "feeling" for the problem, unaided or only partially aided by numerical calculation. A physical feel for the problem is always important. A qualitative understanding of the flow phenomena, aided by general experimental results and observations, will provide the engineer with the ability to proportion many hydraulic structures.

Furthermore, good qualitative understanding coupled with design experience can often avoid the uncertainties of complicated designs, undue analysis, or the need for physical modeling.

Indeed, many present-day environmental engineering devices would not exist if engineers had waited until a satisfactory theory was available to explain the operation of the device. As stated by Stenning and Shearer, “Few systems are pure enough or simple enough to conform very closely to basic theoretical concepts. Most fluid-flow systems are sufficiently complex to require a great deal of judgment in applying the theoretical concepts to them. Experience in the form of empirical data taken by others and in the form of personal observations … and engineering practice is a vital factor in most successful engineering analyses” (Stenning and Shearer 1960).

A significant characteristic of the hydraulic components of man-made environmental engineering systems is that taken individually they are often somewhat “minor” hydraulic structures. These hydraulic components, although vital to the performance of the overall system, often cannot, due to time and budget constraints, be subjected to the degree of analysis or physical modeling that might be performed for a major hydraulic structure. Furthermore, physical models involving two phases (e.g., liquid–solid as in flocculation, or gas–water mixtures as in aeration) that the environmental engineer often encounters will not necessarily yield results which can be extrapolated to the prototype (see Chapter 14). Thus, one must often do the best that can be done with simplified analytic methods and judicious design. This theme underlies much of this book.

A functional, economical design can be best achieved by intelligent combination of theoretical and empirical knowledge. Regardless of the particular combination of theory and empiricism employed, it is essential to identify and understand the phenomena of concern. In addition to those phenomena imparting the desirable and more obvious properties of fluid flow, some fluid flow phenomena may sometimes impart undesirable characteristics. It behooves the designer or analyst to be thoroughly aware of the range of fluid flow phenomena. Such phenomena and a partial indication of the location of their coverage in this book are listed below:

Fluid Flow Phenomena	Reference
Viscosity	Section 1.5
Zero Slip at Solid Boundary	Section 4.2
Momentum Exchange	Sections 2.4, 2.5, 2.7, 4.4, 4.7, 6.4, 12.1, 12.2, 12.5, 12.6
Boundary Layers, Velocity Profiles	Sections 2.5, 4.2, 4.3, 4.7, 6.2, 6.4, 7.7, 7.8, 9.4, 10.3, 12.1, 13.2, 14.3, 15.2, 15.3, 15.6
Jet Flow, Entrainment	Sections 6.2, 6.3, 7.3, 7.5, 7.7, 7.8, 8.4, 8.6, 8.7, 9.4, 9.5, 11.4, 13.3, 14.7, 15.2, 15.5
Laminar and Turbulent Flow	Sections 3.3, 4.2, 4.4, 4.5, 4.6, 4.7, 6.2, 6.5, 7.1, 7.4, 7.5, 7.8, 8.2, 8.6, 9.3, 9.5, 12.7, 13.2, 13.4, 14.3, 14.4, 14.5, 14.6, 14.7, 14.8, 15.6
Dispersion	Sections 14.2, 15.2, 15.4
Cavitation	Sections 6.5, 8.2, 8.6, 11.4, 12.5
Separation and Reattachment	Sections 4.7, 6.3, 6.4, 6.5, 7.7, 8.1, 8.6, 11.5, 14.3, 14.5
Frictional Drag	Sections 4.5, 7.5, 11.3, 13.4, 13.5,14.8
Form Drag	Sections 4.5, 6.5, 7.5, 10.3, 11.3, 11.5, 14.8
Coanda Effect	Sections 7.8, 15.2
Asymmetric Flow in Symmetric Expansions	Section 15.2
Vortices	Sections 4.7, 6.2, 6.4, 6.5, 7.2, 7.6, 7.7, 8.6, 8.7, 8.8, 11.5, 13.3, 14.9, 15.2, 15.3, 15.4
Secondary Currents	Section 4.7
Surface Waves; Subcritical, Critical, and Supercritical Flow	Chapter 7
Hydraulic Jump, Cross Waves	Sections 6.2, 6.5, 7.2, 7.5, 7.6, 7.7, 7.8, 15.2, 15.4
Compressibility; Subsonic, Sonic, Supersonic, and Choked Flow	Chapter 9; Sections 11.2, 15.4
Sediment Transport	Sections 4.7, 13.2, 13.3, 13.4
Flocculation, Floc Breakup	Sections 3.4, 4.4, 14.2, 14.6
Two-Phase Flow	Sections 6.5, 13.3
Density Currents	Section 14.3
Langmuir Circulation	Section 15.5

The fluid flow films prepared under the sponsorship of the National Science Foundation (National Committee for Fluid Mechanics Films 1972) are excellent educational aids dealing graphically with many of these phenomena.

1.4 Definitions and Classifications of Flows

Certain terms are used throughout much of this book and are defined below:

Fluid – a material that deforms continuously and permanently under the application of a shearing stress, which can be in a liquid or gaseous state. Fluids can be Newtonian or non-Newtonian as discussed in Section 3.2.

Conduit – A natural or constructed boundary that confines flow to move in a particular general direction and which has a total dimension in the general direction of flow much larger than its dimensions transverse to the direction of flow.

Prismatic Conduit – A conduit (generally human-made) with constant cross-sectional geometry.

Pipe – A prismatic conduit of circular cross section.

Pressure Conduit – A conduit flowing full so that the minimum pressure in the cross sections is other than atmospheric.

Open Channel – A liquid-conveying conduit having a free water surface.

Steady Flow – Fluid flow in which no fluid properties (other than those associated with high-frequency turbulent fluctuations) vary with time ($\partial/\partial t = 0$), although they may vary spatially.

Constant Flow – Steady flow in a conduit in which the total mass rate of flow does not vary in the direction of flow. For an incompressible flow (constant density – see below), it is only necessary that the volumetric rate of flow not vary in the direction of flow ($\partial Q/\partial s = 0$).

Uniform Flow – Constant flow in which fluid properties do not vary with distance in the direction of flow ($\partial/\partial s = 0$); such flow occurs in sloped open channels under certain conditions (Section 7.3).

Spatially Varied Flow – Flow in a conduit in which the mass rate of flow varies with distance along the conduit.

Unsteady or Time-Varying Flow – Flow in which fluid properties vary with time (in addition to high-frequency turbulent fluctuations).

Incompressible Flow – Flow in which density changes are negligible.

Compressible Flow – Flow having significant density changes.

The significance of the above definitions will become more apparent as the terms are used in the text.

Numerous additional flow classifications are defined in precise terms in the text. These classifications and the section of the text in which they are defined include the following:

One-dimensional flow (Section 2.6)

Parallel flow (Section 2.6)

Potential flow (Section 4.3)

Laminar flow (Section 4.4)

Creeping flow (Section 4.5)

Turbulent flow (Section 4.7)

Critical flow (Sections 7.2, 7.4)

Subcritical flow (Section 7.4)

Supercritical flow (Sections 7.4, 7.5)

Adiabatic flow (Sections 2.6, 9.3)

Nonadiabatic flow (Section 9.3)

Isothermal flow (Sections 2.6, 9.3)

Isentropic flow (Section 9.4)

Choked flow (Section 9.4)

1.5 Viscosity

Viscosity is a very important feature in environmental fluid mechanics. It also has a particularly illuminating history, as recounted here. We will first define the term "law" as used in science. A scientific law (or "first principle") is the description of an observed phenomenon; it does not explain why the phenomenon exists or what causes it. Examples of laws are the Law of Conservation of Mass, Newton's Second Law of Motion, and the First Law of Thermodynamics, all discussed in Chapter 2. Newton's "Law of Viscosity" is not actually a law because it can be derived from the kinetic theories of gases and liquids (Frenkel 1955, Kirshner undated); its mathematical formulation is provided in Chapter 3. Newton provided the first complete proof of the revolution of the Earth and planets around the Sun and correct explanation of the causes of the tides, as discussed in Section 14.5. Newton's discoveries of some of the most fundamental laws of nature are believed to have occurred primarily during a two-year period of seclusion during a Bubonic Plague (Black Death) outbreak just after he had finished college.

Newton's Laws of Motion are embodied in what has been called the single most important equation in the universe: $F = ma$. Force equals mass times acceleration. Newton's Laws of Motion are commonly taught as three separate laws because that is the way Newton presented them in his *Principia* (Newton 1999) in order to directly address misconceptions of the time. The Second Law of Motion is expressed by the famous equation $F = ma$. But the first and third laws are actually corollaries of $F = ma$ (Graber 2004c). The First Law of Motion says that a body at rest tends to remain at rest, and a body in motion tends to remain in motion. It was and is a profound statement, but it simply says that it takes force to accelerate or decelerate a mass, which is quantified by the Second Law. The Third Law of Motion says that for every action there is an equal and opposite reaction, which also derives from the Second Law. $F = ma$ is actually a somewhat simplified statement of the Second Law of Motion, and the law has many ramifications (e.g., conservation of linear and angular momentum). A more generalized form of the equation that applies to much of the work in environmental and water resources engineering is presented in Section 2.4, and an additional discussion of Newton's Laws of Motion is provided in Chapter 10.

Scientists constantly scrutinize laws to test their accuracy and generality. Newton's Laws of Motion are fundamental laws of nature that have stood up to countless experiments and observations in nature and engineered projects. And, although Albert Einstein's Special Theory of Relativity is sometimes said to have modified Newton's Second Law of Motion when objects move at speeds that approach the speed of light because the mass of the objects changes, the fact is that in the form that Newton originally presented his Second Law, i.e., as force equals the time rate of change of momentum, it is completely compatible with Einstein.

In the fourth century B.C.E., Plato and Aristotle believed that the Earth was immobile and that the Sun, planets, and stars revolved around the Earth. However, also in the fourth century B.C.E., the Greek philosopher Philolaus of Croton, in his *Treatise of the Sky*, expressed the opposite, and as it is now known, correct opinion held by the Pythagoreans that the Earth revolves around the Sun and "its circular motion about its own center produces the day and night." (Aczel 2003, p. 12) Then a superb mathematician and the greatest astronomer of the ancient world, Claudius Ptolemy in Alexandria, Egypt, in the second century C.E., came along and proposed a sophisticated mathematical theory of an Earth-centered solar system. This was consistent with the church's interpretation of the Bible (Joshua 10:12–13; Isaiah 38:7–8; Ecclesiastes 1:5), so the church used Ptolemy's theory to justify the Aristotelian view and attacked what came next. What came next were the scientific endeavors of the sixteenth and seventeenth centuries: Copernicus in Poland, Kepler in Germany, and Galileo in Italy, who advanced the modern heliocentric (Sun-centered) view of the solar system, culminating in the work of Newton in England and Foucault in France. During this period, the premature science of Ptolemy became pseudoscience, as the Catholic Church took strong measures to protect its long-held point of view despite new and overwhelming evidence. Copernicus, despite being in Catholic Poland, escaped the Inquisition because his book, *On the Revolution of Heavenly Spheres*, was published the year of his death (and was according to legend delivered to him on his deathbed). However, Galileo was not so fortunate. In "1600, the Inquisition [had] brought the Italian monk and teacher Giordano Bruno ... in chains to ... the center of Rome, tied him to an iron stake, and burned him alive. One of his crimes was his belief that the Earth rotated." (Aczel 2003, p. 9) That same Inquisition threatened Galileo with torture, forced the great scientist, now regarded as the "Father of Physics," to kneel before his prosecutors, forced him to recant his belief about the solar system to avoid a painful death, and sentenced him to house arrest for the rest of his life. (Aczel 2003, p. 10, Hecht 2003) Léon Foucault, incidentally, gave irrefutable proof that the Earth rotated on its axis with his great pendulum demonstration in 1851 at the Paris Observatory. A five-story-tall replica of Foucault's pendulum can be seen today at the Boston Museum of Science.

It should be noted that Ptolemy's incorrect Earth-centered theory was accepted for more than 1300 years. So another lesson in this is that the presumed validity of an idea should not be based on its longevity. Nor, for that matter, should validity be assumed based exclusively on the credentials of the proponent.

The author has addressed erroneous concepts that have been applied to the design of numerous types of environmental engineering facilities. The following table (Table 1.1) (from Graber 2010c) lists numerous concepts of "established practice" that the author has overturned and for which he has provided corrective methods. This is offered as encouragement to others to not simply accept published design methods but rather to critically review their validity and applicability and modify them for specific applications and more generally when appropriate. The first column of the table references papers by the author, which are among those listed in the References section at the end of this book. The second column gives the concept overturned for which corrective methods are provided in the cited papers. The third column lists the original proponents of the erroneous concepts plus some comments. The reader is referred to the cited papers for details. Subsequent chapters will address a number of these concepts. An interesting paper in this context is "Creativity vs. Skepticism within Science" (Ramachandran 2006).

Viscosity is further discussed in Section 3.2, including explanations of kinematic, dynamic, and absolute viscosity.

Table 1.1 Overturned Concepts of "Established Practice"

Reference	Concept Overturned and Corrective Methods	Proponents/Comments
Graber 1974a, 2005	Weir loadings for primary clarifiers	National Research Council/Acknowledged in 1998 Manual of Practice of American Society of Civil Engineers/Water Environment Federation (WEF/ASCE 1998)
Graber 1994, 1997, 1998, 2004d	G-value or RMS velocity gradient for flocculation, floc breakup, mixing, induced circulation in channels, short-circuiting in tanks, and cleansing of filter media during backwashing	Many, including cited references. One major textbook called this "an important unifying concept in modern water or wastewater operations or processes."
Graber 1972, 1974a, 1975a, 2005	Role of short-circuiting in primary sedimentation	Numerous cited references
Graber 2004a	Assumption of uniform flow for spatially varying flow in subsurface drains	American Iron and Steel Institute, U.S. Soil Conservation Service, U.S. Department of Agriculture, U.S. Bureau of Reclamation, American Society of Civil Engineers, U.S. Environmental Protection Agency/Received ASCE's Samuel A. Greeley Award. Author's replacement method now part of ASCE Standard Guidelines (ASCE 2005)
Graber 2004b, 2004c	Conceptual and practical errors relative to spatially varied flows	Various cited references
Graber 2007a, 2007b	Erroneous methods for design of aggregate, geopipe, and geocomposite subsurface drains	Federal Highway Administration, National Cooperative Highway Research Board, Forrester (2001), Koerner (2005)
Graber 2009a	TR-55 curves can substantially underpredict required detention basin storage, or conversely underpredict the peak outflow from the detention	U.S. Soil Conservation Service (now Natural Resources Conservation Service)
Graber 2009b	Standards underpredict the depth	Factory Mutual Insurance Company; American Society of Civil Engineers; Fairfax County, VA
Graber 2010a	Stormwater pumping station wet-well storage is underpredicted and can result in upstream flooding under design storm conditions	American Society of Civil Engineers, Water Environment Federation, Federal Highway Administration
Graber 2010b, 2010c	Erroneous concepts for design of wastewater pressure-distribution systems, rapid sand filter underdrains, and dividing manifolds more generally	Various cited references
Graber 2013a	Assumption of uniform flow for spatially varying flow in street gutters	Federal Highway Administration, ASCE, WEF/ASCE

1.6 Dimensional Units and Notation

1.6.1 Dimensional Units

The four physical units employed in engineering mechanics are those of force, mass, length, and time. Thermal units and electromagnetic units must be introduced to embrace the full range of physical phenomena. Thermal units will be discussed in Chapter 9; electromagnetic phenomena will not be considered. All four are involved in Newton's Second Law of Motion, which thus provides a useful basis for discussing systems of units in many texts, including this one. Newton's Second Law in its simplest form is given by:

$$F = \frac{1}{g_o} ma$$

in which F is the force acting on a system of particles of mass m, a is the system acceleration (length per time squared), and g_o is a proportionality constant that depends on the units of force, mass, and acceleration.

Sets of units in use and the corresponding proportionality constant are given as follows:

Mass	Length	Time	Force	g_o
slug	ft	sec	lbf	1 slug ft/(lbf sec^2)
lbm	ft	sec	poundal	1 lbm ft/(poundal sec^2)
lbm	ft	sec	lbf	32.174 lbm ft/(lbf sec^2)
kilogram	meter	sec	newton	1 kilogram meter/(newton sec^2)
gram	centimeter	sec	dyne	1 gram centimeter/(dyne sec^2)

in which lbm denotes pound-mass and lbf denotes pound-force. The third set is traditionally used in American industry and is known as the foot-pound-second (FPS) system. The fourth is the basis for the SI units (systeme international d'unites) of the standardized metric system (also known as mks units). Mass, length, and time in the fifth system (known as cgs units) are merely multiples of those in the fourth system.

Dimensionless equations are widely used in fluid mechanics so that units of choice may be used and properly checked. In presenting such equations, a common convenience is the assumption that $g_o = 1$ so that $F = ma$ and the term g_o does not have to be employed. However, the slug and poundal, which make $g_o = 1$ in the first two systems above have received little practical acceptance. Nonetheless, the first system has been widely used in fluid mechanics texts, with conversions to lbm made according to 1 slug = 32.174 lbm.

The tradition of assuming $g_o = 1$ will be continued in this text, and equations will be derived and presented without g_o. The English units used in examples will be those of the third system above, with lbm and lbf used to clearly indicate pound-mass and pound-force, respectively, and the above conversion from slugs to lbm employed.

Reid (2000) and Harish (2023) have noted some major errors due to inconsistent use of dimensional units. One is the unintended crashing of NASA's $125 million Mars Climate Orbiter onto the surface of Mars. Others reported by Reid and the running out of fuel by an Air Canada Boeing 747 jet in mid-flight because of a conversion error in calculating the plane's fuel storage, administering an incorrect dosage of a sedative to a hospital patient, and an American International Airways cargo plane landing 13,000 pounds overweight due to a conversion error.

1.6.2 Notation

It is impossible in a text with the breadth and scope of this one to employ notation that is consistent between subject areas and, at the same time, consistent with the notation common to a given subject area. The author has attempted to strike a reasonable balance in this regard.