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*)[1] 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