

## TABLE OF CONTENTS

---

### CHAPTER 1 – INTRODUCTION

1.1 Purpose.....	1-1
1.2 Contents.....	1-1
1.3 Limitations.....	1-1
1.4 Updating.....	1-2
1.5 Design and Construction Criteria.....	1-2
1.6 City and County Storm Water Regulations .....	1-2
1.7 Concept Definitions .....	1-3

### CHAPTER 2 – HYDROLOGY

2.1 Hydrologic Design Policies .....	2-1
2.1.1 Factors Affecting Flood Runoff .....	2-1
2.1.2 Hydrologic Method.....	2-2
2.1.3 Storm Water Conveyance Design Policy .....	2-2
2.1.4 HEC-1 Limitations.....	2-2
2.2 Hydrologic Analysis Procedure Flowchart.....	2-3
2.2.1 Purpose and Use.....	2-3
2.2.2 Design Flowchart.....	2-4
2.3 Design Frequency .....	2-5
2.3.1 Design Frequencies.....	2-5
2.3.2 Rainfall Intensity .....	2-5
2.4 Rational Method .....	2-6
2.4.1 Introduction.....	2-6
2.4.2 Runoff Equation.....	2-6
2.4.3 Time of Concentration .....	2-7
2.4.4 Rainfall Intensity .....	2-8
2.4.5 Runoff Coefficient .....	2-8
2.4.6 Composite Coefficients.....	2-9
2.5 Example Problem - Rational Method .....	2-9
2.6 NRCS Unit Hydrograph .....	2-10
2.6.1 Introduction.....	2-10

2.6.2 Equations and Concepts.....	2-11
2.6.3 Runoff Factor.....	2-16
2.6.4 Modifications for Developed Conditions .....	2-17
2.6.5 Travel Time Estimation .....	2-19
2.6.5.1 Travel Time.....	2-19
2.6.5.2 Time of Concentration.....	2-19
2.6.5.3 Sheet Flow.....	2-19
2.6.5.4 Shallow Concentrated Flow.....	2-21
2.6.5.5 Channelized Flow .....	2-22
2.6.5.6 Reservoirs and Lakes .....	2-22
2.6.5.7 Limitations.....	2-22
Appendix 2A Impervious Area Calculations.....	2-23
Appendix 2B Accumulated Precipitation Data.....	2-26

**CHAPTER 3 – OPEN CHANNEL HYDRAULICS**

3.1 Overview .....	3-1
3.1.1 Introduction.....	3-1
3.1.2 Channel Linings.....	3-1
3.1.2.1 Vegetative.....	3-1
3.1.2.2 Flexible .....	3-1
3.1.2.3 Rigid .....	3-1
3.2 Design Criteria .....	3-2
3.2.1 General Criteria .....	3-2
3.2.2 Return Period .....	3-2
3.2.3 100+1 Flood Analysis .....	3-2
3.2.4 Velocity Limitations.....	3-3
3.3 Manning’s n Values .....	3-3
3.3.1 General Considerations.....	3-3
3.3.2 Selection.....	3-3
3.3.3 Manning’s n Values .....	3-5
3.4 Open Channel Design .....	3-6
3.4.1 Overview .....	3-6
3.4.2 Design of Stable Channels .....	3-6
3.4.3 Permissible Velocity.....	3-7

3.4.4 Selecting Permanent Channel Lining.....	3-7
3.4.5 Tractive Force.....	3-8
3.4.6 Design Procedure Using Permissible Velocity and Tractive Force Procedures .....	3-9
3.4.7 Example Problem .....	3-13
3.5 Riprap Design .....	3-16
3.5.1 Assumptions .....	3-16
3.5.2 Procedure for Riprap Channel Design .....	3-17
3.6 Approximate Flood Limits .....	3-25
3.6.1 Introduction.....	3-25
3.6.2 Floodline Restrictions .....	3-25
Appendix 3A Hydraulic Terms .....	3-26
3A.1 Energy of Flow .....	3-26
3A.2 Steady and Unsteady .....	3-27
3A.3 Uniform and Non-Uniform Flow .....	3-27
3A.4 Froude Number .....	3-27
3A.5 Critical Flow .....	3-27
3A.6 Subcritical Flow .....	3-28
3A.7 Supercritical Flow.....	3-28
Appendix 3B Best Hydraulic Section .....	3-29
3B.1 Introduction .....	3-29
3B.2 Equations .....	3-29
Appendix 3C Open Channel Flow Calculations .....	3-31
3C.1 Design Charts .....	3-31
3C.2 Manning's Evaluation .....	3-31
3C.3 Geometric Relationships .....	3-31
3C.4 Normal Depth Solutions .....	3-32
Appendix 3D Critical Flow Calculations .....	3-34
3D.1 Background.....	3-34
3D.2 Semi-Empirical Equations .....	3-34
3D.3 Froude Number .....	3-35

**CHAPTER 4 – STORM DRAINAGE SYSTEMS**

4.1 Overview .....4-1

    4.1.1 Introduction.....4-1

    4.1.2 Inlet Definition.....4-1

    4.1.3 Criteria.....4-1

4.2 Pavement Drainage.....4-2

    4.2.1 Introduction.....4-2

    4.2.2 Storm Drain Location .....4-2

    4.2.3 Inlet Types and Spacing .....4-2

    4.2.4 Longitudinal Slope .....4-3

    4.2.5 Cross Slope.....4-3

    4.2.6 Curb and Gutter.....4-3

    4.2.7 Median Ditches.....4-3

    4.2.8 Roadside Ditches .....4-3

    4.2.9 Bridge Decks .....4-3

    4.2.10 Median Barriers .....4-4

4.3 Gutter Flow Calculations .....4-4

    4.3.1 Formula .....4-4

    4.3.2 Procedure.....4-4

4.4 Grate Inlet Design .....4-7

    4.4.1 Grate Inlets on Grade .....4-7

        4.4.1.1 Design Steps .....4-7

        4.4.1.2 Example 1 .....4-9

    4.4.2 Grate Inlets in Sag.....4-10

        4.4.2.1 Type 'E' Grate.....4-10

        4.4.2.2 Grated Drop Inlet.....4-12

            4.4.2.2.1 Example 2.....4-12

        4.4.2.3 Open Throat Catch Basin .....4-13

            4.4.2.3.1 Example .....4-13

4.5 Combination Inlets.....4-14

    4.5.1 Combination Inlets on Grade .....4-14

4.6 Hydraulic Gradient.....4-14

    4.6.1 Friction Losses .....4-14

    4.6.2 Velocity Head Losses .....4-14

4.6.3 Entrance Losses.....4-14

4.6.4 Junction Losses.....4-15

4.6.5 Summary .....4-17

4.7 Storm Drain .....4-20

    4.7.1 Introduction.....4-20

    4.7.2 Design Criteria.....4-20

    4.7.3 Capacity .....4-20

    4.7.4 Hydraulic Grade Lines .....4-22

        4.7.4.1 Design Procedure.....4-22

    4.7.5 Minimum Grade .....4-24

    4.7.6 Design Procedures .....4-24

    4.7.7 Rational Method Examples.....4-27

**CHAPTER 5 – DESIGN OF CULVERTS**

5.1 Overview .....5-1

    5.1.1 Definitions.....5-1

    5.1.2 Performance Curves.....5-1

5.2 Culvert Design Procedure Flowchart .....5-2

    5.2.1 Purpose and Use.....5-2

    5.2.2 Design Flowchart.....5-2

5.3 Engineering Design Criteria.....5-3

    5.3.1 Introduction.....5-3

    5.3.2 Criteria.....5-3

    5.3.3 Flood Frequency.....5-4

    5.3.4 Velocity Limitations.....5-4

    5.3.5 Debris Control.....5-4

    5.3.6 Headwater Limitations .....5-4

    5.3.7 Tailwater Considerations .....5-5

    5.3.8 Culvert Inlets.....5-5

    5.3.9 Inlets With Headwalls .....5-6

    5.3.10 Wingwalls and Aprons .....5-7

    5.3.11 Improved Inlets .....5-8

    5.3.12 Material Selection .....5-8

    5.3.13 Outlet Protection.....5-8

5.3.14 Environmental Considerations .....	5-8
5.4 Culvert Flow and Controls and Equations.....	5-8
5.4.1 Introduction.....	5-8
5.4.2 Inlet and Outlet Control.....	5-8
5.4.3 Equations .....	5-9
5.4.3.1 Mild Slope .....	5-9
5.4.3.2 Steep Slope .....	5-11
5.4.3.3 "Slug" Flow.....	5-11
5.5 Design Procedures.....	5-11
5.5.1 Procedures .....	5-11
5.5.2 Tailwater Elevations.....	5-12
5.5.3 Nomographs .....	5-12
5.5.4 Steps in Design Procedure .....	5-14
5.5.5 Performance Curves.....	5-15
5.5.6 Roadway Overtopping .....	5-15
5.6 Culvert Design Example .....	5-16
5.6.1 Introduction.....	5-16
5.6.2 Problem .....	5-16
5.6.3 Input Data.....	5-16
5.6.4 Computations .....	5-17
5.7 Long Span Culverts.....	5-20
5.7.1 Introduction.....	5-20
5.7.2 Structural Aspects .....	5-20
5.7.3 Hydraulic Considerations.....	5-20
5.8 Construction and Maintenance Considerations .....	5-20
Appendix 5A Critical Depth Charts .....	5-21
Appendix 5B Design of Improved Inlets.....	5-23
5B.1 Introduction .....	5-23
5B.2 Outlet Control.....	5-23
5B.3 Inlet Control.....	5-23
5B.4 Common Entrances.....	5-23
5B.5 Capacity Determinations .....	5-24
5B.6 Improved Inlets.....	5-24
5B.7 Beveled-edged Inlets.....	5-25

5B.8 Side-tapered Inlets .....5-25  
 5B.9 Slope-tapered Inlets .....5-26  
 5B.10 Improved Inlet Performance .....5-26  
 Appendix 5C Conventional Nomographs .....5-28

**CHAPTER 6 – STORAGE AND DETENTION**

6.1 Overview .....6-1  
 6.1.1 Introduction.....6-1  
 6.1.2 Detention Facilities Used for Credits.....6-1  
 6.1.3 Location Considerations .....6-1  
 6.1.4 Detention and Retention .....6-1  
 6.1.5 Computer Programs .....6-1  
 6.2 Design Criteria .....6-2  
 6.2.1 Introduction.....6-2  
 6.2.2 General Criteria .....6-2  
 6.2.3 Release Rate.....6-2  
 6.2.4 Storage.....6-2  
 6.2.5 Storage within Parking Areas.....6-2  
 6.2.6 Grading and Depth of Earthen Storage Facility.....6-3  
 6.2.7 Outlet Works.....6-3  
 6.2.8 Off-site Storm Water Detention Facilities .....6-3  
 6.2.9 Dam Safety Law .....6-4  
 6.3 General Procedure .....6-4  
 6.3.1 Data Needs .....6-4  
 6.3.2 Procedure.....6-5  
 6.4 Outlet Hydraulics .....6-6  
 6.4.1 Outlets .....6-6  
 6.4.2 Sharp-Crested Weirs .....6-6  
 6.4.3 Broad-Crested Weirs .....6-6  
 6.4.4 V-Notch Weirs .....6-7  
 6.4.5 Orifices .....6-8  
 6.5 Construction and Maintenance Considerations .....6-8  
 6.6 Underground Storage.....6-9  
 Appendix 6A Calculations .....6-10

6A.1 Routing Calculations .....	6-10
Appendix 6B Example Problem .....	6-3
6B.1 Example .....	6-13
6B.2 Inflow Hydrograph .....	6-13
6B.3 Stage-Storage Curve.....	6-13
6B.4 Stage-Discharge Curve .....	6-13
6B.5 Storage Characteristics Curve.....	6-13
6B.6 Routing Calculations .....	6-13

## **CHAPTER 7 – ENERGY DISSIPATION**

7.1 Overview .....	7-1
7.2 Design Criteria .....	7-1
7.2.1 General Criteria .....	7-1
7.2.2 Erosion Hazards .....	7-1
7.2.3 Recommended Dissipators.....	7-1
7.3 Riprap Aprons .....	7-2
7.3.1 Uses .....	7-2
7.3.2 Procedure.....	7-2
7.3.3 Design Considerations.....	7-5
7.4 Example Problems .....	7-6
7.4.1 Example 1 .....	7-6
7.4.2 Example 2 .....	7-6



## LIST OF FIGURES

---

### CHAPTER 2

2-1	NRCS (SCS) Type II Rainfall Distribution.....	2-12
2-2	Solution of Runoff Equation.....	2-12
2A-1	Composite CN with Connected Impervious Area.....	2-24
2A-2	Composite CN with Unconnected Impervious Area.....	2-24

### CHAPTER 3

3-1	Manning's $n$ Related to Velocity, Hydraulic Radius and Vegetal Retardance.....	3-10
3-2	$K_b$ Factor for Maximum Shear Stress on Channel Bends.....	3-19
3-3	Protection Length, $L_p$ , Downstream from Channel Bend.....	3-20
3-4	Riprap Lining Bend Correction Coefficient.....	3-21
3-5	Riprap Lining Specific Weight Correction Coefficient.....	3-22
3-6	Riprap Lining $d_{30}$ Stone Size—Function of Mean Velocity and Depth.....	3-23
3-7	Riprap Lining Thickness Adjustment for $d_{85}/d_{15} = 1.0$ to $2.3$ .....	3-24
3A-1	Energy in Open Channel Flow.....	3-26
3A-2	Definition Sketch of Specific Energy.....	3-27
3C-1	Trapezoidal Channel Capacity Chart.....	3-33
3D-1	Open Channel Geometric Relationships for Various Cross Sections.....	3-36

### CHAPTER 4

4-1	Grate Inlet Coefficient - On Grade.....	4-8
4-2	Standard Drop Inlet Grate NCDOT Std. 840.16 (2012).....	4-11
4-3	Type 'E' Grate NCDOT Std. 840.03 (2012).....	4-11
4-4	Summary of Energy Losses.....	4-18
4-5	Energy and Hydraulic Grade Lines for Storm Drainage Under Constant Discharge.....	4-19
4-6	Storm Drainage Computation Form.....	4-25
4-7	Hydraulic Grade Line Computation Form.....	4-26
4-8	Hypothetical Storm Drain System Layout.....	4-28

**CHAPTER 5**

5-1 Headwater Water Depth for Concrete Pipe Culverts With Inlet Control - English Units... 5-13

5-2 Head for Concrete Pipe Culverts Flowing Full;  $n=0.012$  ..... 5-14

5-3 Culvert Design Form - Metric Version..... 5-19

5A-1 Critical Depth for Circular Pipe ..... 5-21

5A-2 Critical Depth for Rectangular Section..... 5-22

5C-1 Head for Concrete Box Culverts Flowing Full..... 5-28

5C-2 Head for Structural Plate Corr. Metal Pipe Culverts Flowing Full..... 5-29

5C-3 Headwater Depth for Box Culverts with Inlet Control ..... 5-30

5C-4 Headwater Depth for CM Pipe Culverts with Inlet Control..... 5-31

5C-5 Headwater Depth for Concrete Pipe Culverts with Inlet Control ..... 5-32

**CHAPTER 6**

6-1 Example Stage-Storage Curve ..... 6-4

6-2 Example Stage-Discharge Curve ..... 6-5

6-3 Sharp-Crested Weir ..... 6-6

6-4 Broad-Crested Weir ..... 6-7

6-5 V-Notch Weir..... 6-7

6A-1 Storage Characteristics Curve ..... 6-11

**CHAPTER 7**

7-1 Design of Riprap Apron Under Minimum Tailwater Conditions ..... 7-3

7-2 Design of Riprap Apron Under Maximum Tailwater Conditions ..... 7-4

7-3 Riprap Apron Schematic for Uncertain Tailwater Conditions ..... 7-4

## LIST OF TABLES

---

### CHAPTER 2

2-1	Recommended Hydrologic Methods.....	2-2
2-2	Rainfall Intensities - Charlotte, North Carolina .....	2-5
2-3	Frequency Factors for Rational Formula .....	2-7
2-4	Recommended Runoff Coefficient Values.....	2-8
2-5	1-Year, 24-hour Precipitation Data .....	2-13
2-6	2-Year Precipitation Data: 2-Year, 6-Hour Balanced Storm Rainfall Distribution.....	2-13
2-7	10-Year Precipitation Data: 10-Year, 6-Hour Balanced Storm Rainfall Distribution.....	2-14
2-8	25-Year Precipitation Data: 25-Year, 6-Hour Balanced Storm Rainfall Distribution.....	2-14
2-9	50-Year Precipitation Data: 50-Year, 6-Hour Balanced Storm Rainfall Distribution.....	2-15
2-10	100-Year Precipitation Data: 100-Year, 6-Hour Balanced Storm Rainfall Distribution.....	2-15
2-11	Hydrologic Soil Groups for Charlotte-Mecklenburg .....	2-16
2-12	Runoff Curve Numbers .....	2-18
2-13	Roughness Coefficients (Manning's $n$ ) <sup>1</sup> for Sheet Flow .....	2-21
2A-1	Composite Curve Numbers .....	2-25

### CHAPTER 3

3-1	Recommended Manning's $n$ Values for Natural Channels.....	3-5
3-2	Recommended Manning's $n$ Values for Artificial Channels.....	3-6
3-3	Maximum Allowable Design Velocities for Vegetated Channels .....	3-8
3-4	Manning's $n$ Values for Structural Channel Linings.....	3-11
3-5	Retardance Classification For Vegetal Covers.....	3-12
3-6	Maximum Velocities for Unprotected Soils In Existing Channels .....	3-13
3-7	Manning's Roughness Coefficient for Temporary Lining Materials .....	3-15
3-8	Permissible Shear Stresses for Riprap and Temporary Liners .....	3-16
3B-1	Best Hydraulic Section Coefficients.....	3-30
3D-1	Critical Depth Equations for Uniform Flow in Channel Cross Sections .....	3-35

**CHAPTER 4**

4-1 Inlet Capacity Chart ..... 4-6

4-2 Values of K for Change in Direction of Flow in Lateral ..... 4-15

4-3 Manning's *n* Values..... 4-22

4-4 Hydrologic Data ..... 4-27

4-5 Storm Drain System Calculations ..... 4-27

**CHAPTER 5**

5-1 Inlet Coefficients ..... 5-6

5B-1 Comparison of Inlet Performance for 6 ft x 6 ft Concrete Box Culvert ..... 5-27

**CHAPTER 6**

6B-1 Storage Facility Routing Calculations ..... 6-14