

HIGHWAY DRAINAGE GUIDELINES



2007

**American Association of State
Highway and Transportation Officials
444 North Capitol Street, N.W., Suite 249
Washington, DC 20001
(202) 624-5800
www.transportation.org**

AASHTO Highway Drainage Guidelines

Foreword

The Highway Subcommittee on Design, as part of its charge, prepares and keeps current publications pertaining to principles, methods, and procedures of roadway design, including practices to protect and to enhance the quality of the environment. As the subject of highway drainage is important to many disciplines and many phases of highway engineering, the Subcommittee requested and received approval from the Standing Committee on Highways to establish a task force to prepare needed publications on the subject of highway drainage. Consequently, the Task Force on Hydrology and Hydraulics was established and first met in February 1970, developed a statement of purpose, and outlined a program of activity. The purpose of the Task Force is to assist the Subcommittee in developing guidelines and in formulating policy for highway disciplines, giving due consideration to safety and the environment.

Pursuant to this purpose, the Task Force on Hydrology and Hydraulics began the preparation of guidelines covering topics on major areas of highway hydraulic design. To the extent practicable, each Guideline is a stand-alone volume, but reference to other guidelines in the series is utilized to avoid unnecessary repetition. Since these Guidelines are intended to provide an overview, discussion, and design philosophy for each of the covered topics, technical information is kept to a minimum by making reference to appropriate publications and to the AASHTO *Model Drainage Manual* which contains recommended design policy, criteria, procedures, aids and example problems.

The following Guidelines were originally published as separate volumes: I, II and III in 1973, IV in 1975, V in 1977, and VII in 1982. Consolidated editions were published in 1973 of I–III, in 1975 of I–IV, in 1979 of I–VI, in 1982 of I–VII, and in 1987 of I–VIII which was also printed in the current loose-leaf format. The 1992 edition of the Guidelines contains rewritten Volumes I–III, updated volumes IV–VIII, and new volumes IX, X, and a Glossary. A new, separate Volume XI was published in 1994. The 1999 edition of the Guidelines is a metric conversion of the 1992 edition and also contains new Guidelines, Volumes XI, XII, XIII, and XIV, which are in metric format. This 2007 Edition contains both metric (SI) and U.S. Customary units, replaces the Volume designations with Chapter designations, and contains a new Guideline, Chapter 15.

The Highway Subcommittee on Design gratefully acknowledges the efforts of members of the Task Force on Hydrology and Hydraulics in preparing the Guidelines and the cooperation of the States participating in this endeavor.

Preface

As early as 1866, Congress first authorized the use of the metric system, devised in France about the time of the French Revolution, for measuring weights in the United States. International standardization began in Paris in 1875 when the International Bureau of Weights and Measures (IBWM) was established under the jurisdiction of the General Conference on Weights and Measures (CGPM). In 1960, the CGPM adopted an extensive revision and simplification called “System International d’Unites”, which is universally known by its abbreviation of SI.

In 1968, Congress adopted an act requiring a United States metric study. The report to Congress in 1971 recommended that the nation change to the SI system deliberately and carefully. Two factors mandated this change—the adoption of the metric system by the remainder of the world and the changing global economy.

The resultant Metric Conversion Act of 1975 (15 U.S.C. 2056) declared a national policy of coordinating and encouraging the increased use of the metric system and provided for a U.S. Metric Board to coordinate the **voluntary** conversion to the metric system. As the trend of U.S. industries losing their share of world markets continued, Congress attempted to keep the United States competitive in the international trade arena by adopting the Omnibus Trade and Competitiveness Act of 1988. Section 5164(b) of the Trade and Competitiveness Act amended the Metric Conversion Act of 1975 to declare that the metric system is the **preferred** system of weights and measures for U.S. trade and commerce. It also **required** each Federal agency to convert to the metric system by the end of fiscal year 1992.

On May 3, 1990, the U.S. Department of Transportation issued Order 1020.1C which established policy and administrative procedures for the transition to metric. As a result, the Federal Highway Administration (FHWA) formed a Metric Work Group which developed a conversion plan and a timetable. The Metric Work Group found the implementation deadline of 1992 to be impracticable and proposed a five-year schedule. On this basis, an NCHRP Project 20-40 was established by the American Association of State Highway and Transportation Officials (AASHTO) in order to convert documents published by the association to the International System of Units (SI) of measurement by October 1, 1996, to comply with the FHWA mandates.

Since the federal conversion date for these mandates has been left optional for States, this guideline is being provided in dual units. The SI number and unit are shown first followed by the U.S. Customary number and unit in parentheses, e.g., 1 m (3.3 ft). If the U.S. Customary number is not a direct conversion and is a comparable value to the SI measurement, a bracket is used, e.g., 1 mm [1 inch].

AASHTO Highway Drainage Guidelines

Table of Contents

Chapter	Title
1	Hydraulic Considerations in Highway Planning and Location
2	Hydrology
3	Erosion and Sediment Control in Highway Construction
4	Hydraulic Design of Culverts
5	The Legal Aspects of Highway Drainage
6	Hydraulic Analysis and Design of Open Channels
7	Hydraulic Analysis for the Location and Design of Bridges
8	Hydraulic Aspects in Restoration and Upgrading of Highways
9	Storm Drain Systems
10	Evaluating Highway Effects on Surface Water Environments
11	Highways along Coastal Zones and Lakeshores
12	Stormwater Management
13	Training and Career Development of Hydraulics Engineers
14	Culvert Inspection, Material Selection, and Rehabilitation
15	Guidelines for Selecting and Utilizing Hydraulics Engineering Consultants
Appendix	Glossary of Highway-Related Drainage Terms

CHAPTER 1

TABLE OF CONTENTS

1.1 INTRODUCTION.....	1-1
1.2 GENERAL CONSIDERATIONS	1-1
1.2.1 Definitions	1-2
1.2.1.1 Planning	1-2
1.2.1.2 Location	1-2
1.2.2 Coordination	1-3
1.2.2.1 Coordination within the Transportation Agency.....	1-4
1.2.2.2 Coordination with Other Agencies.....	1-4
1.2.2.3 Public Involvement	1-5
1.2.3 Legal Considerations	1-5
1.2.3.1 Permits	1-6
1.2.3.2 Regulations.....	1-6
1.2.3.3 Laws.....	1-7
1.2.3.4 Federal Emergency Management Agency	1-7
1.2.4 Related Considerations	1-8
1.2.4.1 Design-Related Considerations	1-9
1.2.4.2 Construction-Related Considerations.....	1-9
1.2.4.3 Maintenance-Related Considerations.....	1-10
1.2.5 Environmental Considerations	1-10
1.2.5.1 Water Quality	1-10
1.2.5.2 Fish and Wildlife.....	1-11
1.2.5.3 Other Environmental Considerations	1-12
1.3 SPECIFIC CONSIDERATIONS.....	1-12
1.3.1 Stream Geomorphology	1-13
1.3.1.1 Types of Streams.....	1-13
1.3.1.1.1 Braided Streams	1-14
1.3.1.1.2 Straight Streams	1-14
1.3.1.1.3 Meandering Streams	1-14
1.3.1.2 Islands	1-15
1.3.1.3 Delta Formations and Alluvial Fans	1-16
1.3.1.4 Aggradation and Degradation	1-16
1.3.2 Highway Alignment.....	1-17
1.3.2.1 Horizontal Alignment	1-17
1.3.2.1.1 Existing Alignment	1-17
1.3.2.1.2 New Location or Relocation	1-18
1.3.2.2 Vertical Alignment.....	1-18
1.3.3 Location of Stream Crossings.....	1-19
1.3.3.1 Physical Considerations	1-19
1.3.3.1.1 Confluences.....	1-19
1.3.3.1.2 Tidal Areas.....	1-20

1.3.3.2	Land Use Considerations	1-20
1.3.3.3	Type of Structure	1-21
1.3.4	Encroachments	1-21
1.3.4.1	Longitudinal Encroachments	1-21
1.3.4.2	Transverse Encroachments	1-23
1.3.5	Ice and Debris	1-24
1.3.6	Location of Storm Drainage Facilities	1-24
1.3.7	Location of Utilities	1-25
1.3.8	Floodplain Development and Use	1-26
1.4	PRELIMINARY SURVEYS	1-27
1.4.1	Topographic Data	1-27
1.4.2	Channel Characteristics	1-28
1.4.3	Hydrologic Data	1-28
1.4.3.1	Basin Characteristics	1-28
1.4.3.2	Precipitation	1-29
1.4.3.3	Flood Data	1-29
1.4.3.4	Highwater Information	1-29
1.4.3.5	Existing Structures	1-30
1.4.4	Environmental Data	1-30
1.4.4.1	Fish and Wildlife	1-30
1.4.4.2	Vegetation	1-30
1.4.4.3	Water Quality	1-31
1.4.5	Field Review	1-31
1.5	PRELIMINARY HYDRAULIC REPORTS	1-32
1.6	REFERENCES	1-32
APPENDIX 1A		1-34

CHAPTER 2

TABLE OF CONTENTS

2.1 INTRODUCTION.....	2-1
2.2 FACTORS AFFECTING FLOOD RUNOFF	2-2
2.2.1 Physiographic Characteristics.....	2-2
2.2.1.1 Drainage Area	2-3
2.2.1.2 Shape Factor.....	2-4
2.2.1.3 Slope	2-4
2.2.1.4 Land Use	2-4
2.2.1.5 Soil and Geology.....	2-5
2.2.1.6 Storage Area - Volume	2-5
2.2.1.7 Elevation	2-6
2.2.1.8 Orientation of the Basin	2-7
2.2.1.9 Configuration of Channel and Floodplain Geometry.....	2-7
2.2.1.10 Stream and Drainage Densities	2-7
2.2.2 Site-Specific Characteristics	2-8
2.2.2.1 Aggradation and Degradation	2-8
2.2.2.2 Ice and Debris	2-8
2.2.2.3 Seasonal and Progressive Changes in Vegetation.....	2-9
2.2.2.4 Channel Modifications.....	2-9
2.2.3 Meteorological Characteristics	2-9
2.2.3.1 Rainfall.....	2-10
2.2.3.2 Snow	2-11
2.2.3.3 Temperature, Wind, Evaporation and Transpiration.....	2-11
2.2.3.4 Mixed Population Floods	2-12
2.3 DATA SOURCES	2-12
2.3.1 Categories of Hydrologic Data	2-13
2.3.2 Sources of Hydrologic Data.....	2-13
2.3.2.1 Runoff Data.....	2-13
2.3.2.2 Rainfall Data	2-15
2.3.2.3 Flood History and Historical Floods.....	2-16
2.3.2.4 Flood History of Existing Structures.....	2-16
2.3.2.5 Paleoflood Data.....	2-17
2.4 ELEMENTS OF RUNOFF PROCESS.....	2-17
2.4.1 Infiltration	2-18
2.4.2 Detention and Depression Storage.....	2-20
2.4.3 Stream Flow and Flood Hydrograph.....	2-20
2.4.4 Hydrograph Parameters	2-22
2.4.4.1 Time of Concentration	2-22
2.4.4.1.1 Overland Flow.....	2-22
2.4.4.1.2 Swale, Ditch or Stream Channel Flow	2-23

2.4.4.1.3 Storm Drain or Culvert Flow	2-24
2.4.4.2 Lag Time, Rise Time and Time to Peak	2-24
2.4.5 Unit Hydrographs	2-25
2.5 MEASUREMENTS OF FLOOD MAGNITUDES.....	2-25
2.5.1 Direct Measurements of Flood Magnitudes	2-25
2.5.2 Indirect Measurements of Flood Magnitudes	2-26
2.5.3 Ordinary Highwater and Mean Annual Flood	2-26
2.6 FLOOD PROBABILITY AND FREQUENCY AS APPLIED TO HIGHWAY HYDROLOGY	2-27
2.6.1 Concepts of Probability and Frequency Analysis.....	2-27
2.6.2 Floods Considered in Hydrologic and Hydraulic Analysis	2-28
2.6.2.1 Base Flood and Super Flood.....	2-28
2.6.2.2 Overtopping Flood.....	2-28
2.6.2.3 Design Flood.....	2-28
2.6.2.4 Maximum Historical Flood.....	2-29
2.6.2.5 Probable Maximum Flood	2-29
2.6.3 Design Flood Frequency.....	2-29
2.6.3.1 Policy Alternative	2-30
2.6.3.2 Economic Assessment Alternative	2-30
2.6.3.3 Highway Classification.....	2-31
2.6.3.4 Flood Hazard Criteria	2-31
2.6.3.4.1 Sensitivity to Increased Flood Magnitude	2-32
2.6.3.4.2 Loss of Life.....	2-32
2.6.3.4.3 Property Damages.....	2-32
2.6.3.4.4 Traffic Interruption	2-33
2.6.3.4.5 Economics and Budgetary Constraints.....	2-33
2.7 METHODS FOR ESTIMATING FLOOD PEAKS, DURATIONS AND VOLUMES	2-33
2.7.1 Individual Station Flood Frequency Analysis	2-34
2.7.1.1 Development of Flood-Frequency Curve	2-34
2.7.1.1.1 Graphical Method	2-34
2.7.1.1.2 Mathematical Method.....	2-35
2.7.1.2 Extrapolating Flood-Frequency Curves.....	2-35
2.7.1.3 Transfer of Data.....	2-36
2.7.2 Regional Flood-Frequency Analysis	2-36
2.7.2.1 Index-Flood Method	2-36
2.7.2.2 Multiple Regression Analysis—Watershed Characteristics	2-36
2.7.2.2.1 USGS-FHWA Urban Method	2-37
2.7.2.2.2 USGS Regional or Local Rural Methods	2-38
2.7.2.3 Multiple Regression Analysis—Channel/Characteristics Method	2-38
2.7.3 Empirical Hydrologic Methods	2-39
2.7.3.1 Rational Method	2-39
2.7.3.2 British Method.....	2-40

2.7.3.3 NRCS T.R. 55 Method.....	2-40
2.7.4 Unit Hydrograph Methods	2-40
2.7.4.1 Finite Time Unit Hydrograph.....	2-41
2.7.4.2 Synthetic Unit Hydrograph	2-41
2.7.4.2.1 Ten-Minute Unit Hydrographs.....	2-42
2.7.4.2.2 Dimensionless Hydrograph.....	2-42
2.7.5 Regional Hydrographs	2-42
2.7.6 Mathematical Models.....	2-43
2.7.6.1 HYDRAIN Computer System.....	2-44
2.7.6.2 HEC-1/HEC-HMS Models	2-44
2.7.6.3 NRCS TR-20 Method	2-45
2.7.6.4 The Stormwater Management Model (SWMM).....	2-45
2.7.6.5 The Stanford Watershed or Hydrocomp (HSP) Model.....	2-45
2.7.6.6 Penn State Urban Runoff Model	2-46
2.7.6.7 The Massachusetts Institute of Technology Catchment (The MITCAT) Model.....	2-46
2.7.6.8 USACE STORM Model	2-46
2.7.6.9 ILLUDAS Model	2-46
2.7.6.10 USGS “Dawdy” Model	2-47
2.7.7 Accuracy of Methods for Estimating Peak Discharges.....	2-47
2.8 CHARACTERISTICS AND ANALYSIS OF LOW FLOWS	2-48
2.9 STORAGE AND FLOOD ROUTING FOR STORMWATER MANAGEMENT.	2-49
2.9.1 Storage Characteristics.....	2-49
2.9.2 Storage Size and Location	2-50
2.9.3 Determination of Storage Volume and Flood Routing Procedures	2-51
2.10 DOCUMENTATION.....	2-51
2.11 REFERENCES.....	2-52

CHAPTER 3

TABLE OF CONTENTS

3.1 INTRODUCTION.....	3-1
3.2 PURPOSE AND OBJECTIVES	3-2
3.3 EROSION AND SEDIMENT-RELATED PLANNING AND LOCATION CONSIDERATIONS	3-4
3.3.1 Identification of Erosion Sensitive Areas	3-5
3.3.2 Identification of Sediment Sensitive Areas.....	3-5
3.3.3 Coordination	3-6
3.3.3.1 Coordination Within the Transportation Agency.....	3-6
3.3.3.2 Coordination with Other Agencies.....	3-6
3.4 EROSION AND SEDIMENT-RELATED GEOMETRIC CONSIDERATIONS	3-6
3.4.1 Alignment and Grade.....	3-7
3.4.2 Cross Section	3-7
3.5 PLAN DEVELOPMENT	3-8
3.5.1 Temporary Erosion and Sediment Control Measures	3-9
3.5.1.1 Ground Cover.....	3-9
3.5.1.2 Channel Liners	3-10
3.5.1.3 Diversion Dikes and Ditches.....	3-13
3.5.1.4 Filter Berms.....	3-15
3.5.1.5 Temporary Slope Drains	3-16
3.5.1.6 Brush Barriers	3-18
3.5.1.7 Silt Fences	3-19
3.5.1.8 Check Dams	3-21
3.5.1.9 Straw Bales	3-23
3.5.1.10 Riprap.....	3-23
3.5.1.11 Sediment Basins	3-26
3.5.1.11.1 Planning and Location	3-26
3.5.1.11.2 Design	3-29
3.5.1.12 Phased Erosion and Sediment Control Plans	3-30
3.5.2 Permanent Erosion and Sediment Control Measures.....	3-30
3.5.2.1 Vegetation	3-30
3.5.2.2 Slopes	3-31
3.5.2.3 Channels.....	3-32
3.5.2.3.1 Sizing and Shape	3-33
3.5.2.3.2 Alignment and Grade	3-33
3.5.2.3.3 Linings	3-34
3.5.2.3.4 Grade Control Structures	3-36
3.5.2.4 Shoulder Drains.....	3-38

3.5.2.5 Culverts.....	3-38
3.5.2.6 Underdrains	3-40
3.6 CONSTRUCTION	3-41
3.6.1 Scheduling Operation	3-41
3.6.2 Clearing and Grubbing	3-42
3.6.3 Construction Operations in Rivers, Streams, and Impoundments.....	3-42
3.6.4 Excavation and Embankment Construction	3-44
3.6.5 Bridge Construction	3-45
3.6.6 Culvert Construction	3-46
3.6.7 Borrow Pits, Waste Areas, and Haul Roads	3-48
3.6.8 Maintenance of Control Features	3-48
3.6.9 Enforcement	3-52
3.7 REFINEMENT OF METHODS	3-53
3.7.1 Research and Development	3-53
3.7.2 Feedback.....	3-53
3.8 REFERENCES	3-54

CHAPTER 4

TABLE OF CONTENTS

4.1 INTRODUCTION.....	4-1
4.2 DATA COLLECTION	4-2
4.2.1 Topographic Features.....	4-2
4.2.2 Drainage Area	4-2
4.2.3 Channel Characteristics	4-2
4.2.4 Fish Life.....	4-3
4.2.5 Highwater Information.....	4-3
4.2.6 Existing Structures.....	4-3
4.2.7 Field Review	4-4
4.3 CULVERT LOCATION	4-4
4.3.1 Plan	4-5
4.3.2 Profile.....	4-6
4.4 CULVERT TYPE	4-8
4.4.1 Shape and Cross Section.....	4-8
4.4.1.1 Circular.....	4-8
4.4.1.2 Pipe Arch and Elliptical	4-8
4.4.1.3 Box or Rectangular.....	4-8
4.4.1.4 Arches.....	4-9
4.4.1.5 Multiple Barrels.....	4-9
4.4.2 Materials	4-9
4.4.3 End Treatments	4-10
4.4.3.1 Projecting	4-10
4.4.3.2 Mitered	4-10
4.4.3.3 Pipe End Sections.....	4-10
4.4.3.4 Headwalls and Wingwalls.....	4-11
4.5 HYDRAULIC DESIGN.....	4-12
4.5.1 Design Flood Discharge.....	4-12
4.5.2 Headwater Elevation	4-12
4.5.3 Tailwater	4-14
4.5.4 Outlet Velocity.....	4-14
4.5.5 Culvert Hydraulics.....	4-14
4.5.5.1 Conditions of Flow.....	4-15
4.5.5.1.1 Inlet Control.....	4-15
4.5.5.1.2 Outlet Control	4-16
4.5.5.2 Performance Curves	4-16

4.5.6	Entrance Configurations.....	4-18
4.5.6.1	Conventional.....	4-18
4.5.6.2	Beveled	4-21
4.5.6.3	Side-Tapered Inlets	4-22
4.5.6.4	Slope-Tapered Inlets	4-24
4.5.7	Barrel Characteristics	4-24
4.5.8	Outlet Design.....	4-25
4.6	SPECIAL HYDRAULIC CONSIDERATIONS.....	4-26
4.6.1	Anchorage	4-26
4.6.2	Piping.....	4-28
4.6.2.1	Joints	4-29
4.6.2.2	Anti-Seep Collars.....	4-29
4.6.2.3	Weep Holes.....	4-29
4.6.3	Junctions and Bifurcations	4-30
4.6.4	Training Walls.....	4-30
4.6.5	Sag Culverts	4-31
4.6.6	Irregular Alignment.....	4-31
4.6.7	Cavitation	4-31
4.6.8	Tidal Effects and Flood Protection.....	4-31
4.7	MULTIPLE-USE CULVERTS.....	4-32
4.7.1	Utilities.....	4-32
4.7.2	Stock and Wildlife Passage	4-32
4.7.3	Land Access.....	4-32
4.7.4	Fish Passage	4-32
4.8	IRRIGATION.....	4-35
4.9	DEBRIS CONTROL.....	4-35
4.9.1	Debris Control Structure Design	4-36
4.9.2	Maintenance	4-36
4.10	SERVICE LIFE.....	4-36
4.10.1	Abrasion	4-37
4.10.2	Corrosion.....	4-38
4.11	SAFETY.....	4-39
4.12	DESIGN DOCUMENTATION.....	4-39
4.12.1	Compilation of Data	4-39
4.12.2	Retention of Records	4-40

4.13	HYDRAULIC-RELATED CONSTRUCTION CONSIDERATIONS.....	4-40
4.13.1	Verification of Plans	4-40
4.13.2	Temporary Erosion Control	4-40
4.13.3	Construction and Documentation	4-41
4.14	HYDRAULIC-RELATED MAINTENANCE CONSIDERATIONS.....	4-41
4.14.1	Maintenance Inspections.....	4-41
4.14.2	Flood Records	4-41
4.14.3	Reconstruction and Repair	4-41
4.15	REFERENCES.....	4-42

CHAPTER 5

TABLE OF CONTENTS

5.1	INTRODUCTION.....	5-1
5.2	LAWS IN GENERAL.....	5-2
5.3	FEDERAL LAWS.....	5-3
5.3.1	National Environmental Policy Act (NEPA)	5-4
5.3.2	Flood Insurance.....	5-5
5.3.3	Navigable Waters.....	5-6
5.3.4	Fish and Wildlife	5-8
5.3.5	Tennessee Valley Authority (TVA).....	5-9
5.3.6	Coastal Zone Management	5-9
5.3.7	Executive Orders.....	5-10
5.4	STATE LAWS.....	5-11
5.4.1	Common Law.....	5-11
5.4.1.1	Classification of Waters	5-11
5.4.1.1.1	Surface Waters.....	5-12
5.4.1.1.2	Stream Waters.....	5-12
5.4.1.1.3	Floodwaters	5-12
5.4.1.1.4	Groundwaters.....	5-13
5.4.1.2	Surface Water Rules and Applications.....	5-13
5.4.1.2.1	Civil Law Rule (Natural Drainage Rule).....	5-13
5.4.1.2.2	Application of the Civil Law Rule.....	5-14
5.4.1.2.3	Common Enemy Doctrine	5-15
5.4.1.2.4	Application of the Common Enemy Doctrine	5-15
5.4.1.2.5	Reasonable Use Rule	5-15
5.4.1.2.6	Application of the Reasonable Use Rule	5-16
5.4.1.3	Stream Water Rules.....	5-16
5.4.1.4	Floodwater Rule	5-17
5.4.1.5	Groundwater Rules.....	5-17
5.4.2	Statutory Law.....	5-18
5.4.2.1	Eminent Domain	5-18
5.4.2.2	Water Rights.....	5-18
5.4.2.2.1	Riparian Doctrine	5-19
5.4.2.2.2	The Doctrine of Prior Appropriation	5-19
5.4.2.3	Flood Control, Drainage and Irrigation Districts	5-20
5.4.2.4	Agricultural Drainage Law.....	5-20
5.4.2.5	Environmental Laws	5-20
5.4.2.6	Highway Agency Rules.....	5-21

5.5 LOCAL LAWS	5-21
5.5.1 Local Ordinances.....	5-21
5.5.2 Flood Disaster Protection Act of 1973	5-22
5.6 COMMON DRAINAGE COMPLAINTS.....	5-22
5.6.1 Diversion	5-23
5.6.2 Collection and Concentration	5-23
5.6.3 Augmentation	5-23
5.6.4 Obstruction	5-24
5.6.5 Erosion and Sedimentation.....	5-24
5.6.6 Groundwater Interference.....	5-24
5.7 LEGAL REMEDY	5-25
5.7.1 Inverse Condemnation.....	5-25
5.7.2 Injunction.....	5-25
5.7.3 Legislative Claims	5-26
5.7.4 Tort Claims.....	5-26
5.7.5 Tort Liability of State Highway Agencies.....	5-27
5.8 INVOLVEMENT OF THE HYDRAULICS ENGINEER.....	5-28
5.8.1 Planning and Location Considerations	5-29
5.8.2 Design Considerations.....	5-29
5.8.2.1 Documentation	5-29
5.8.2.2 Engineer Liability	5-30
5.8.3 Liaison with Legal Staff.....	5-30
5.8.4 Engineering Evidence.....	5-31
5.8.5 Negotiation	5-31
5.8.6 The Engineer as a Witness	5-31
5.8.6.1 Engineering Testimony	5-31
5.8.6.2 Conduct When a Witness.....	5-32
5.8.7 Engineer's Conduct Toward the Opposing Party	5-33
5.9 REFERENCES	5-33

CHAPTER 6

TABLE OF CONTENTS

6.1	INTRODUCTION.....	6-1
6.2	CONSIDERATIONS FOR ESTABLISHING CRITERIA.....	6-2
6.3	PLANNING AND LOCATION.....	6-2
6.3.1	Planning	6-3
6.3.1.1	Coordination with Other Agencies.....	6-3
6.3.1.1.1	Local Drainage Systems	6-5
6.3.1.1.2	Flood Control.....	6-5
6.3.1.1.3	Floodplain Management	6-5
6.3.1.1.4	Conservation.....	6-6
6.3.1.1.5	Fish and Wildlife	6-6
6.3.1.1.6	Irrigation	6-7
6.3.1.1.7	Permits	6-7
6.3.1.2	Cooperative Projects	6-7
6.3.2	Location	6-8
6.3.2.1	Longitudinal Encroachments.....	6-8
6.3.2.2	Transverse Encroachments.....	6-10
6.4	SURVEYS.....	6-11
6.4.1	Topographic Features.....	6-20
6.4.2	Channel Characteristics	6-20
6.4.3	Fish and Wildlife	6-21
6.4.4	Highwater Information.....	6-22
6.4.5	Hydrologic Data.....	6-23
6.5	HYDROLOGY	6-23
6.6	HYDRAULICS OF OPEN CHANNELS.....	6-23
6.6.1	Types of Flow	6-24
6.6.2	Open Channel Equations.....	6-25
6.6.3	Analysis of Open-Channel Flow.....	6-27
6.6.3.1	Factors Affecting Open-Channel Flow	6-27
6.6.3.2	Stable Stage-Discharge Relationships.....	6-28
6.6.3.2.1	Single-Section Analysis.....	6-29
6.6.3.2.2	Water Surface Profiles.....	6-29
6.6.3.2.3	Control Sections	6-30
6.6.3.3	Unstable Stage-Discharge Relationships.....	6-30
6.6.3.4	Flow and Velocity Distribution.....	6-35

6.6.4	Special Analysis Techniques	6-36
6.6.4.1	Two-Dimensional Analysis	6-36
6.6.4.2	Water and Sediment Routing	6-36
6.6.4.3	Unsteady Flow Analysis	6-38
6.7	FLUVIAL GEOMORPHOLOGY	6-38
6.7.1	Alluvial Streams	6-39
6.7.1.1	Stream Types	6-39
6.7.1.1.1	Straight Streams	6-41
6.7.1.1.2	Braided Streams	6-41
6.7.1.1.3	Meandering Streams.....	6-42
6.7.1.2	Graded or Poised Streams	6-44
6.7.1.3	Stream System Response	6-44
6.7.2	Nonalluvial Channels	6-46
6.7.3	Stream Classification Methods.....	6-46
6.8	THE EFFECTS OF CHANNEL ALTERATIONS	6-51
6.8.1	Channel Realignment	6-52
6.8.1.1	Slope Modification	6-52
6.8.1.2	Section Modification.....	6-53
6.8.2	Conveyance Modification	6-54
6.9	CHANNEL STABILIZATION AND BANK PROTECTION.....	6-56
6.9.1	Stabilization Considerations.....	6-56
6.9.2	Selection of Protective Measures	6-57
6.9.3	Revetments	6-57
6.9.4	Using Vegetation for Stream Bank Stabilization	6-59
6.10	ROADSIDE DRAINAGE CHANNELS	6-59
6.10.1	Safety and Aesthetics	6-60
6.10.2	Shape	6-60
6.10.3	Lining	6-60
6.10.4	Superelevation.....	6-63
6.10.4.1	Supercritical Flow.....	6-64
6.10.4.2	Subcritical Flow	6-64
6.10.5	Chutes and Flumes	6-64
6.10.6	Grade Control Structures	6-65
6.10.7	Transitions	6-65
6.10.7.1	Supercritical Flow Transitions.....	6-66
6.10.7.2	Subcritical Flow Transitions	6-66
6.10.8	Confluences	6-66
6.10.9	Bends and Curves	6-67

6.11	STRUCTURAL CONSIDERATIONS.....	6-68
6.11.1	Subsurface Investigations	6-69
6.11.2	Reinforcement for Rigid Linings	6-69
6.11.3	Buoyancy and Heave	6-70
6.11.4	Seepage Control Filter Blankets	6-70
6.12	CONSTRUCTION-RELATED HYDRAULIC CONSIDERATIONS.....	6-71
6.13	MAINTENANCE-RELATED HYDRAULIC CONSIDERATIONS.....	6-71
6.13.1	Maintenance during Contract Period	6-72
6.13.2	Hydraulic-Related Maintenance Considerations	6-72
6.14	REFERENCES.....	6-72

CHAPTER 7

TABLE OF CONTENTS

7.1 INTRODUCTION.....	7-1
7.2 PLANNING AND LOCATION.....	7-1
7.2.1 Location of Stream Crossing	7-2
7.2.2 Structure Type.....	7-3
7.2.3 Environmental Considerations	7-3
7.2.4 Coordination with Other Agencies	7-4
7.2.4.1 Water Resources Agencies.....	7-5
7.2.4.2 Permits and Approvals	7-5
7.2.5 Stream Morphology	7-6
7.2.5.1 Types of Streams.....	7-7
7.2.5.1.1 Braided Streams.....	7-7
7.2.5.1.2 Straight Streams.....	7-8
7.2.5.1.3 Meandering Streams	7-10
7.2.5.2 Islands, Delta Formations, and Alluvial Fans	7-12
7.2.5.3 Aggradation and Degradation	7-14
7.2.6 Confluences	7-15
7.2.7 Tidal Areas.....	7-17
7.2.8 Floodplain Levees and Encroachments.....	7-17
7.2.9 Replacement, Repair, and Rehabilitation.....	7-18
7.3 DATA COLLECTION	7-19
7.3.1 Topographic Features.....	7-19
7.3.2 Land Use and Culture	7-19
7.3.3 Hydrologic Data.....	7-20
7.3.3.1 Flood Data	7-20
7.3.3.2 Basin Characteristics	7-20
7.3.3.3 Precipitation	7-22
7.3.3.4 Highwater Information	7-22
7.3.4 Existing Structures	7-23
7.3.5 Channel Characteristics	7-24
7.3.6 Environmental Data	7-24
7.3.7 Site Plan	7-25
7.3.8 Field Reviews.....	7-26
7.4 HYDROLOGIC ANALYSIS	7-26
7.5 HYDRAULIC ANALYSIS OF THE STREAM.....	7-28
7.5.1 Stage-Discharge Relationships	7-28
7.5.2 Types of Stage-Discharge Relationships	7-30
7.5.2.1 Stable.....	7-30
7.5.2.2 Unstable.....	7-30

7.6	STREAM-CROSSING DESIGN	7-31
7.6.1	Criteria	7-31
7.6.2	Highway-Stream Crossing Systems	7-33
7.6.2.1	Highway Profile and Alignment	7-34
7.6.2.2	Waterway Openings	7-39
7.6.2.2.1	Location	7-39
7.6.2.2.2	Size	7-43
7.6.2.2.3	Auxiliary Openings	7-44
7.6.2.2.4	Replacement Bridges	7-45
7.6.2.3	Structural Alternatives	7-45
7.6.2.3.1	Bridge or Culvert	7-45
7.6.2.3.2	Piers	7-47
7.6.2.3.3	Abutments	7-48
7.6.2.3.4	Foundations	7-49
7.6.2.3.5	Superstructures	7-50
7.6.2.4	Channel Modification	7-54
7.6.3	Analysis of the Stream Crossing System	7-56
7.6.3.1	Hydraulic Performance of the Crossing System	7-57
7.6.3.2	Backwater	7-58
7.6.3.3	Flow Distribution	7-59
7.6.3.4	Velocity	7-60
7.6.3.5	Scour	7-61
7.6.3.5.1	General Scour	7-63
7.6.3.5.2	Local Scour	7-65
7.6.3.5.3	Natural Scour	7-65
7.6.3.5.4	In-Stream Borrow Areas, Commercial Mining, and Dredging for Navigation and Flood Control	7-66
7.6.3.5.5	Combined Effects of General, Local, and Natural Scour	7-68
7.6.3.6	Stream Environment	7-68
7.6.3.7	Economic Analysis	7-69
7.6.4	Protective and Preventive Measures	7-71
7.6.4.1	Pier Foundations	7-71
7.6.4.1.1	Preventive Measures at Piers	7-72
7.6.4.1.2	Protective Measures at Piers	7-75
7.6.4.2	Abutments and Approach Fills	7-76
7.6.4.2.1	Protective and Preventive Measures along Embankments	7-77
7.6.4.2.2	Protective and Preventive Measures at Abutments	7-78
7.6.4.3	Bank Stabilization and River Training	7-81
7.6.4.4	Buoyant, Drag, Debris, and Ice Forces on Bridge Superstructures	7-82
7.6.5	Dolphins and Fender Systems	7-83
7.7	DECK DRAINAGE	7-85
7.7.1	Deck Inlets	7-85
7.7.2	Bridge End Drains	7-86
7.8	DESIGN DOCUMENTATION	7-86
7.8.1	Design Data for Permanent Records	7-87

7.8.2	Post-Construction Data	7-87
7.9	CONSTRUCTION-RELATED HYDRAULIC CONSIDERATIONS.....	7-88
7.9.1	Hydrologic Information.....	7-88
7.9.2	Cofferdams, Caissons, and Falsework	7-88
7.9.3	Contractor Crossings and Work Areas.....	7-88
7.9.4	Borrow Areas	7-89
7.10	HYDRAULIC-RELATED CONSTRUCTION CONSIDERATIONS.....	7-90
7.10.1	Verification of Plans.....	7-90
7.10.2	Plan Changes	7-90
7.10.3	Borrow Areas	7-90
7.10.4	Detours	7-91
7.10.5	Environmental and Ecological Aspects.....	7-91
7.10.6	Feedback.....	7-92
7.11	MAINTENANCE-RELATED HYDRAULIC CONSIDERATIONS.....	7-92
7.12	HYDRAULIC-RELATED MAINTENANCE CONSIDERATIONS.....	7-93
7.12.1	Maintenance Inspections	7-93
7.12.2	Flood Damages.....	7-93
7.12.2.1	Remedial Construction and Repair	7-94
7.12.2.2	Recurring Damage	7-94
7.13	REFERENCES.....	7-95

CHAPTER 8

TABLE OF CONTENTS

8.1 INTRODUCTION.....	8-1
8.2 PLANNING CONSIDERATIONS.....	8-1
8.2.1 Coordination and Cooperation.....	8-2
8.2.1.1 Other Agencies.....	8-2
8.2.1.2 Utilities.....	8-3
8.2.1.3 Property Owners.....	8-3
8.2.2 Permits and Approvals.....	8-3
8.2.2.1 National Flood Insurance Program.....	8-4
8.2.2.2 Federal Water Pollution Control Act (FWPCA)—Section 404.....	8-5
8.2.2.3 National Pollutant Discharge Elimination System (NPDES).....	8-5
8.2.2.4 Navigation.....	8-6
8.2.2.5 Coastal Zone Management Act.....	8-7
8.2.2.6 State Permits.....	8-7
8.2.3 Replace or Rehabilitate Structures.....	8-7
8.2.4 Environmental Considerations.....	8-8
8.3 TYPES OF RESTORATION AND UPGRADING	8-9
8.3.1 Horizontal or Vertical Alignment Adjustments.....	8-9
8.3.2 Cross Section Changes.....	8-9
8.3.2.1 Widening Roadway.....	8-10
8.3.2.2 Flattening Foreslopes.....	8-10
8.3.2.3 Adding Traffic Lanes.....	8-10
8.3.3 Urban Reconstruction.....	8-11
8.3.4 Safety Projects.....	8-11
8.3.5 Rehabilitation and Replacement of Bridges and Culverts.....	8-12
8.4 DATA COLLECTION	8-12
8.4.1 Condition Survey of Existing Structures.....	8-12
8.4.2 Past Hydraulic Performance.....	8-13
8.4.3 Identification of Other Problems with Existing Structures.....	8-14
8.5 HYDROLOGIC CONSIDERATIONS.....	8-15
8.5.1 Evaluation of Observed Flood Discharge.....	8-15
8.5.2 Changes in Hydrologic Methods.....	8-16
8.5.3 Land Use Changes.....	8-17
8.5.4 Hydrologic and Hydraulic Investigations.....	8-19
8.6 HYDRAULIC CONSIDERATIONS.....	8-19
8.6.1 Economic Analysis of Alternatives.....	8-20
8.6.2 Consequences of Change in Hydraulic Performance of Existing Structures.....	8-21

8.6.2.1	Adding Traffic Lanes.....	8-21
8.6.2.1.1	With Median.....	8-21
8.6.2.1.2	Without Median.....	8-22
8.6.2.2	Safety Projects	8-24
8.6.2.3	Culvert Replacement and Rehabilitation	8-25
8.6.2.3.1	Culvert Replacement	8-25
8.6.2.3.2	Culvert Rehabilitation	8-25
8.6.2.4	Bridge Replacements	8-26
8.6.2.5	Changes in Type of Structure	8-27
8.6.2.6	Culvert Extensions	8-28
8.6.2.7	Structures in Urban Areas	8-29
8.6.3	Influence of Adjacent Structures	8-30
8.6.3.1	Upstream Structures	8-30
8.6.3.2	Downstream Structures	8-31
8.6.4	Improvements in Hydraulic Performance of Existing Structures	8-31
8.6.4.1	Improved Inlets	8-32
8.6.4.2	Adding Guide Banks.....	8-32
8.6.4.3	Channel Modifications.....	8-33
8.6.4.4	Bridge Modification.....	8-35
8.6.4.5	Debris Control.....	8-35
8.6.5	Obsolete Structures.....	8-35
8.6.6	Added Structures	8-36
8.7	CONSTRUCTION-RELATED CONSIDERATIONS DURING HYDRAULIC DESIGN	8-37
8.7.1	Providing for Drainage during Construction	8-38
8.7.1.1	Contractor Crossings.....	8-38
8.7.1.2	Detours.....	8-39
8.7.2	Stage Construction.....	8-40
8.7.3	Roadway Realignment.....	8-40
8.8	EROSION AND SEDIMENTATION CONTROL.....	8-41
8.9	REFERENCES	8-41

CHAPTER 9

TABLE OF CONTENTS

9.1 INTRODUCTION.....	9-1
9.2 PLANNING AND COORDINATION	9-2
9.2.1 Drainage Involvement by Others	9-2
9.2.2 Cooperative Projects	9-3
9.3 DRAINAGE DATA	9-3
9.3.1 Sources of Drainage Data	9-3
9.3.2 Types of Drainage Data	9-4
9.4 HYDROLOGY	9-5
9.4.1 Calibration of Computations.....	9-5
9.4.1.1 Hydrologic Calibration.....	9-5
9.4.1.2 Hydraulic Calibration.....	9-5
9.5 ELEMENTS OF SYSTEM DESIGN	9-6
9.5.1 Pavement Drainage	9-6
9.5.1.1 Curb and Gutter Flow.....	9-6
9.5.1.2 Surface Drainage of Pavements	9-8
9.5.1.2.1 Pavement Texture	9-8
9.5.1.2.2 Mechanics of Flow on Pavements	9-9
9.5.1.2.3 Ruts and Puddles	9-12
9.5.1.3 Inlets	9-12
9.5.1.3.1 Inlet Location.....	9-12
9.5.1.3.2 Inlet Size	9-14
9.5.1.3.3 Grate Inlets	9-14
9.5.1.3.4 Curb-Opening Inlets	9-17
9.5.1.3.5 Slotted Drain Inlets.....	9-18
9.5.1.3.6 Combination Inlets	9-19
9.5.1.3.7 Bridge Deck Inlets	9-20
9.5.1.4 Design Criteria	9-21
9.5.1.4.1 Flood Frequency	9-22
9.5.1.4.2 Allowable Water Spread.....	9-23
9.5.1.4.3 Surface Water Depth.....	9-24
9.5.2 Storm Drains	9-24
9.5.2.1 Hydraulics of Storm Drains.....	9-25
9.5.2.1.1 Open-Channel vs. Pressure Flow.....	9-25
9.5.2.1.2 Storm Drain Outfalls.....	9-27
9.5.2.1.3 Head Losses in Storm Drains	9-28
9.5.2.1.4 Hydraulic Gradeline	9-29

9.5.2.2	Storm Drain Design Criteria	9-30
9.5.2.2.1	Flood Frequency	9-31
9.5.2.2.2	Maximum Highwater	9-32
9.5.2.2.3	Minimum Velocities	9-32
9.5.2.3	Design Process and System Planning	9-32
9.5.2.4	Appurtenant Structures	9-34
9.5.2.4.1	Access Holes	9-34
9.5.2.4.2	Junction Chambers	9-36
9.5.3	Roadside Channels	9-37
9.5.4	Storage Facilities	9-37
9.5.4.1	Types of Facilities	9-38
9.5.4.1.1	Detention Facilities	9-39
9.5.4.1.2	Retention Facilities	9-41
9.5.4.1.3	Recharge Facilities	9-42
9.5.4.2	Inflow and Outflow Structures	9-42
9.5.4.3	Safety	9-43
9.5.5	Stormwater Pumping Stations	9-44
9.5.5.1	General Considerations	9-44
9.5.5.2	Location	9-44
9.5.5.3	Hydrology	9-45
9.5.5.4	Storm Drain Collection Systems	9-46
9.5.5.5	Types of Stations	9-46
9.5.5.6	Station Design	9-47
9.5.5.6.1	Number and Capacity of Pumps	9-47
9.5.5.6.2	Sump Pump	9-48
9.5.5.6.3	Types of Pumps	9-48
9.5.5.6.4	Types of Power	9-48
9.5.5.6.5	Sump Design	9-50
9.5.5.6.6	Pump On-Off Settings	9-50
9.5.5.6.7	Pump Controls	9-51
9.5.5.6.8	Discharge Piping	9-51
9.5.5.6.9	Flap Gates and Check Valves	9-51
9.5.5.6.10	Roof Hatches and Monorails	9-51
9.5.5.6.11	Trash Racks and Grit Chambers	9-52
9.5.5.6.12	Ventilation	9-52
9.5.5.6.13	Telemetry	9-52
9.5.5.7	Specifications	9-52
9.5.5.8	Equipment Certification and Testing	9-52
9.5.5.9	Construction	9-53
9.5.5.10	Maintenance	9-53
9.5.5.11	Retrofitting Existing Stations	9-53
9.5.5.12	Architectural Considerations	9-53
9.5.5.13	Total Annual Cost	9-54
9.5.5.14	Safety	9-54
9.5.5.15	Reliability	9-54

9.5.6	Outfalls.....	9-54
9.5.6.1	General Outfall Considerations.....	9-55
9.5.6.2	Design and Analysis of Outfalls.....	9-57
9.5.6.2.1	Hydrology.....	9-57
9.5.6.2.2	Hydraulics.....	9-58
9.5.7	Siphons.....	9-59
9.5.7.1	Systems for Draining Subsurface Water	9-60
9.5.7.2	Horizontal Drains	9-62
9.5.7.3	Pipe Underdrains.....	9-63
9.5.7.4	Vertical Wells.....	9-65
9.5.7.5	Subgrade Drainage Systems.....	9-66
9.5.7.6	Edge Drain Collector Systems	9-67
9.6	FACTORS AFFECTING DESIGN.....	9-68
9.6.1	Utilities.....	9-68
9.6.2	Easements	9-70
9.6.3	Service Life of Drainage Pipe.....	9-71
9.6.4	Erosion, Sedimentation, and Water Quality.....	9-74
9.6.5	Attractive Nuisance Mitigations	9-74
9.6.6	Legal Factors.....	9-75
9.7	COMPUTER MODELS.....	9-76
9.7.1	General Features	9-76
9.7.2	Hydrology	9-77
9.7.2.1	Peak Discharge Determination.....	9-77
9.7.2.2	Surface Hydrologic Simulation.....	9-78
9.7.3	Storm Drain Inlets.....	9-78
9.7.4	Underground Appurtenances	9-79
9.7.4.1	Conduit Systems.....	9-79
9.7.4.1.1	Hydraulic Gradeline	9-79
9.7.4.1.2	Supercritical Flow.....	9-80
9.7.4.2	Other Losses.....	9-80
9.7.5	Water Quality.....	9-80
9.7.6	Cost Estimating.....	9-80
9.8	DOCUMENTATION.....	9-81
9.9	CONSTRUCTION.....	9-82
9.9.1	Construction-Related Hydraulic Considerations	9-82
9.9.2	Hydraulic-Related Construction Considerations	9-85
9.10	MAINTENANCE.....	9-86
9.10.1	Maintenance-Related Hydraulic Considerations	9-86
9.10.2	Hydraulic-Related Maintenance Considerations	9-87
9.10.2.1	Maintenance Inspections	9-87

9.10.2.2	Performance Evaluation.....	9-87
9.11	REFERENCES	9-87

CHAPTER 10

TABLE OF CONTENTS

10.1 INTRODUCTION.....	10-1
10.1.1 Purpose of the Chapter	10-2
10.1.2 Role of the Hydraulics Engineer	10-2
10.1.3 Environmentally Sensitive Surface Water Environments	10-4
10.1.4 Surface Water Effect and Significance	10-4
10.1.5 Threshold Value.....	10-5
10.1.6 Reversible and Irreversible Effects	10-5
10.1.7 Legal Constraints	10-5
10.1.8 Organization of the Chapter.....	10-6
10.1.9 Survey and Data Collection	10-7
10.1.10 Implementing Environmental Plans.....	10-7
10.2 ESTIMATING SURFACE WATER EFFECTS.....	10-7
10.2.1 Quantity Effects	10-7
10.2.1.1 Surface Water Inventory	10-8
10.2.1.2 Floodplain Inventory	10-10
10.2.1.3 Runoff Peaks and Volumes.....	10-10
10.2.2 Quality Effects	10-16
10.2.2.1 Sediment	10-16
10.2.2.1.1 Sediment Transport.....	10-16
10.2.2.1.2 Sediment Data.....	10-17
10.2.2.1.3 Estimating Existing Sediment Regimes.....	10-18
10.2.2.1.4 Construction Erosion	10-19
10.2.2.1.5 Sediment Effects.....	10-21
10.2.2.1.6 Significance of Sediment Effects.....	10-26
10.2.2.2 Mineral and Chemical.....	10-26
10.2.2.3 Character and Aesthetics.....	10-35
10.2.2.3.1 Character.....	10-35
10.2.2.3.2 Aesthetics.....	10-35
10.2.3 Climatological Effects	10-36
10.2.3.1 Data	10-36
10.2.3.2 Temperature	10-37
10.2.3.3 Season Delimitation	10-38
10.2.3.4 Precipitation	10-38
10.2.4 Biological Effects.....	10-40
10.2.5 Socioeconomic Effects.....	10-41
10.3 MITIGATING SURFACE WATER EFFECTS.....	10-41
10.3.1 Quantity Effects	10-42
10.3.1.1 Surface Water Inventory	10-43
10.3.1.2 Floodplains.....	10-43
10.3.1.3 Runoff Peaks and Volumes.....	10-44

10.3.2	Quality Effects.....	10-47
10.3.2.1	Erosion and Sediment.....	10-47
10.3.2.2	Mineral and Chemical	10-47
10.3.2.3	Character and Aesthetics	10-51
10.3.3	Climatological Effects.....	10-51
10.4	STREAM MODIFICATION AND MITIGATIVE PRACTICES.....	10-51
10.4.1	Need for Mitigative Practices.....	10-51
10.4.2	Design Discharge for Fish Migration.....	10-52
10.4.3	Fish Passage through Highway Structures	10-54
10.4.3.1	Fish Migrations.....	10-55
10.4.3.2	Swimming Capability of Fish.....	10-56
10.4.3.3	Types of Stream Fisheries	10-58
10.4.3.3.1	Tributary Streams to Large Lakes and Rivers.....	10-58
10.4.3.3.2	Steep Mountain Streams.....	10-58
10.4.3.3.3	Intermittent Streams	10-58
10.4.3.3.4	Groundwater Streams.....	10-58
10.4.3.3.5	Estuarine Streams.....	10-59
10.4.3.4	Data Collection for Stream Modifications.....	10-59
10.4.3.5	Fish Passage Design	10-60
10.4.3.5.1	Flow Depths	10-61
10.4.3.5.2	Structures with Natural Substrate Bottoms	10-63
10.4.3.5.3	Baffled and Sill Structures	10-65
10.4.3.5.4	Slot Orifice Structures.....	10-67
10.4.4	Mitigating Channel Modification Effects.....	10-68
10.4.4.1	Amount of Habitat.....	10-69
10.4.4.2	Quality of Habitat.....	10-69
10.4.4.2.1	Geomorphology.....	10-70
10.4.4.2.2	Pool and Riffle Sequence	10-72
10.4.4.2.3	Substrate.....	10-74
10.4.4.2.4	Stream and Bank Cover.....	10-75
10.4.4.2.5	Minimum Flow Requirements	10-78
10.4.4.2.6	Riparian Vegetation.....	10-78
10.4.4.2.7	Water Quality	10-79
10.4.4.2.8	Construction Coordination	10-80
10.5	LAKE AND POND MODIFICATIONS AND MITIGATING PRACTICES ...	10-80
10.5.1	Features	10-80
10.5.2	Ecosystems	10-81
10.5.3	Water Characteristics.....	10-82
10.5.4	Classifications.....	10-83
10.5.4.1	Source.....	10-84
10.5.4.2	Physical	10-84
10.5.4.3	Size	10-85
10.5.4.4	Productivity	10-85
10.5.5	Reservoir-Related Problems	10-86

10.5.6	Sedimentation	10-87
10.5.7	Nutrient Enrichment.....	10-88
10.5.8	Other Pollutants	10-89
10.5.9	Circulation.....	10-90
10.5.10	Sensitivity	10-90
10.5.11	Evaluating Effects.....	10-91
10.5.12	Data Collection for Lakes and Ponds.....	10-93
10.5.13	Mitigating Measures	10-94
10.5.13.1	Migration Routes	10-94
10.5.13.2	Lake Size.....	10-95
10.5.13.3	Littoral Zone Substrate	10-95
10.5.13.4	Diversion.....	10-96
10.5.14	Ponds.....	10-96
10.6	WETLANDS MODIFICATIONS AND MITIGATING PRACTICES.....	10-96
10.6.1	Introduction.....	10-96
10.6.1.1	Function of Wetlands	10-98
10.6.1.2	Regulatory Requirements for Wetlands Considerations	10-98
10.6.2	Classification of Wetlands	10-100
10.6.3	Wetlands Hydrology	10-103
10.6.4	Potential Highway Effects to Wetlands	10-103
10.6.4.1	Water Depth	10-103
10.6.4.2	Seasonal Patterns	10-104
10.6.4.3	Erosion and Sedimentation	10-105
10.6.4.4	Suspended Solid Concentration	10-105
10.6.4.5	Chemical Regime.....	10-106
10.6.4.6	Dissolved Oxygen (DO) Regime	10-107
10.6.4.7	Nutrient Loading.....	10-107
10.6.4.8	Pollutants	10-108
10.6.5	Estimating Highway Effects on Wetlands	10-109
10.6.5.1	Baseline Data	10-109
10.6.5.2	Highway Location.....	10-110
10.6.5.3	Water Quality.....	10-110
10.6.5.4	Wetlands Hydrology	10-111
10.6.5.5	Evaluation of Mitigation Alternatives.....	10-111
10.6.6	Mitigation Measures	10-112
10.6.6.1	Location	10-112
10.6.6.2	Tidal Wetlands Crossings	10-113
10.6.6.3	Inland Wetlands Crossing Hydraulics.....	10-115
10.6.6.4	Erosion and Sedimentation	10-117
10.6.6.5	Migration of Aquatic Biota.....	10-117
10.6.6.6	Constructing New Habitat.....	10-117
10.6.6.7	Compensation	10-119
10.6.7	Wetlands Banking.....	10-119
10.7	SURVEYS AND DATA COLLECTION.....	10-120

10.7.1	Determining the Need.....	10-121
10.7.1.1	Project Nature.....	10-121
10.7.1.2	Public Input	10-121
10.7.1.3	Development by Others.....	10-122
10.7.2	Level of Effort.....	10-122
10.7.3	Office Survey and Data Collection.....	10-122
10.7.3.1	Data Availability	10-122
10.7.3.2	Preliminary Environmental Estimates	10-124
10.7.4	Limited Field Studies	10-124
10.7.5	Complete Field Studies.....	10-125
10.7.5.1	Determining General Objectives	10-125
10.7.5.2	Selecting Study Parameters	10-126
10.7.5.3	Selecting Sampling Sites	10-126
10.7.5.4	Temporal Sample Distribution	10-127
10.7.5.5	Sampling Frequency.....	10-127
10.7.6	Study Level.....	10-127
10.7.6.1	Planning Level.....	10-127
10.7.6.2	Project Level.....	10-128
10.7.6.3	Construction Level	10-129
10.8	REFERENCES.....	10-129

CHAPTER 11

TABLE OF CONTENTS

11.1 INTRODUCTION.....	11-1
11.1.1 Purpose of this Chapter	11-1
11.1.2 Areas Covered by this Chapter	11-1
11.1.2.1 Coastal Zone	11-1
11.1.2.2 Lakeshore.....	11-1
11.1.3 Role of the Hydraulics Engineer	11-1
11.1.3.1 Highway Planning Considerations.....	11-2
11.1.3.2 Highway Location Considerations.....	11-2
11.1.3.3 Legal Considerations	11-2
11.1.3.4 Construction Considerations.....	11-2
11.1.4 References.....	11-2
11.2 DATA COLLECTION	11-3
11.2.1 Hydrologic and Hydraulic Data	11-3
11.2.1.1 Meteorological Data.....	11-3
11.2.1.2 Hydraulic Data	11-3
11.2.2 Engineering Data	11-4
11.2.3 Environmental Data	11-4
11.2.4 Regulatory Data	11-4
11.3 SHORELINE TOPOGRAPHY	11-4
11.3.1 Beaches	11-5
11.3.1.1 Sand Beaches	11-6
11.3.1.2 Sand Dunes	11-6
11.3.1.3 Non-Sand Beaches	11-7
11.3.1.4 Beach Sediment Variability	11-7
11.3.2 Bluffs and Headlands.....	11-7
11.3.3 Mud Flats	11-8
11.3.4 Wetlands	11-8
11.3.5 Estuaries.....	11-9
11.3.6 Inlets.....	11-9
11.3.7 Lake Shoreline	11-10
11.4 CHARACTERISTICS OF WAVES AND CURRENTS	11-11
11.4.1 Overview.....	11-11
11.4.2 Gravity Waves	11-11
11.4.2.1 Wave Characteristics	11-11
11.4.2.2 Relative Depth	11-12
11.4.2.3 Wave Generation	11-12
11.4.3 Wave Transformations.....	11-13
11.4.3.1 Shoaling	11-13

11.4.3.2	Breaking	11-13
11.4.3.3	Refraction	11-13
11.4.3.4	Diffraction	11-14
11.4.3.5	Decay	11-14
11.4.4	Tsunamis.....	11-14
11.4.5	Tides	11-14
11.4.6	Currents	11-15
11.4.7	Storm Surges	11-15
11.4.8	Longshore Current.....	11-16
11.4.9	Longshore Transport	11-16
11.5	DESIGN CONSIDERATIONS	11-16
11.5.1	Introduction	11-16
11.5.2	Design Waves.....	11-17
11.5.2.1	Wave Distribution	11-17
11.5.2.2	Source of Wave Observation Data	11-17
11.5.2.3	Wind and Wave Setup	11-17
11.5.2.4	Waves over Flooded Areas.....	11-18
11.5.3	Wave Action on Lakes and Tidal Basins.....	11-18
11.5.4	Tidal Flow through Structures.....	11-18
11.5.5	Scour.....	11-19
11.5.6	Environmental Concerns	11-20
11.6	SHORE PROTECTION DEVICES.....	11-20
11.6.1	Seawalls.....	11-21
11.6.2	Revetments	11-22
11.6.2.1	Rigid Revetment.....	11-22
11.6.2.2	Flexible Revetment.....	11-23
11.6.3	Retards.....	11-24
11.6.4	Jetties.....	11-24
11.6.4.1	Stone.....	11-25
11.6.4.2	Precast Concrete Blocks	11-25
11.6.5	Groins	11-26
11.6.5.1	Materials.....	11-26
11.6.5.1.1	Stone.....	11-27
11.6.5.1.2	Concrete	11-27
11.6.5.1.3	Steel.....	11-27
11.6.5.1.4	Timber	11-27
11.6.5.2	Alignment.....	11-28
11.6.5.3	Permeability.....	11-28
11.6.6	Breakwater Systems	11-28
11.6.7	Bulkheads	11-30
11.6.8	Beach Nourishment	11-31
11.7	PLANNING FOR SHORELINE CHANGES.....	11-31
11.7.1	Shoreline Changes	11-31

11.7.2	Rate of Shoreline Change	11-32
11.7.3	Sea Level Rise.....	11-32
11.7.4	Considerations in Planning for the Future	11-33
11.7.4.1	Condition Assessment.....	11-33
11.7.4.2	Objectives of a Vulnerability Study.....	11-33
11.7.4.3	Coastal Highway Vulnerability Model	11-34
11.7.4.4	Emergency Evacuation Plan	11-35
11.8	CONSTRUCTION AND MAINTENANCE CONSIDERATIONS	11-35
11.8.1	Construction-Related Considerations	11-35
11.8.2	Maintenance-Related Considerations	11-35
11.8.2.1	Maintenance during Construction.....	11-36
11.8.2.2	Perpetual Maintenance.....	11-36
11.9	REFERENCES.....	11-36
11.9.1	Cited References	11-36
11.9.2	Additional Publications.....	11-37
11.9.3	Web-Related References.....	11-39

CHAPTER 12

TABLE OF CONTENTS

12.1 INTRODUCTION.....	12-1
12.1.1 History	12-1
12.1.2 Potential Impacts.....	12-2
12.2 REGULATIONS.....	12-4
12.2.1 Federal Regulations	12-4
12.2.2 State and Local Regulations.....	12-6
12.3 IMPLEMENTATION OF STORMWATER MANAGEMENT DESIGN.....	12-7
12.3.1 Best Management Practices	12-9
12.3.2 Facility Types.....	12-10
12.3.2.1 Enhanced Ponds: Wet Detention/Extended Detention	12-10
12.3.2.1.1 Wet Detention Ponds	12-10
12.3.2.1.2 Extended Detention Ponds.....	12-11
12.3.2.2 Stormwater Wetland Basins	12-11
12.3.2.3 Infiltration Facilities	12-12
12.3.2.4 Filtering Devices	12-13
12.3.2.5 Water Quality Inlets	12-13
12.3.2.5.1 Vegetative Systems.....	12-14
12.3.3 Design Aspects.....	12-15
12.3.3.1 Ponds	12-15
12.3.3.2 Infiltration Facilities	12-17
12.3.3.3 Filtering Devices	12-18
12.3.4 Documentation	12-19
12.4 CONSTRUCTION.....	12-20
12.4.1 Pre-Bid/Preconstruction Conference.....	12-21
12.4.2 Construction of Best Management Practices	12-21
12.4.2.1 Ponds/Basins	12-22
12.4.2.2 Infiltration Facilities/Filtering Devices	12-23
12.4.2.3 Vegetative Systems	12-23
12.4.3 Grading	12-24
12.4.4 Inspection/Quality Control.....	12-25
12.4.5 Certification and Documentation	12-25
12.4.6 Training and Communication	12-26
12.5 MAINTENANCE.....	12-26
12.5.1 Maintenance/Inspection Programs	12-27
12.5.2 Documentation	12-28
12.5.3 Maintainability	12-29
12.5.4 Budgetary Requirements.....	12-30

12.5.5 Training	12-30
12.6 FUTURE ISSUES.....	12-31
12.7 CITED REFERENCES.....	12-32
12.8 BIBLIOGRAPHY.....	12-32
APPENDIX 12A COMMON HIGHWAY RUNOFF CONSTITUENTS AND THEIR PRIMARY SOURCES	12-35
APPENDIX 12B DAM INSPECTION CHECKLIST	12-36
APPENDIX 12C A COMPARATIVE ASSESSMENT OF THE EFFECTIVENESS OF CURRENT URBAN BEST MANAGEMENT PRACTICES	12-41

CHAPTER 13

TABLE OF CONTENTS

13.1 INTRODUCTION.....	13-1
13.2 RECOMMENDED KNOWLEDGE OF RELATED DISCIPLINES	13-1
13.2.1 Planning and Environmental Assessment	13-2
13.2.2 Right-of-Way	13-2
13.2.3 Surveying	13-2
13.2.4 Agency Policy and Procedures	13-3
13.2.5 Roadway Design	13-3
13.2.6 Pavement Design	13-3
13.2.7 Structural Design	13-4
13.2.8 Environmental Design	13-4
13.2.9 Geotechnical Design	13-4
13.2.10 Material Properties	13-5
13.2.11 Quantity and Cost Estimation	13-5
13.2.12 Construction	13-5
13.2.13 Maintenance	13-5
13.2.14 Legal Issues	13-6
13.3 CAREER DEVELOPMENT	13-6
13.3.1 Mastery of Basic Drainage Design Technology	13-6
13.3.2 Experience in Basic Drainage Design	13-7
13.3.3 Professional Engineer Status	13-7
13.3.4 Training and Education in Advanced Hydraulics Engineering	13-7
13.3.5 Instructing and Public Speaking	13-8
13.3.6 Experience in Complex Hydraulic Design	13-9
13.3.7 Management Training and Experience	13-9
13.4 OTHER ISSUES	13-10
13.4.1 Research and Development	13-10
13.4.2 Continuing Education Credit	13-10
13.4.3 Record Keeping	13-11
13.4.4 Engineer Versus Technician	13-12
13.5 CONCLUSION	13-12
APPENDIX 13A BASIC HIGHWAY DRAINAGE DESIGN INTRODUCTION ..	13-14
APPENDIX 13B GENERAL HIGHWAY DRAINAGE DESIGN	13-17
APPENDIX 13C URBAN STORM DRAIN DESIGN	13-31
APPENDIX 13D BRIDGE WATERWAYS ANALYSIS	13-36

APPENDIX 13E RIVER MECHANICS13-39

CHAPTER 14

TABLE OF CONTENTS

14.1	INTRODUCTION.....	14-1
14.2	INSPECTION.....	14-2
14.2.1	Safety	14-2
14.2.1.1	OSHA Regulations	14-2
14.2.1.2	Special Considerations	14-2
14.2.2	Frequency of Inspection.....	14-3
14.2.3	Inspection Protocol	14-4
14.2.3.1	Preliminary Information	14-4
14.2.3.2	Equipment Needed	14-5
14.2.3.3	Inspector Qualifications	14-5
14.2.4	Site Visit	14-6
14.2.4.1	Roadway Surface and Side Slopes	14-6
14.2.4.2	Waterway	14-7
14.2.4.2.1	Culvert Inlet.....	14-7
14.2.4.2.2	Culvert Outlet	14-7
14.2.4.2.3	Inside of Culvert	14-8
14.2.5	Special Investigation Procedures	14-10
14.2.5.1	Failure of a Culvert during Construction.....	14-10
14.2.5.2	Failure of an Existing Culvert	14-12
14.2.5.3	Special Techniques.....	14-13
14.2.6	Inspection Report Form and Documentation	14-13
14.2.7	Distribution of Information.....	14-13
14.3	FACTORS INFLUENCING SERVICE LIFE	14-14
14.3.1	Corrosion	14-15
14.3.1.1	Hydrogen Ion Concentration (pH).....	14-16
14.3.1.2	Soil Resistivity	14-16
14.3.1.3	Chlorides	14-17
14.3.1.4	Sulfates	14-17
14.3.1.5	Industrial Effluents	14-17
14.3.1.6	Stray Electrical Current	14-17
14.3.2	Abrasion.....	14-18
14.3.2.1	Debris	14-18
14.3.2.2	Bedload.....	14-19
14.3.3	Loss of Structural Integrity	14-20
14.3.3.1	Joint Separation	14-20
14.3.3.2	Misalignment.....	14-21
14.3.3.3	Deflection	14-21
14.3.3.4	Seam Defects.....	14-22
14.3.3.5	Stream/Roadway Embankment Erosion.....	14-22

14.4 MATERIAL SELECTION AND ESTIMATING SERVICE LIFE	14-22
14.4.1 Culvert Materials	14-23
14.4.1.1 Concrete Culverts	14-23
14.4.1.2 Corrugated Metal Pipe	14-24
14.4.1.2.1 Corrugated Steel Pipe	14-24
14.4.1.2.2 Corrugated Aluminum Pipe	14-25
14.4.1.3 Plastic Pipe	14-25
14.4.1.3.1 High-Density Polyethylene	14-26
14.4.1.3.2 Polyvinyl Chloride	14-26
14.4.1.4 Other	14-27
14.4.2 Protective Coatings	14-27
14.4.2.1 Zinc Galvanizing	14-27
14.4.2.2 Aluminizing	14-27
14.4.2.3 Asphaltic Coatings	14-28
14.4.2.3.1 Bituminous	14-28
14.4.2.3.2 Fiber-Bonded Bituminous	14-29
14.4.2.3.3 Asphalt Mastic	14-29
14.4.2.3.4 Polymerized Asphalt	14-29
14.4.2.4 Polymeric Sheet Coating	14-29
14.4.2.5 Concrete Coatings	14-29
14.4.3 Alternative Materials	14-30
14.5 CULVERT REPAIR	14-30
14.5.1 Rehabilitation Methods	14-31
14.5.1.1 Grouting	14-31
14.5.1.2 Invert Paving and Plating	14-31
14.5.1.3 Sliplining	14-32
14.5.1.4 Trenchless Relining	14-34
14.5.1.4.1 Cured-in-Place Pipe Lining	14-35
14.5.1.4.2 Fold and Form Lining	14-36
14.5.1.4.3 Polyvinyl Chloride (PVC) Pipe Lining System	14-37
14.5.1.4.4 Pipe Bursting	14-37
14.5.1.4.5 Joint Sealing	14-38
14.5.1.5 Cement Mortar Lining	14-38
14.5.1.6 Epoxy Lining	14-38
14.5.2 Replacement Methods	14-38
14.5.2.1 Open Cut (Trench) Method	14-39
14.5.2.2 Trenchless Excavation Construction (TEC) Methods	14-39
14.5.2.2.1 Pipe Jacking	14-39
14.5.2.2.2 Horizontal Earth Boring (HEB)	14-41
14.5.2.2.3 Utility Tunnels (UT)	14-42
14.6 REFERENCES	14-43
APPENDIX 14A	14-45
14A.1 Culvert Inspection Rating Form (Adapted from Reference (12))	14-45

14A.2	CalTrans Guide for the Protection of Reinforced and Unreinforced Concrete against Acid and Sulfate Exposure Conditions	14-46
14A.3	U.S. Bureau of Reclamation Criteria for Sulfate-Resisting Concrete Pipe.....	14-46
14A.4	CalTrans Service Life Chart.....	14-47
14A.5	AISI Service Life Chart (22).....	14-48

CHAPTER 15

TABLE OF CONTENTS

15.1	INTRODUCTION.....	15-1
15.1.1	In-house vs. Consultant	15-2
15.2	TYPES OF CONSULTANT CONTRACTS.....	15-2
15.2.1	Project Site-Specific Contracts	15-2
15.2.2	On-Call Contracts	15-2
15.2.3	Combination Contracts	15-3
15.2.4	Support Services	15-3
15.2.5	General Engineering Consultants	15-3
15.2.6	Design-Build Contracts	15-3
15.2.7	Inspection and Remedial Maintenance	15-4
15.3	CONSULTANT SELECTION PROCESS	15-4
15.3.1	Advertisement or Solicitation	15-4
15.3.2	Expressions of Interest.....	15-5
15.3.3	Short Listing (or Qualification Screening)	15-5
15.3.3.1	Criteria	15-5
15.3.4	Request for Proposals	15-6
15.3.5	Review and Selection	15-6
15.3.6	Debriefing.....	15-7
15.4	REQUEST FOR PROPOSALS (RFP)	15-7
15.4.1	Elements of RFP	15-7
15.4.2	Schedules	15-7
15.4.3	Other Contract Requirements	15-8
15.5	SCOPE OF SERVICES	15-8
15.5.1	Purpose	15-8
15.5.2	Duration.....	15-8
15.5.3	Elements of Work	15-8
15.5.4	Staffing Required.....	15-9
15.5.5	Labor and Cost.....	15-9
15.5.6	Support Services	15-9
15.5.7	Consultant Responsibilities	15-9
15.5.8	Certification.....	15-10
15.5.9	Items Provided by the Agency.....	15-10
15.6	QUALIFICATIONS OF CONSULTANT HYDRAULICS ENGINEERS	15-10
15.6.1	Firm qualifications.....	15-10
15.6.2	Hydraulics Engineering Group.....	15-10
15.6.3	Survey Support	15-12
15.6.4	CADD Support	15-12

15.6.5	Structural and Geotechnical Engineering Support.....	15-12
15.6.6	Highway Engineering Support	15-12
15.6.7	Regulatory Permitting.....	15-12
15.6.8	Wetlands	15-12
15.6.9	Other Support	15-13
15.6.10	Past Performance	15-13
15.7	TECHNICAL PROPOSAL REVIEW	15-13
15.7.1	Review Criteria.....	15-13
15.7.2	Review Team.....	15-13
15.7.3	Scoring Scale.....	15-14
15.7.4	Review Notes.....	15-14
15.7.5	Interviews or Oral Presentation	15-14
15.7.6	Scoring.....	15-14
15.7.7	Consultant Selection	15-14
15.8	PROJECT SPECIFIC CONTRACTS.....	15-15
15.8.1	Hydraulics Engineer in a Lead Role	15-15
15.8.2	Hydraulics Engineer in a Supporting Role	15-15
15.9	DESIGN-BUILD CONTRACTS.....	15-15
15.9.1	Performance Specification.....	15-15
15.9.2	Mile Stone Review	15-16
15.9.3	Regulatory Permits	15-16
15.10	INSPECTION AND REMEDIATION (IR) CONTRACTS.....	15-16
15.10.1	Inspection.....	15-16
15.10.2	Remediation Design.....	15-17
15.10.3	Permits	15-17
15.10.4	Implementation	15-17
15.11	ASSIGNMENTS TO ON-CALL CONSULTANTS.....	15-17
15.11.1	Task Scope.....	15-17
15.11.2	Independent Estimate.....	15-17
15.11.3	Consultant Task Proposal and Cost Estimate	15-18
15.11.4	Negotiation	15-18
15.11.5	Notice to Proceed.....	15-18
15.11.6	Clear Direction	15-18
15.11.7	Project Management	15-18
15.12	EVALUATION OF CONSULTING ENGINEERS' WORK.....	15-18
15.13	SUB-CONSULTANTS.....	15-19
15.14	DEVELOPMENT OF CONSULTANT BASE.....	15-19
15.14.1	Progressive Contracts and Assignments	15-20
15.14.2	Multiple Smaller Contracts.....	15-20

15.14.3	Training	15-20
15.15	REFERENCES	15-21
Appendix 15A	STANDARD FORM 330 FOR DOCUMENTING FIRM QUALIFICATIONS.....	15-23
Appendix 15B	SAMPLE CRITERIA FOR EVALUATING FIRM QUALIFICATIONS.....	15-37
Appendix 15C	SAMPLE EVALUATION AND RATING CRITERIA FOR CONSULTANT PROPOSALS	15-38
Appendix 15D	SAMPLE DESIGN AND REPORT STANDARDS.....	15-41
Appendix 15E	SAMPLE SCOPE OF SERVICES	15-62

GLOSSARY OF HIGHWAY-RELATED DRAINAGE TERMS

TABLE OF CONTENTS

G.1	OVERVIEW.....	G-1
G.2	GLOSSARY	G-3
G.3	REFERENCES.....	G-151
G.3.1	Cited References	G-151
G.3.2	Uncited.....	G-156