John E. Gribbin

INTRODUCTION TO

Hydraulics and Hydrology

WITH APPLICATIONS FOR STORMWATER MANAGEMENT

Fourth Edition

Introduction to Hydraulics and Hydrology with Applications for Stormwater Management

FOURTH EDITION

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Essex County College

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In memory of my father,
John B. Gribbin,
Associate Professor of Civil Engineering at Manhattan College

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Preface

This text was originally written to fill a long-standing need to treat the topics of stormwater runoff and hydraulics together in one book. It is intended to be used by students of civil engineering, civil engineering technology, and surveying, as well as practitioners in industry and government. The topics presented are relevant to public works, land development, and municipal engineering and planning—in fact, to any designer (both engineer and technician) who must deal with the conveyance of stormwater in any aspect of his/her work.

The book contains features designed to make the learning process more accessible and streamlined, such as:

- Many easy-to-follow examples
- Numerous clear diagrams, charts, and topographic maps to illustrate concepts developed in the text
- Case studies based on real-world projects
- A list of objectives starting each chapter to help focus the readers' attention
- Design charts in the appendices to relate examples and problems to real situations
- Inclusion of "Further Focus" features to provide deeper insight into specific topics
- A comprehensive glossary of important terms

This fourth edition marks a significant improvement to the text by rearrangement of information and addition of new material. Several topics have been expanded, including buoyancy, stream routing, unit hydrograph, and runoff computation by the Rational Method. Expanded treatment of the unit hydrograph includes the NRCS dimensionless unit hydrograph.

A new feature, called "Further Focus," helps direct the reader's attention to various topics and provides additional background and sharpened interest.

One new case study of culvert design has been added and one of the case studies of detention design has been replaced with a more relevant example. New figures have been added and the number of problems at the end of chapters has been increased.

The subjects of hydraulics and hydrology include many more topics than those presented in this text. Hydraulics texts are available that treat engineering hydraulics in a comprehensive manner, and there are hydrology texts that deal only with the engineering aspects of hydrology, but this book pares down the many topics of hydraulics and hydrology to the most basic and common areas dealing with stormwater management encountered by the designer on a day-to-day basis.

Principal topics include the following:

- Background concepts such as historical overview and basic notions of computation and design
- Fluid mechanics
- Fundamental hydrostatics and hydrodynamics
- Flow through hydraulic devices commonly used in stormwater management
- Open channel hydraulics
- Fundamental concepts of rainfall and runoff
- Runoff computation (Rational and NRCS Methods)
- Design of culverts
- Design of storm sewers
- Design of detention basins

One of the outstanding features of the book is the treatment of runoff computations. Thorough analysis and practice of watershed delineation are included to hone this skill, which is so essential to runoff analysis but often lacking in designers' training.

Another outstanding feature of the text is the comprehensive appendices, which include excerpts from several relevant design manuals in use today. Students and others using the text will continually refer to the design charts located in Appendixes A through D when studying examples and working problems. Mastering the use of the charts is indispensable to learning the techniques of problem solving in the real world. The student will learn not only the use of the charts but also the theory and rationale used to create them.

For example, when analyzing a culvert problem, the student learns to recognize the correct chart in Appendix B and then uses it to derive key numerical values needed for the problem's solution. References to specific appendix sections are included throughout the text to guide the reader in their proper use.

One of the overarching premises used in framing the text is the belief that students need to learn engineering principles by solving problems by hand without the aid of computer software. When they are practitioners on the job, they can utilize the software, knowing the processes that are being used to compute the answers. And having worked the problems by hand, they will be able to distinguish meaningful answers from erroneous answers.

In addition to developing the readers' hydraulic theory and runoff computation techniques, one of the goals of the text is to introduce some of the rudimentary stormwater management design processes that are used in civil engineering practice. To accomplish this, realistic design problems and case studies are included that rely on actual design charts. However, the text should not be construed as a complete design manual to be used on the job, nor is it intended to be. Good engineering practice requires the use of a variety of comprehensive sources found in professional publications and design manuals prepared by government agencies.

Design manuals are now published primarily online and change constantly. A good design professional should review the online manuals periodically to ensure use of current data and design approaches.

In developing the various topics throughout the text, the author has assumed certain prior knowledge on the part of the reader. This includes the fundamental concepts of land surveying, interpretation of topographic maps, profiles, and cross sections, and the use of the engineer's scale. Also, other engineering concepts such as the formation of free-body diagrams and the resolution of forces and moments are prerequisites to a full understanding of the text.

SUPPLEMENTS

An Instructor Resource on CD is available for this text. This is an educational resource that creates a truly electronic classroom. It is a CD-ROM containing tools and instructional material that enrich your classroom and shorten instructor's preparation time. The elements of the instructor resource link directly to the text and tie together to provide a unified instructional system. With the instructor resource you can spend your time teaching, not preparing to teach (ISBN 978-1-1336-9269-0). Features contained in the instructor resource include:

- **Solutions Manual**. Solutions to end of chapter problems.
- **PowerPoint® Presentations**. Slides for each chapter of the text provide the basis for a lecture outline that helps you present concepts and materials as well. Key points and concepts can be graphically highlighted for student retention.
- **Quizzes**. Additional test questions are provided for each chapter.
- **Image Gallery**. This database of key images taken from the text can be used in lecture presentations, as transparencies, for tests and quizzes, and with Powerpoint presentations.

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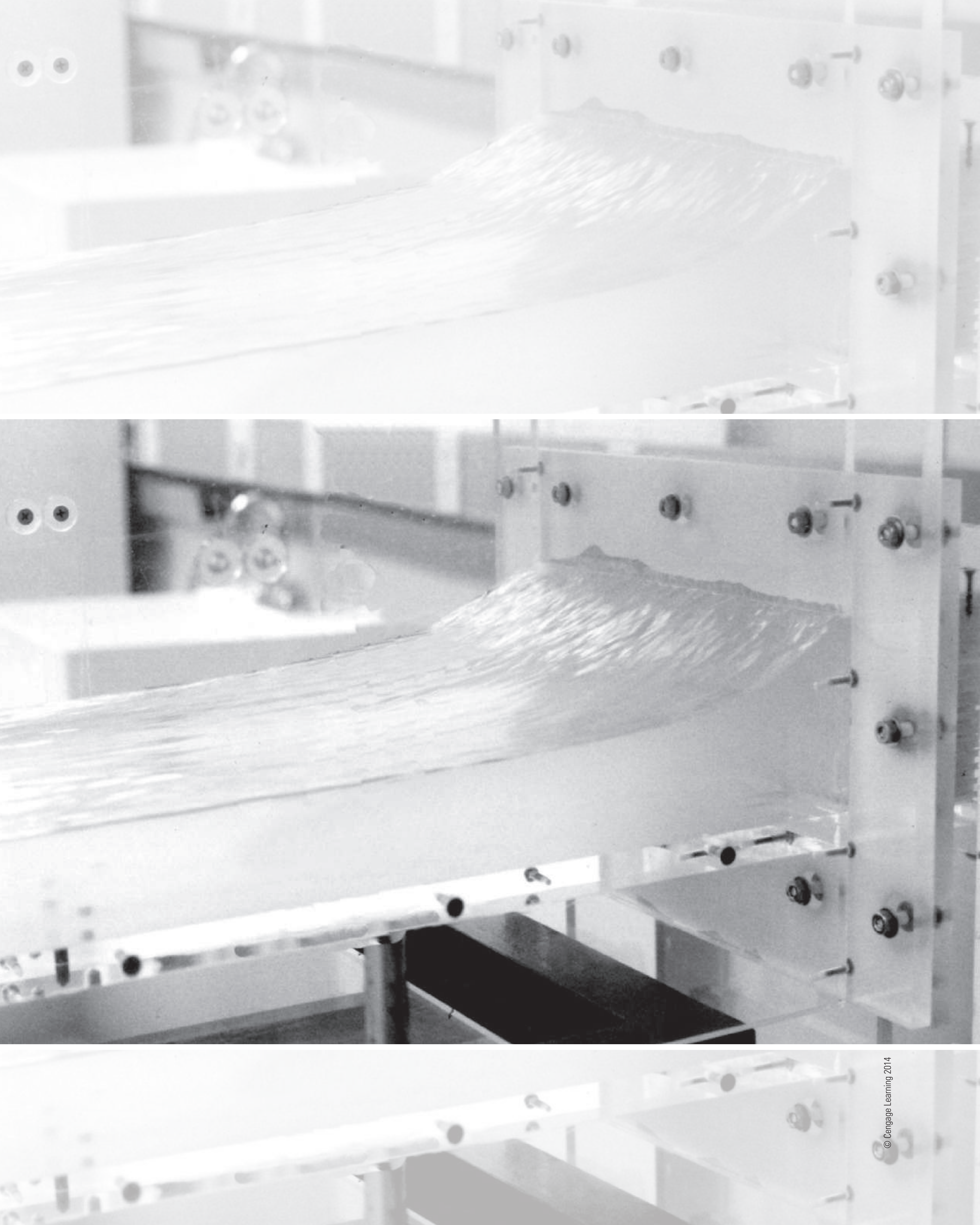
Introduction to Hydraulics and Hydrology with Applications for Stormwater Management



1

Hydraulics and Hydrology in Engineering

Engineers cannot avoid confronting the problems posed by rainfall and its consequent runoff. Some of mankind's earliest endeavors centered on this age-old battle with the forces of nature in the form of water. For most of our history, engineers and their predecessors dealt with water problems by utilizing various rule-of-thumb solutions, that is, whatever seemed to work. Only in recent times have these endeavors taken on a systematic body of laws and quantitative formulas.

In this chapter, we take a brief trip through the world of engineering hydraulics and hydrology of yesterday and today. We will look at the various aspects of modern stormwater management and review some general principles of engineering design.

OBJECTIVES

After completing this chapter, the reader should be able to:

- Place hydraulic/hydrologic engineering in a historical perspective
- Define stormwater management
- Explain the roles of public agencies in stormwater management
- Recognize the factors involved in engineering design
- Perform computations using the appropriate significant figures
- Convert between metric units and English units

1.1 HISTORY OF WATER ENGINEERING

People first started manipulating water on a large scale as a response to the need for irrigation in early agrarian society. The first known large-scale irrigation project was undertaken in Egypt approximately five thousand years ago. In the following millennia, many other water projects sprang up in the Mediterranean and Near Eastern worlds. These included dams, canals, aqueducts, and sewer systems. The

FIGURE 1-1 ROMAN AQUEDUCT IN TUSCANY, ITALY.

(Courtesy of Jack Breslin.)

conveyance of water through pipes was also developed in ancient times. In China, bamboo pipes were used as early as 2500 B.C., and the Romans utilized lead and bronze pipes by 200 B.C.

The Romans' prowess as engineers was amply demonstrated in their hydraulic systems. The famous aqueducts were among the wonders of the world and remained in use through two millennia (see Figure 1-1). The Greeks, although not the engineers that the Romans were, nonetheless made significant contributions to the theories of hydraulics. Archimedes is considered the earliest contributor to hydraulics based on truly scientific work. In about 250 B.C., he published a written work on hydrostatics that presented the laws of buoyancy (Archimedes' Principle) and flotation. He is generally considered the Father of Hydrostatics.

During the period from 500 B.C. to the Middle Ages, irrigation and water supply systems were constructed and maintained in such diverse locations as China, the Roman Empire, and North America. Such engineering was designed and constructed by artisans using rules of thumb, artisans who, despite Archimedes' work, lacked the benefits of scientific inquiry. The great Roman engineers, for example, did not understand the concept of velocity, and it was not until A.D. 1500 that the connection between rainfall and streamflow was taken seriously.

As the Roman Empire declined, many of the advances made during the Greco-Roman period were forgotten, only to be rediscovered during the Renaissance. It was during this period that hydraulics began to be developed as a science.

The first effort at organized engineering knowledge was the founding in 1760 of the *Ecole des Ponts et Chaussées* in Paris. In 1738, Daniel Bernoulli published his famous **Bernoulli equation**, formulating the conservation of energy in hydraulics. During the eighteenth and nineteenth centuries, referred to as the classical period of hydraulics, advances in hydraulic engineering laid the groundwork for further developments in the twentieth century.

FIGURE 1-2 THE CITY OF LOWELL, MASSACHUSETTS, WAS THE SITE OF A FAMOUS SERIES OF WATER POWER EXPERIMENTS CONDUCTED BY JAMES FRANCIS AND URIAH BOYDEN. THE PUBLICATION OF THE RESULTS IN 1855 CONTRIBUTED GREATLY TO THE FIELD OF HYDRAULIC ENGINEERING. HERE, TWO ASSISTANTS ARE SHOWN MEASURING WATER LEVELS.

(Courtesy of University of Massachussets Lowell, Locks and Canal Collection.)

Despite the domination of the French during the classical period, work was conducted in other countries as well. In England, for instance, John Smeaton was very active in many aspects of hydraulic engineering and was the first to call himself a **civil engineer**.

As late as 1850, however, engineering designs were still based mainly on rules of thumb developed through experience and tempered with liberal factors of safety. Since that time, utilization of theory has increased rapidly. Today, a vast amount of careful computation is an integral part of most project designs. Figure 1-2 depicts one of many hydraulic experiments conducted in Lowell, Massachusetts, in the mid-1800s that contributed greatly to the field of hydraulic engineering.

1.2 MODERN PRACTICE OF STORMWATER MANAGEMENT

Civil engineers work with water wherever it affects the structures and infrastructure of civilization. The role of the civil engineer and technician in connection with the many diverse effects of water may be grouped into three broad categories:

1. Flood control—managing the natural flow of stormwater to prevent property damage and loss of life
2. Water resources—exploiting the available water resources for beneficial purposes such as water supply, irrigation, hydroelectric power, and navigation
3. Water quality—managing the use of water to prevent its degradation due to pollutants both natural and man-made.

Although the first role listed above, flood control, constitutes the primary focus of this text, the other two are no less important. All three areas constitute projects designed and carried out by people working in both the private and public sectors.

As an example of private endeavors in flood control, imagine that an entrepreneur wishes to construct a factory surrounded by a parking area. He or she must engage a civil engineer to design proper grading and a storm sewer system to convey any rainfall occurring on the site. In addition, a detention basin might be required to prevent any adverse effect of runoff from the factory site to adjacent properties.

Although these problems will be solved by an engineering firm contracting directly with the owner, public agencies become involved as well, since all designs affecting the public welfare must be reviewed and approved by the appropriate local, county, and state agencies.

Examples of public endeavors in flood control are many and may be as simple as the design of a pipe culvert under a newly constructed road to allow free passage of a stream or as complex as the extensive levee and pump system surrounding the city of New Orleans, Louisiana. The disastrous flooding that resulted from Hurricane Katrina in 2005 showed how important flood control can be. Each of these public projects may be designed by engineers employed by public agencies or by private engineers contracting directly with the appropriate public agency.

In a typical privately owned land development project, the engineer representing the developer works with the engineer representing the regulating agency to solve any stormwater runoff problems. The relationship between the engineers is at once adversarial and cooperative as they work to protect the respective interests of the private developer and the public. In this way, they create the best possible project.

The term **stormwater management** as used in this text refers to the engineering practices and regulatory policies employed to mitigate the adverse effects of stormwater runoff. These endeavors usually are associated with runoff problems resulting from various types of land development.

1.3 LEGAL AND ENVIRONMENTAL ISSUES

Over the past three decades, legal and environmental issues have dramatically changed the way civil engineers practice their art, and hydraulic/hydrologic engineering is no exception. Stormwater management was once based on the principles of good engineering practice, but now design must also satisfy a myriad of regulations enforced by several levels of public agencies.

When hydraulic and hydrologic design affects the public, there is a legal issue, and when it affects the environment, there is an environmental issue. These two issues usually overlap, since anything that affects the environment most often affects the public. Although legal and environmental issues abound throughout all areas of civil engineering, we will look at only a few that affect stormwater management on a regular basis.

When rain falls from the sky, it strikes the earth and then runs downhill, impelled by gravity across the land to join the streams and rivers that eventually carry it to the sea. Our society considers all such motion of water to be naturally occurring, and if the water does damage along its path, such as erosion or flooding, no legal blame is assigned to any person. But the minute people alter their land in such a way as to change the course of the stormwater, they become liable for any damage done as a result of the alteration. The two ways in which land development generally affects downstream property are by concentrating the flow of stormwater and by increasing the quantity of that flow.

The practice of stormwater management must take these problems into consideration and mitigate them. Mitigation is achieved by a variety of methods, including rerouting the flow, dispersing the flow, lining the ground with erosion protection, and providing a detention basin.

Another problem that occurs in hydraulic and hydrologic design is the pollution of stormwater. Development of the land can and usually does result in several unwanted pollutants mixing into the stormwater as it runs off the developed site. These include salts and oils from paved areas or fertilizer, pesticides, and silt particles from vegetated areas. Stormwater management mitigates these problems by providing vegetative filters, siltation basins, catch basins, and recharge basins.

Wetlands are an environmental feature that has come into prominence throughout the past two decades. Wetlands are areas of land, usually naturally occurring, that retain water throughout much of the year. They are beneficial to the ecosystem and are particularly sensitive to disruption by the effects of development. Extra care must be taken to identify, delineate, and protect these areas when they are on or adjacent to a land development project.

Design engineers work hand in hand with regulators in addressing and solving the problems raised by legal and environmental issues. In the following section, we will briefly outline the regulating bodies and the roles they perform.

1.4 PUBLIC AGENCIES

Over the past few decades, life in the United States has become much more regulated. Naturally, the field of civil engineering design has acquired its own array of specialized rules. The trend toward increased regulation has generally relied on the concept that the government may regulate anything that affects the health and welfare of the public. In civil engineering, this means that just about everything may be regulated.

Regulating began at the local level with the proliferation of zoning ordinances by municipalities everywhere. Zoning has become more and more complex over the years, especially over the past three decades. Originally the concept was simple: A factory, for instance, cannot be constructed in an area of town reserved for residential development. Today zoning regulates not only the type of development but also details of the infrastructure, such as pavement thicknesses for roads, key parameters in storm sewer design, and detailed methodology for detention design.

Local municipal zoning and land development ordinances are administered by the municipal engineer, a civil engineer employed by or under contract to the municipality, and the zoning officer (also called the building inspector), an employee of the municipality trained in building code enforcement.

One level above municipal is the county in which the project is located. County governments have jurisdiction over certain roads designated as county roads and usually most of the bridges and culverts in the county, except those under state highways. Thus, if the stormwater flowing from a project flows onto a county road or through a county culvert, the county engineering department has regulatory power over the project. In addition, the Natural Resources Conservation Service (NRCS), formerly called the Soil Conservation Service, regulates soil erosion aspects of development work through local offices around the country. In many areas, these are called Soil Conservation District (SCD) offices and are semiautonomous regulatory agencies using regulations promulgated by the NRCS, a federal agency.

The next level of regulation consists of a few specially created regional, semiautonomous agencies that have jurisdiction over certain geographical problem areas. They are usually associated with environmentally sensitive areas, which require more intense scrutiny than the rest of the land to be developed. These include flood control districts, wetland districts, and timberland districts.

The next level of regulation is the state. State laws governing land development are administered by specially created agencies such as the state Department of Environmental Protection, which typically has jurisdiction over any project that affects a state-regulated entity, including, for instance, wetlands, streams, and water fronts or state-owned entities such as highways and culverts.

Finally, the most overreaching level of regulation is the federal government. Federal laws such as the 1972 Clean Water Act are administered by federal agencies including the Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers. Another federal agency that affects hydraulic and hydrologic design is the Federal Highway Administration, a division of the Department of Transportation. This agency affects local everyday projects principally through the publication of design manuals developed through research.

1.5 ENGINEERING DESIGN

All engineers and technicians, electrical, mechanical or civil, are engaged in design. The civil designer works on projects that can be as daunting in scope as a 500-foot-high dam complete with hydroelectric power station or as mundane as a concrete pipe laid in a trench.

Regardless of the size of the project, the design process requires the complete specification of every aspect of the structure so that it can then be constructed on the basis of the resulting specifications. That is, the engineer or technician must think of every detail of the structure and successfully convey his or her thoughts to the builder.

DESIGN PROCESS

In designing a structure, several important steps are required to transform an initial idea into a clear and fully developed document ready for construction. The example of a storm sewer pipe can be used to illustrate the general steps in performing a typical design:

1. **Concept.** Determine the basic concept of the design. In this case, it is to convey stormwater from one location to another.
2. **Base Map.** Prepare a base map showing the topographic features of the project site together with any pertinent property boundaries. A good base map is essential to the successful design process.
3. **Design Development.** Sketch alternative layouts of the pipe on the base map. Also, research other factors affecting the design, such as soil conditions,

structural loading on the pipe, potential interference with other subsurface utilities, drainage area, and meteorological data.

4. **Calculations.** Perform appropriate engineering computations of key design quantities—in this case, the anticipated amount of stormwater to be conveyed by the pipe and the resulting pipe size. The calculations should be in written form and contain any assumptions made. They should be checked by another designer.
5. **Prepare Drawings and Specifications.** Prepare drawings showing the layout in plan and profile including any details and notes needed to describe the structure for use by the builder in constructing the project. Include written specifications if necessary.

DESIGN OUTCOME

Design is an endeavor that is enriched with experience. As more and more projects are completed, good practitioners acquire a deeper appreciation for the larger picture surrounding the design and weave that broader perspective into their work. It is not enough to imagine only the proper functioning of the structure; other factors must also be taken into consideration, such as proper maintenance, cost, safety during construction, and availability of materials. Because the design process is such a complex and ever-growing intellectual endeavor, an exhaustive definition is virtually impossible. However, certain basic elements can be identified.

Design is the process of determining the complete specification of a structure so that it will:

1. Perform its intended function under all foreseeable circumstances without failing
2. Be able to be constructed at a cost within the budget of the owner
3. Be able to be maintained easily and effectively
4. Conform to all applicable local, county, state, and federal laws and regulations
5. Not interfere with other structures or utilities that could be constructed in its vicinity in the future
6. Be able to be constructed in a safe manner
7. Remain intact and functional throughout its intended lifetime
8. Not present a safety hazard to the public throughout its lifetime
9. Not unduly degrade the environment either during construction or throughout its lifetime
10. Be aesthetically pleasing

Each structure must be designed by using all of these factors regardless of its apparent simplicity. In later chapters, we will see how to employ the principles of design listed here in some commonly encountered projects related to hydraulic and hydrologic engineering.

1.6 ENGINEERING COMPUTATIONS

Almost all engineering designs require some computing of numbers. Although the use of calculators and computers makes computing relatively easy, an understanding of certain basic principles of computing is important to a successful design process.